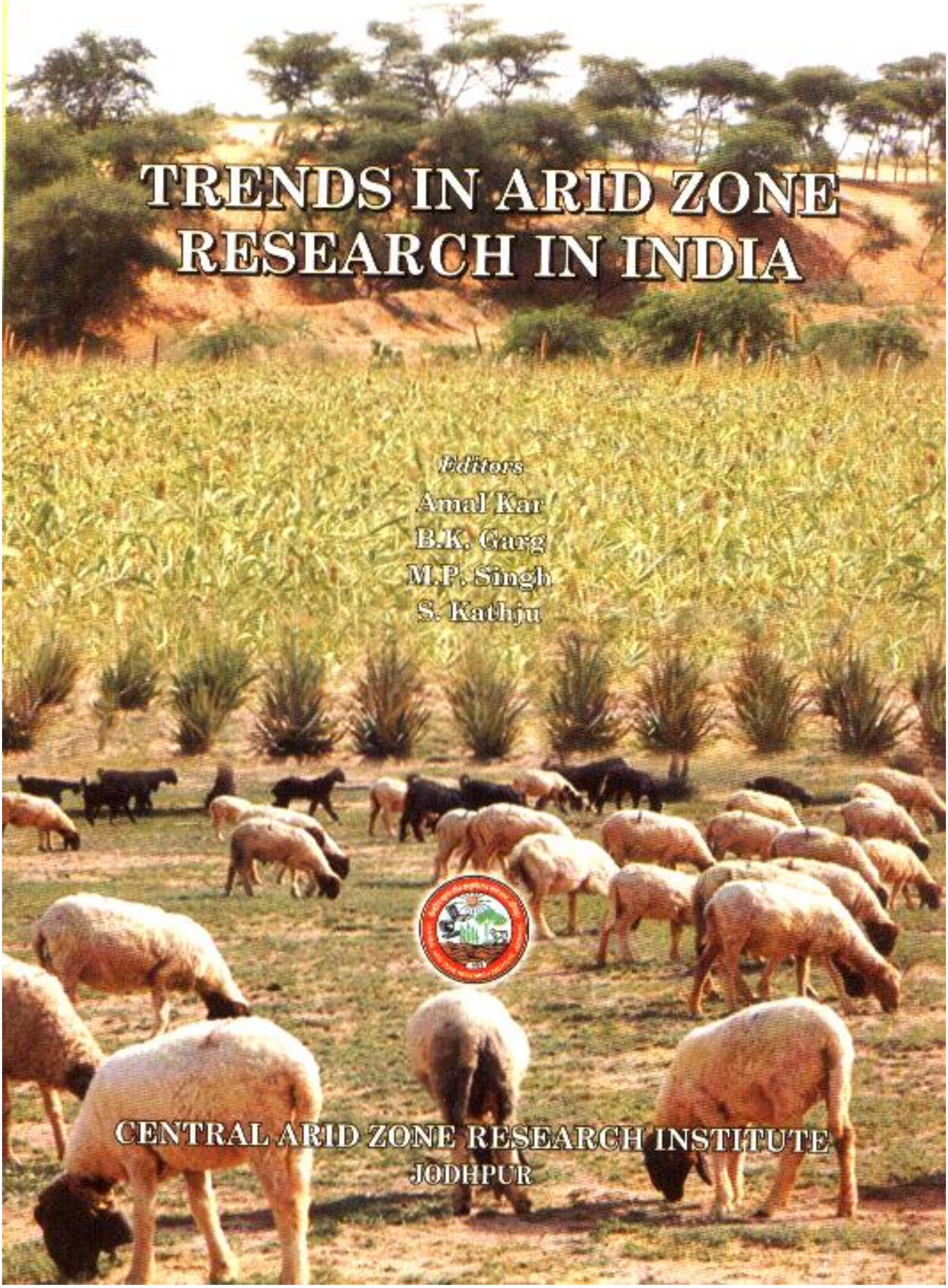
TRENDS IN ARID ZONE RESEARCH IN INDIA



Editors
Amal Kar
B.K. Garg
M.P. Singh
S. Kathju

CENTRAL ARID ZONE RESEARCH INSTITUTE
JODHPUR

TRENDS IN ARID ZONE RESEARCH IN INDIA

Editors
Amal Kar
B.K. Garg
M.P. Singh
S. Kathju

CENTRAL ARID ZONE RESEARCH INSTITUTE, JODHPUR

(Indian Council of Agricultural Research, New Delhi)

Correct Citation
Trends in Arid Zone Research in India (Eds. Amal Kar, B.K. Garg, M.P. Singh, S. Kathju. Central Arid Zone Research Institute, Jodhpur. 481 p.

Published by
Director, Central Arid Zone Research Institute, Jodhpur 342 003

DTP: S.B. Sharma

Cover photos: Vijendra Jayalwal

Printed by Evergreen Printers, Jodhpur Tel.: 0291-2747767

FOREWORD

The art-and-science of catching rainwater when it falls is an ancient wisdom. This wisdom if revised and reinforced with modern science and technological inputs can meet water needs of the arid ecosystem. In famine of 1899, Maharaja Ganga Singh seeing the suffering of his subject had felt the urgency of bringing water to Bikaner through a canal. Traditional wisdom had also realized that every last man or woman not only has water needs but can also contribute to manage this resource. No one understands the value of a single drop of water better than the desert dweller.

Droughts in Indian arid zone are because of geographic location that does not favour abundant monsoon rainfall, poor quality and excessive depth of groundwater (limiting its use for irrigation), absence of perennial rivers and forests, poor water holding capacity of soils and huge drawal of limited groundwater resources.

New and innovative ways of generating and promoting technological options that take into account social and economic conditions of the people involved, use bottom-up approaches by involving people in decision-making, apply vast indigenous knowledge and adopt integrated farming system approaches in arriving at solutions for complex problems of the arid ecosystem are the need of the hour. Growing of crops, fruit trees, grasses in various combinations will minimize risk of crop failures and also provide stability to farm-income. And various rainwater harvesting structures, traditional or modern, may prove to be a boon for giving crucial irrigations to the crop plants. Along with early, long-term forecast of monsoon with better understanding and mathematical modeling would be a great help to planners and farmers of the zone.

Experts of the various fields would help farmers in minimizing damages due to various exigencies. And then the farmers can toil to make the earth smile that will shower with bountiful crop.

A person who loves his or her work is like a plant in the right spot; There growth is maximized and the yield is greatest - Jeff Cox.

On the occasion of Golden Jubilee of the Central Arid Zone Research Institute, this book *Trends in Arid Zone Research in India* with 14 exhaustive reviews, covering many aspects of the arid system, by the learned team of scientists, is an invaluable addition.

I am sure that the publication will not only help researchers in identifying gaps and thrust areas but will also channelize properly arid-zone research. I take this opportunity to compliment all contributors and editors for completing this mammoth and challenging task on time.

November 19, 2009 **MANGALA RAI**

Secretary, Department of Agricultural Research & Education
and
Director General, Indian Council of Agricultural Research
Dr. Rajendra Prasad Road, Krishi Bhawan, New Delhi 110001, India

PREFACE

The arid regions contribute significantly to the economy of India in terms of employment, land holding, mineral assets, crop, forage and livestock production, including dairy products and industrial production. This, despite a hostile climate and limited natural resource base. Whereas the advent of Indira Gandhi Canal has made water available for irrigation and drinking purpose, improper utilization of this most scarce resource has led to severe land degradation in the command area. Likewise whereas the fixation of sand dunes has contained movement of sand dunes and made possible their utilization for cultivation or plantation, curtailing the apprehension of desert expansion, desertification is still occurring through lateral routes of degradation of pasture lands, wind erosion and deposition, water erosion, salinization of irrigated lands and ill managed mining activities. Shortage of forages for a very high population of livestock in the country is often making life miserable for the livestock husbandry practitioners, denting the traditional social fabric of the region. Loss of biodiversity is fueling the process of desertification and disturbing ecological equilibrium. There is a long list of the issues that need addressing.

All this is happening in spite of the many scientific and technological advances. The researchers have been monitoring the status of natural resources on a continuous basis and making suggestions for rehabilitation. Techniques have been developed and updated for increasing production through improved varieties, package of cultivation and plantation practices, protection measures and value addition. In fact scientists have responded to the requirements of the farmers under the changing scenarios and they have developed know-how to enable them to cope up with the situation. Techniques of water harvesting and its efficient utilization have been developed. Alternate land use system models suitable for the local conditions have been developed. These await large-scale adoption, the bottlenecks not withstanding.

As CAZRI completes 50 years of its establishment, it is apt to retrospect the work the Institute has carried out, together with that of the sister organizations pursuing similar activities, to identify the gaps still remaining and define the agenda for further research in the light of the contemporary challenges. The present compendium has been synthesized with this objective. I compliment the editors and contributing authors for their efforts and hope that this treatise will be of use to the researchers, development personnel and others claiming a stake in arid zone development.

NV Patil
Director

PROLOGUE

The hot arid zones experience an annual rainfall between 100 and 500 mm. It comes under the influence of the sub-tropical high pressure belt extending from north-west Africa to Asia. The Indian hot arid zone occupies an area of 0.32 million km^2 forming a continuous stretch in the north western states of Rajasthan, Gujarat, Punjab, Haryana and scattered landmasses in the peninsular states of Maharashtra, Karnataka and Andhra Pradesh. An area of 70,000 km^2 is the cold desert in the country in the Ladakh region of Jammu and Kashmir State. Low and erratic rainfall, extreme temperatures (-5.7 to 50.0°C), long sunshine duration (6.6-10 hours), low relative humidity (30%-80%) high wind velocity (9-13 kmph) and high evapotranspiration (1600-1800 mm) are characteristic features of the region. The soils are poor in nutrients, wind erosion occurs on a mammoth scale and paucity of water is a perennial bottleneck.

Despite these hostile conditions, the region supports a large human and livestock population and a variety of flora and fauna. However, the ever increasing human and livestock population and developmental activities exert enormous pressure on the slender natural resource base of the region. A major challenge is desertification due to wind erosion/deposition, water erosion, water logging and salinity. Degradation of permanent pastures has led to loss of fodder resources, constraining livestock husbandry, the backbone of the economy of the region all through the ages. Of late, industrial effluents and mining are also contributing to desertification.

Realizing the gravity of the problems of the arid regions, the Government of India established a Desert Afforestation Research Station at Jodhpur in the year 1952. Upon the recommendation of UNESCO Adviser C.S. Christian the Station was reorganized into a multi-disciplinary entity, the Central Arid Zone Research Institute (CAZRI) in 1959. This is one of the three desert Institutes established on the recommendation of UNESCO. In 1967, this came under the administrative control of the Indian Council of Agricultural Research. There were major changes in the arid landscape since then. The Indira Gandhi Canal was built and command area developed over a vast piece of land. There were changes in land use and cropping pattern. The Institute kept pace with the changes by incorporating the aspects of broad-spectrum interests in its research agenda. Meanwhile many other institutions came into existence in the region with expanded workforce to strengthen the research on issues pertaining to development of the arid zone. Some of these outfits were carved out of the disciplines in which CAZRI initiated and pursued work for quite some time such as forestry and arid horticulture.

Appraisal of natural resources and their judicious utilization was one of the prime concerns of CAZRI. The Institute has surveyed a larger part of the hot arid zone of India. The data on natural resources viz., landform, soil, vegetation, surface and ground water, present land use and land degradation status etc., were integrated into a conceptual framework of Major Land Resource Units (MLRUs). These may be utilized as decision support aids for formulating developmental plans. Mapping using satellite imagery has helped in precise estimation of the extent of wind erosion/deposition, water erosion, salinity/alkalinity and other desertification processes. Information was generated on now concealed courses of the Saraswati River using satellite imagery and geophysical depth soundings. The exercise has helped locate perennial sources of ground water in the desert.

Novel approaches were tried and traditional practices refined for water harvesting. Improved designs of *tanka* (cistern) for various capacities, improved *nadi* with synthetic lining, and *khadin* were standardised. Improved *tankas* with high storage capacity were constructed to meet the year long drinking and cooking water requirements of the people in water scarce areas. Watershed development work was taken up with various other departments. For rehabilitation of depleted aquifers, techniques of recharge were suggested.

One of the early works of CAZRI was on sand dune stabilization that received wide acclaim and adoption. The technique was applied by the state forest department for stabilizing sand dunes over vast desert landscape, which prevented the movement of these dunes and blockage of roads and rail tracks and has contributed in almost obliterating once frequent sand storms. The technique was also emulated outside the country to stabilize dunes in other parts of the world. Likewise, shelterbelt plantation was undertaken on large scale drawing from the research carried out at the Institute. The Institute introduced and made selection of fast growing exotic tree and shrub species from various isoclimatic regions of the world.

The soils of the region were studied in detail for all parameters. These were mapped in Entisols, Aridisols and Alfisols soil orders. The requirement of different crops and other land uses were standardized. Carbon sequestration studies were undertaken. The phosphatase producing fungi and VA-mycorrhizal fungi were isolated and work on their application is under progress. The techniques of rehabilitation of gypsum and limestone mined areas were standardised with optimum combination of water harvesting technique, soil profile modifications and plant species.

Animal husbandry is the major vocation of a large segment of arid zone population. The Institute carried out pioneering work on range management and pasture development in arid environment. The promising strains of desert grasses and forage legumes were screened and improved strains of grasses were released for mass production. Technology for bulk grass seed production was developed. Pelleting technique was developed to ensure higher germination of seeds. Carrying capacities under various systems for different animals were standardized. Trials have also been conducted for increasing forage production. The productivity and adaptability of various goat breeds were studied by the animal scientists. Supplementary feeds and mineral mixtures were developed for the animals. A number of value added products were developed and popularised.

Improved varieties of jujube developed by CAZRI were very popular and made a big impact in the arid regions. The Institute has developed early maturing fruit fly tolerant varieties. Propagation techniques were developed for the fruits suitable for arid regions. Water harvesting through microcatchments, optimum spacing, fertiliser requirement, post-harvest technology, etc. have also been standardised.

Crops improvement is an important component of CAZRI's research priorities. Through in house and externally supported and co-ordinated or network projects, improvement work was undertaken in respect of millets and arid legume crops. Many varieties were developed and released or are in the pipeline. Under genetic improvement of trees, progenies of plus trees and seed orchards were established. Protocols for micropropagation of certain fruit and forest plants were developed. Work on mushroom cultivation under arid ambience is under progress. Steps were taken to document the floral biodiversity and conserve the endangered species. Work was initiated on medicinal plants and isolation of pharmaceutical products from indigenous vegetation. Nano-technology is being improve soil phosphate availability.

Over the last five decades, the Institute devised and field tested methodologies for judicious utilisation of water. For optimal use of limited water resources techniques of drip and sprinkler systems of irrigation for different crops were standardised. Nutrient requirement and management trials were also undertaken and recommendations prepared for different crops cultivated in the region. Suitable dryland techniques for production of crops boding well with the rainfall pattern of the region were developed to efficiently utilise the precipitation and stored soil moisture. Plant protection measures were developed for management of pests, diseases and weeds in the arid production systems. The network project on rodents operates from the Institute as headquarters. Farming systems suitable for alternate land use for the arid regions were studied and the results made available for the benefit of the cultivators.

CAZRI is among one of the few institutes in the region that began early work on utilization of non-conventional energy. The solar appliances developed by the Institute include water heater, still, cooker, dryer, sprayer cum duster and candle machine etc. The scientists of the institute have also developed agricultural tools that reduce drudgery during operations, besides designing and fabricating machines and improving implements. The Institute has developed several products from plants of the region including *Aloe vera*, *Citrullus colocynthis*, *Salvadora oleoides*, *Prosopis juliflora*, etc. A few of them are being patented. The non-conventional animal products, like cheese, whey and *kulfi* from goat milk, are also the contributions of CAZRI.

A few of the recent success stories of CAZRI are ethephon based formulation for producing more gum from *Acacia senegal,* solar driers for henna and other farm produce, conservation of germplasm and land races for posterity, Maru Sena in the control of diseases, vegetables growing in Jaisamer area, popular reference maps of resources, degradation etc. Many farmers have developed commercial nurseries adopting technique developed by CAZRI. Fruit vendors sell fruit in the name of CAZRI to capitalize the reputation of the Institute in proving quality fruit varieties.

The CAZRI has linkages with other organizations working for the arid zone development. Different organizations located in the arid region *viz.*;, Arid Forestry Research Institute, Rajasthan Agricultural University, Bikaner, CCS Agricultural University, Hisar, SD Agricultural University, SK Nagar, National Research Centre on Camel, Bikaner, National Research Centre on Arid Horticulture, Bikaner, NRC on Equine, and Central Sheep and Wool Research Institute, Avikanagar, Desert Regional Station of Zoological Survey of India, Botanical Survey of India, State Forest Department and State Agriculture Department, Groundwater Department, Regional Remote Sensing Service Centre, Jodhpur, JNV University, Jodhpur; Defence Laboratory and many others including non government organizations work for the common cause of alleviating the standard of lives of the people inhabiting the arid regions. Besides, the linkages of CAZRI extend to many of the national organizations like NRAA, IMD, BIS, MoEF, and international organizations like ICRISAT, ICARDA, UNESCO, UNCCD etc for information sharing and R&D co-operation.

The Central Arid Zone Research Institute has completed 50 years of its establishment this year. On the occasion of the Golden Jubilee of CAZRI, it was decided to bring out a publication to take stock of the work carried out on various aspects of research and development in the arid regions. While CAZRI was one of the first research organizations commissioned for carrying out research on issues pertaining to arid regions of the country, and the Institute has delivered the results, it is only apt to incorporate the contribution of the other organizations working for similar cause while making the compilation to present a holistic picture of the developments. We made a call to the sister organizations to join in this venture and I am happy to state that the response was very positive despite a very short timeframe offered to them. While the compilers are short of receiving some valuable inputs from a few contributors for lack of time, they are constrained to be content with the available material in order that the publication is out before the landmark event of International Conference on Nurturing Arid Zone for People and the Environment: Issues and Agenda for the 21st Century, which is the closing event for the year long Golden Jubilee Celebrations of CAZRI. I commend the efforts of both the contributors and the editors for completing the onerous task in-time. I hope this compendium will benefit all those personnel and organizations sharing a stake in arid zone research and development.

KPR Vittal

Director, National Institute of Abiotic Stress Management

And Formerly Director, CAZRI

Contents

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 1-47 pp.

Desertification and its Control Measures

Amal Kar[1], P.C. Moharana[1], P. Raina[1], Mahesh Kumar[1],
M.L. Soni[1], P. Santra[1], Ajai[2], A.S. Arya[2] and P.S. Dhinwa[2]

[1]*Central Arid Zone Research Institute, Jodhpur*
[2]*Space Applications Centre, Ahmedabad*

Desertification is not about advancing boundaries of existing deserts, but about land degradation in the arid, semi-arid and the dry sub-humid regions that together form the drylands (Anon., 1995). Secular variation in climate that has resulted in periodic expansion and contraction of the desert boundaries as well as regional-scale changes in vegetation condition (Tucker *et al.*, 1991; Nemani *et al.*, 2003; Hickler *et al.*, 2005) is but one driver of desertification. Human activities constitute the other major driver. Globally it has been estimated that out of 5169 million hectare (mha) area of the drylands (constituting 40% of the global land surface), about 1035 mha (or 20% of the total area; 17% slight to moderately affected; 3% strongly affected) is affected by desertification (Thomas, 1995). While 467 mha area is estimated to be susceptible to water erosion, 432 mha is assessed to be under wind erosion. Dregne and Chou (1992) and Dregne (2000) estimated that approximately 3% area of the drylands are irrigated croplands, 9% are rainfed croplands, and 88% rangelands. According to them about 30% of the irrigated croplands, 47% of the rain-fed croplands and 73% of the rangelands are degraded.

The global estimates so far are based on guesswork for a Global Assessment of Human-Induced Soil Degradation (GLASOD; Oldeman, 1988), and its modified version, Assessment of the Status of Human-induced Soil Degradation in South and Southeast Asia (ASSOD; UNEP, 1997), both commissioned by the UNEP. Since the assessments contained largely the opinions of 'experts' in different regions, rather than robust quantitative approaches, the data received some criticism (Olsson, 1993, Prince, 2002). Many reviewers suggested caution in using the data (Thomas and Middleton, 1994; Middleton and Thomas, 1997; Reynolds and Stafford-Smith, 2002). The structure for the biophysical parameter evaluation was however robust, developed by Dregne (1983), and is still valid. Another controversy arose from the Dregne (1983) scheme and the GLASOD assessment excluding the hyper-arid regions (~8% of the global land area) from the ambit of desertification assessment. This exclusion was based on an understanding since the first United Nations Conference on Desertification (UNCOD, 1977), that the hyper-arid areas were irreversibly desertified. Contrary to this view, the hyper-arid areas are also populated and have substantial land-based economic activities. Based on some regional studies of NDVI changes, Hellden and Tottrup (2008) reported a general 'greening up' of the dryland areas, but cautioned against using the result for interpretation as systematic desertification trend. Sivakumar (2007) suggested that 'dramatic changes in agricultural practices during the last several decades' were a major driver of desertification.

In India, approximately 50.8 m ha land (15.8% of the country's geographical area) is arid, 123.4 m ha (37.6%) is semi-arid and 54.1 m ha (16.5%) area is in the dry sub-humid region (MoEF, 2001; NBSS&LUP, 2001). In other words, drylands cover about 228 m ha area (69% of the total geographical area of the country).

Defining Desertification: Changing Paradigm

Defining desertification is becoming increasingly difficult with time. Ever since Lavauden (1927) first used the term 'desertification' to describe severely overgrazed lands in Tunisia (Dregne, 2000), followed by Aubreville (1949) who used the term to mean excessive soil erosion due to deforestation in the French West Africa, the term has undergone a number of etymological shifts and intended meaning, but an universally acceptable definition is still eluding the scientific community. Worldwide interest in the term first surfaced in the context of the first UNCOD in 1977, which was held in the background of a long drought in the sub-Saharan Africa during the early 1970s. The term was then defined as diminution of the biological potential of land in any ecosystem. Since the definition failed to focus on the degradation problems of the drylands, especially in Africa, the 1992 UN Conference on Environment and Development (UNCED) negotiated a more acceptable definition as 'land degradation in arid, semi-arid, and dry sub-humid areas, resulting from various factors, including climatic variation as well as human activities' (Anon., 1992). The UN Convention to Combat Desertification (UNCCD) accepted this definition (Anon., 1995) for all practical purposes, but different national and regional needs and aspirations from UNCCD soon started to imply meaning to the definition and attempted to modify it. The most common usage so far has been to bracket desertification with land degradation, so that the environmental problems of drylands and non-dry lands are equally taken care of through international funding under the UNCCD. In Africa the emphasis is more on drought, and so 'drought and desertification' has become a familiar term. Incidentally, African drylands are the major beneficiaries of the UN effort on desertification. Geist and Lambin (2004) suggested that the prominent core variables that drive degradation are climatic, economic, institutional, national policies, population growth and remote influences. Herrmann and Hutchinson (2005) have discussed the changing contexts of desertification debate. Baartman *et al.* (2007) provide a summary literature review of the current research on desertification processes and solutions, with emphasis on the results from the European Union projects on desertification.

Overall, the prevailing desertification concept (also called the 'desertification paradigm' by Safriel and Adeel, 2005) suggests that apart from drought, the non-sustainable management and land uses within the drylands often lead to over-exploitation of the natural resources and a decline in productivity, the consequent desertification, followed by poverty and migration. By contrast some researchers recognise that the typical land uses of the desert and dryland dwellers provide some of the best possible strategies to cope with the uncertainties, and that desertification does not automatically follow from those land uses, but is more contextual (Bharara, 1993; Mortimore, 1998; Warren, 2002). Reynolds *et al.* (2007) suggested a different pathway of interaction between the demographic and socio-political drivers and the inherently low productivity of the drylands, and termed it as the dryland livelihood paradigm. A third paradigm, called the 'counter-paradigm' was proposed by Safriel and Adeel (2008) who suggested that to meet the challenges of inherently low productivity and other constraints, the land users would apply innovative means to surmount the problems of desertification, poverty and other consequences, and the efforts will be supported and sustained by policies and infrastructural facilities, and thereby make the system more sustainable than before. The debate reached a high point when a draft White Paper on monitoring and assessing desertification (for CCD's consideration) proposed that "desertification is best to be treated as an extreme case of land degradation, which is expressed in a persistent reduction or loss of biological and economic productivity of lands that are under uses by people whose livelihoods depend on this productivity, yet the reduction or loss of this productivity is driven by that use" (Vogt *et al.*, 2009a). The proposal adds to the prevailing confusion, and attempts to shift the focus away from the Sahel and the non-drylands and by implication from a large number of poor nations. Possibly it also reflects the frustration of alienated segments of the dryland dwellers for not being counted in the global effort. The second draft of the document has slightly modified the definition as "desertification is an end state of the process of land degradation; this process is expressed by a persistent reduction or loss of biological and economic productivity of lands that are under uses by people. The livelihood of many of these people at least partly depends on this productivity, yet the reduction or loss of the productivity is driven by its use" (Vogt *et al.*, 2009b). The confusion still persists.

Despite the prevailing confusion on definition, the simplicity of the 1992 definition of desertification helped researchers to bring in sharp focus, after the UNCOD (1977), the special environmental and socio-economic problems of the drylands, and more specifically of the arid lands (including the hyper-arid lands) to the policy planners and the global financial institutions. It triggered gradual development of an assessment and monitoring system for land degradation in the drylands of many developing countries, as well as of the availability of funds for improvements in socio-economic conditions and environment. A paradigm shift in the thought process for the combating programme from improvement of environment alone in the early decades to a programme of sustainable livelihood from improved environment and poverty alleviation is now making desertification control programmes more attractive and participatory in several affected nations. A slight relaxation in adherence to the 1992 definition has also benefited several developing, but dominantly non-dryland nations (e.g. Vietnam, Indonesia, Sri Lanka). Unfortunately, degradation is still measured largely through qualitative rather than quantitative methods. This sometimes becomes an easier means to exaggerate the situation to get funding (Warren and Olsson, 2003). Paradoxically, despite the awareness, the researches, and the funding for decades, drylands (especially of Africa) still continue to be the most handicapped among the major ecosystems, especially in terms of land productivity and human well-being (Adeel *et al.*, 2005).

There is now a growing feeling among researchers that apart from identifying the hot spots of desertification for control measures, it is necessary to identify and measure the biophysical and socio-economic factors (drivers) that put pressure on the land resources and cause significant degradation, leading to a longer-term fall in production from the land. There is also a better perception that (1) the dryland human-environment systems are coupled, dynamic and co-adapting, so that their structure, function and inter-relationships change over time; (2) the systems, including the scales of processes, occur in nested, hierarchical planes, necessitating their operations over multiple scales; (3) often the critical variables that determine the system dynamics are much slower than the processes that lead to geological 'disasters'; and (4) the thresholds of the variables are not static but can change with time, which may lead to some unexpected outcomes like faster degradation or slower recovery (Reynolds and Stafford Smith, 2002; Reynolds *et al.*, 2007). Researches on developing realistic models to factor these understandings in appropriate models to assess desertification are continuing at many learned centres, but demand a large database. Hopefully, once developed such models will help in providing robust early warning of desertification (Kar and Takeuchi, 2003).

Here we present highlights of research on desertification and its control in the arid zone of India, with special emphasis on the Thar Desert in the western part of Rajasthan State. Earlier review on the subject is available in Kar and Faroda (1998, 1999), Dhir (2003), Narain and Kar (2006, 2007) and Kar *et al.* (2007a).

Desertification Assessment and Mapping

Past Assessment

The first attempt to assess and map desertification in India was carried out by Central Arid Zone Research Institute (CAZRI) in 1977 in connection with the first UN Conference on Desertification (UNCOD) at Nairobi, when the processes of desertification in arid western Rajasthan, covering the Indian part of the Thar Desert, were mapped at 1:2 Million scale as per the guidelines and nomenclature supplied by the UN. A detailed map and a report were also prepared for a small representative administrative block in Jodhpur district, the Luni Development Block (Singh *et al.*, 1978).

Since then a number of attempts have been made to assess the extent of land degradation at country level, irrespective of whether they exist in the drylands or not. Most of these were based on a compilation at state level of the different kinds of low-yielding or waste/barren lands that are mentioned in the land revenue records of the villages. Based on such a compilation in 1994 the Ministry of Agriculture (MOA), Govt. of India, suggested that 107.6 million ha (mha) area of the country was affected by different degradation processes (32.7% of the total area), while a previous assessment mentioned in the said compilation had suggested 173.6 mha (Anon., 1994). Another assessment by the National Bureau of Soil Survey and Land Use Planning in 2004 found the total degraded area in the country as 146.8 mha, i.e., 44.7% of total area (Samra and Sharma, 2005). Since it was generally believed at bureaucratic circle that desertification was synonymous with wastelands (desertification= deserted or waste land), the data was matched with the country-wide wasteland categories mapped at 50,000 scale by various national research institutes and compiled by the National Remote Sensing Agency (NRSA; now NRSC), and released in 2005. The exercise revealed wide variations between the two kinds of assessment. The wasteland mapping suggested that the country had 55.27 mha of wastelands (17.45% of country's area). As Kar (1996a) pointed out, individual perceptions, methods of assessment and attempts to exaggerate the effects of local droughts often played their role in the land degradation estimation at country level.

Attempt was made by the Indian Council of Agricultural Research (ICAR) and the Department of Space (DOS) to harmonize the existing data through a dialogue process among the major institutions that were involved in the earlier exercises (Table 1). Using satellite images the Forest Survey of India also maps degradation in the different forest categories at regular time intervals. The emphasis has always been to identify the physical status of degradation for taking up remedial land development activities, rather than to take a holistic view, including the driving forces and the pressure variables, for addressing the root causes of socio-economic nature that compel people to degrade the land.

Table 1. Past assessment of land degradation in India and their harmonization (area in mha)

Degradation category	MOA (1994)	NBSS&LUP (2004)	NRSA-coordinated Wastelands (2005)	ICAR-DOS harmonized (2007)
Water erosion	57.155	93.680		82.570
Ravines	2.678		4.320	
Flooding		0.212		
Wind erosion	11.160	9.271		12.400
Water logging	3.197	14.299	0.890	0.880
Salt-affected	6.323	5.944	3.900	6.740
Soil acidity		16.034		17.940
Mining/industrial wastes	0.425			0.190
Shifting cultivation	2.378		2.400	
Degraded forests	24.897			
Complex/special problem	0.089	7.381		

Meanwhile, in the early-1990s, CAZRI carried out a satellite-based mapping of desertification in western Rajasthan at 1:1 Million-scale, for which the 1:250,000-scale false colour composites of Landsat-TM images for 1989-1991 were visually interpreted. A set of field indicators was developed for gathering ground truth for the mapping, which was found relevant even during subsequent studies (Kar and Takeuchi, 2003, modified after Singh *et al.*, 1992). The map, first printed in small format was updated and published at 1:1M scale in 2005.

According to the above mapping, out of 20.875 m ha area mapped, 19.175 m ha (92% of the total mapped area) was degraded, and the rest was free from any degradation. While 33% area was slightly affected, 35% area was moderately affected and 24% severely. Wind erosion constituted the largest area (~76% of the total mapped; 25% slightly affected, 35% moderately and 15% severely). Water erosion was mapped in 15% area, while waterlogging and salinity was mapped in 6% area.

Current Assessment of Degradation*

In view of the non-availability of a countrywide land degradation status map of India, a task of desertification/land degradation status mapping (DSM) was taken up in 2004. This was also to fulfil the county's commitment towards preparation of a regional DSM under the Thematic Programme Network-1 (TPN-1) of UNCCD. The final maps were prepared at 1: 1M scale, using data from the Advanced Wide Field Sensor (AWiFS) on board the Indian Remote Sensing Satellite, IRS-P6-Resourcesat. The data were acquired during the years 2003, 2004 and 2005. Ground truth was also collected to verify the mapped features.

The task was coordinated by the Space Applications Centre (SAC), and was executed in collaboration with the following institutions in the country: Central Arid Zone Research Institution (CAZRI), Jodhpur; National Bureau of Soil Survey & Land Use Planning (NBSSLUP), Bangalore; All India Soil & Land Use Survey (AIS&LUS), Delhi; Maharashtra Remote Sensing Applications Centre (MRSAC), Nagpur; Madhya Pradesh Remote Sensing Applications Centre (MPRSAC), Bhopal; Orissa Remote Sensing Applications Centre (ORSAC), Bhubneshwar; Arunachal Pradesh Remote Sensing Centre (APRSAC), Itanagar; Uttar Pradesh Remote Sensing Applications Centre (UPRSAC), Lucknow; Bihar State Remote Sensing Applications Centre (BIRSAC), Patna; Jharkhand Space Applications Centre (JSAC), Ranchi; Birla Institute of Technology (BIT), Ranchi; Jammu University, Jammu; Jawahar Lal Nehru University (JNU), New Delhi; Institute of Remote Sensing (IRS), Anna University, Chennai; University of

* This section is based on information provided by Drs. Ajai, A.S. Arya and P.S. Dhinwa.

Rajasthan, Jaipur; Directorate of Environment & Remote Sensing (DERS), Srinagar; and Earth Observations System (EOS), Indian Space Research Organisation (ISRO), Bangalore.

A national classification system was first developed through a pilot project in selected districts of the country, in which SAC, CAZRI and few other institutions were involved (SAC, 2007a). The team evolved a basic framework of classification from the existing classification systems, keeping in view the sensor limitations to identify a feature and the requirements at national level. Efforts were made to minimize the classification units so that the map becomes easy to read. Details of the methodology are illustrated in Fig. 1.

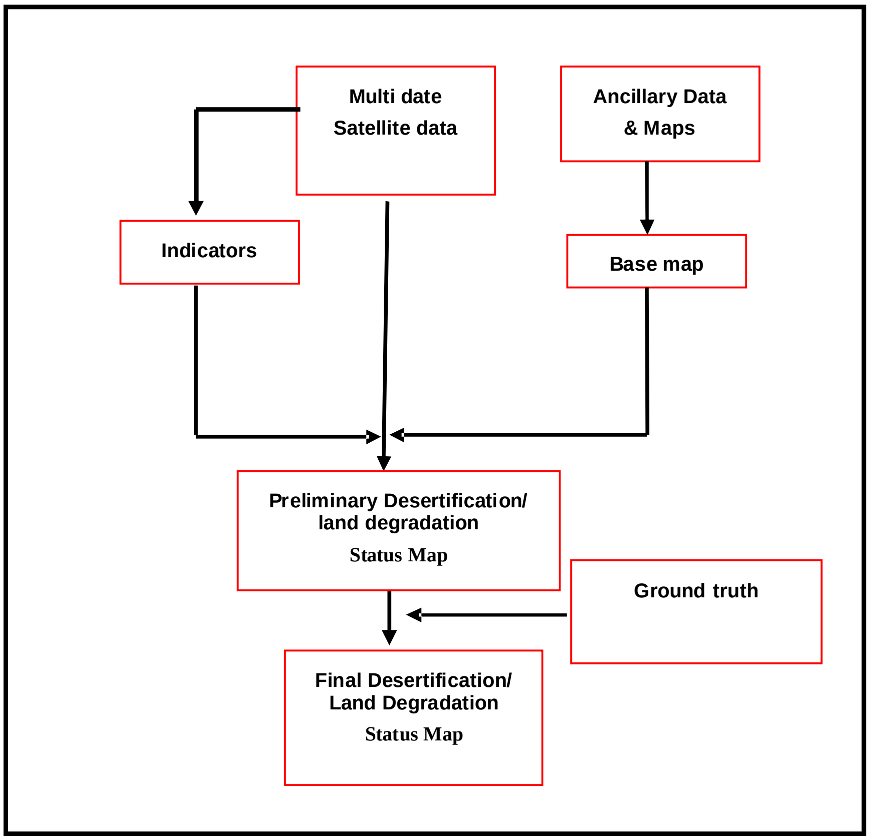


Fig. 1. Methodology for preparation of desertification status map.

Altogether 12 land use/land cover categories, 13 degradation processes and 2 severity classes (high and low) were identified for mapping. The severity class high has been used for severe degradation, while low has been used for slight to moderate degradation. It was recognized that due to sensor limitations, distinction between slight and moderate degradation would be difficult through visual interpretation. For our discussion, we shall use the term severe for 'high' category and slight to moderate for 'low' category.

The mapping reveals that leaving aside the islands India has 105.48 mha (32.07% of country's area, excluding the islands) under different land degradation categories. Notable among these, water erosion covers 33.56 mha, followed by vegetation degradation (31.66 mha) and wind erosion (17.56 mha). In the Himalayas, frost shattering covers 10.21 mha. Among the arid and semi-arid states, Rajasthan has the maximum degraded area (21.8% of the country), followed by Jammu and Kashmir (12.8%), Maharashtra (12.7%), and Gujarat (12.7%). The total area affected by desertification within arid region is 34.89 mha, while that in the semi-arid region is 31.99 mha (SAC, 2007b). Table 2 provides a summary of degradation in the arid, semi-arid and dry sub-humid regions of India.

Table 2. Current status of desertification in the drylands of India (area in mha)

Type of degradation	Arid	Semi-arid	Dry sub-humid	Total
Water erosion	3.67	17.67	4.87	26.21
Wind erosion	16.16	1.60	0.01	17.77
Vegetation degradation	1.97	8.43	7.23	17.63
Salinity/alkalinity	3.03	0.71	0.23	3.97
Water logging	0.00	0.07	0.59	0.66
Barren/Rocky	0.00	1.16	0.00	1.16
Man-made (mining, etc.)	0.00	0.08	0.03	0.11
Mass movement	3.66	0.50	0.30	4.46
Frost shattering	6.39	1.77	1.31	9.47
Frost heaving	0.01	0.00	0.00	0.01
Total	34.89	31.99	14.57	81.45

The spatial pattern of degradation in the hot arid parts of Punjab and Haryana (Fig. 2), and in Karnataka and Andhra Pradesh (Fig. 3) reveal very few areas of concern, while the map of the cold arid part of Jammu & Kashmir (Fig. 4) shows the dominance of frost shattering and mass movement as degradation processes in a largely barren topography. Compared to this the arid areas of Rajasthan and Gujarat have larger areas under different kinds of degradation, as we shall discuss in the next section.

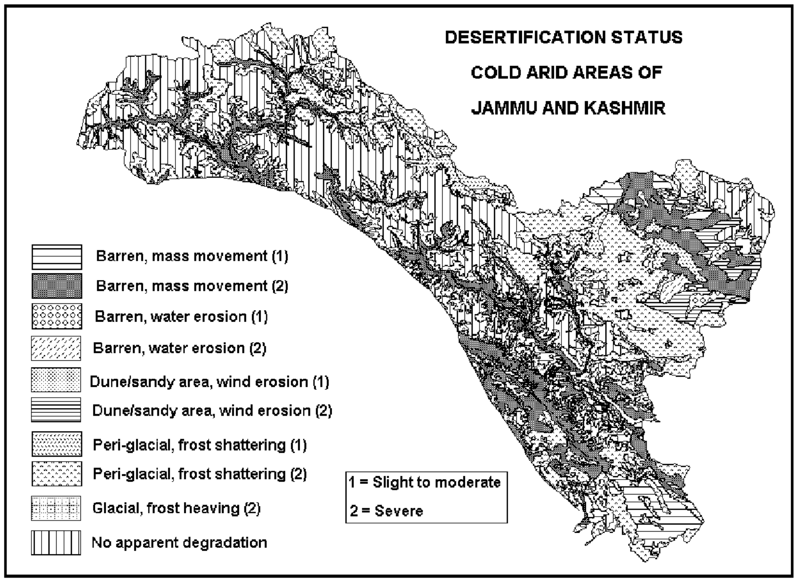


Fig. 2. Desertification status in hot arid areas of Punjab and Haryana.

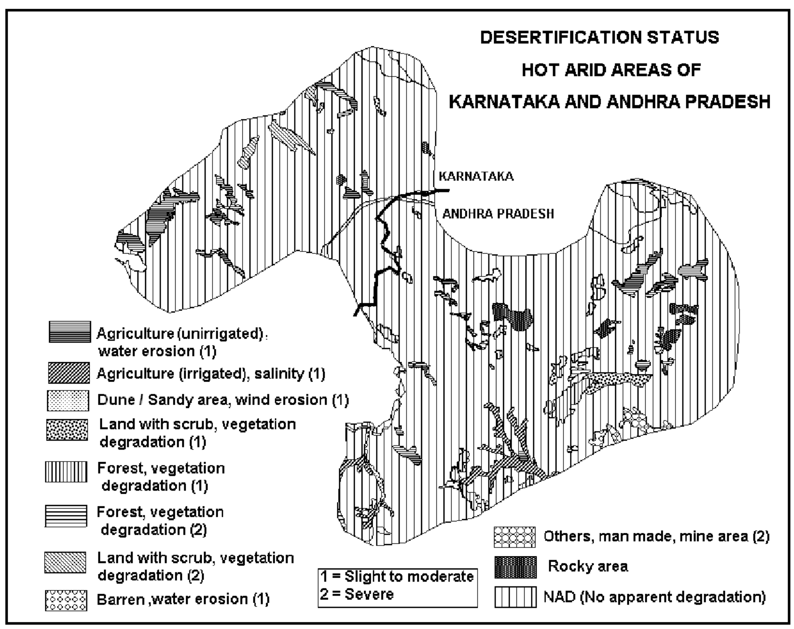


Fig. 3. Desertification status in hot arid areas of Karnataka and Andhra Pradesh.

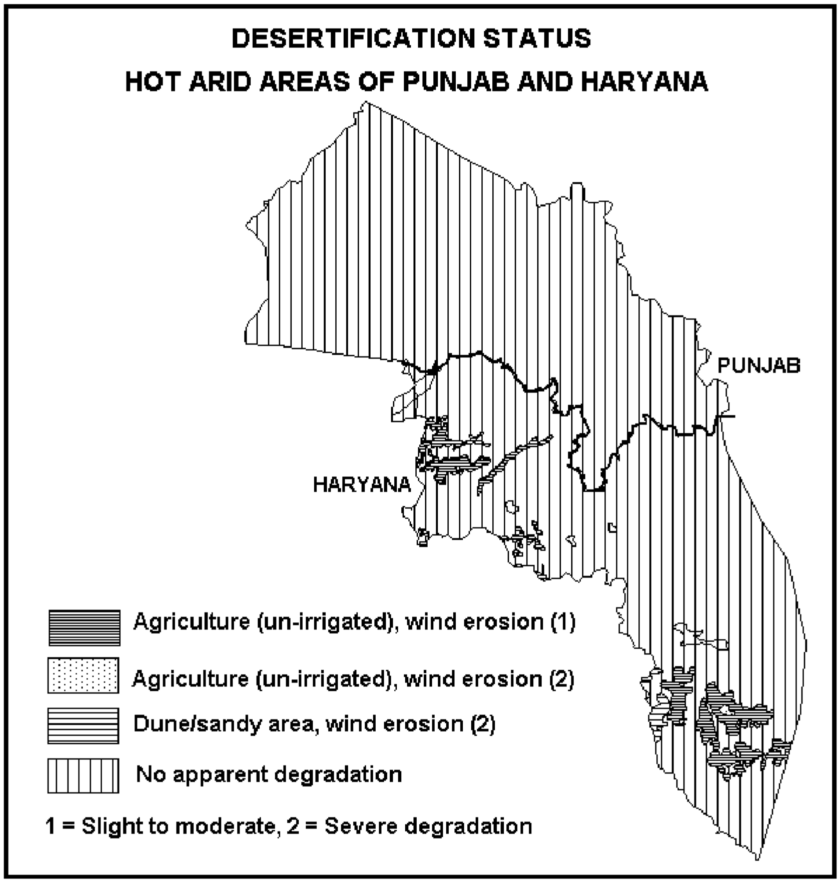


Fig. 4. Desertification status in cold arid areas of Jammu and Kashmir.

Desertification Status in Arid Rajasthan and Gujarat

Mapping of desertification in different land uses in the arid western part of Rajasthan and Gujarat reveals that ~76% area of western Rajasthan is affected by wind erosion, encompassing all the major land uses, but mostly croplands and dunes/sandy areas, while water erosion has affected ~2% (mostly in croplands and scrublands), salinization ~2% (mostly in croplands) and vegetation degradation ~3% (especially in scrublands and forests). Mining activities have spoiled so far only 0.10% area, and degraded rocky areas cover 1% area (Table 3). About 18% area is severely degraded and 66% slight to moderately, while 16% area is not affected by degradation. In arid Gujarat, water erosion is the most dominant process, affecting ~43% of the total area (mostly in croplands), followed by salinity (38%), while vegetation degradation (10%) and wind erosion (5%) cover some areas (Table 3). About

Table 3. Desertification in different land uses in arid western Rajasthan (based on visual interpretation of 1:500,000 scale AWiFS satellite imagery (2003-04)

Land use	Type of degradation	Area (km^2)	% of total mapped area
Cropland (rainfed)	Wind erosion (slight-moderate)	62868	29.88
	Wind erosion (severe)	12584	5.98
	Water erosion (slight-moderate)	1143	0.54
	Water erosion (severe)	39	0.02
	Salinity (slight-moderate)	1928	0.92
	Salinity (severe)	118	0.06
Cropland (irrigated)	Wind erosion (slight-moderate)	27906	13.26
	Wind erosion (severe)	380	0.18
	Water erosion (slight-moderate)	1350	0.64
	Salinity (slight-moderate)	527	0.25
	Salinity (severe)	2	0.00
	Water logging (slight-moderate)	177	0.08
	Water logging (severe)	6	0.00
Scrubland	Vegetation (slight-moderate)	4655	2.21
	Vegetation (severe)	61	0.03
	Wind erosion (slight-moderate)	11640	5.53
	Water erosion (slight-moderate)	926	0.44
	Water erosion (severe)	64	0.03
	Salinity (slight-moderate)	135	0.06
	Salinity (severe)	530	0.25
Sand dune/sandy area	Wind erosion (slight-moderate)	17462	8.30
	Wind erosion (severe)	22046	10.48
	Water erosion (slight-moderate)	416	0.20
Forest	Vegetation (slight-moderate)	1066	0.51
	Vegetation (severe)	72	0.03
Barren land	Wind erosion (slight-moderate)	4675	2.22
	Salinity (severe)	1311	0.62
Mining	Mining (slight-moderate)	111	0.05
	Mining (severe)	91	0.04
Rocky		2129	1.01
Total degraded area		176418	83.85
Settlement		274	0.13
Not affected		33692	16.01
Water bodies/drainage		15	0.01
Total mapped area		210399	100.00

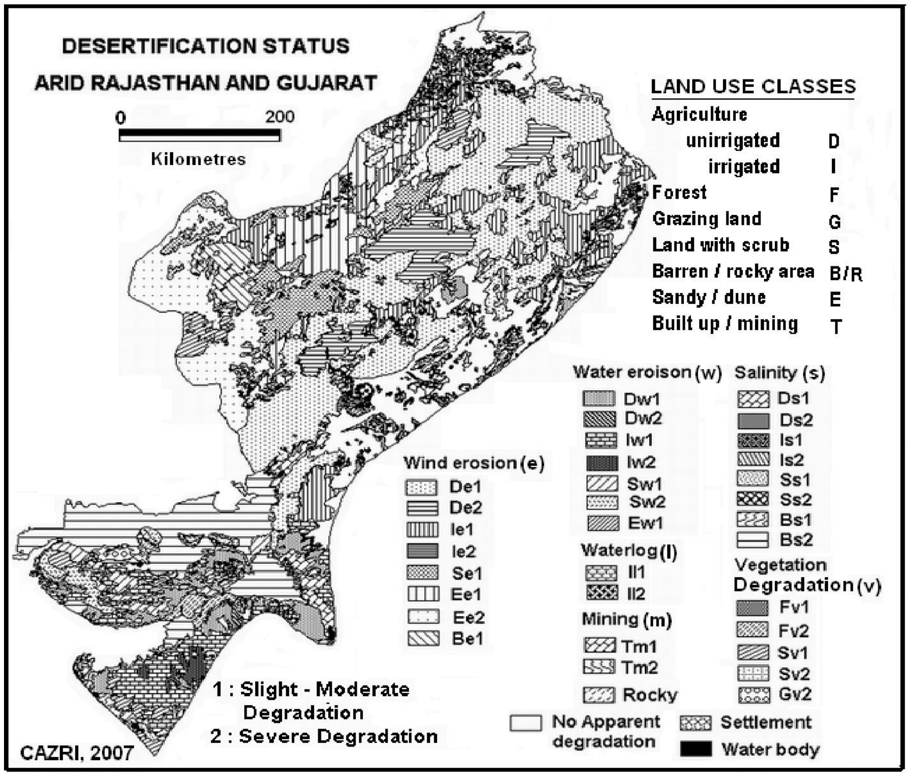


Fig. 5. Desertification status in arid Rajasthan and Gujarat.

44% area is severely affected, and 53% slight to moderately, and 3% area is not affected. Inclusion of the Great Rann of Kachchh and the Little Rann inflate the area under severe degradation (Kar *et al.*, 2007a). Fig. 5 shows the spatial pattern of desertification in different land uses in the arid parts of Rajasthan and Gujarat.

Biophysical Processes of Degradation in Western Rajasthan

Arid western part of Rajasthan, which contains the Indian segment of the Thar Desert and accounts for ~62% of the country's hot arid area, faces a major challenge of desertification due to recurrent drought and increasing human and livestock pressures. Studies at Central Arid Zone Research Institute have revealed that the major physical manifestations of desertification in western Rajasthan is wind erosion/deposition, followed by water erosion, as well as water logging and salinity (Ghose *et al.*, 1977). Degradation of natural vegetation is widespread, as most of the permanent pastures have been very severely exploited for fuelwood and fodder. With time, industrial effluents and mining are also gradually becoming important factors of desertification. Mismanagement of land has been found to be a major cause of the problems (Singh *et al.*, 1992, 1994; Kar, 1996a; Narain and Kar, 2006). Overall, 30% area of western Rajasthan is slightly affected by desertification, while 41% is moderately affected, 16% severely, and 5% very severely. Thus, more than 60% area of western Rajasthan requires intensive management to contain desertification. Centuries-old and time-tested traditional wisdom of integrating agriculture with livestock farming, utilizing perennial trees and grasses to support animal wealth, and efficient systems of water harvesting and its use are now either forgotten, or are seriously threatened by modernisation. Under these circumstances the arid western part of Rajasthan is becoming more vulnerable to desertification. In the following section we shall describe the major processes of degradation in western Rajasthan.

Wind erosion

Wind erosion is the most dominant problem in western Rajasthan, where the terrain is dominantly sandy with sparse natural vegetation cover. The summer wind speed is high, reaching often a gust speed of 60-80 km h^{-1} or more during sandstorms, especially between March and July, before the monsoon rains set in. Broadly, a decreasing rainfall and soil moisture gradient from east to west, as well as increasing wind strength in that direction, along with the high erodibility of aeolian sediments determine the spatial pattern of wind erosion (Kar, 1993). Following the modified Chepil formula, Kar (1993a) constructed a non-dimensional wind erosion index to estimate the efficacy of wind erosion across the desert. When mapped, the index values matched well with the pattern of aeolian bedform perturbation noticed in the field and on satellite imagery. For example, barchans, the naturally occurring modern crescentic dunes, start forming mostly in areas bounded by 120 contour of the index. This conforms approximately to the 250 mm isohyet in the southern part of the desert, but not in the northern part where the wind speed is less. Crescentic dunes become taller and more clustered beyond the 480 contour to form elliptical fields of megabarchanoid dunes. Based on such understanding of the relationship between aeolian bedform perturbation pattern and contour values a new scale of wind erosion index was prepared. According to it, the southwestern part of Jaisalmer district is under extremely high wind erosion potential (index 480 and above), while the area roughly between Barmer, Shergarh, Phalodi and Jaisalmer has very high erosion potential (index 120-479). The area to the east of Barmer and Shergarh, and up to Nagaur, and east of Bikaner, including Jodhpur, Pachpadra and Sanchor, has moderate to high erosivity (index 30-119). Rest of the area in the east and north, including Jalor, Pali, Sikar, Churu, Suratgarh and Ganganagar, qualified for low to very low erosion potentials (<30).

Table 4. Desertification in different land uses in arid Gujarat (based on visual interpretation of 1:500,000 scale AWiFS satellite imagery (2003-04)

Land use	Type of degradation	Area (km^2)	% of total mapped area
Cropland (rainfed)	Wind erosion (slight-moderate)	1875.42	2.50
	Water erosion (slight-moderate)	9693.33	12.93
	Water erosion (severe)	373.29	0.50
	Salinity (slight-moderate)	3066.33	4.09
	Salinity (severe)	278.05	0.37
Cropland (irrigated)	Wind erosion (slight-moderate)	2072.99	2.76
	Water erosion (slight-moderate)	13128.49	17.51
	Water erosion (severe)	1618.08	2.16
	Salinity (slight-moderate)	46.66	0.06
Scrubland	Vegetation (slight-moderate)	3851.77	5.14
	Water erosion (slight-moderate)	4741.31	6.32
	Water erosion (severe)	2561.91	3.42
	Salinity (slight-moderate)	462.03	0.62
Forest	Vegetation (slight-moderate)	239.90	0.32
	Vegetation (severe)	2328.93	3.11
Grassland	Vegetation (severe)	1188.35	1.58
Barren land	Salinity (slight-moderate)	272.07	0.36
	Salinity (severe)	24460.60	32.62
Rocky		24.89	0.03
Total degraded area		72287.40	96.40
Settlement		50.73	0.07
Not affected		2464.25	3.29
Water bodies/drainage		181.20	0.24
Total mapped area		74983.58	100.00

The inherent erodibility of the sediments also determines the wind erosion. Kar and Joshi (1995) used the proportion of dry soil aggregates of more than 0.84 mm size to map five classes of wind erodibility in the region. When mapped, much of western Rajasthan came under severe and very severe categories of wind erodibility, irrespective of whether the areas had similar high wind erosivity or not. This has implication for actual risk of erosion. For example, the north-eastern part of the desert has moderate to low erosivity, but the very high erodibility imposed by the dune-covered sandy terrain suggests that it has a high risk of wind erosion.

Ramakrishna *et al.* (1990) developed a curvilinear relationship between the mean daily wind speed and the measured rates of sand erosion from a bare barchan surface at Shergarh, according to which the minimum daily wind speed that initiated sand movement was 4 km h^{-1}. Beyond 9 km h^{-1} the sand movement increased rapidly, and over 14 km h^{-1} the mobility rate was very high. Sandstorm continuing for days together is a common feature in the western part of Thar Desert during summer months. Taking the time-averaged wind speed of 39 km h^{-1} for a typical sandstorm, and the threshold wind speed as 4 m sec^{-1}, Kar (1994, 2009) calculated the sand transport rate on bare pediments of Pokaran-Jaisalmer area as 195 kg m^{-1} width h^{-1}. Using the long-term average wind speed for the sand-shifting summer months the average sand transportation rate for the area was then calculated as 35.16 t per m width per year. The annual potential deflation was found to be ~7 t m^{-2}, and the potential rate for lowering of the sandy surface as 3.38 m y^{-1}. The finding highlights the degree of vulnerability of the sandy terrain of western Thar to wind erosion (Kar, 2009).

Measurements over sand dunes during severe gusty winds at Shergarh revealed that sand grains up to 0.2 mm size were eroded at the rate of 46 kg m^{-2} $hour^{-1}$ (Ramakrishna *et al.*, 1990). At Selvi near Pokaran, the rate of movement of an isolated barchan of 2.25 m height was found to be 1.70 m in 3 days of sandstorm when the average wind speed was 29 km h^{-1}, i.e., 0.57 m per day (Kar, 1994). The average movement of the barchan for the period 1987-1990 was 31.7 m. A maximum sand transport rate of 530 kg m^{-2} day^{-1} was recorded from the crest of the dune during a particularly windy (wind speed 6.9 m s^{-1}) day in April 1989 (Ramakrishna *et al.*, 1994). This barchan formed part of a group of 16 barchans along a 5000 m long and 250m wide corridor on a rhyolite pediment. Bulk sand transport analysis for the group, supported by repeated measurement for a four-year period (1985-1989), revealed that an average-sized barchan intercepted ~22 m^3 of sand during a year, and the group together 346 m^3. Since the average streamer length in the corridor was ~3 km, the sustenance of the dunes could be curtailed if the streamer was released beyond 3 km upwind (Kar, 2009).

Gupta *et al.* (1981) found the minimum threshold velocity as 5 km h^{-1} at Bikaner and 10 km h^{-1} at Jaisalmer. The critical wind velocity for the above two sites was determined as 15 km h^{-1} and 25 km h^{-1}, respectively. Gupta and Aggarwal (1980) recorded a loss of 9.6 cm topsoil from a bare sandy plain and 0.2 cm from a stubble-covered sandy plain, during the strong wind regime of April-June 1977. During the high wind regime of April-June

1990 at Bikaner, Gupta (1993) recorded a soil loss of 1449 t ha^{-1} from bare sandy plain as compared to only 22 t ha^{-1} from a crop field with a cover of 45 cm tall pearl millet stubble. Long stubbles of small grain crops have usually been found to be more effective than an equal quantity of short stubble.

It has been found that the loss from a sandy soil is much higher than that from a loamy sand soil, and that clod formation and vegetation are also important considerations. During a sand storm with a mean wind speed of 20 km h^{-1}, the erosion from a bare sandy soil at Bikaner was 273.7 kg ha^{-1} day^{-1}, while at Jodhpur a loamy sand soil with clod formation lost only 15.6 kg ha^{-1} day^{-1} under similar wind condition. During the same wind regime the grass cover on a sandy soil at Chandan near Jaisalmer reduced the erosion to 76.7 kg ha^{-1} day^{-1} (Gupta, 1993; Table 5). Particles smaller than 0.05 mm size were found to be least erodible.

Table 5. Soil loss under different wind speeds and terrain conditions in western Rajasthan

Mean wind speed (km h^{-1})	Soil loss (kg ha^{-1} day^{-1})		
	Bikaner (sandy)	Jodhpur (loamy sand)	Chandan (sandy)
5	0.5	0.3	1.0
10	120.8	1.4	8.0
20	273.7	15.6	76.7
40	1605.2	no data	1276.0

Excessive tillage before the kharif sowing has also been found to lower the percentage of clods greater than 5 mm size, and thus significantly increase the wind erosion. Reduced tillage, on the other hand, maintains a good clod-size distribution, and reduces wind erosion (Gupta and Gupta, 1981; Table 6).

Table 6. Effects of tillage on wind erosion at Jodhpur

Soil treatment	Average condition of clods >5 mm			Wind speed (km h^{-1})		Soil eroded (t ha^{-1})
	Clod (%)	Clod length (cm)	Clod width (cm)	Max.	Min.	
Ploughed	42.4	7.9	6.5	29.1	26.0	0.50
Ploughed and planked	12.7	2.1	1.2	29.1	26.0	40.1

Land use practices have also been found to significantly influence wind erosion. In the sandy plains, fields deep ploughed using tractors lost soil heavily during the 22-day long sandstorm of June, 1985, while the soils under 8-12% cover of natural vegetation were protected (Dhir *et al.*, 1992; Table 7). During the same sandstorm event deflation from a field cleared of vegetation cover at Chandan was 15-18 cm, and the soil lost was to the tune of 3100-3700 t ha^{-1} (Kar, 1994).

Table 7. Control of land use on wind erosion during a sandstorm in western Rajasthan

Land use/management	Number of sites	Mean soil loss (t ha^{-1})	
		Range	Mean
Cultivated			
Long fallow	12	124-320	207
Untilled since previous crop	16	220-377	283
Tilled	11	756-1180	932
Disc ploughed	3	2630-3160	2837
Pasture land			
Undegraded	6	Nil	Nil
Degraded	9	217-683	472

To assess the impact of grazing in rangeland ecosystems of the Thar Desert, aeolian mass fluxes (kg m^{-2}) were measured by dust catcher at an overgrazed *Lasiurus sindicus* dominated rangeland site (average density 5700 tussocks ha^{-1}) at Jaisalmer and a controlled *Lasiurus sindicus* rangeland site (average density 8300 tussocks ha^{-1}) at Chandan (60 kms E of Jaisalmer) during June-July 2004. The mass flux (q) (kg m^{-2}) of wind-eroded aeolian sediments decreased with height from the surface for all observation periods at both sites. The average rate of mass flux during this period at lowermost sampling height (0.6 m) was 0.028 kg m^{-2} day^{-1} at the overgrazed rangeland of Jaisalmer and 0.013 kg m^{-2} day^{-1} at the controlled grazing rangeland of Chandan. The two-parameter power decay function [$q(z) = a\ z^{-b}$, where $q(z)$ is the measured mass flux at an height of z (m) from soil surface; a and b are parameters of the equation] was the best to describe mass-height profile of aeolian sediments collected by the dust catcher. Parameter a of the power decay function indicated the amount of eroded aeolian sediments at a height of 1 m. Parameter b indicated the degree of stratification of atmosphere in terms of concentration of aeolian sediments. More the value of b >0, more is the stratification of the atmosphere. At both sites, the parameters a and b were significantly correlated with average wind speed (r = 0.48 and 0.57, respectively). It was also observed that better fitting of mass flux with height occurred when the parameter b was high. This indicated that during severe dust storm events, when the atmosphere was stratified into a number of distinct layers, power decay function performed better than during mild dust storm events. The only limitation of the above power decay function is the computation of mass flux at surface (z=0), which becomes infinity. Therefore, this mass-height relationship is most suitable for suspension flow at 0.15 m from surface and above. Overall, the mass fluxes at overgrazed site were higher than the mass fluxes at controlled grazing site. During the period from mid-June to mid-July, mass fluxes were the maximum at both overgrazed and controlled grazing sites and were also best fitted in power decay relationship (Mertia *et al.*, submitted). The mass transport rate (kg m^{-1} day^{-1}) was almost three times higher at the overgrazed site than at controlled grazing site during mid-June to mid-July. Notably, the only difference between these two sites was the level of grazing pressure, which resulted in huge difference in mass transport rates. Presently, majority of the rangelands in the Thar Desert are unprotected and contribute significantly to aeolian dust load in the atmosphere, with possible adverse feedback to the regional climate.

The amount of soil nutrient being lost from the desert with every sandstorm is still to be budgeted. Soni *et al.* (2007) reported that strip cropping of legumes with pasture grass (1:3 ratio) reduced the soil loss (20.5 t ha^{-1}) in comparison to the bare field left after their sole cropping (48 t ha^{-1}), and provided higher soil available nitrogen over their sole cropping. The loss of soil organic carbon and total nitrogen was to the tune of 44 to 48 kg ha^{-1} and 3.0 to 3.2 kg ha^{-1}, respectively in bare soil left after sole cropping. The highest available nitrogen (133.3 kg ha^{-1}) was recorded with grass + clusterbean strip cropping, followed by grass + moth bean (130.0 kg ha^{-1}), which was 14.8 and 43.0% higher over sole cropping of clusterbean (116.0 kg ha^{-1}) and moth bean (91.0 kg ha^{-1}), respectively. By contrast, a pasture encouraged sediment deposition, providing a net gain of 62.8 kg ha^{-1} soil organic carbon and 4.8 kg ha^{-1} of total nitrogen. Raina (1992) reported that the loss of organic carbon from a degraded cropland was 50.3% as compared to 29.4% from a degraded pasture. In case of K, the decrease was 55% in cropland and 12% in pastureland.

High human and livestock pressures, reducing the plant cover through overgrazing and fuelwood collection, expansion of croplands to marginal areas without assured water supply, and deep ploughing of sandy terrain with tractors, even along the slopes of sand dunes, have not only accentuated the erosion in the region, but has also enlarged its area (Singh *et al.*, 1992; Kar, 1996a). Thus, with each episode of dust-sand storm, the soils get gradually depleted of the already poor reserve of silt and clay as well as the plant nutrients. The dust emitted from the desert surfaces, especially as particulate matters having diameter less than 10 µm (PM_{10}) and those having diameter less than 2.5 µm ($PM_{2.5}$), have substantial resident time in the atmosphere, during which they also get carried downwind, impacting precipitation and radiation, and a host of other problems (Kar and Takeuchi, 2004). Adverse effects of the dust on respiratory and cardiovascular activity of desert dwellers as well as on other health parameters have been reported (Santra and Mertia, 2006). Field measurements at Jaisalmer and Chandan revealed that PM_{10} and $PM_{2.5}$ load were on an average 20.0% and 15.5% of the total mass transport, respectively. The $PM_{2.5}$ load in eroded sediment was slightly higher at Chandan (16.6%) than at Jaisalmer (13.9%) due to higher percentage of silt (<0.02 mm) and clay (<0.002 mm) in parent soil material at Chandan than at Jaisalmer. The abundance of *Lasiurus sindicus* grass clumps at protected rangeland sites in Chandan area was found to have greatly reduced the emission of hazardous PM_{10} and $PM_{2.5}$ in the atmosphere.

Apart from excessive tractor use in sandy terrain, a shift in land use is also noticed. Net area sown in western Rajasthan has increased from less than 37% of the total area in 1956-57 to about 50% by the end of the century. Enlarging the areas of cultivation to less suitable marginal sandy areas, including higher slopes of sand dunes, land levelling in dune-covered irrigated areas, and other factors of sand destabilization are also accelerating the aeolian processes (Kar, 1996b; Kar *et al.*, 2007a). Continuous cultivation of shallow sandy soils has also affected crop productivity, especially because the limited soil nutrients are plundered with the harvest of crops, and these are never replenished to the desired level. Available P, which cannot be supplied by fixation like nitrogen, suffers the most and becomes a crucial factor in decline of productivity (Tsunekawa *et al.*, 1997).

Broadly, the western-most part of Thar Desert with finer soils is the major source of atmospheric dust, which is carried eastwards and gradually settles in the eastern part of Rajasthan and adjoining parts of Uttar Pradesh (UP) and Madhya Pradesh (MP). This pattern is reflected in the satellite-derived aerosol index over the region (Kar, 2008, 2009). The problem becomes more glaring during the drought years due to reduced plant cover and drier soils. Apart from erosion of topsoil containing precious little organic matter, damages to crop plants, burial of good agricultural lands and infrastructures, and disruption of transportation network are the other major impacts of severe wind erosion (Kar, 1986, 1996b).

Water erosion

Water erosion in the form of sheet, rill and gully erosion is usually a problem in the areas of average annual rainfall exceeding 350 mm, where high rainfall intensity, moderate to steep slope and shallow soils add to the problem. Large areas of Saurashtra and Kachchh uplands, and many areas along the eastern part of Thar Desert where average annual rainfall varies from 350 to 500 mm, are affected by high water erosion. Destruction of vegetation cover and excessive ploughing of shallow soils, especially on the sloping lands, accelerate the problem. Neotectonic activities also lead to high acceleration of erosion, as in the arid tracts of Kachchh and Saurashtra, where the erosion is largely related to a slow upliftment of the terrain over the centuries that leads to a change in base level, downcutting of streams and formation of ravinous land, or stripping of alluvial cover (Kar, 1993b). Superimposed on this pattern are the effects of cultivation on marginal lands, deep ploughing, etc., but the signatures of the two are difficult to separate. Estimation of areas affected by sheet wash is difficult and debated.

Flash floods also lead to localized high erosion and sedimentation across the desert, and thus changes in land productivity. For example, in July 1979, high intensity monsoon rainfall for 5 days at a stretch in the southern part of the desert affected nearly 108799 ha of agricultural land with either rill and gully formation or coarse sand deposition due to shifting channels. Crops were damaged over 87186 ha area. Similarly, two spells of high intensity monsoon rains in July and August, 1990, created flooding and soil erosion in the same region (Sharma and Vangani, 1992; Vangani, 1997). In August 2006 high-intensity rainfall for three days in Barmer-Jaisalmer tract not only resulted in yearlong flooding of some interdune plains, but also led to erosion of topsoil and nutrients from the upper catchment and their deposition in the lower catchment. The stream network, revived after more than half a century, however, did not deviate from the simulated channel courses for the area (Kar *et al.*, 2007b and c). Part of the human misery in the wake of the flood lay in unscientific land use practices. It has been noticed that the shallow sandy channels of the desert are hardly able to accommodate much of the run-off generated during the long spells of high intensity monsoon rainfall, and leads to flooding. The floodwater often gushes out along some old and abandoned channels. It is only when such old courses are under human use systems that obstruct the free passage of floodwater that the suffering becomes glaring (Kar, 1995).

Water logging and salinity

Gradual spread of canal irrigation in western Rajasthan during the last four decades, especially through the Gang, the Bhakra and the Indira Gandhi Canal network that brings Himalayan water to the desert, has vastly changed the agricultural scenario in the command areas, and has brought prosperity, but it has also brought in its wake the problems of water logging and secondary salinization. The Indira Gandhi Canal system that presently irrigates ~1 mha, utilizing 8588 million m^3 water from the Himalayas, partly runs through a palaeochannel-dominated alluvial plain that has clay and gypsum beds at 5-8 m depth, which act as barriers to deep drainage. Lack of proper drainage, excess irrigation, seepage from the canals and wrong drainage planning under such situation have resulted in a rise in water table, followed by salinity build-up. The average rate of rise in water table in the command areas of the Indira Gandhi Canal is 0.88 m per year, while that in the Gang Canal command is 0.53 m per year, and in the Bhakra canal command 0.66 m per year. Within the Gang Canal command, the Ghaggar flood plain is experiencing a rise of 0.77 m per year. In the southern part of Thar Desert tank irrigation is leading to salinity-alkalinity build-up.

Groundwater irrigation is also causing deterioration of the land quality, especially where the water is rich in residual sodium carbonate (RSC). According to Minhas and Gupta (1992) about 84% groundwater in western Rajasthan is of poor quality. Often the water has EC >2.2 dS m^{-1} and up to 10 dS m^{-1}, coupled with high RSC (up to 20 me L^{-1}). Irrigation with such waters leads to the development of secondary salinization in the soils of the region (Gupta *et al.,* 2000). Land degradation mapping in the districts of Barmer, Jalor, Pali, Jodhpur and Sikar revealed the problems of high soil pH (8.6-10.5), unusual hardness, restricted water infiltration and decreased nutrient availability to plants in the soils irrigated with high RSC water, so much so that even after frequent ploughing during the rainy season and application of higher doses of farmyard/organic manure land productivity could not be restored (Raina and Sen, 1991; Raina *et al.*, 1991; Raina, 1997). Although sodicity and pH profiles of the soils show that the subsurface soil layers are little affected even after long-term use of alkali water (Bajwa *et al.*, 1989a,b), chemical changes brought about in the surface soil layers greatly reduce the percolation of water to deeper layers, and also hamper root proliferation of crop plants. Joshi and Dhir (1992) noticed significant deterioration in physico-chemical composition of the soils when water with >5 meL^{-1} RSC was applied in the mean annual rainfall zone of 200-300 mm. In the arid tracts of Haryana, Singh *et al.* (2008) found that irrigation with water of RSC 12-16 me L^{-1} for a period of six years and under different crop rotations led to development of high soil pH (9.4-9.7), reduced infiltration rate of soils and build up of ESP up to 66.1. In the Malkosani, Pipar and Bhagasani soil series in the southern part of Jodhpur district, irrigation for at least 27 years with groundwater rich in carbonate and bicarbonate has increased the level of inorganic carbon in soil by 64, 44, 14 g m^{-2}, respectively, with simultaneous rise in pH by 0.2 to 0.4 units (Singh *et al.*, 2007a, 2009). The emergence of seedling, growth of crop and yield of harvest are severely affected under such situations (Joshi, 1992).

In the seaward margin of the coastal alluvial plains very high pumping of potable ground water has led to an intrusion of saline seawater into the aquifers. Since the farmers have no other choice for watering the crops, they continue to use the groundwater, even after its quality deteriorates due to seawater intrusion (Kar, 1996a).

Vegetation degradation

Western Rajasthan has ~5.5 mha of rangelands but much of it is in a highly degraded state, especially due to the unrestricted grazing by a large number of livestock (23 million; density 113 per km^2), fuelwood collection and other needs. The common grazing lands around villages, which include Gochar (culturable waste), Oran or Jhor (permanent pasture, usually around a temple) and Agor (pasture around a pond), are also severely degraded as these are highly exploited, neglected and encroached upon. In arid Gujarat, the once-excellent grassland of Banni area in Kachchh district has also suffered immensely, where large areas of the nutritive grass species have been colonised by *Prosopis juliflora* shrubs, compelling the government to take up a programme of their eradication. A major casualty of natural vegetation degradation is a gradual replacement of the depleted useful species by the aggressive alien colonisers that may not have much feed and fodder value (Shankar and Kumar, 1987; Kumar, 1997). Two major small shrubs of sand dunes in Jaisalmer-Bikaner-Churu tract, *Calligonum polygonoides* and *Leptadania pyrotechnica*, which are excellent sand binders, are uprooted in huge numbers every year, threatening their existence in some areas, and aiding wind erosion.

On an average the area with good grass species in the less than 300 mm average annual rainfall zone has declined from about 7% earlier to 1% now, while in the more than 300 mm average annual rainfall zone the decline in tree and shrub cover is from 8% earlier to 1-2% now (Mertia, 1996). As the plant stands become more isolated, it gradually leads to a more heterogeneous distribution of soil fertility, which provokes further degradation (Schlesinger *et al.*, 1990). Dhir (1990) has summarised the condition of the pastures in western Rajasthan (Table 8).

Mine wastes

Mine spoils are gradually becoming a source of land degradation in the arid areas, although such degradation presently affects small area. Since rainfed cropping does not provide any assured income, many farmers are giving their land on lease for open cast mining of evaporaites or hard rocks of economic importance like sandstone, limestone, marble, etc. Unplanned open cast mining and a common apathy towards reclamation of the land on which mine refuses are dumped, are also threatening land quality (Saxena *et al.*, 1997). Some of the mined materials, like limestone, China clay, Fuller's Earth, calcite and gypsum generate fine particles which are washed downslope with run off and get deposited in adjoining cultivated fields as a less pervious layer, favouring stagnation of water and salinity build-up. Quarrying activities in the catchment areas of small watersheds also reduce water inflow to the ponds. Due to very poor plant nutrients and high pH and exchangeable sodium, magnesium, sulpher and phosphorus in the overburden/mine dump, their rehabilitation is a difficult proposition (Saxena and Chatterji, 1995), but can be achieved (Kumar *et al.*, 1998; Praveen-Kumar *et al.*, 2004).

Table 8. Pastureland condition in arid western Rajasthan

Pasture condition	Mean annual productivity (kg ha^{-1})	Basal cover of vegetation				Ephemeral contribution
		Total vegetation (%)	High perennials (%)	Low perennials (%)	Poorly edible species (%)	
Excellent-good	1500-2000	13-18	7-15	3-8	<3	Negligible
Moderately degraded	700-1500	13-18	3-7	5-10	5-8	Significant
Severely degraded	200-700	Variable	0-3	1-5	2-6	Major
Desertified	<200	<1	Nil	Negligible	<1	Major

Industrial wastes

Industrial effluents are becoming a significant source of land and water pollution in arid Rajasthan, especially due to the release of untreated effluents of textile dying and printing industry into the ephemeral channels, on the banks of which the units are established to have good access to potable water. Such discharge into the Jojari River near Jodhpur has affected at least 5500 ha, while along the Luni River at Balotra it has contaminated more than 7000 ha, and along the Bandi River downstream of Pali more than 22000 ha (Singh and Ram, 1997; Moharana and Singh, 1998), especially as the potable shallow groundwater wells, which are traditionally used for drinking and irrigation purposes became contaminated. A reservoir constructed at Nehda, ~50 km downstream of Pali on the Bandi River to conserve water for drinking and minor irrigation now collects the polluted water from Pali and transmits the pollutants further downstream. On an average the effluent waters have pH >9, RSC of ~35 me L^{-1}, and SAR exceeding 150. The problem has become a rallying point for different water users, and has led to the commissioning of effluent treatment plants at Pali and Balotra, but a solution is still to be found. Recent studies by Centre for Science and Education, New Delhi, has revealed that despite the establishment of common effluent treatment plants (CETP) at Pali and Balotra, there are problems of lower capacity of the plants than the discharge, bypassing of the CETP to channelize untreated effluents to the river, inability of the CETP to treat all the harmful elements, etc. The concentrations of arsenic, copper, lead and zinc in the groundwater in village wells downstream of Pali are alarmingly high and pose health hazard (CSE, 2006, 2007).

Degradation Related to Groundwater Depletion

Groundwater is the most precious and limited resource that has been used in this desert in a most wanton manner during the last three decades for making the land more productive. As electricity became available across the desert and Green Revolution technologies spread from the mid-1970s, irrigated winter cropping became the most sought after farming practice, with no regulation on water use. Since there is much less recharging of the aquifers, this over-use of groundwater has ultimately resulted in a gradual emptying of the aquifers. Currently all the districts in the desert, except the canal-dominated Hanumangarh district, are experiencing over-exploitation. Conditions are very alarming in the districts of Jhunjhunun, Sikar, Nagaur, Jodhpur, Pali and Jalor. A recent satellite-based study on temporal changes in micro-gravity has re-confirmed the acute stage of groundwater use in the region (Rodell *et al.*, 2009). As more fresh water is being exploited from the aquifers, there is increasing danger of saline and toxic water incursion, affecting human health and soil quality. Moreover, depletion of groundwater is forcing farmers to shift back to rain-fed cropping in the sandy terrain, with adverse socio-cultural consequences. Since the farmers had previously resorted to large-scale levelling of sandy undulation and uprooting of natural vegetation to introduce irrigated crops, the reverting back to rainfed cropping increases the vulnerability of the land to wind erosion manifold (Kar *et al.*, 2007a).

Soil quality deterioration

As the vulnerability of the land to wind erosion is increasing, so also is the loss of soil nutrients. Broadly the soil organic carbon (SOC) content in the wind-eroded sandy soils is 50% less than that in the non-eroded sandy soils. In the central part of western Rajasthan the SOC was depleted between 1975 and 2002 by 10.4%. In the arid western Rajasthan as a whole, the SOC stock in a meter deep soil has declined from ~825 Tg in 1975 to ~747 Tg by 2002. Lands with Typic Torripsamments and Lithic Torriorthents, having very poor vegetation status and extensive fallow, were severely depleted of SOC, while Typic Haplocambids with higher vegetation cover had the minimum loss. The mean emission of CO_2 from soil profiles (i.e., 0-100 cm deep soil column) in a test area of 22850 km^2 was estimated as 11.2 Tg and inorganic carbon sequestration as 0.39 Tg. Mean depletion of available phosphorus during 1975-2002 is by 21.9% and potassium by 17.6% (Singh *et al.*, 2007a). The degraded soils also registered a loss of silt by 39-47%, and clay by 41-64%. Since the average minimum SOC density is estimated to vary from 800 g m^{-2} (skeletal soil) to 3300 (fine loamy), and the estimated maximum possible limit for carbon sequestration in an un-tilled land with year-round vegetation canopy in the region is 4200-4600 g m^{-2}, there is a limit to derive benefit of carbon trapping through vegetation and other means in the desert. Approximately 200 to 850 g m^{-2} of SOC may get oxidized due to high temperature, ploughing, etc., if the prevailing situations remain (Kar *et al.*, 2007a; Singh *et al.*, 2007b).

Combating Desertification

National programmes

Long before the UNCCD's emphasis on the need to combat desertification, India developed its own programmes for controlling land degradation as well as to address the root cause of land degradation, i.e., poverty and social upliftment. Two specific programmes, the desert development programme (DDP) and the drought-prone area development programme (DPAP), were undertaken from the 1980s. The DDP districts were chosen on the basis of their aridity index, and the irrigated area being less than 50% of the cultivated land. By the mid-1990s the DDP was extended to 235 arid development blocks in 40 districts within seven states (Rajasthan, Gujarat, Haryana, Andhra Pradesh, Karnataka, Jammu & Kashmir, and Himachal Pradesh), especially for controlling desertification and to conserve, develop and harness land, water and other natural resources for restoring ecological balance in the long run through sand dune stabilization, afforestation, watershed development, soil and water conservation, etc., and to raise the level of production, income and employment through irrigation, afforestation and dryland farming. Areas under the non-arid drylands were covered under DPAP. India also has a national policy to bring 33% of the country's land area under forest. By 2003 the country had ~21% (67.8 mha) of its total area under different kinds of forests while the total tree cover (70% canopy density) outside forests was

3.04% (9.99 mha). By 2005 the country executed watershed development programme in 45.6 mha area). Sample studies in the semi-arid parts of the country suggest that the watershed development might have reduced the soil loss by 0.82 t ha^{-1} y^{-1}, and runoff rate by 13%, while increasing cropping intensity by 64% (Joshi *et al.*, 2005). Despite the above and a host of other centrally-sponsored and state-sponsored development programmes, the impacts are slow due to the periodic drought/flood, rise in population, leakages and shear vastness of the area to be tackled. In some cases the results are proving to be counter-productive (e.g. unrestricted utilization of groundwater for irrigation that has almost exhausted the potable water in large areas). As we have discussed earlier, problems of water logging and salinity have come up in parts of the canal-irrigated areas, and the soil nutrients are getting depleted fast due to continuous use of the land for cropping.

The country is gradually learning from some of the past steps that did not bring long-term solution to the concerned problems. For example, after spending millions of rupees on drought relief it has been found that government interventions through relief measures, including supply of drinking water, subsidies on food and fodder resources, organising cattle camps, wage employment to needy people, food for work programme, nutrition and health improvement programme, etc., did not necessarily lead to any long-term strategies for coping with future droughts, although the short-term measures helped people to withstand the current drought (Narain and Kar, 2005, 2007). This problem is now being addressed by linking a number of welfare programmes for asset creation and capacity building that can help people to be less dependent on relief.

Considering the emerging problems and new paradigms, it has now been assessed by the country's planners and policy makers that feeding the continuously increasing population of the country and to meet their demands and aspiration from the resources of the finite land area would be difficult in the coming decades, especially as the agriculture and allied activities will also face the challenges of climate change. In order to increase production from the land and at the same time to maintain sustainability it has been argued that a Second Green Revolution in the rainfed areas would be essential. It has been felt that an integrated crop-livestock-fish-biomass farming system approach to synergise natural resources conservation, development and management in the rainfed areas would be the best course to bring the changes. Also, it has been suggested that the community based organizations should be given more encouragement, and that new packages of incentives, services, technological options and labour support need to be given to farmer groups willing to adopt sustainable farming systems.

In order to put the plans into action, the XI Five-Year Plan of the country (2007-2012) has prepared a road map of massive work under the following natural resources management (NRM) programmes: (1) comprehensive NRM under watershed programmes (36.6 m ha); (2) location-specific NRM outside the watershed area (8.4 m ha); (3) farming systems based NRM outside the watershed areas (30 m ha); and (4) decentralized food security through dryland crops from rainfed areas, through a financial outlay of more than Rs. 8200 billion (Planning Commission, 2007). National Rural Employment Generation Scheme (NREGS), which speaks of providing at least 100 days' employment in a year to a rural family (150 days proposed for the calamity-stricken areas), has been made the essential tool for the creation of natural resource assets as well as for poverty alleviation and stabilization of rural income. The NREGS has already become popular in the rural areas, though it has created problems of agricultural labour and other manpower shortages.

We provide here an overview of the major desertification control technologies in the country, with emphasis on the technologies developed by CAZRI.

Sand dune stabilization

Considering that wind erosion and associated sand dune mobilization are the major forms of degradation in Thar Desert, development of appropriate technologies on sand dune stabilization was given a high priority in western Rajasthan since the 1950s. Mechanical and chemical methods to control wind erosion are neither economical nor feasible here, because the land, including sand dunes, belongs mostly to poor farmers. Therefore, CAZRI has developed vegetative methods for sand dune stabilization and shelterbelt plantation (Bhimaya and Kaul, 1960; Kaul, 1985).

Sand dune stabilization technology includes: (a) protection of the area from human and livestock encroachment; (b) creation of micro-wind breaks on the dune slopes, using locally available shrubs either in a checker board pattern or in parallel strips across the direction of wind; (c) direct seeding or transplantation of indigenous and exotic species; (d) plantation of grass slips or sowing of grass seeds on leeward side of micro-wind breaks; (e) management of revegetated sites (Muthana, 1982; Kaul, 1985; Harsh and Tewari, 1993). The technology has been widely adopted by Rajasthan state, and is also being followed by other neighbouring states. However, the efforts have so far been made to carry out plantation mostly on the Government-held land on the sand dunes. Therefore, although approximately 300,000 ha area of sand dunes has been stabilised through CAZRI technologies, people's participation is still poor due to the choice of many exotic species that do not provide much returns to the farmers, except fuelwood. CAZRI, therefore, has suggested that replacement of exotic trees and shrubs by the locally adapted species (Table 9) can provide some economic return (Venkateswarlu, 1993; Narain and Kar, 2006). Shrubs and grasses are better sand binders than the trees, but protection of grass cover is a problem, especially because of uncontrolled grazing on the dunes and sandy plains. In the inaccessible sand dunes of the extreme western part, which are not being held privately and have very little grazing pressure, aerial broadcast of palletised seeds of *Lasiurus sindicus* grass and suitable trees and shrubs has been tried (Shankarnarayan and Kumar, 1986).

Table 9. Suitable plant species for sand dune stabilization in western Rajasthan (after Venkateswarlu, 1993)

Annual rainfall (mm)	Trees	Shrubs	Grasses
150-300	*Prosopis juliflora, Acacia tortilis, A. senegal*	*Calligonum polygonoides*, Ziziphus nummularia*, Citrullus colosynthis**	*Lasiurus sindicus**
300-400	*A. tortilis, A. senegal, P. juliflora, P. cineraria*, Tecomella undulata*, Parkinsonia aculeata, Acacia nubica, Dichrostachys glomerata, Colophospermum mopane, Cordia rothii*	*Ziziphus mauritiana, Z. nummularia, C. polygonoides, C. colosynthis*	*Cenchrus ciliaris*, C. setigerus*, L. sindicus*, Saccharum munja**
400-550	*A. tortilis, P. cineraria*, P. juliflora, A. senegal, Dalbargia sisoo*, Ailanthus excelsa*, Albizzia lebbeck*, P. aculeate*, T. undulata*, D. glomerata, C. mopane*	*Z. mauritiana*, Cassia auriculata**	*C. ciliaris*, C. setigerus*, S. munja*, Panicum antidotale**

* *Indigenous species.*

Farmers protect and manage their fields during critical periods through crop residue management, fencing and boundary plantation. Due to population pressure, the earlier practice of keeping a part of the dune fallow is becoming increasingly difficult. Many farmers prefer to cultivate their dunes regularly and accept some degradation and consequent dune movement, rather than leave the land for fencing and for less lucrative proposals like growing grasses. It has been estimated that if the Government is to continue this effort at the rate of Rs. 13,000 ha^{-1}, then at least Rs.

117,000 million will be required to cover the moderately and severely affected areas in western Rajasthan (Venkateswarlu and Kar, 1996). Therefore, sand fixation by government efforts alone appears to be a difficult task in near future, and people's participation has to be invoked for its success on large scale.

Following are important considerations to make sand dune stabilization more attractive to stakeholders (Narain and Kar, 2007):

In the first place, technology should be cheaper and acceptable. Cost of fencing is a major cost, which could be neutralised by 'social fencing' through people's participation.

Involving people from planning to execution stage to evoke a sense of belonging to the community, and utilization of resources on community basis is necessary.

Sharing of resources by the landowners and landless people on equitable basis in a transparent manner is needed.

Farmers need to be educated about the tangible and intangible gains from the programme.

Demonstration models should be created through community participation.

Shelterbelt plantation

Erection of shelterbelts along the boundaries of crop fields helps to reduce wind velocity in the lee of the shelter by ~76% at 2 to 10 times height distance (Raheja, 1963). It also reduces injury to the tender seedlings due to sand blasting and hot desiccating wind. CAZRI has recommended a three-row wind break of *Acacia tortilis*, *Cassia siamea* and *Prosopis juliflora* as the side rows and *Albizzia lebbek* as the central row. Studies have also shown that plantation across the wind of a 13 m wide tree belt, interspersed with 60 m wide grass belt, provides the best results. Shelterbelts also reduce the loss of moisture from fields in the lee of shelters. At least 14% higher soil moisture and 70% more grain yield from pearl millet were recorded in the lee of shelters, as compared to that in areas without shelters (Gupta, 1993; Gupta *et al.*, 1997).

Despite such good results shelterbelts in arable lands are not very popular with farmers, because in many cases the trees are considered to be hindrance to agricultural operations and inter-field movement. CAZRI, therefore, suggests now to plant trees on field boundaries across the direction of wind. Vegetative hedges, which also serve the purpose of protecting crops from the animals, are other option for shelterbelts. Creation of shelterbelts is more a problem of education and extension rather than that of technology. Mertia *et al.* (2006) have provided a detailed review of the technology and its adoption in the western part of the Thar.

Soil and water conservation

To tackle the problem of water erosion, several soil and water conservation practices have been suggested and demonstrated. Dhruva Narayana (1993) provides details of these technologies in the country. Contour bunding (low rainfall area), graded bunding (medium to high rainfall area), bench terracing, contour tillage, contour sowing, etc., are the suggested practices on arable land. Water logging in the vertisol areas can be reduced through ridge and furrow system, while deep ploughing at 3-4 years' interval in areas having hardpan at moderate depth ensures better infiltration and root growth. In areas where gravel forms a significant part of the surficial material, but subsurface is less stony (e.g. in parts of arid Gujarat), periodic tillage reduces the chance of surface sealing, and hence the danger of water erosion. It also enhances moisture conservation. Mixing of crop residues and organic matter with light-textured soils has helped to increase soil moisture and crop yield. Conservation ditches along contours in the deep black soils of Bellary region of Karnataka state proved very successful.

Small and medium gullies on non-arable land are reclaimed through clearing and levelling of gully bed, followed by construction of contour bunds and check dams. Gully plugging and stabilization of gully heads through peripheral bunds, chutes and forest plantation need also to be adopted. For deep gullies a closure-cum-vegetative measure, as well as check dams are the usual practices. In the drier part of the desert, especially in Barmer and Jaisalmer districts, a novel traditional system of rainwater conservation for growing winter crops in conserved moisture takes care of erosion control in catchment and use of water and sediments for sustainable agriculture. Locally called Khadins, the system consists of an embankment across a drainage line with spillway arrangement, and collects the rainfall and the sediments from surrounding catchment area. As the water seeps through the sediments it partly recharges the groundwater. The soil moisture is then used for growing high-value winter crops like wheat and mustard. CAZRI has improved the design of Khadin with inlet structures for efficient water intake and spillway system for draining the excess water downslope (Prasad *et al.*, 2004).

Integrating the soil and water conservation technologies for arid areas with improved rainfed agricultural practices, CAZRI provides research support to the state on integrated watershed management technologies, where treatments for runoff and soil loss, rainwater harvesting and recycling of water for irrigation, conservation forestry, agronomic treatments, groundwater recharge and management, etc., are being executed and demonstrated to the stakeholders for adoption (Narain and Kar, 2007).

Water logging and salinity-alkalinity

For amelioration of soils degraded by high RSC water, CAZRI has standardized the technology of gypsum application to soils. Although commonly gypsum is used @ 100% of the requirement by soil, it has been demonstrated that application of gypsum in the first year @ 50% gypsum requirement of soil for ameliorating the degraded soil and an extra amount of gypsum to neutralize the excess RSC in irrigation water (i.e., RSC in excess of 5 meq L^{-1}; 0.30 t ha^{-1} gypsum is required to neutralize 1 meq L^{-1} RSC), followed by the use of Zinc sulphate @ 25 kg ha^{-1} in second year, can lower soil pH by 0.3 to 0.4 units and SAR by 6.4 to 10.7, and at the same time improve the nutrient status of the soil (Joshi, 1992, Joshi and Dhir, 1991, 1994). Joshi and Bohra (2008) found that in the saline and RSC-water-irrigated soils which have turned sodic, the application of gypsum at the 100% of gypsum requirement by soil plus the amount needed to neutralize the RSC in water in excess of 5 meq L^{-1} was more effective in soil improvement, crop growth parameters and grain yield, but the benefit: cost ratio was higher when gypsum was applied @ 50% gypsum requirement of the soil. A variety of crops are now grown in the region with waters having high RSC, especially after the gypsum treatment of the soil.

Much of waterlogging and salinity-alkalinity hazard is associated with wrong irrigation planning. This can be partly countered by vertical and horizontal subsurface drainage, as has been done in parts of the alluvial soils of Haryana and black soils of Karnataka (Abrol and Gupta, 1990; Rao and Singh, 1990). This is also being done in the Indira Gandhi Canal command area. Bio-drainage through plantation of species like *Eucalyptus camendulensis*, *Dalbergia sisoo*, *Prosopis cineraria* and *Tecomella undulata* along the margins of the waterlogged stretches has also been taken up (Kapoor, 1997). A number of afforestation and agro-forestry techniques are also available for rehabilitating the salt-affected soils (Gill *et al.*, 1990). Tree species like *Prosopis chilensis, P. juliflora, Tamarix auriculata, T. troupii, T. aphylla, Acacia nilotica, A. auriculaeformis, Casuarina obesa, C. equisetifolia,* and *Eucalyptus camaldulensis* are highly tolerant of soil salinity and are used for reclamation (Jain, 1981, 1984; Shankarnarayan and Kolarkar, 1988). The farmers are being educated about the judicious use of canal water, crop rotation and soil management practices.

Management of permanent pastures and rangelands

In order to revert the process of grazing land degradation CAZRI has developed methods of their reseeding with useful grasses, shrubs and trees, depending on their soil and terrain conditions, and different management schedules, including grazing procedures based on carrying capacity. Improved varieties of nutritious grasses and legumes, including *Cenchrus ciliaris*, *Cenchrus setigerus* and *Lasiurus sindicus*, have been developed and released for mass production. Additionally, technology for bulk grass seed production and its pelleting has been developed. Improved silvi-pastoral systems, involving combinations of top feed species like *Ziziphus nummularia, Dichrostychus nutans, Colophospermum mopane, Prosopis cineraria,* etc., and the grasses like *C. ciliaris, C. setigerus, L. sindicus, Dichanthium annulatum* and *Panicum antidotale*, have also been evolved. A carrying capacity of 4.5-6.9 sheep ha^{-1} in sandy soils and 9.0-13.8 sheep ha^{-1} in loamy sand soils have been achieved with good management (Abrol and Venkateswarlu, 1995). The successful implementation of such plans, however, depends on the whole-hearted community participation, which is slowly picking up. Special work plan is also necessary to integrate the results of scientific research on pasture development with a system of management practices of the orans and gochars at the level of elected village bodies like the Panchayats, as well as by the temple trusts, NGOs, etc.

Management of arable land

Since cropping is a major land use in the region, management of arable lands is most important for combating desertification. A number of management practices have been evolved and successfully tried by CAZRI for controlling degradation of croplands and improvement in crop yield. These are highlighted below.

Minimum tillage

In the sandy soils farmers normally practice deep tillage after every 3-4 years and a tillage pass of disking and harrowing to reduce clod percentage in surface soils, but it encourages wind erosion and hard pan development below the depth of tillage, often leading to surface crusting. A limited tillage after the first monsoon showers, on the other hand, has been found to be a better proposition in western Rajasthan (Gupta *et al.*, 1997). In loamy sand soil the production of mung bean, clusterbean and cowpea could be increased with the limited tillage of one disking and sowing (Gupta, 1993). In a sandy soil the tillage needs to be further reduced.

Stubble mulching

This is widely practiced by farmers for controlling wind erosion from arable lands. Usually farmers leave the crop residues in field after grain harvest. Best results were found by putting crop residues @ 2-5 t h^{-1} and leaving pearl millet stubbles of 45 cm height in the fields (Misra, 1964). However, availability of crop residues in arid areas is low. Therefore, it is now suggested to uproot the perennial weeds and put these on soil surface as organic mulch.

Agroforestry

Traditional agroforestry

In order to avoid the risk of frequent drought, farmers in western Rajasthan traditionally grow arable crops in association with perennial trees, shrubs and grasses. Besides ensuring some production even during the worst drought, the traditional agroforestry components provide most of the requirement from the land, including food, fodder, fuel, timber, etc. The common tree, shrub, crop and grass combinations in the traditional agroforestry systems in different rainfall zones of western Rajasthan are given in Table 10. *Prosopis cineraria* (Khejri) and *Ziziphus nummularia* (Bordi) are the two most important multipurpose woody components in traditional agro-forestry system of the region.

Improved agroforestry

CAZRI has developed a number of improved agro-forestry packages for the arid region. It has been found that the net economic returns are the highest from agri-pastoral system (B:C ratio 1.87), followed by that from agroforestry (1.69), silvi-pasture (1.66), agri-horticulture (1.46) and sole production of crops (1.24) (Bhati, 1997). The higher returns from agri-pastoral system are especially because of the importance of livestock component in the farming systems prevailing in the region. It also safeguards the vulnerable terrain from drought and desertification.

The most dominant and useful tree in crop fields is *Prosopis cineraria*, whose shade effects on crop performance remains only up to 2-3 m from the tree trunk. A tree density of 100 to 200 plants ha^{-1} has been found optimum for minimum interference with the yield of various dryland crops. *Tecomella undulata*, *Hardwickia binnata* and *Holoptelea integrifolia* are the other important tree components. Growing of pearl millet and clusterbean with grasses *L. sindicus* and *C. ciliaris* between rows of *A. tortilis* and *Z.*

rotundifolia were found to be highly compatible and remunerative in terms of grain and fodder yield. A strip cropping of grasses and kharif legumes in 1:2 ratio has been recommended, with a strip width of 5 m.

Table 10. Common tree, shrub, crop and grass combinations in western Rajasthan

Annual rainfall (mm)	Habitat	Tree/shrub species association	Associations of crops/grasses
100-150	Sand dunes, interdunes	*Calligonum polygonoides – Haloxylon salicornicum – Leptadenia pyrotechnica*	Pearl millet, clusterbean; *Lasiurus sindicus*
150-200	Rocky, gravelly pediments	*Ziziphus nummularia,- Capparis decidua*	Pearl millet, green gram, moth bean, clusterbean; *Cymbopogon jwarancusa, Aristida* spp., *Cenchrus ciliaris*
200-250	Sandy undulating plains	*Calotropis procera – C. polygonoides – Clerodendrum spp.*	Pearl millet, green gram, moth bean, sesame; *Cenchrus ciliaris* with *C. setigerus*
250-300	Alluvial plains, with carbonate pans at 80-150 cm depth	*Prosopis cineraria – Z. nummularia – C. decidua*	Pearl millet, clusterbean, green gram, moth bean, sesame; *Cenchrus ciliaris* with *C. setigerus*
250-300	Alluvial plains but soils are moderately saline	*Salvadora oleoides – P. cineraria – C. decidua*	Clusterbean, pearl millet and sesame and wheat (irrigated areas); *Cenchrus setigerus, Sporobolus* sp.
275-325	Sandy undulating plains	*P. cineraria – Tecomella undulata*	Pearl millet, clusterbean, green gram, moth bean; *Cenchrus ciliaris* with *C. setigerus*
300-350	Alluvial plains	*P. cineraria*	Pearl millet, clusterbean, green gram, moth bean; *Cenchrus ciliaris*
300-350	Alluvial plains (irrigated)	*P. cineraria – Acacia nilotica*	Sorghum, cumin, pearl millet, mustard, wheat

Silvi-pastoral system has been found to be best suited for areas receiving <200 mm rainfall, or in degraded rocky-gravelly areas. The most highly compatible trees with grasses are: *Acacia senegal, A. tortilis, Albizzia lebbek, Tecomella undulata, Colophospermum mopane, Dychrostasis nutans, Hardwickia binnata, Z. nummularia and Z. rotundifolia*. Among the pasture legumes *Clitoria ternatea* and *Lablab purpureus* showed good compatibility with *L. sindicus* and *C. ciliaris*. Production from a silvipastoral system with *A. tortilis* and *C. ciliaris* was higher than that from a pure pasture (Muthana *et al.*, 1985). The carrying capacity of a pure pasture was found to be 3.9

sheep ha^{-1} after 9 years of establishment, while that from a silvi-pastoral system was 8.5 sheep after 7 years (Tewari and Harsh, 1998). Under goat grazing, *Z. nummularia* with grass strips in 1:2 ratio led to higher economic returns due to weight gain of the animals and higher wool production (Bhati, 1997).

Rehabilitation of mine spoil areas

As described earlier, mine spoils are gradually becoming a source of land degradation in arid areas. Due to very poor plant nutrients, high pH and toxic elements in the overburden/mine dump, their rehabilitation is difficult. CAZRI has developed technologies for rehabilitating limestone, gypsum and lignite mine spoil areas, and has demonstrated these at representative mine waste for limestone, gypsum and lignite. The technology involves land shaping, development of micro-catchments for run-off to single row plants, soil treatment for enhancing micro-biological activities, half-moon structures for individual plants, and a ridge and furrow system for soil and water conservation. Planting of species like *Prosopis juliflora*, *Salvadora persica*, *Acacia tortilis*, *Albizzia amara*, *Parkinsonia aculeata*, *Dichrostachys nutan*, *Capparis decidua*, *Desmostachya bipinnata*, *Cenchrus ciliaris*, etc., have yielded better results. The best solution is to raise the plants in poly-pots in a nursery, and to transplant them after 6-9 months. Saxena *et al.* (1997) listed the suitable tree, shrub, and grass species for rehabilitation of different kinds of mine spoils. Kumar *et al.* (1998) and Sharma *et al.* (2001) have discussed the details of successful rehabilitation of a gypsum-mined land near Barmer. Praveen-Kumar *et al.* (2004) have elaborated on the technology developed for rehabilitating land spoiled by dumping of lignite mine waste in the region. It has been found that the richness and diversity of planted species increased sharply initially after the treatment, but decreased subsequently and stabilized with time.

Treatment of industrial effluents

The alarmingly high effluent problem downstream of Pali, Balotra and Jodhpur is a major concern, but still eludes a solution. A number of Common Effluent Treatment Plants (CETP) have been established to take the existing loads from the clusters of textile dying and printing mills for treatment, but are reported to be operating at less than half of the designed capacity. Also, all the harmful elements cannot be sensed by the plants. Aggarwal *et al.* (1994) identified nine tree species which could be grown with the textile effluent water in arid areas, if the water is treated properly. The plants are *Eucalyptus camaldulensis*, *Acacia nilotica*, *A. tortilis*, *Azadirachta* *indica*, *Hardwickia binnata*, *Colophospermum mopane*, *Prosopis cineraria*, *P. juliflora* and *Tecomella undulata*. However, considering the fact that high concentrations of heavy metals and undesirable elements like arsenic have been reported, danger of their contaminating the plants and then moving into the food chain cannot be ruled out. Also, the pH, RSC and SAR of the effluents are exceptionally high, which will surely damage the soil.

Conclusions

We conclude our review by highlighting the salient achievements so far in desertification assessment, monitoring and control measures. We find that CAZRI's pioneer efforts in satellite-based mapping of desertification for the UN system and for local needs provided valuable data on western Rajasthan. Till the middle of this decade similar maps for the rest of India were not available. After decades of guesswork, the country has finally come out with a systematic national map on land degradation/desertification, which is based on visual interpretation of recent satellite images, and has been prepared with the active cooperation of a large number of national and state level institutions. Despite having a problem of resolution, this effort can be furthered for rapid monitoring at periodic interval. It is also necessary to gradually shift to a digital mapping system, with minimum emphasis on visual interpretation. This will help to nullify observer's bias, and thus a major source of ambiguity in mapping the severity classes (Kar, in press).

Researches on desertification control measures have provided many new technologies that are able to improve the land condition and at the same time provide benefit to the landholders. It is now possible to suggest a number of alternatives to the farmers and other land users, which can decelerate the process of desertification, improve the quality of land and produce more from it in a sustainable manner. There is a need for faster propagation of the technologies to the stakeholders, and for large area adoption. There is also a need for periodic interaction between the land users, the researchers, the bureaucrats and the development organizations, so that all the stakeholders can benefit from co-learning processes.

Proper implementation of the control programme will be difficult if the country does not have an appropriate national land use policy, as well as a drought policy, at least for the more vulnerable arid regions. At the same time land reform and gender empowerment need to be carried out through enactment of relevant laws. It is also necessary to develop policies on management of grazing lands and other common property resources, as well as on water resources.

References

Abrol, I.P. and Gupta, R.K. 1990. Alkali soils and their management. In *Technologies for Wasteland Development* (Eds. I.P. Abrol and V.V. Dhruva Narayana), pp. 317-334. Indian Council of Agricultural Research, New Delhi.

Abrol, I.P. and Venkateswarlu, J. 1995. Sustainable development of arid areas in India with particular reference to western Rajasthan. In *Land Degradation and Desertification in Asia and the Pacific Region* (Eds. A.K. Sen and Amal Kar), pp. 135-153. Scientific Publishers, Jodhpur.

Adeel, Z., Safriel, U., Niemeijer, D., White, R., Kalbermatten, G., Glantz, M., Salem, B., Scholes, B., Niamir-Fuller, M., Ehui, S. and Yapi-Gnaore, V. 2005. *Esosystem and Human Well-being: Desertification Synthesis*. Millennium Ecosystem Assessment, World Resources Institute, Washington.

Aggarwal, R.K., Praveen-Kumar, Harsh, L.N. and Sharma, B.M. 1994. Effect of textile industrial effluents on the growth of tree species and soil properties in an arid environment. *India Forester* 120: 40-47.

Anonymous 1992. Managing fragile ecosystems: Combating desertification and drought. In *Chapter 12, Agenda 21, United Nations Conference on Environment and Development, Rio de Janeiro*. A/CONF.151/4 (Part II), United Nations, New York, pp. 46-66.

Anonymous 1994. *Draft Report on Status of Land Degradation in India*. Department of Agriculture & Cooperation, Ministry of Agriculture, New Delhi, 102 p.

Anonymous 1995. *United Nations Convention to Combat Desertification*. Interim Secretariat for the Convention to Combat Desertification, Geneva, 71 p.

Aubreville, A. 1949. *Climats, Forets et Desertification de l'Afrique Tropicale*. Societe d' Editions Geographiques, Maritimes et Coloniales. Paris, 255 p.

Baartman, J.E.M., Godert, W.J., van Lynden, W.J., Reed, M.S., Ritsema, C.J. and Hessel, R. 2007. *Desertification and Land Degradation: Origins, Processes and Solutions – A Literature Review*. Report 4, Scientific Reports Series, ISRIC, The Netherlands, 71 p.

Bajwa, M.S. and Josan, A.S. 1989a. Prediction of sustained sodic irrigation effects on soil sodium saturation and crop yield. *Agricultural Water Management* 16: 217-228.

Bajwa, M.S. and Josan, A.S. 1989b. Effect of gypsum and sodic irrigation water on soil and crop yield in rice-wheat rotation. *Agricultural Water Management* 16: 53-61.

Bharara, L.P. 1993. Livestock migration and pastoralism in Rajasthan Desert. In *Desertification and its Control in the Thar, Sahara and Sahel Regions* (Eds., A.K. Sen and Amal Kar), pp. 219-247. Scientific Publishers, Jodhpur.

Bhati, T.K. 1997. Management of dryland crops in Indian arid ecosystem. In *Desertification Control in the Arid Ecosystem of India for Sustainable Development* (Eds. Surendra Singh and Amal Kar), pp. 298-307. Agro-Botanic Publishers, Bikaner, Bhimaya, C.P. and Kaul, R.N. 1960. Some afforestation problems and research needs in relation to erosion control in arid and semi-arid parts of Rajasthan. *Indian Forester* 87: 354-367.

CSE 2006. *CSE Study on Pollution of Bandi River by Textile Industries in Pali Town*. Centre for Science and Environment, New Delhi, 13p.

CSE 2007. *Report on the Pollution in Bandi River by Textile Industries*. Centre for Science and Environment, New Delhi, 17p.

Dhir, R.P. 1990. Land degradation in the arid zone. In *Technologies for Wasteland Development*, pp. 93-107. Indian Council of Agricultural Research, New Delhi.

Dhir, R.P. 2003. Thar Desert in retrospect and prospect. *Proceedings, Indian National Science Academy* 69A(2): 167-184.

Dhir, R.P., Kolarkar, A.S. and Singh, H.P. 1992. Soil resources of the Thar. In *Perspectives on the Thar and the Karakum* (Eds. Amal Kar, R.K. Abichandani, K. Anantharam and D.C. Joshi), pp. 60-85. Department of Science and Technology, Govt. of India, New Delhi.

Dhruva Narayana, V.V. 1993. *Soil and Water Conservation Research in India*. Indian Council of Agricultural Research, New Delhi, 454 p.

Dregne, H.E. 1983. *Desertification of Arid Lands*. Harwood Academic Publishers, Chur, 242 p.

Dregne, H.E. 2000. Desertification: Problems and challenges. *Annals of Arid Zone* 39: 363-371.

Dregne, H.E. and Chou, N-T. 1992. Global desertification: Dimensions and costs. In *Degradation and Restoration of Arid Lands* (Ed. H.E. Dregne), pp. 249-281. Texas Tech. University, Lubbock.

Geist, H.J. and Lambin, E.F. 2004. Dynamic causal patterns of desertification. *BioScience* 54: 817-829.

Ghose, B., Singh, S. and Kar, A. 1977. Desertification around the Thar - A geomorphological interpretation. *Annals of Arid Zone* 16: 290-301.

Gill, H.S., Abrol, I.P. and Gupta, R.K. 1990. Afforestation of salt-affected soils. In *Technologies for Wasteland Development* (Eds. I.P. Abrol and V.V. Dhruva Narayana), pp. 355-380. Indian Council of Agricultural Research, New Delhi.

Gupta, J.P., Joshi, D.C. and Singh, G.B. 2000. Management of arid agro-ecosystem In *Natural Resource Management for Agricultural Production in India* (Eds. J.S.P. Yadav and G.B. Singh), pp. 557-668. Indian Society of Soil Science, New Delhi.

Gupta, J.P. 1993. Wind erosion of soils in drought prone areas. In *Desertification in Thar, Sahara and Sahel Regions* (Eds. A.K. Sen and Amal Kar), pp 91-105. Scientific Publishers, Jodhpur.

Gupta, J.P. and Aggarwal, R.K. 1980. Sand movement studies under different land used conditions of Western Rajasthan. In *Arid Zone Research and Development* (Ed. H.S. Mann), pp. 109-114. Scientific Publishers, Jodhpur.

Gupta, J.P. and Gupta, J.N. 1981.A note on wind erosion from a cultivated field in western Rajasthan. *Journal of Indian Society of Soil Science* 29: 278-279.

Gupta, J.P., Aggarwal, R.K. and Raikhy, N.P. 1981. Soil erosion by wind from bare sandy plains in western Rajasthan, India. *Journal of Arid Environments* 4: 15-20.

Gupta, J.P., Kar, A. and Faroda, A.S. 1997. Desertification in India: Problems and possible solutions. *Yojana* 41(8): 55-59.

Harsh, L.N. and Tewari, J.C. 1993. Sand dune stabilization, shelterbelts and silvi-pastoral plantation in dry zones. In *Desertification and Its Control in the Thar, Sahara and Sahel Regions* (Eds. A.K. Sen and A. Kar), pp. 269-279. Scientific Publishers, Jodhpur.

Hellden, U. and Tottrup, C. 2008 Regional desertification: A global synthesis. *Global and Planetary Change* 64: 169-176.

Herrmann, S.M. and Hutchinson, C.F. 2005. The changing contexts of the desertification debate. *Journal of Arid Environments* 63: 538-555.

Hickler, T., Eklundh, L., Seaquist, J.W., Smith, B., Ardo, J., Olsson, L., Sykes, M. and Sjostrom, M. 2005. Precipitation controls Sahel greening trend. *Geophysical Research Letters* 32 L 21415.

Jain, B.L. 1981. Salt balance studies in saline water irrigated soils. *Journal of the Indian Society of Soil Science* 29: 160-166.

Jain, B.L. 1984. Saline water management for higher productivity. *Indian Farming* 34: 41-43.

Joshi, D.C. 1992. Amelioration of soils degraded due to irrigation with high residual carbonate/saline water. In *Rehabilitation of Arid Ecosystem* (Eds. A.S. Kolarkar, D.C. Joshi, and K.D. Sharma), pp. 157-166. Scientific Publishers, Jodhpur.

Joshi, D.C. and Bohra, P.C. 2008. Sustainable management of saline and residual carbonate water irrigated soils. *Current Agriculture* 32: 15-21.

Joshi, D.C. and Dhir, R.P. 1991. Rehabilitation of degraded sodic soils in an arid environment by using residual Na-carbonate water for irrigation. *Arid Soil Research and Rehabilitation* 5: 175-185.

Joshi, D.C. and Dhir, R.P. 1992. Amelioration of degraded saline lands in the arid regions of Rajasthan. *Current Agriculture* 16: 33-44.

Joshi, D.C. and Dhir, R.P. 1994. Amelioration and management of soils irrigated with sodic water in the arid region of India. *Soil Use and Management* 10: 30-34.

Joshi, P.K., Jha, A.K., Wani, S.P., Joshi, L. and Shiyani, R.L. 2005. *Meta-Analysis to Assess Impact of Watershed Program and People's Participation*. Comprehensive Assessment Research Report 8, Comprehensive Assessment Secretariat, IWMI, Colombo, 18 p.

Kapoor, A.S. 1997. *Bio-drainage: A Case Study*. Indira Gandhi Nahar Board, Govt. of Rajasthan, Jaipur, 30 p.

Kar, A. (in press) Linking wind erosion with human use system in the sandy terrain of Thar Desert: A spatio-temporal analysis with digital remote sensing and GIS. In *Geoinformatics in Geomorphology* (Eds. S. Anbazhagan, S.K. Subramanian and X. Yang), CRC Press, USA.

Kar, A. 1986. Physical environment, human influences and desertification in Pushkar-Budha Pushkar lake region, India. *The Environmentalist* 6: 227-232.

Kar, A. 1993a. Aeolian processes and bedforms in the Thar Desert. *Journal of Arid Environments* 25: 83-96.

Kar, A. 1993b. Neotectonic influences on morphological variations along the coastline of Kachchh, India. *Geomorphology* 8: 199-219.

Kar, A. 1994. Sand dunes and their mobility in Jaisalmer district. In *India: Geomorphological Diversity* (Eds. K.R. Dikshit, V.S. Kale and M.N. Kaul), pp. 395-418. Rawat Publications, Jaipur.

Kar, A. 1995. Geomorphology of arid western India. In *Quaternary Environment and Geoarchaeology in India* (Eds. S. Wadia, R. Korisettar and V.S. Kale), pp. 168-190. Memoir 32, Geological Society of India, Bangalore.

Kar, A. 1996a. Desertification processes in arid western India. In *Towards Solving the Global Desertification Problem* (Eds. T. Miyazaki and A. Tsunekawa), Vol. 4, pp. 20-29. National Institute for Environmental Studies, Tsukuba.

Kar, A. 1996b. Morphology and evolution of sand dunes in the Thar Desert as key to sand control measures. *Indian Journal of Geomorphology* 1: 177-206.

Kar, A. 2008. Climate change impact on the Thar Desert. *Geography & You* Sept-Oct, pp. 36-41.

Kar, A. 2009. An analysis of climate change through quantification of forms and processes in the Thar Desert. In *Earth System Sciences* (Eds. A. Kumar, R.A. Kushwaha and B. Thakur), Vol. 2, pp. 363-381. Concept, New Delhi.

Kar, A. and Faroda, A.S. 1998. *Indicators and Benchmarks for Measuring Desertification: A View from the Thar Desert*. Consultant's Report to UN Secretariat on Convention to Combat Desertification, Geneva, 24 p.

Kar, A. and Faroda, A.S. 1999. Desertification in drylands of India: Processes and Control. In *Fifty Years of Dryland Agricultural Research in India*, (Eds. H.P. Singh, Y.S. Ramakrishna, K Sharma and B. Venkateswarlu), pp. 93-104. Central Research Institute for Dryland Agriculture, Hyderabad.

Kar, A. and Joshi, D.C. 1995. Sand movement and control of aeolian hazard. In *Land Degradation and Desertification in Asia and the Pacific Region* (Eds. A.K. Sen and Amal Kar), pp. 19-40. Scientific Publishers, Jodhpur.

Kar, A. and Takeuchi, K. 2003. Towards an early warning system for desertification. In *Early Warning Systems*. UNCCD Ad Hoc Panel, Committee on Science and Technology. UN Convention to Combat Desertification, Bonn, Germany, pp. 37-72.

Kar, A. and Takeuchi, K., 2004. Yellow dust: an overview of research and felt needs. *Journal of Arid Environments* 59: 167-187.

Kar, A., Moharana, P.C. and Singh, S.K. 2007. Desertification in arid western India. In *Dryland Ecosystem: Indian Perspective* (Eds. K.P.R. Vittal, R.L. Srivastava, N.L. Joshi, A. Kar, V.P. Tewari, and S. Kathju), pp.1-22. Central Arid Zone Research Institute, Jodhpur, and Arid Forest Research Institute, Jodhpur.

Kar, A., Moharana, P.C., Singh, S.K. and Goyal, R.K. 2007a. Deluge in the Thar Desert: Turning calamity into an opportunity for agriculture. *ICAR News* 13(2): 4-5.

Kar, A., Moharana, P.C., Singh, S.K., Goyal, R.K. and Rao, A.S. 2007b. Barmer flood, 2006: Causes and consequences. In *Flood of August 2006 in Arid Rajasthan: Causes, Magnitude and Strategies* (Eds. A.S. Faroda and D.C. Joshi), pp. 26-39. State of Art Report, Scientific Contribution No. INCOH/SAR-29/2007; INCOH, Roorkee.

Kaul, R.N. 1985. Afforestation of dune areas. In *Sand Dune Stabilization, Shelterbelts and Afforestation in Dry Zones*, pp. 75-85. FAO Conservation Guide10. FAO, Rome.

Kumar, S. 1997. Vegetation of the Indian arid ecosystem. In *Desertification Control in the Arid Ecosystem of India for Sustainable Development* (Eds. S. Singh and A. Kar), pp. 71-79. Agro Botanical Publishers (India), Bikaner.

Kumar, S. Sharma, K.D., Sharma, B.K. and Gough, L.P. 1998. Richness, diversity and evenness of vegetation upon rehabilitation of gypsum mine spoiled lands in the Indian arid zone. *Annals of Arid Zone* 37: 139-145.

Lavauden, L. 1927. Les forets du Sahara. *Revue des Eaux et Forets* 6: 265-277; 7: 329-341.

Mertia, R.S. 1996. Impact of grazing on the vegetation in the Thar desert, India. In *Towards Solving the Global Desertification Problem* (Eds. T. Miyazaki and A. Tsunekawa), Vol. 4, pp. 57-64. National Institute for Environmental Studies, Tsukuba.

Mertia, R.S., Prasad, R., Gajja, B.L., Samra, J.S. and Narain, P. 2006. *Impact of Shelterbelts in Arid Region of Western Rajasthan*. CAZRI, 76 p.

Mertia, R.S., Santra, P., Kandpal, B.K. and Prasad, R. submitted. Mass-height profile and total mass transport of wind eroded aeolian sediments from rangelands of Indian Thar Desert. *Aeolian Research* (submitted in 2009).

Middleton, N. and Thomas, D. (Eds.). 1997. *World Atlas of Desertification* (Second Edition). UNEP and Arnold, London, 182 p.

Minhas, P.S. and Gupta, R.K. 1992. *Quality of Irrigation Water: Assessment and Management*. ICAR, New Delhi, 123 p.

Misra, D.K. 1964. Agronomic investigations in arid zone. In *Proceedings of the Symposium on Problems of Indian Arid Zone,* pp. 165-169. CAZRI, Jodhpur.

MoEF 2001. *India: National Action Programme to Combat Desertification in the Context of United Nations Convention to Combat Desertification (UNCCD). Volume I: Status of Desertification*. Ministry of Environment & Forests, Government of India, New Delhi. 294 p.

Moharana, P.C. and Singh, S. 1998. Industrial effluent and its impact on degradation of landforms in western Rajasthan: A spatial analysis using GIS. *Deccan Geographer* 36: 27-39.

Mortimore, M.J. 1998. *Roots in the African Dust*. Cambridge University Press, Cambridge.

Muthana, K.D. 1982. A review of sand dune stabilization and afforestation. *Proceedings of the Workshop on the Problems of the Deserts in India*. Miscellaneous Publication 49, pp. 363-368. Geological Survey of India, Calcutta.

Muthana, K.D., Sharma, S.K. and Harsh, L.N. 1985. Study of silvipastoral systems in arid zone. *My Forest* 21: 231-233.

Narain, P. and Kar, A. (Eds.) 2005. *Drought in Western Rajasthan: Impact, Coping Mechanism and Management Strategies*. Central Arid Zone Research Institute, Jodhpur, 104 p.

Narain, P. and Kar, A. 2006. Desertification. In *Environment and Agriculture* (Eds. K.L. Chadha and M.S. Swaminathan), pp. 81-96. Malhotra Publishing House, New Delhi.

Narain, P. and Kar, A. 2007. Desertification and its control in India. In *Human and Nature – Working Together for Sustainable Development of Drylands* (Wds. A. El-Beltagy, M.C. Saxena and T. Wang), pp. 84-94. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

NBSS&LUP 2001. *Agro-ecological Sub-regions of India for Planning and Development*. NBSS&LUP Publication, Nagpur.

Nemani, R.R., Keeling, C.D., Hashimoto, H., Jolly, W.M., Piper, S.C., Tucker, C.J., Myneni, R.B. and Running, S.W. 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* 300: 1560-1563.

Oldeman, L.R. 1988. *Guidelines for General Assessment of the Status of Human-induced Soil Degradation*. ISRIC, Wageningen.

Olsson, L. 1993. Desertification in Africa – A critique and an alternative approach. *GeoJournal* 31: 23-31.

Planning Commission 2007. *Report of the Working Group on Natural Resources Management. Eleventh Five Year Plan (2007-2012).* Volume I: Synthesis. Planning Commission, Govt. of India.

Prasad, R., Mertia, R.S. and Narain, P. 2004. Khadin cultivation: A traditional runoff farming system in Indian Desert needs sustainable management. *Journal of Arid Environments* 58: 87-96.

Praveen-Kumar, Kumar, S., Sharma, K.D., Choudhary, A. and Gehlot, K. 2004. Lignite mine spoil characterization and approaches for its rehabilitation. *Arid Land Research and Management* 19: 47-60.

Prince, S.D. 2002. Spatial and temporal scales for detection of desertification. In *Global Desertification: Do Humans Cause Deserts*? (Eds. J.F. Reynolds and D.M. Stafford Smith), pp. 23-40. Dahlem University Press, Berlin.

Raheja, P.C. 1963. Shelter-belts in arid climates and special techniques for tree planting. *Annals of Arid Zone* 2: 1-13.

Raina, P. 1992. Influence of sandy soil degradation on the fertility status. *Current Agriculture* 16: 45-54.

Raina, P. 1997. Mapping of soil degradation by remote sensing in arid regions of Rajasthan. *Current Agriculture* 21: 89-96.

Raina, P. and Sen, A.K. 1991. Soil degradation studies under different land use systems in an arid environment. *Annals of Arid Zone* 30: 11-15.

Raina, P., Joshi, D.C. and Kolarkar, A.S. 1991. The mapping of soil degradation using remote sensing on alluvial plain, Rajasthan, India. *Arid Soil Research and Rehabilitation* 7: 145-161.

Ramakrishna, Y.S., Rao, A.S., Singh, R.S., Kar, A. and Singh, S. 1990. Moisture, thermal and wind measurements over two selected stable and unstable sand dunes in the Indian desert. *Journal of Arid Environment*s 19: 25-38.

Ramakrishna, Y.S., Kar, A., Rao, A.S. and Singh, R.S. 1994. Micro-climate and mobility of a barchan dune in the Thar Desert. *Annals of Arid Zone* 33(3): 203-214.

Rao, K.V.G.K. and Singh, O.P. 1990. Waterlogging and salinity problems: The management alternatives. In *Technologies for Wasteland Development* (Eds. I.P. Abrol and V.V. Dhruva Narayana), pp. 335-344. Indian Council of Agricultural Research, New Delhi.

Reynolds, J.F. and Stafford Smith, D.M. (Eds.) 2002. *Global Desertification: Do Humans Cause Desertification?* Dahlem Workshop Report 88, Dahlem University Press, Berlin, 438 p.

Reynolds, J.F., Stafford Smith, D.M., Lambin, E.F., Turner, B.L. II, Mortimore, M., Batterbury, S.P.J., Downing, T.E., Dowlatabadi, H., Fernandez, R.J., Herrick, J.E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F.T., Ayarza, M. and Walker, B. 2007. Global desertification: Building a science for dryland development. *Science* 316: 847-851.

Rodell, M., Velicogna, I. and Famiglietti, J.S. 2009. Satellite-based estimates of groundwater depletion in India. *Nature* 460(7258): 999-1002.

SAC 2007a. Desertification Monitoring and Assessment using Remote Sensing and GIS: A Pilot Project under TPN-1 UNCCD. Space Applications Centre, ISRO, Ahmedabad, 93 p.

SAC 2007b. Desertification and Land Degradation Atlas of India. Space Applications Centre, ISRO, Ahmedabad, 74 p.

Safriel, U. and Adeel, Z. 2005. Dryland systems. In *Ecosystems and Human Well-being: Current State and Trends* (Eds. R. Hassan, R. Scholes and N. Ash), Vol. 1, pp. 625-658. Island Press, Washington.

Safriel, U. and Adeel, Z. 2008. Development paths of drylands: Thresholds and sustainability. *Sustainability Science* 3: 117-123.

Samra, J.S. and Sharma, P.D. 2005. Quality of soil resources in India. *Souvenir, International Conference on Soil, Water and Environmental Quality – Issues and Strategies*, pp. 1-23. Indian Society of Soil Science, New Delh.

Santra, P. and Mertia, R.S. 2006. Air pollution through particulate matter and its impact on human health. *Science Reporter* (June), pp 28-29.

Saxena, S.K. and Chatterji, P.C. 1995. Mine spoils of arid and semi-arid areas and their rehabilitation. In *Land Degradation and Desertification in Asia and the Pacific Region* (Eds. A.K. Sen and A. Kar), pp. 233-244. Scientific Publishers, Jodhpur.

Saxena, S.K., Sharma, K.D. and Sharma, B.K. 1997. Rehabilitation of mined wastelands in Indian arid ecosystem. In *Desertification Control in the Arid Ecosystem of India for Sustainable Development* (Eds. S. Singh and A. Kar), pp. 334-341. Agro Botanical Publishers (India), Bikaner.

Schlesinger, W.H., Reynolds, J.F., Cunnighan, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A. and Whitford, W.G. 1990. Biological feedbacks in global desertification. *Science* 247: 1043-1048.

Shankarnarayan, K.A. and Kolarkar, A.S. 1988. Some promising tree species suitable for afforestation in salt-affected soils of arid zone. *Proceedings, International Symposium on Salt-affected Soils*, Vol. 2, pp. 281-285. Central Soil Salinity Research Institute, Karnal.

Shankar, V. and Kumar, S. 1987. *Grazing Resources of Jaisalmer: Ecology and Development Planning with Special Reference to Sewan Grasslands*. Monograph 21, CAZRI, Jodhpur.

Shankarnarayan, K.A. and Kumar, S. 1986. Aerial seeding of sand dunes. I. Trends in seed germination and seedling distribution. *Journal of Tropical Forestry* 2: 126-131.

Sharma, K.D. and Vangani, N.S. 1992. Surface water resources in the Thar desert and adjoining arid areas of India. In *Perspectives on the Thar and the Karakum* (Eds. A. Kar, R.K. Abichandani, K. Anantharam, and D.C. Joshi), pp. 130-140. Department of Science and Technology, Govt. of India, New Delhi.

Sharma, K.D., Kumar, S. and Gough, L.P. 2001. Rehabilitation of gypsum-mined lands in the Indian Desert. *Arid Land Research and Management* 15: 61-76.

Singh, S. and Ram, B. (Eds.) 1997. *Impact Assessment of Industrial Effluent on Natural Resources along the Jojri, the Bandi and the Luni Rivers*. Central Arid Zone Research Institute, Jodhpur, 135 p.

Singh, S.K., Mahesh Kumar, Sharma, B.K. and Tarafdar, J.C. 2007a. Depletion of organic carbon, phosphorus and potassium under pearl millet based cropping system in the arid region of India. *Arid Land Research and Management* 21: 119-131.

Singh, S.K., Mahesh Kumar and Sharma, B.K. 2007b. Changes in soil properties under pearl millet production system of arid Rajasthan. *Journal of the Indian Society of Soil Science* 57: 24-30.

Singh, S., Ghose, B. and Kar, A. 1978. Geomorphic changes as evidence of palaeoclimate and desertification in Rajasthan desert, India (Luni Development Block: A case study). *Man & Environment* 2: 1-13.

Singh, S., Kar, A., Joshi, D.C., Kumar, S. and Sharma, K.D. 1994. Desertification problem in western Rajasthan. *Annals of Arid Zone* 33(3): 191-202.

Singh, S., Kar, A., Joshi, D.C., Ram, B., Kumar, S., Vats, P.C., Singh, N., Raina, P., Kolarkar, A.S. and Dhir, R.P. 1992. Desertification mapping in western Rajasthan. *Annals of Arid Zone* 31: 237-246.

Singh, S., Singh, S., Pramod Kumar and Tikkoo, A. 2008. Response of crop rotation to sodic waters and amendments in loamy sands of southern Haryana. *Annals of Arid Zone* 47: 111-116.

Sivakumar, M.V.K. 2007. Interactions between climate and desertification. *Agricultural and Forest Meteorology* 142: 143-155.

Soni, M.L., Yadava N.D., Beniwal R.K., Singh J.P. and Sunil Kumar. 2007. Production potential of arid legumes under grass based strip cropping system in arid rainfed condition of western Rajasthan. *Journal of Arid Legumes* 4(1): 9-11.

Tewari, J.C. and Harsh, L.N. 1998. Forestry research in arid tract of India. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and Manjit Singh), pp. 307-322. CAZRI, Jodhpur.

Thomas, D.S.G. 1995. Desertification: causes and processes. In *Encyclopedia of Environmental Biology* (Ed. W.A. Nierenberg), Vol. 1, pp. 463-473. Academic Press, San Diego.

Thomas, D.S.G. and Middleton, N. 1994. *Desertification: Expanding the Myth*. John Wiley, London.

Tsunekawa, A., Kar, A., Yanai, J., Tanaka, U. and Miyazaki, T. 1997. Influence of continuous cultivation on the soil properties affecting crop productivity in the Thar Desert, India. *Journal of Arid Environments* 36: 367-384.

Tucker, C.J., Dregne, H.E. and Newcombe, W.W. 1991. Expansion and contraction of the Sahara Desert from 1980-1990. *Science* 253: 299-301.

UNCOD 1977. *Round-up, Plan of Action and Resolutions*. United Nations Conference on Desertification, Nairobi, 43 p.

UNEP 1997. *World Atlas of Desertification*. Second edition. United Nations Environment Programme, Nairobi, and Edward Arnold, London.

Vangani, N.S. 1997. water erosion and flash flood hazards in Indian arid ecosystem. In *Desertification Control in the Arid Ecosystem of India for Sustainable Development* (Eds. S. Singh and A. Kar), pp. 131-138. Agro Botanical Publishers (India), Bikaner.

Venkateswarlu, J. 1993. Problems and prospects in desertification control - Role of Central Arid Zone Research Institute. In *Desertification and its Control in the Thar, Sahara and Sahel Regions* (Eds. A.K. Sen and Amal Kar), pp. 249-267. Scientific Publishers, Jodhpur.

Venkateswarlu, J. and Kar, A. 1996. Wind erosion and its control in arid north-west India. *Annals of Arid Zone* 35: 85-99.

Vogt, J., Hill, J., Bied-Charreton, M., Rohrig, J., Safriel, U., Sokona, Y., von Maltitz, G., and Zougmore, R. 2009. Introduction. In *Integrated Methods for Monitoring and Assessing Desertification/Land Degradation Processes and Drivers (Land Quality)*. White Paper of DSD Working Group 1, Version 2, 19 August 2009. Drylandscience for Development Consortium (DSD), 173 p.

Vogt, J., Hill, J., Safriel, U., Sokona, Y. and Bied-Charreton, M. 2009. Introduction. In *Integrated Methods for Monitoring and Assessing Desertification/Land Degradation Processes and Drivers (Land Quality)*. White Paper of DSD Working Group 1, Version 1, 22 May 2009. Drylandscience for Development Consortium (DSD), 126 p.

Warren, A. 2002. Land degradation is contextual. *Land Degradation and Development* 13: 449-459.

Warren, A. and Olsson, L. 2003. Desertification: Loss of credibility despite the evidence. *Annals of Arid Zone* 42: 271-288.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 48-61 pp.

Climate Variability and Crop Production in Arid Western Rajasthan

A.S. Rao

Central Arid Zone Research Institute, Jodhpur-342 003, India

The hot arid region of India extends over an area of 317,090 km^2, covering seven administrative states of India viz., Rajasthan, Gujarat, Haryana, Punjab, Maharashtra, Karnataka and Andhra Pradesh. Two states, Rajasthan and Gujarat, account for 81.5% of the total hot arid areas in India (Krishnan, 1968a, b). There are different methods of characterizing aridity of an area. In order to take up development work that would provide the largely agriculture-dependent inhabitants the capabilities to withstand impact of drought and other natural hazards in the drylands, including arid areas, Government of India followed the concept of demarcating arid and semi-arid areas on the basis of tehsil-wise water balance to determine moisture index. If the moisture index was below -66.6%, the area was considered arid and if it was between -33.3 to -66.6% it came under semi-arid zone. Based on this demarcation areas were identified for Desert Development Programme (in arid areas) and Drought Prone Area Programme (in semi-arid areas). This chapter discusses the climatic characteristics in the arid western part of Rajasthan state.

Climate and its Variability

Arid Rajasthan is characterized by limited seasonal precipitation with erratic distribution, high atmospheric temperature that has large diurnal and seasonal variation, strong insolation and persisting wind regime. Consequently, there are high crop water requirements. The weather conditions remain too dry, even in normal years, for most part of the year and are inhospitable for successful crop growth.

Rainfall and its distribution

Normal dates of sowing rain (>25 mm week^{-1}) in western Rajasthan are between 1st and 15th July, but the monsoon sometimes sets in as late as 3rd week of July in the eastern part and 1st week of August in the western part. Sowing rains have also been found to occur at times as early as 1st week of June in the eastern part and 2nd week of June in the western part. Such early or late commencement of sowing rains lead to large variability in year-to-year crop productivity. The assured crop growing period in western Rajasthan varies from 25 to 90 days under shallow soils and 35 to 105 days under deep soils (Rao *et al.*, 1994).

The mean annual rainfall in the region varies from 185 mm at Jaisalmer to more than 467 mm at Sikar (Fig. 1). About 80-90% of the annual rainfall is received during the southwest monsoon when west-southwesterly moving depressions are the main sources for *kharif* crops. The depressions originating from the Arabian Sea during May or early June move in east-northeasterly direction and also cause rainfall but such events occur with a lesser frequency of once in 2 or 3 years. The western disturbances during winter also cause precipitation, especially in the northern districts, which favour the *rabi* crops. The high inter-annual variability in rainfall is reflected in its high degree of coefficient of variation, ranging from 36% in the eastern part to 65% in the western part. This variability in annual rainfall is the most important factor, influencing the crop and pasture yields in the region.

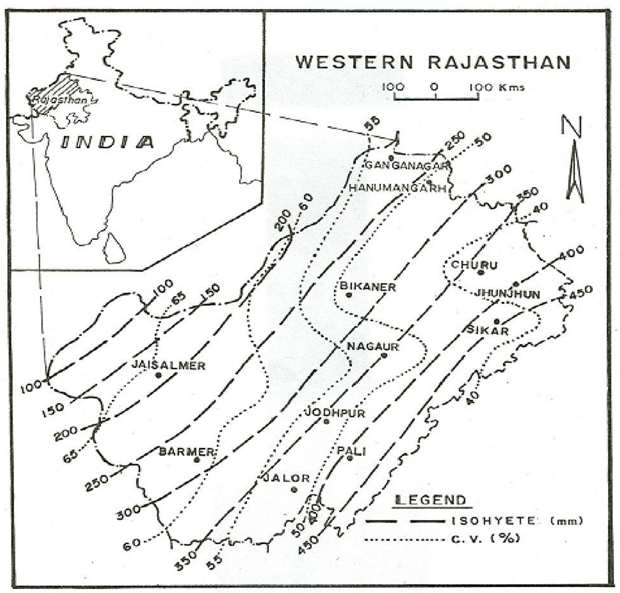


Fig. 1. Spatial distribution of annual rainfall in western Rajasthan.

Solar radiation and duration of sunshine

Solar radiation is generally high throughout the year in western Rajasthan. During winter, it varies between 15.12 and 17.71 MJ m^{-2} day^{-1} and in summer months the values range from 22.79 to 26.50 MJ m^{-2} day^{-1}, with a mean of 22 MJ m^{-2} day^{-1}. The daily duration of bright sunshine hours in the area remains above 10 h day^{-1} in May and reduces to 6.6 h day^{-1} in July and August. In winter it is above 8.8 h day^{-1}.

Air and soil temperatures

The region experiences extreme air and soil temperatures, which considerably increase the demand for water requirements by vegetation/crops. During winter, mean maximum air temperature varies from 22.4°C to 29.0°C and minimum temperatures between 4.1°C and 14.3°C. Air temperatures sharply increase from April onwards and stands highest during May till pre-monsoon showers sets in the area. Summer air temperatures vary between 31.2°C and 42.0°C with peak values as high as 50.0°C. Temperatures fall during the monsoon period (June-September), but rise by about 3.0°C to 5.0°C after the recession of the monsoon and again start falling up to -5.7°C from December onwards due to winter conditions. Soil temperatures follow the diurnal and annual cycles of air temperatures, and shoots up to 62.0°C during May and June, when in general, it is higher than air temperatures by 10.0°C (Ramakrishna *et al.*, 1990).

Relative humidity

Relative humidity in the region is often less than 30% during summer months, but gradually increases to 80% by monsoon and then decreases from October onwards, following the withdrawal of the monsoon. Low humidity, combined with strong wind regime, leads to advection, a phenomenon that causes evaporation loss more than the energy actually available through solar radiation.

Wind regime

The winds over the region blow from southwest during the monsoon and from northeast during the winter. Winds during the winter are low. From April onwards a strong wind regime builds up along with the increasing temperature, and reaches 15 to 18 km h^{-1}. Peak winds occasionally reach as high as 60-80 km h^{-1} during severe dust storms. Strong wind regime during May and June cause wind erosion, depleting soil fertility.

Evapotranspiration rates

The extreme climatic conditions in the region result in high evapotranspiration rates. The potential evapotranspiration rates are 1.3 to 3.5 mm day^{-1} during winter months of December and January. By May, the values rise to 3.7 to 9.5 mm day^{-1}. During monsoon period the evapotranspiration rates are 5.2 to 10.6 mm day^{-1}, but decrease from October onwards till December. The annual potential evapotranspiration ranges from 1400 mm in the eastern part to more than 2000 mm year^{-1} in the western part of arid western Rajasthan.

Weather Extremes

Frequency and nature of drought

The region is frequently prone to severe drought due to low and erratic rainfall. The frequency of agricultural drought at four locations of arid Rajasthan, as per Ramana Rao *et al.* (1981), is given in Fig. 2. Out of 108 years (1901-2008), the region experienced agricultural drought in one part or the other in 52 to 62 years, which suggest drought occurs in the region once in three years to alternate year.

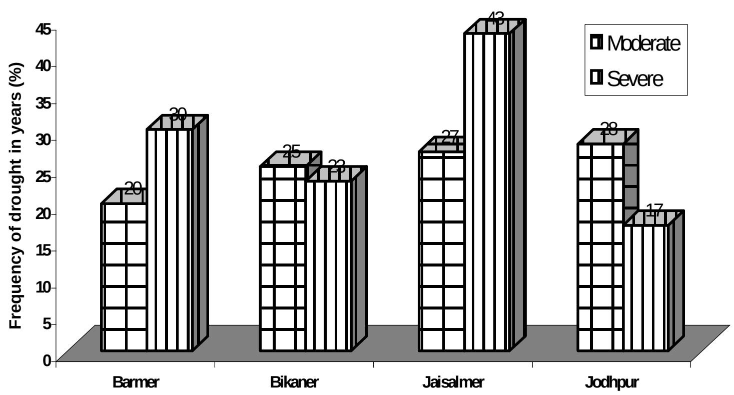


Fig. 2. Frequency of agricultural drought in four districts of western Rajasthan (1901-2008).

Jaisalmer district is most prone to drought. During 1901-2008, the agricultural drought occurred here in 70% of the years, out of which 43% of the years experienced severe drought and 27% years moderate. Barmer district experienced severe drought in 30% years and moderate drought in 20% years. Bikaner experienced severe agricultural drought in 23% years and moderate in 25% years, whereas Jodhpur district experienced severe drought in 17% years and moderate drought in 28% years.

Often, drought persists continuously for 2 to 6 years. Prolonged drought was experienced in the region during the decades 1901-10, 1911-20, 1932-40, 1961-70, 1981-90 and in 2001-2006, with 1918 and 2002 standing out as the worst drought years during the recorded period (Fig. 3). The moderate to severe drought frequency varies from 1 out of 5 years in Churu district to 2 to 3 out of 5 years in Barmer and Jaisalmer districts (Rao, 1997; Rao *et al.*, 1997; Rao and Vijendra, 2005).

Fig. 3. Decade-wise drought situation in western Rajasthan.

Probability of occurrence of early, mid and late season drought

The weekly rainfall pattern at Jodhpur during 1971 to 2008 indicated that the rainfall distribution was fairly good in 17 years, whereas in the remaining 21 years, the region experienced drought at one stage or the other. Further classification of these 21 years' drought, based on weekly rainfall distribution, showed that the probability of early season drought was 26% (9 years), mid-season drought in 9% (3 years) and late season drought in 26% (9 years). Among the three categories of drought, the impact on grain yield of pearl millet and pulses was felt more under mid-season and late-season drought (Table 1). If the drought is severe at early season of the crop and reduction in rainfall in subsequent crop stages, the impact of such severe drought is felt in the region on food, fodder and drinking water.

Table 1. Impact of seasonal drought on crop production in Jodhpur district

Kind of drought situation	Rainfall (mm)	Grain yield of pearl millet (kg ha^{-1})	Grain yield of kharif pulses (kg ha^{-1})
Normal	452	323	456
Early season drought	248	169 (-48%)	404 (-11%)
Mid-season drought	255	49 (-85%)	350 (-23%)
Late-season drought	298	90 (-72%)	176 (-61%)

Impact of drought on livestock population

The region supports a large livestock population, out-numbering humans by about 4 times in Jaisalmer district, 3 times in Barmer, 2 times in Bikaner and 1.5 times in Banaskantha, Jalor and Jodhpur districts, as against only one-half in the rest of the country. Ahuja (1994) showed that the supply of forage was 37% shorter than the demand at the current level of livestock population. During severe drought years, the normal forage productivity was declined by 82% in rainfall zone of <200 mm, 74% in 200 to 300 mm rainfall zone and 42% in 300 to 500 mm rainfall zone (Shankarnarayan and Singh. 1990). Consequently, during drought years, the livestock population decreases in the Indian arid zone due to scarcity of fodder and water. Sheep, goat, buffalo and cows were the worst affected during drought years. The consecutive drought during 1985, 1986 and 1987 resulted in decrease of livestock population (26% in cattle, 7% in sheep; Source: DAH, 2005).

Flood Scenario

Floods in this arid region are rare as compared to drought. The decadal-wise frequency of the flood-causing rainfall (called flood years), however, indicated that it occurs with a frequency of 2 to 3 out of 10 years. The decades 1911-1920, 1941-1950 and 1981-1990 were notable in this respect (Fig. 4). Broadly such rainfall has been recorded in alternate decades, e.g., in 1970-1979 and in 1990-1999. Widespread flood-causing rainfall was witnessed during 1908, 1917, 1944, 1975, 1983 and 1997 (Table 2). During 1917, the average rainfall in the region was exceeded by +161%. Such widespread excess rainfall was not recorded in subsequent years (Rao *et al.*, 2006).

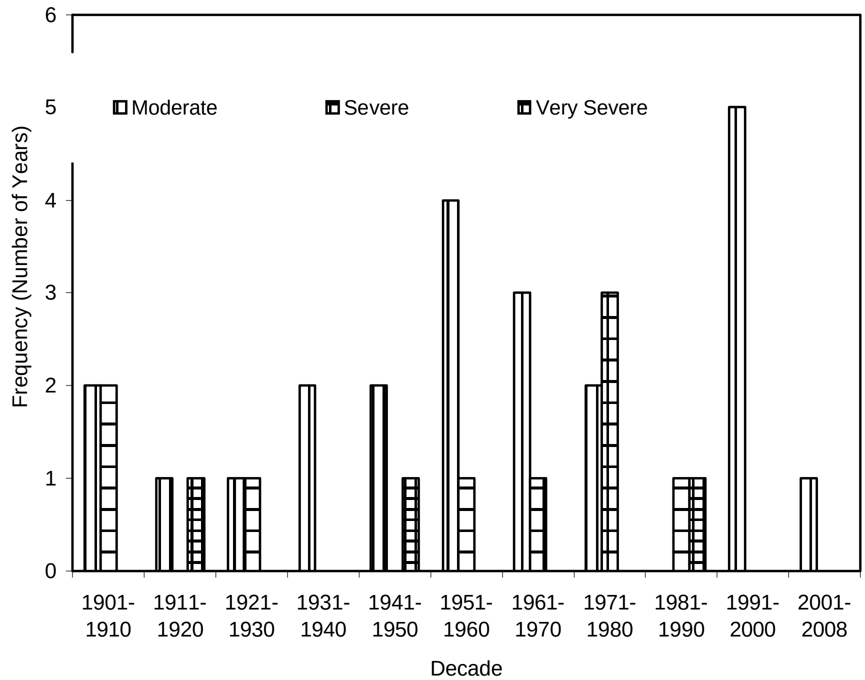


Fig. 4. Fig 4. Decade-wise flood years in western Rajasthan.

Table 2. Rainfall (mm) during flood years in arid Rajasthan

	1908	1917	1944	1975	1983	1997
Rainfall (mm)	660	782	548	597	535	543
Departure (%)	+120	+161	+83	+99	+78	+81

Cold and Heat Wave Conditions

Extreme temperatures are frequently encountered in arid Rajasthan, which cause great threats to the growth and productivity of agricultural crops in both *kharif* and *rabi* seasons. The cold or heat wave conditions many times follow in a sequence, affecting crops at various stages of growth. Often air temperature falls below -4.4°C in winter, resulting in frost injuries in *rabi* crops like mustard, castor, cumin, gram, barley, taramira and vegetables. In association with passing western disturbances, severe cold wave conditions prevail during December and January. The districts of Churu, Jhunjhunun, Ganganagar, Hanumangarh, Sikar, Jaisalmer and Bikaner are more affected by intense cold wave conditions.

Climate Change in Arid Rajasthan

The impact of projected climate change by the end of 21st Century (IPCC, 2007) is more likely in arid region than in the semi-arid or sub-humid regions of India. The arid phase of northwest India has a history of about 3000 years (Pant and Maliekel, 1987). In the northwest India, covering Punjab, Haryana, west Rajasthan and west Madhya Pradesh, there was a marginal increase in the rainfall by 141 mm and fall in air temperature by -0.52°C in the past 100 years (Pant and Hingane 1988; Rao and Miyazaki, 1997). The secular trends in annual rainfall in the arid western Rajasthan showed no significant change during 1901 to 2008 (Fig. 5).

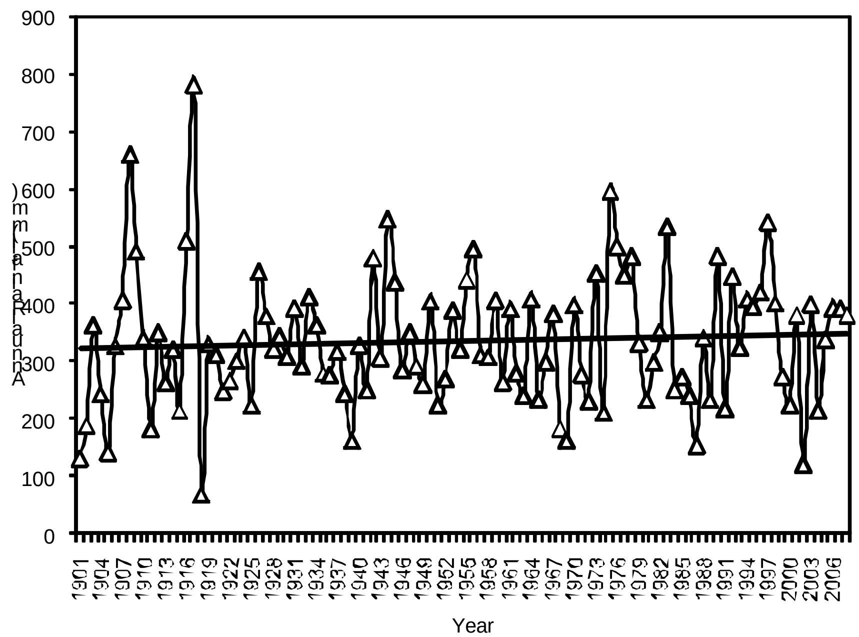


Fig. 5. Long-term rainfall trend in western Rajasthan.

To know the impact of introduction of large-scale irrigation through *Indira Gandhi Nahar Parjyojana* (IGNP) canal into the region, past hundred years of annual rainfall and air temperature data were analyzed from selected locations along the tracts of the canal (Rao, 1996, 2005). Long-term annual rainfall at Ganganagar showed an overall increasing trend at the rate of 1.18 mm year^{-1}. Even during drought years, Ganganagar area received higher rainfall than the other arid areas, attributed to the irrigation imposed for longer periods that supplied the moisture to rainfall systems and also indirectly through energy balance from increased vegetation. However, increase in rainfall was not observed in adjoining Bikaner and Jaisalmer districts, where the irrigation was introduced since past 1-3 decades.

Strategies to cope up weather extremes and climate change

Early warning of drought and crop/forage yields

Simulation of crop production from arid regions had several difficulties due to temporal and spatial variability in rainfall, high evapotranspiration rates and heterogeneity in land use or crop acreage. Because of our limited knowledge in understanding the assimilation of carbon by various arid zone crops, by and large we have to depend on regression models or soil moisture simulation models for explaining the crop/forage yield.

For drought and crop surveillance over the region, computer models like the SPAW (Soil-Plant-Air-Water) and CERES-millet have been tested and modified at CAZRI. The SPAW model was used for assessment of soil moisture and crop stress conditions under pearl millet, which could explain 89% of pearl millet yield in Jodhpur district. The relationship between pearl millet grain yield (kg/ha) and water stress index (WSI) of SPAW model was Y = -45.38 WSI + 526.18 (r=0.9427) (Rao and Saxton, 1995; Rao *et al.*, 2000).

Of the various crop growth simulation models developed by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT), using the DSSAT (Decision Support System for Agrotechnology Transfer), the CERES-millet model was used for simulation of pearl millet (Ramakrishna *et al.*, 1994), which predicted grain yield and other parameters closer to the observed yield.

RANGETEK model was used for prediction of forage yield of promising arid grasses like *Lasiurus sindicus, Cenchrus ciliarias, C. setigerus* (Singh *et al.*, 1996a, b). The model was used for real-time simulation of daily soil water content, soil evaporation and plant transpiration to forecast forage production in terms of a ratio of actual to potential transpiration (yield index). The deviations between recorded and estimated forage yield using the model were from 8 to -12% (Singh *et al.*, 1996a). The studies on *C. ciliaris* revealed that the predicted yields using the RANGETEK model were between -10% and +15% of actual forage records (Singh *et al.*, 1996b). These 1-dimension model combined with a knowledge based geo-spatial Decision Support System (DSS) could be an effective tool for drought early warning and management by farmers, experts and general end-users.

Evapotranspiration rates and water-use efficiency of crops

Evapotranspiration requirements of crops were measured in gravimetric lysimeters, keeping the crop under unstressed conditions (100%PET rates of irrigation). The crop coefficients at different growth stages, water-use efficiency (kg/ha/mm) were computed for planning scarce water resources of arid area for increasing the productivity per unit of water. The evapotranspiration requirements of various arid zone crops along with range of crop coefficients are given in Table 3.

Table 3. Evapotranspiration, crop coefficients and water-use efficiency of arid zone crops

Name of crop	Seasonal evapotranspiration (mm)	Crop coefficient	Water-use efficiency (kg ha^{-1} mm^{-1})
Pearl millet (cv. HHB 67)	317-416	0.34-1.35	3.87-7.68
Clusterbean (cv.Maru guar)	425-803	0.42-1.17	2.17-2.92
Green gram (cv.S-8)	293-340	0.36-1.10	2.82-2.36
Mothbean (cv.Maru moth)	246-347	0.3-1.2	2.3-3.5
Cowpea (cv. Charodi-1)	301-322	0.50-1.19	3.24-5.85
Mustard (cv. Bio-902)	533-570	0.80-2.13	4.51-4.76

Rainwater harvesting for coping with drought

Rainwater harvesting is an old practice in arid Rajasthan. Both *in-situ* as well as *ex-situ* techniques can be utilized to harvest runoff rainwater for productive uses like drinking and supplementary irrigation purposes. It is estimated that nearly 300 mcm of water for human consumption, 350 mcm for livestock and 6800 mcm for irrigation is required by 2010 (Venkateswarlu *et al.*, 1990).

Crop contingency plan for delayed monsoon condition

CAZRI (Narain *et al.*, 2006) prepared contingency plans for delayed monsoon. Delay in monsoon reduces the water availability period and need strategies to grow crops, which match and yield better under such conditions.

Such contingency plans were found useful to obtain better economic returns compared to traditional systems.

Use of weather based Agro-Advisory Service

Weather based agro-advisory bulletins to farmers provide information on a real-time basis so that they can avail advantage of climatic information to minimize crop losses caused by unfavourable weather. Since 1998 CAZRI is issuing bi-weekly agro-advisory bulletins based on Medium Range Weather Forecasts prepared by National Centre for Medium Range Weather Forecast (NCMRWF). The information on the type of weather situations likely to be encountered and the method to be adopted for efficient management of inputs, is provided to the farmers in advance for minimizing weather related risks.

To measure the economic impact of agro-advisory services (AAS), a three-year survey in Manai, Narva and Palri Mangalia villages of Jodhpur district was conducted during 2003 to 2006. The economic analysis on benefit-cost ratio for *kharif* and *rabi* crops indicated that for pearl millet the benefit-cost (B:C) ratio was 2.15 to 3.17 for AAS farmers, whereas for non-AAS farmers it was 0.73 to 2.80. In case of mustard, farmers were much benefited as the B:C ratio for AAS was 1.92 to 2.25 against 1.64 to 2.13 for non-AAS farmers (Rao, 2008).

Conclusions

The climate of arid western Rajasthan is characterized by limited seasonal precipitation with erratic distribution, high atmospheric temperatures with large diurnal and seasonal variation, intense solar radiation and strong wind regime, considerably influencing the crop production. Annual rainfall in the region varies from 185 mm at Jaisalmer to 467 mm at Sikar. Solar radiation ranges 15 to 27 $MJ/m^2/day$ with air temperatures ranging from -6 to 50°C. The overall impact of extreme climatic conditions in the region result high evapotranspiration rates of 1400-2000 mm $year^{-1}$. Besides weather variability, the impact of projected climate change is more likely on crop production in arid region than in semi-arid or sub-humid regions of India. However, the secular trends in annual rainfall of arid Rajasthan revealed that there was no significant change in annual rainfall of arid Rajasthan during the past century, but climate change may influence frequency and intensity of extreme weather events like drought, flood, cold and heat wave conditions.

Drought affects crop production in the Indian arid region than any other disaster. The spatial variability of incidence of agricultural drought shows that it occurs in 25% of the years at Sikar compared to 70% at Jaisalmer. Between 1901 and 2008, the region experienced 58 moderate to severe droughts. Floods in the area occur with a frequency of 2/3 years out of 10 years and its frequency is much less compared to drought. Widespread floods were reported in 1900, 1917, 1944, 1975, 1983 and 1997. Another serious threat in arid agriculture is due to extreme temperatures that occur during *rabi* and summer seasons. In association with passing western disturbances during December to January, severe cold wave conditions prevail in the entire northwestern and northern parts of India. Temperatures in arid Rajasthan rise up to 50°C in summer and on the contrary, falls below -5°C in winter period resulting frost injuries.

The studies showed the crop losses can be minimized by better utilization of natural resources from early weather warnings, rain water harvesting, use of proper contingency plans in case of delayed monsoon, irrigation of scarce water based on crop water requirements and by use of weather dependent agro-advisories on timely sowing, irrigation, harvesting dates, expected pests and diseases and their eradication, anticipated drought, heat and cold waves conditions.

References

Ahuja, L.D. 1994. Livestock production on rangelands in the Indian arid zone. In *Sustainable Development of the Indian Arid Zone - A Research Perspective* (Eds. R.P. Singh and Surendra Singh), pp. 179-190. Scientific Publishers, Jodhpur.

DAH 2005. Annual Report. Department of Animal Husbandry, Jaipur, Rajasthan.

IPCC 2007. *Climate Change – Impacts, Adaptation and Vulnerability*. Report of Working Group-II, Contributions to the Inter-governmental Panel on Climate Change. Fourth Assessment Report. IPCC, 23 p.

Krishnan, A. 1968a. Delineation of different climatic zones of Rajasthan and their variability. *Indian Journal of Geography* 3(1): 35-40.

Krishnan, A. 1968b. Delineation of different climatic zones of India. In *Proceedings of the XXI International Geographical Congress - Symposium on Arid Zone*, pp 11-19.

Pant, G.B. and Hingane, L.S. 1988. Climatic changes in and around the Rajasthan Desert during the 20th Century. *Journal of Climatology* 8: 391-401.

Pant, G.B. and Maliekal, J.A. 1987. Holocene climatic changes over north-west India - An appraisal. *Climatic Change* 10: 183-194.

Narain, P., Rathore, L.S., Singh, R.S. and Rao, A.S. 2006. Drought Assessment and Management in Arid Rajasthan. CAZRI, Jodhpur, and NCMRWF, Noida, 64 p.

Ramakrishna, Y.S., Rao, A.S., Singh, R.S., Kar, A. and Singh, S. 1990. Moisture, thermal and wind measurements over two selected stable and unstable sand dunes in the Indian desert. *Journal of Arid Environments* 19: 25-38.

Ramakrishna, Y.S., Rao, A.S. and Singh, A.S. 1991. Studies on water and energy use efficiency of pearl millet. In *Proceedings of the National Seminar on Hydrometeorology*, Publication 5, pp. 13-17. MPKV, Rahuri,

Ramakrishna, Y.S., Joshi, N.L., Rao, A.S. and Singh, H.P. 1994. Performance of modified CERES Millet Model under arid and semi-arid conditions. *Rainfed Agriculture-Research Newsletter* 4: 3-5. Central Research Institute for Dryland Agriculture, Hyderabad.

Ramana Rao, B.V., Sastri, A.S.R.A.S. and Ramakrishna, Y.S. 1981. An integrated scheme of drought classification as applicable to Indian arid region. *Idojaras* 85: 317-322.

Rao, A.S., Ramakrishna, Y.S. and Venkateswarlu, J. 1994. Determination of crop growing period in arid and semi-arid regions of Rajasthan. *Annals of Arid Zone* 33: 229-231.

Rao, A.S. and Saxton, K.E. 1995. Analysis of soil water and water stress for pearl millet in an Indian arid region using the SPAW model. *Journal of Arid Environment* 29: 155-167.

Rao, A.S. 1996. Climatic changes in the irrigated tracts of Indira Gandhi Canal Region of arid western Rajasthan, India. *Annals of Arid Zone* 38: 111-116.

Rao, A.S. 1997. Impact of droughts on Indian arid ecosystem. In *Desertification Control in the Arid Ecosystem of India for Sustainable Development* (Eds. Surendra Singh and Amal Kar), pp. 120-130. Agro Botanical Publishers (India), Bikaner.

Rao, A.S. and Miyazaki, T. 1997. Climatic changes and other causative factors influencing desertification in Osian (Jodhpur) region of the Indian arid zone. *Journal of Arid Land Studies* 7(1): 1-11.

Rao, A.S., Gupta, J.P. and Faroda, A.S. 1997. Changing climatic scenarios and strategies for drought management in the Indian arid region. *Drought Network News*, Nebraska 9(1): 8-11.

Rao, A.S., Joshi, N.L. and Saxton, K.E. 2000. Monitoring of productivity and crop water stress in pearl millet using the SPAW model. *Annals of Arid Zone* 39: 151-161.

Rao, A.S., Singh, R.S., Joshi, N.L. and Ramakrishna, Y.S. 2000. Evapotranspiration, water and radiation utilization of clusterbean (*Cyamopsis tetragonolaba*). *Indian Journal of Agricultural Sciences* 70: 149-153.

Rao, A.S and Singh, R.S. 2003. Evapotranspiration, water-use efficiency and thermal time requirements of greengram (*Phaseolus radiatus)*. *Indian Journal of Agricultural Sciences* 73: 18-22.

Rao, A.S and Singh, R.S. 2004. Water and thermal characteristics of cowpea (*Vigna unguiculata* L. Walp.). *Journal of Agrometeorology* 6: 39-46.

Rao, A.S. and Vijendra K Boken. 2005. Agricultural drought monitoring and management in India. In *Monitoring and Prediction of Drought: A Global*

Study (Eds. Vijendra K. Boken, A.P. Cracknell and R.L. Heathcote), pp. 297-312. Oxford University Press, New York.

Rao, A.S., Purohit, R.S., Mertia, R.S., Poonia, S. and Sharma, M.D. 2006. Meteorological aspects of floods in arid Rajasthan. *Maru Krishi Chainika* (in Hindi) 10: 32-39.

Rao, A.S. and Singh, R.S. 2007. Evapotranspiration rates and water-use efficiency of 'HHB 67' pearl millet (*Pennisetum glaucum* L) under arid climatic conditions. *Indian Journal of Agricultural* Sciences 77: 16-19.

Rao, A.S. 2008. Weather-based agro-advisory services for food security in the Indian arid region. *Journal of Agrometeorology* (Special issue, Part 2): 535-540.

Shankarnarayan, K.A. and Singh, K.C. 1990. Rehabilitation of degraded pastureland in the arid region of Rajasthan. In *Technologies for Wasteland Development* (Eds. I.P. Abrol and V.V. Dhruvanarayana). ICAR, New Delhi, pp. 21-31.

Singh, K.C., Rao, A.S. and Singh, H.P. 1996a. Estimation of production potential and yield of sewan (*Lasiurus sindicus)* grass in *Thar* Desert of Rajasthan. *Indian Journal of Agricultural Sciences* 66: 413-417.

Singh, K.C., Rao, A.S. and Singh, H.P. 1996b. Forage yield of *Cenchrus ciliaris* pasture and its prediction in the arid region of Rajasthan. *Annals of Arid Zone* 35: 155-157.

Singh, R.S., Rao, A.S., Joshi, N.L. and Ramakrishna, Y.S. 2000. Evapotranspiration rates and water utilization of mothbean under two soil moisture conditions. *Annals of Arid Zone* 39: 21-8.

Singh, R.S., Rao, A.S. and Laxminarayan 2007. Water and heat-use efficiency of mustard (*Brassica juncea* L. Czern. & Coss) and its yield response to evapotranspiration rates under arid conditions. *Journal of Agrometeorology* 9: 236-241.

Venkateswarlu, J., Sen, A.K., Dubey, J.C., Joshi, N.L., Kar, A., Kolarkar, A.S., Purohit, M.L., Ramakrishna, Y.S., Rao, A.S. and Sharma, K.D. 1990. *Water 2000 AD - The Scenario for Arid Rajasthan*. CAZRI, Jodhpur, 49 p.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 62-77 pp.

Land Use of Arid Lands in India

Balak Ram

Central Arid Zone Research Institute, Jodhpur

Land use is the human modification of natural environment of wilderness into built environment. Land cover is the observed bio-physical cover on the earth's surface while land use is the arrangement, activities, and inputs people undertake in a certain land cover type to produce, change or maintain it (FAO, 2005). India has about 18% of world's human and 15% of livestock population to be supported with only 2.4% of the world's geographical area and 1.5% of forest and pasture land. Per capita availability of land in the country has reduced from 0.4 ha in 1950-51 to 0.14 ha in 2000-01. With the prevailing trend it may be further reduced to 0.077 ha by 2020.

In the hot arid ecosystem of India low and erratic rainfall, extremes of temperature, high evaporation loss, saline and meagre groundwater, absence of perennial streams, and dune-covered and rocky/gravelly terrain, are the major factor influencing the land uses. Agriculture, which is the most dominant land use, is mainly rainfed and subjected to high risk and uncertainty. The cold arid Ladakh region of Jammu and Kashmir state is situated in the high Himalayan Mountain, where arable land is very limited and the length of growing period (LGP) is short. Human activities are very limited and so are the livelihood sources.

Before the 1960s land use studies were primarily based on revenue and land records data. Thereafter the use of topographical maps and aerial photographs made it possible to show the spatial distribution of different land use systems. After the 1970s satellite remote sensing and GIS virtually revolutionized the research on land use mapping and monitoring of changes over time and space. This chapter provides a short review of the major findings on land use studies on arid ecosystem of India.

Land Use: A Historical Perspective

History of land use and land classification system in the arid ecosystem is reported by Roychaudhury (1966, 1970). Evolution of land use in north-west arid zone of India has been reported by Whyte (1960), Bharadwaj (1965) and Randhawa (1980). According to these studies land use in the region evolved through the Neolithic Period when man had taken up sedentary life and had domesticated the animals. They first settled along the rivers and near water points, and later on shifted to other marginal areas. James Todd's Annals and Antiquities of Rajasthan (1929; reprinted 1978) and Erskine's Western Rajputana States Residency and Bikaner Agency Gazetteer (1909) highlight the land use system that prevailed during British Period but no systematic account is given. Classical treatise of Nainsi Mohto (Singh, 1969; Jain, 1974) on *Marwar-ra Pargana-ri Vigat* provides an account of cultivated area and crops being produced in the 'Khalsa' villages which were directly administered by the rulers. No account was available for villages under the *Jagirdars*. After the settlement of land holdings, abolition of *Jamindari* system and reorganization of states, the use of each land holding, including the area under different crops as per cadastral map of a village began to be recorded in a register called the *Girdawari*, and it continues till today.

Kanitkar (1952) estimated that out of 88597 miles^2 area in Rajputana desert only 20694 miles^2 was available for cultivation, while net sown area was 8124 miles^2. Irrigated area was nearly 1486 miles^2. Banerji (1952) while defining the role of vegetation in desert control estimated 320 miles^2 of '*Khalsa*' area under forest department. Total *khalsa* area was 5,545 miles^2. Thus forest covered only 5.8% area. Culturable waste covered 523 miles^2. Nearly 31,000 miles^2 was with the *Jagirdars*.

Land Use Classification System

The Land Records Office at tehsil or taluka level keeps land use record of each village under their jurisdiction using a 44-column proforma. This classification system categorizes fallow lands into three sub-classes under individual and government holdings; area irrigated by different sources and subclasses of rainfed, double cropped and net sown areas. Based on this format the State-level Directorate of Economics and Statistics compiles and publishes annually the land use data by adopting a 16-point format and 12 land use classes. Irrigated area is not included in this classification system, but is given separately under irrigation. At national level the land use data is published by the Directorate of Economics and Statistics, Department of Agriculture and Cooperation, under a nine-fold classification system. The district Census Handbook published by the Directorate of Census Operations also includes land use data in five classes, viz., forest, irrigated area, rainfed area, culturable waste and permanent pastures, and area not available for cultivation. The spatial pattern of the land uses was partly available from the large-scale topographical sheets prepared by Survey of India.

Systematic mapping of land uses in the arid zone began after the establishment of Central Arid Zone Research Institute in 1959, especially as a component of integrated basic resources survey and mapping. Taking into consideration various land use classification systems available then, the typical problems of arid zone and the feasibility of mapping, A.K. Sen evolved a land use classification system for the Indian arid zone, which is summarized in Sen (1978, 1982). Sen (1972a, I977a, b) also developed aerial photo interpretation techniques to classify and map different land use categories. The classification contains 15 land use categories. Cultivated lands were classified into seven categories based on the intensity of cultivation to avoid repetition of land use survey every year, since the annual extent of cropped area varies and depends on the intensity, distribution and amount of rainfall. Wastelands were classified into four categories viz., sandy, saline, rocky/stony and rocky and gravelly waste, to which were added subsequently the gullied waste, mud waste and waterlogged areas. It formed a basis for the future nation-wide land use/land cover mapping from satellite data (Gautam and Narayan, 1988; NRSA, 1989) that identifies six land use/land cover categories under Level-I and 24 categories under Level-II, as well as the wasteland mapping units (NRSA, 1986, 1991). The satellite-based classification system was further refined during the Integrated Mission for Sustainable Development (IMSD) project of ISRO, when classification up to Level-III was possible (i.e., kharif and rabi croplands; dense and open forest/grassland cover; NRSA, 1995a; Balak Ram, 2002). The classification system has further evolved in recent years with the availability of higher-resolution satellite images.

Land Use Mapping

Quantitative information on land uses and cropping systems was reported by Mishra and Kachhawa (1962), Bose and Malhotra (1964), Sen and Abraham (1966), Mishra (1967), Ahmed (1968), and Qureshi (1969). The first systematic land use mapping at district level in the desert was carried out in Bikaner district when the reconnaissance survey and mapping was done at Quarter Inch scale (Sen *et al.*, 1982), and their relationship with geomorphic units was identified (Sen and Singh, 1977). District level semi-detailed land use survey at 1:50,000 scale and final mapping at 1:250,000 scale was initiated with Jodhpur district in 1974 (Anon. 1982), followed by Nagaur district in 1978 (Chatterji and Kar, 1989). The process was followed subsequently in the districts of Jaisalmer (Chatterji and Kar, 1992), Kachchh

(Balak Ram and Sen, 1988; Balak Ram and Chauhan, 1994; Singh and Kar, 1996), Jalor (Singh *et al*., 1996), Sikar (Balak Ram and Chauhan, 1992, Balak Ram and Gheesa Lal, 1996), Abohar tehsil of Ferozepur district (Anon., 1992a), and Jamnagar (Balak Ram and Gheesa Lal, 1995). Reconnaissance land use mapping was also carried out in Mahendragarh district of Haryana (Anon., 1981). Semi-detailed land use mapping on watershed basis in 34,440 km^2 area of the upper Luni basin was carried out in Guhiya (Balak Ram *et al.*, 1983), Bandi (Balak Ram and Gheesa Lal, 1988), Jojri and upper Luni catchments (Shankarnarayan and Kar, 1983). Subsequently, using Indian remote sensing satellite data land use mapping was carried out in Ganganagar, Hanumangarh, Churu and Jhunjhunun districts for integrated analysis (Gheesa Lal, 1999; Balak Ram and Chauhan, 1999, 2001, 2002; Balak Ram *et al*., 2003; Balak Ram and Chauhan, 2006). Semi-detailed land use mapping at 1:50,000 scale was also undertaken in Churu (Sen and Ram, 1980), Jhunjhunun (Balak Ram *et al.*, 1999), Ganganagar (Sen and Gupta, 1980) and Jaisalmer districts (Sen and Gheesa Lal, 1980) at the request of Rajasthan Government.

Detailed land use mapping at cadastral scale (1:6336) was carried out in 1972 in five villages for Daijar Operational Research Project area in Jodhpur district (Sen *et al*., 1978). Gheesa Lal (1974) mapped the land use in Borunda village of Nagaur district. Detailed study on land use and cropping pattern was carried out in Balesar, Doli and Jhanwar villages of Jodhpur district in relation to soils (Balak Ram and Joshi, 1984; Chatterji, 1987a,b), in six villages of Bikaner district for suggesting development (Gheesa Lal *et al.*, 1991), and in eleven villages of five desert districts for DDP work. This was followed by land use mapping of Ganaganagar.

Sen (I972b) brought out an Agricultural Atlas of Rajasthan, and linked the agro-demographic aspects with land use systems (Sen, 1976, 1984). In Haryana, Singh (1972a,b) worked out land use efficiency at the level of assessment circles by taking a number of parameters. Singh (1976) also provided details of land use, cropping pattern, settlement pattern and agricultural production in the then districts of Haryana. The publication includes a number of thematic maps showing district-level information on various aspects of agriculture and its development.

Under the Nationwide Land Use/Land Cover Mapping project, coordinated by NRSA, the land use/land cover mapping of nine districts of arid Rajasthan was carried out (Balak Ram and Singh, 1995). Balak Ram and Chauhan (2007) carried out land cover mapping of Nawalgarh tehsil of Jhunjhunun district using land Cover Classification System (LCCS) of FAO and GeoVIS softwate. Under the Wasteland Updating Project of NRSA, the wastelands of Bikaner (Balak Ram and Chauhan, 2005), Barmer (Balak Ram and Chauhan, 2005; Balak Ram *et al*., 2006), Jalor (Balak Ram and Chauhan, 2005) and Jodhpur districts (Balak Ram *et al*., 2005) were mapped. Under the NATP project on Land Use Planning for Management of Agricultural Resources in Arid Agro-ecosystem, detailed land use mapping in eight watersheds of Rajasthan, Punjab, Haryana, Gujarat and Tamil Nadu regions was carried out (Balak Ram *et al*., 2004). So far land use mapping has been completed in 43, 919 km^2 area at reconnaissance level, 23, 9274 km^2 area at semi-detailed level and 1413 km^2 area at detailed level.

Land use/land cover mapping in other arid areas of the country was carried out by various organizations under National-wide Land Use/Land Cover Mapping Project (NRSA, 1995b, 2005). HARSAC and RRSSC-J (1991) carried out district-wise land use/land cover mapping of Haryana using satellite data. Rao *et al.* (1882) carried out integrated survey of Anantpur district, while Rajshekhar (1994) on land use pattern of Rayalseema region of Andhra Pradesh. CMDR (2008) carried out land and forestry accounting in Karnataka.

Present Land Use

As per land use statistics of 2005-06 out of 42.5 mha area of hot arid ecosystem, cultivated lands constitute 63.67%. This includes 51.69% net sown area, 6.26% current fallow and 5.72% other fallow land. Net and gross irrigated areas are 17.26% and 26.75%, respectively. Double cropped area is 14.09%. Among the other uses, forestland occupies 5.72%, pasture 3.21%, land put to non-agricultural uses 5.3%, barren and uncultivable land 9.10% and miscellaneous tree crops and groves 0.18%. Land use statistics of the hot arid zones of Rajasthan, Gujarat, Punjab, Haryana, Andhra Pradesh and Karnataka as per revenue data are summarized in Tables 1 to 3.

Satellite-based mapping has revealed that the region has 9.12 mha or 21.56% area under wastelands (NRSA, 2005) of different categories. Arid western Rajasthan has its 29.4% area under wastelands, Andhra Pradesh 22.27%, Gujarat 13.17%, Karnataka 11.22%, Haryana 3.58% and Punjab 4.07%. Sandy wastes are most dominant in Rajasthan, barren rocky/stony waste and salt affected lands in Gujarat, and degraded forest and land with/without scrub in Andhra Pradesh and Karnataka. Pearl millet, cluster bean, moth, mustard and wheat are the important crops in arid Rajasthan, cotton, wheat, rice and mustard in Haryana and Punjab, groundnut, cotton and castor in Gujarat and green gram, red gram, groundnut and sunflower in Andhra Pradesh and Karnataka.

Table 1. Land use in arid zone of Rajasthan and Gujarat

Land Use Category				
	Area in ha	Area in %	Area in ha	Area in %
Total geographical area	20820512		9350400	
Forest	455012	2.19	599300	6.41
Land put to non-agril. uses	955830	4.59	361900	3.87
Barren & uncultivable land	1008118	4.84	2116300	22.63
Permanent pasture	815500	3.92	374900	4.01
Misc. tree crops & groves	8780	0.04	0	0
Culturable waste	3678757	17.66	1766100	18.89
Other fallow	1707894	8.20	4800	0.05
Current fallow	1533467	7.37	242000	2.59
Net sown area	10657154	51.19	3885100	41.55
Total cropped area	12731704	61.15	4477800	47.89
Area sown more than once	2074550	9.96	592700	6.34
Net irrigated area	2699952	12.97	1052700	11.26
Gross irrigated area	3773656	18.12	1234100	13.20

In the cold arid region, out of 9.67 mha total area (in Leh and Kargil districts) the reporting area is only 64,626 ha. Rest of the area is covered by snow and hill ranges. Out of the total reporting area cultivated lands constitute 30.92%, which includes 29.67% net sown area, 0.53% current fallow and 0.72% other fallow land. Forest occupies 0.1% area, land put to non-agricultural uses 6.32%, barren and uncultivable land 45.03%, pasture 1.69%, miscellaneous tree crops and groves 2.49% and culturable waste 12.36%. Wasteland statistics of NRSA (2005c) revealed 5.06 mha (88.28% of the total geographical area) under wastelands in the two districts. This includes 52.6% barren rocky/stony waste, 12.05% steep sloping area, 30.15% snow covered area, 2.68% sands and 0.18% degraded pastures. Ragi, wheat, barley, millet and apricot are important crop of this region.

Land Use Changes

Between 1982-83 and 2005-06 net irrigated and double cropped area in hot arid region has increased by 128% and 70%, respectively. Net sown area has increased by 2.4% only, current fallow by 1.7% and other fallow land by 12.1%. More impetus has been given to irrigated cash crops. The area under forest has increased by 4.6% and land put to non-agricultural uses by 16.6%. On the other hand, the area under culturable waste has declined by 18.6%, pasture by 7.7%, miscellaneous tree crops and groves by 36.8% and barren and uncultivable land by 2.2%. The area statistics for the two reporting years in the region is provided in Table 4.

Table 2. Land use in arid zone of Punjab and Haryana

Land Use Category	Punjab		Haryana	
	Area in ha	Area in %	Area in ha	Area in %
Total geographical area	1711000		1741000	
Forest	30000	1.75	7000	0.40
Land put to non-agril. uses	137000	8.01	119000	6.84
Barren & uncultivable land	7000	0.41	43000	2.47
Permanent pasture	0	0	0	0
Misc. tree crops & groves	0	0	0	0
Culturable waste	5000	0.29	3000	0.17
Other fallow	0	0	0	0
Current fallow	23000	1.34	98000	5.63
Net sown area	1509000	88.20	1471000	84.49
Total cropped area	2841000	166.0	2799000	160.8
Area sown more than once	1332000	77.85	1328000	76.28
Net irrigated area	1507000	88.08	1175000	67.49
Gross irrigated area	2847100	166.4	2159000	124.0

Arid western Rajasthan has recorded substantial increase of 42% in net sown area, while forest has increased by 67.4%. Area under culturable waste has declined by 26.3%. This shows that though marginal lands have been brought under cultivation, the intensity of cultivation, particularly in rainfed lands, has not increased to that extent. This has increased the fallow lands. Environmentally sensitive common lands have become more victims of degradation by nature and man. Uneconomic use and over-exploitation of natural resources have caused problems like secondary salinization, water-logging, mined spoil areas, degradation of groundwater, intensification of sand movement, blockade of natural drainage and spread of industrial effluents. Silting and pollution of irrigation tanks/ponds, degradation of mangroves and reduction in biomass are the other impacts.

Table 3. Land use in arid zone of Andhra Pradesh and Karnataka

Land Use Category	Andhra Pradesh		Karnataka	
	Area in ha	Area in %	Area in ha	Area in %
Total geographical area	5211365		3665638	
Forest	1020142	19.57	318118	8.68
Land put to non-agril. uses	451389	8.66	225167	6.14
Barren & uncultivable land	515568	9.89	140311	3.83
Permanent pasture	33936	0.65	141911	3.87
Misc. tree crops & groves	19522	0.38	48921	1.34
Culturable waste	218628	4.20	71633	1.95
Other fallow	304403	5.84	159923	4.36
Current fallow	365864	7.02	395992	10.80
Net sown area	2281913	43.79	2163662	59.03
Total cropped area	2480395	47.60	2628186	71.70
Area sown more than once	198482	3.81	464524	12.67
Net irrigated area	443657	8.51	623814	17.02
Gross irrigated area	539607	10.35	817231	22.29

In the cold arid region, horizontal and vertical development of agricultural is not up to the mark. Between 1982-83 and 2005-06 the net sown area has increased by 5.1%, other fallow land by 151.1%, land put to non-agricultural uses by 37.23%, and double cropped area by 86.3%. On the other hand the area under culturable waste has declined by 19.16%, miscellaneous tree crops and groves by 45.9% and current fallow by 52.77%. As per forest department there is 13166 km^2 forestland and 13130 km^2 area under wildlife conservation. Table 5 provides the area statistics for the two reporting years in the region.

Table 4. Land use changes in hot arid region, 1982-83 to 2005-06

Land use category	1982-83		2005-06		Change (%)
	Area in ha	% of total area	Area in ha	% of total area	
Total geographical area	42829684		42499915		
Forest	2322431	5.42	2429572	5.72	4.6
Land put to non-agricultural uses	1930099	4.51	2250286	5.30	16.6
Barren and uncultivable land	3915880	9.14	3830297	9.01	-2.2
Pasture land	1479660	3.46	1366247	3.22	-7.7
Miscellaneous	122223	0.29	77223	0.18	-36.8
Culturable waste	7051399	16.46	5743118	13.51	-18.6
Other fallow	1941449	4.53	2177020	5.12	12.1
Current fallow	2612994	6.10	2658323	6.25	1.7
Net area sown	21453549	50.09	21967829	51.69	2.4
Area sown more than once	3520892	8.22	5990256	14.09	70

Table 5. Land use changes in cold arid region (1982-83 to 2005-06)

Land use category	1982-83		2005-06		Change (%)
	Area in ha	% of total area	Area in ha	% of total area	
Total geographical Area	9670100		9670100		
Total reporting Area	65077		64626		
Forest	64	0.10	64	0.10	-
Land put to non-agricultural uses	2976	4.57	4084	6.32	37.23
Barren & uncultivable land	29727	45.68	29740	46.02	0.04
Pasture land	-	0	1093	1.69	Abs
Miscellaneous	3218	4.94	1612	2.49	-49.51
Culturable waste	9881	15.18	7988	12.36	-19.16
Area sown more than once	1038	1.60	1934	2.99	5.10
Net irrigated area	18803	28.89	17518	27.11	-4.29

* Reporting area is only 0.67% of the total geographical area.

In western Rajasthan, Directorate of Agriculture, Government of Rajasthan occasionally brings out district-level trends in land use (e.g., from 1956-57 to 1990-91; Anon., 1992b). Based on field mapping, Balak Ram (1988) provided a quantitative account of land use changes in Siwana region between 1960-61 and 1985-86 at village, tehsil and regional level. Since then, several studies have been carried out on land use change mapping. Notably, Balak Ram and Rastogi (2004) mapped the land use changes in Kachchh district, while such mapping has recently been completed in Jaisalmer district (Balak Ram and Chauhan, 2009). Balak Ram and Gupta (2003) assessed the impact of industrial effluents on land use changes along the Jojri, the Bandi and the Luni rivers. Cincotta and Pangare (1991) discussed agricultural land use changes and pastoralism in Gujarat, while Chaurasia *et al.* (1996) discussed land use change in Punjab. Nautiyal *et al*. (2005) described ecological impacts of land use intensification in the Himalayas. Analyses of the earlier trends are summarized in Balak Ram and Gheesa Lal (1997, 1998) and Balak Ram (2003).

Issues and Challenges

Important issue and challenges of hot arid region are risky and traditionally subsistence rainfed farming with low productivity, degraded grazing and forest land, traditional and low productive animal husbandry, mined spoil areas, over-exploitation and injudicious use of ground water, land degradation and drought. In cold arid region the important issues are soil and water erosion, traditional use and non-managed pasture and forest land, subsistence and segregated farming system, poor system of animal husbandry and livestock production, neglected human and cultural value, under-utilized and ill-managed rain and river water. These are being constantly addressed by different government and non-government programmes through numerous institutions of research and development, but the vastness of the country, vagaries of climate and very high population pressure make the impacts manifest either slowly to, or are reversed fast.

References

Ahmad, E. 1968. A geographical approach to the problem of land use in the Indian desert. *The Geographer* 21: 141-147.

Anon. 1981. *Natural Resources Analysis and Development Proposals for Mahendragarh District, Haryana*. CAZRI, Jodhpur, 148 p.

Anon. 1982. *Basic and Human Resources of Jodhpur district, Rajasthan*. CAZRI, Jodhpur, 142 p.

Anon. 1992. *Integrated Natural and Human Resources Appraisal of Abohar Tehsil, Ferozpur District, Punjab*. CAZRI, Jodhpur, 61 p.

Anon. 1992b. *Trends in Land Use Statistics, etc. of Agriculture*. Directorate of Agriculture, Government of Rajasthan, Jaipur, 343 p.

Balak Ram 1988. *Recent Changes in Land Use in an Arid Environment - A Case Study of Siwana Region, Rajasthan*. *Ph.D. Thesis*, University of Jodhpur, 370 p.

Balak Ram and Chauhan, J.S. 2007. Application of LCCS of FAO and GeoVIS software in land cover mapping - A case study of Nawalgarh tehsil, Jhunjhunun district, Rajasthan. *Indian Cartographer* 27:330-338.

Balak Ram and Chauhan, J.S. 1992. Remote sensing in mapping the vulnerability and dynamics of the gullied lands in Sikar district, Rajasthan. *Indian Cartographer* 12: 47-50.

Balak Ram and Chauhan, J.S. 1994. Satellite based appraisal of landuse and related problems in coastal desert of India. *Indian Cartographer* 14: 152-153.

Balak Ram and Chauhan, J.S. 1999. Misuse of land and environmental degradation under hot arid eco-system. In *Geological Evolution of North Western India* (Ed. B.S.Paliwal), pp. 369-679. Scientific Publishers, Jodhpur.

Balak Ram and Chauhan, J.S. 2001. Delineation and management of wastelands in Haumangarh district, Rajasthan, using IRS LISS-III remotely sensed data and GIS. *Indian Cartographer* 20: 47-52.

Balak Ram and Chauhan, J.S. 2002. Impact assessment of IGNP Canal on land use in Hanumangarh district, using remotely sensed data. *Indian Cartographer* 22: 200-205

Balak Ram and Chauhan, J.S. 2005. Appraisal of sandy wastelands using remote sensing and GIS for sustainable management in Barmer district of arid Rajasthan In *Eighth Annual India ESRI User Conference*. Noida, pp.1-7.

Balak Ram and Chauhan, J.S. 2005. Mapping culturable lands in Bikaner district, Rajasthan for sustainable uses and development. In *8th Annual International Conference of Map India*. New Delhi, pp. 1-7.

Balak Ram and Chauhan, J.S. 2005. Mapping wastelands of Jalor district, Rajasthan for sustainable development using IRS LISS-III data. *Indian Journal of Ge*ography 16: 7-14.

Balak Ram and Chauhan, J.S. 2006. Trend analysis of groundwater irrigation and its impact on agro-ecosystem in Jhunjhunun district of Rajasthan. *Indian Cartographer* 26: 162-170.

Balak Ram and Chauhan, J.S. 2009. Assessment of land use changes using remote sensing and GIS in Jaisalmer district of arid Rajasthan. In *Proceedings of the 10th ESRI India User Conference on Geography in Action*. NOIDA, pp.1-5.

Balak Ram and Ghecsa Lal. 1995. Land use problems and potentialities of hot arid coastal region of India. *India Cartographer* 15: 34-39.

Balak Ram and Gheesa Lal 1988. Mapping the landuse characteristics of an arid environment: A case study of Bandi watershed, western Rajasthan. *Indian Cartographer* 8: 359-366.

Balak Ram and Gheesa Lal, 1997. Landuse and agriculture in Indian arid ecosystem. In *Desertification Control in the Arid Ecosystem of India for Sustainable Development* (Eds. Surendra Singh and Amal Kar), pp. 80-92. Agro Botanical Publishers (India), Bikaner,

Balak Ram and Gheesa Lal, 1998. Land use. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and Manjit Singh), pp.127-139. CAZRI, Jodhpur.

Balak Ram and Gheesa Lal 1996. Trend in land utilisation and environmental degradation in Sikar district, Rajasthan. *Indian Cartographer* 16: 276-283.

Balak Ram and Gupta, I.C. 2003. Assessment of industrial effluents induced degradation of natural resources in arid environment. In *Human Impact on Desert Environment* (Eds. Pratap Narain, S. Kathju, Amal Kar, M.P. Singh and Praveen Kumar), pp. 225-237. Arid Zone Research Association of India and Scientific Publishers, Jodhpur.

Balak Ram and Joshi, D.C. 1984. Land use soil relationship in arid zone. *The Deccan Geographer* 22: 505-510.

Balak Ram and Rastogi, A. 2004. Mapping land use changes in Kachchh district, Gujarat using remotely sensed data. In *Proceedings, Map India Conference*, New Delhi, pp. 1-7.

Balak Ram and Sen, A.K. 1988. Feasibility of the application of remote sensing techniques for landuse mapping in rocky desert. In *Proceedings of Symposium on Remote Sensing in Agriculture*, pp. 222-230. Ahmedabad.

Balak Ram and Singh, S. 1995. Remote sensing in sustainable landuse planning of an arid environment. In *Proceedings of the Symposium on Remote Sensing of Environment with special emphasis on Green Revolution*. Ludhiana, pp. 189-194.

Balak Ram 2002. Sub-classification of desertic sandy areas using IRS LISS-III remote sensing data. In *Resource and Environmental Monitoring*. ISPRS & SIS, Vol.34, Part 7, pp. 765-769, Hyderabad.

Balak Ram 2003. Impact of human activities on land use changes in arid Rajasthan. In *Human Impact on Desert Environment* (Eds. Pratap Narain, S. Kathju, Amal Kar, M.P. Singh and Praveen Kumar), pp. 44-59. Arid Zone Research Association of India and Scientific Publishers, Jodhpur,

Balak Ram, Gheesa Lal and Chauhan, J.S. 2006. Remote sensing and GIS based appraisal of wastelands for sustainable development - A case study of Barmer district (Rajasthan) India. In Environment, Agriculture and Poverty, vol. I (Ed., Ali Mohammad, Abdul Munir, H.S. Siddiqui and R. Abrahim), pp. 35-54. Concept, New Delhi.

Balak Ram, Gheesa Lal and Sen, A.K. 1983. Land use in the Guhiya catchment. *Annals of Arid Zone* 22: 65-75.

Balak Ram, Gheesa Lal, Chauhan, J.S. and Malakar, A.R. 2003. Cartographic appraisal of land use for sustainable development in Churu district, Rajasthan, using remote sensing and GIS. *Indian Cartographer* 23: 16-25.

Balak Ram, Narain, P. and Joshi, D.C. (Eds.) 2004. *Natural Resources Appraisal for Land Use in Arid Agro-ecosystem*. CAZRI, 106 p.

Balak Ram, Pratap Narain, Sharma, J.R., Nagaraja, R. and Jayanthi, S. 2005.*Wastelands Management in Arid Western Rajasthan*. CAZRI, 6 p.

Balak Ram, Sen, A.K. and Chauhan, J.S. 1999. Recent land use developments in Jhunjhunun district - mapping by IRS LISS-I data. In *Arid Ecology - Resources, Hazards and Development Policies* (Eds. S.C.Kalwar, M.K. Khandelwal and B.L.Gupta), Vol. 2, pp. 272-280. Pointer Publishers, Jaipur.

Banerji, J. 1952. The role of vegetation in desert control. In *Proceedings of Symposium on Rajputana Desert*, pp. 277-283.. National Institute of Sciences in India, New Delhi.

Bharadwaj, O.P. 1961. Arid zone of India and Pakistan. In *History of Land Use in Arid Region*. UNESCO, Paris, pp. 143-174.

Bose, A.B. and Malhotra, S.P. 1964. Man, land and livestock in arid zone. In *Proceedings of Symposium on Problems of Indian Arid Zone,* pp. 266-273. New Delhi.

Chatterji, P.C. (Ed.) 1987a. *Benchmark Integrated Basic Resources Survey of Doli Village, Jodhpur District*. CAZRI, Jodhpur, 54 p.

Chatterji, P.C. (Ed.) 1987b. *Benchmark Integrated Basic Resources Survey of Jhanwar Village, Jodhpur District*. CAZRI, Jodhpur, 56 p.

Chatterji, P.C. and Kar, A. (Eds.) 1989. *Natural and Human Resources of Nagaur District*. CAZRI. Jodhpur, 142 p.

Chatterji, P.C. and Kar, A. (Eds.) 1992. *Integrated Natural and Human Resources Appraisal of Jaisalmer District*. CAZRI, Jodhpur, 156 p.

Cincotta, R.P. and Pangare, G. 1991. Population growth, agricultural change and natural resource transition: Pastoralism amidst the agricultural economy of Gujarat. *Proceedings, Indian National Conference of Composite Feed,* pp.17-35. Anand.

CMDR 2008. *Natural Resource Accounting in Karnataka- A study of the Land and Forestry Sector (excluding mining*). Dharwar, 240 p.

Erskine, K.D. 1909. *Western Rajputana States Residency and Bikaner Agency*. Gazetteer Vol. 3-A.

FAO 2005. *Land Cover Classification System*: *Classification Concepts and User Manual, Software Version-2*. FAO, Rome, 190 p.

Gautam, N.C. and Narayan, L.R.A. 1988. Landsat MSS data for land use and land cover mapping - A case study of Andhra Pradesh. *Journal of Indian Society of Remote Sensing* 11(3): 15-27.

Gheesa Lal, Balak Ram and Malakar, A.R. 1991. Significance of detailed landuse mapping for resource management and micro-level planning in arid environment. *Indian Cartographer* 11: 246-254.

Gheesa Lal 1974. Borunda village and its vicinity - A study of rural settlement pattern and its landuse from aerial photographs. Unpublished project report, I.P.I., Dehradun, 51p.

HARSAC 1991. *Districtwise land use/land cover mapping of Haryana using Satellite Data*. HARSAC and RRSSC-JU. HARSAC/TR/1/91, 198 p.ISPRS/GBPIHED.

Jain, J.K. (Ed.) 1974. *Marwar-ra Pargana-ri Vigat*. Part II. Rajasthan Oriental Research Institute. Jodhpur, 52 p.

Kanitkar, M.V. 1952. Rajputana desert and its reclamation by dry farming methods. In *Proceedings of Symposium on Rajputana Desert*. National Institute of Sciences in India, New Delhi, pp. 260-265.

Mishra, D.K. and Kachhawa, S.S. 1962. Mehendi cultivation in Rajasthan. *Indian Farming* 11(2): 20-21.

Mishra, V.C 1967. *Geography of Rajasthan*. National Book Trust India, New Delhi, 188 p.

Nautiyal, S., Rajan, K.S., Shivsoki, R., Rao, K.S., Maikhuri, R.K. and Bist, I.S. 2005. Land use intensification and its ecological impacts in Himalayas of India - Lessons for scenario development in mountainous region. www.ISPRS.org/ Pub./related/

NRSA 1995c. *Report on Area Statistics of Land use/Land cover Generated using Remote Sensing Techniques*. Hyderabad, 71 p.

NRSA 1986. *Manual of Procedure for Wasteland Mapping using Remote Sensing Techniques*. Hyderabad, 50 p.

NRSA 1989. *Manual of Nationwide Landuse/Land Cover Mapping using Satellite Imagery*. Part I. Hyderabad, 58 p.

NRSA 1995a. *Integrated Mission for Sustainable Development - Technical Guidelines*. Hyderabad, 134 p.

NRSA 1995b. *Wasteland Atlas of India*. Hyderabad, 55 p.

NRSA 2005. *Wasteland Atlas of India*. NRSA, Hyderabad, 95p.

Qureshi, M.H. 1969. *Agricultural Geography of Central Luni Basin*. *Ph.D. Thesis*, University of Jodhpur.

Rajshekhar 1994. Land use pattern in Rayalseema region of Andhra Pradesh. *Economics and Population Weekly*, June, 1994.

Randhawa, N.S. 1980. *A History of Agriculture in India*. Vol. 1, ICAR, New Delhi, 541 p.

Rao, P., Raju, P. and Kareemuddin, M. 1982. Application of photo-interpretation and remote sensing techniques for integrated survey of Anantapur district, A.P. *Journal of Indian Society of Remote Sensing* 10(2): 45-53.

Raychaudhury, S.P. 1966. Land classification in ancient India (2500 B.C. to A.D. 600). *Indian Journal of History of Sciences* 1(2): 107-111.

Raychaudhury, S.P. 1970. *History of Land Use in India*. Land Resources Division, Planning Commission, New Delhi, 178 p.

Sen, A.K. 1972a. Land utilisation mapping to estimate the wastelands of arid zone in Rajasthan by photo interpretation technique. *Indian National Science Academy Bulletin* No. 44, pp. 67-71.

Sen, A.K. 1976. Some agro-demographic aspects in different agro-climatic regions of Rajasthan. *Annals of Arid Zone* l5: 121-128.

Sen, A.K. 1984. Land use pattern and over-exploitation in Indian arid zone In *Agro-forestry in Arid and Semi-arid Zones* (Ed. K.A. Shankarnarayan), pp. 80-87.CAZRI, Jodhpur.

Sen, A.K. 1972. *Agriculture Atlas of Rajasthan*. ICAR, New Delhi, 57 p.

Sen, A.K. 1977a. Aerial photo-interpretation to analyse the land use pattern of sand dunes. *Geographical Review of India* 39(4): 346-357.

Sen, A.K. 1977b. Land use mapping by aerial photo-interpretation techniques. In *Desert Ecosystem and Its Improvement* (Ed. H.S. Mann), pp. 85-100. CAZRI. Jodhpur,

Sen, A.K. 1978. *Land use Classification System in Indian Arid Zone*. CAZRI Monograph No. 9, 43 p.

Sen, A.K. and Abraham, C.T. 1966. Crop belts and cropping patterns of Rajasthan. *Annals of Arid Zone* 5(1): 105-116.

Sen, A.K. and Balak Ram 1980. *Land Utilisation Survey in Churu District, Rajasthan*. CAZRI, Jodhpur, 41 p.

Sen, A.K. and Gheesa Lal 1980. *Land Utilisation Survey in Jaisalmer District, Rajasthan*. CAZRI. Jodhpur, 32 p

Sen, A.K. and Gupta, K.N. 1980. *Land Utilisation Survey in Ganganagar District, Rajasthan*. CAZRI, Jodhpur, 45 p.

Sen, A.K. and Singh, S. 1977. Geomorphic significance of land use in Bikaner district. *Annals of Arid Zone* 16(1): 13-24.

Sen, A.K., Gheesa Lal and Abraham, C.T. 1982. Landuse of Bikaner district. In *Proceedings of the Workshop on the Problems of Deserts in India*. GSI Publication. No. 49, Calcutta, pp. 303-312.

Sen, A.K., Vangani, N.S. and Abraham, C.T. 1978. Landuse Mapping for Operational Research by photo- interpretation techniques in Daijar area. *Deccan Geographer* 16(1): 417.

Sen, A.K. 1982. Standardisation of land use mapping in arid zone. In *Proceedings of Workshop on the Problems of the Deserts in India*. GSI Publication No. 49, Calcutta, pp. 291-302.

Shankarnarayan, K.A. and Kar, A. (Eds.). 1983. *Upper Luni Basin: An Integrated Analysis of Natural and Human Resources for Development Planning*. CAZRI, Jodhpur. 577p.

Singh, F. (Ed.) 1969. *Marwar-ra Pargana-ri Vigat*. Part III. Rajasthan Oriental Research Institute. Jodhpur, 552 p.

Singh, J. 1972a. Spatio-temporal developments in land use efficiency in Haryana by assessment circles 1951-56 to 1961-66. *Geographical Review of India* 34 (4): 314-326.

Singh, J. 1972b. A new technique for measuring agricultural productivity in Haryana (India). *The Geographer* 19: 15-33.

Singh, J. 1976. *Agricultural Geography of Haryana*. Vishal Publications. Kurukshetra, 457 p.

Singh, S. and Kar, A. (Eds.) 1996. *Integrated Natural and Human Resources Appraisal for Sustainable Development of Kachchh District*. CAZRI, Jodhpur, 165p.

Singh, S., Sharma, K.D. and Joshi, D.C. (Eds.) 1995. *Integrated Natural and Human Resources Appraisal for Sustainable Development of Jalor District*. CAZRI, Jodhpur, 108 p.

Todd, J. 1978. *Annals and Antiquities of Rajasthan.* M.N. Publication, New Delhi, vol. I. 631p and vol. II. 637p.

White, R.O. 1960. *Evaluation of Land Use in South Western Asia*. FAO, Rome, 118p.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 78-112 pp.

Variability in Arid Soil Characteristics

Praveen-Kumar, J.C. Tarafdar, D.K. Painuli, P. Raina, M.P. Singh, R.K. Beniwal, M.L. Soni, Mahesh Kumar, P. Santra and M. Shamsuddin

Central Arid Zone Research Institute, Jodhpur

Arid region in India is spread over in 38.7 million hectare area. Out of the total, 31.7 m ha lies in hot and remaining 7 m ha lies in cold region (Fig. 1). The hot arid region occupies major part of northwestern India (28.7 m ha) and remaining 3.13 m ha is in southern India. The northwestern arid region occurs between 22^{0}30' and 32^{0}05'N latitude and 68^{0}05' to 75^{0}45' E, covering western part of Rajasthan, northwestern Gujarat and south-western parts of Haryana and Punjab. In southern India it occupies parts of Andhra Pradesh, Karnataka and Maharashtra. About 62% area of arid region falls in western Rajasthan followed by 20% in Gujarat and 7% in Haryana and Punjab. Andhra Pradesh, Karnataka and Maharashtra together constitute about 11% area of arid region. The boundary between arid and semi arid region in Rajasthan cuts across the Jalore and Pali districts, goes roughly along the boundaries of Nagaur and Ajmer. The arid zone extends to Mahendragarh and Hissar districts of Haryana; Sangrur, Bhatinda and Firozepur districts of Punjab; Jamnagar, Kachchh, Banaskantha, Mehsana, Surendra Nagar and Rajkot districts of Gujarat. The arid districts of Haryana and Punjab exactly border to north of western Rajasthan, while districts of Gujarat touch the southern boundary. Thus arid zone in India forms a contiguous tract, keeping western Rajasthan in the centre.

In the arid regions of Rajasthan, Haryana, Punjab and eastern Gujarat, aeolian and alluvium are the major formations. These aeolian and alluvial parent materials are the quaternary formations. During that period this region witnessed wide spread alluvial sedimentation. However, the overall environment was semi arid (Dhir, 1989; Dhir *et al.*, 1994; Gupta *et al.,* 2000). This alluvium was reworked by the subsequent activities. Since the last glacial period the region has experienced two major periods of aridity separated by a long period of amelioration of climate during which natural vegetation reached its maximum extent (Singh, 1977). The Dune forming aeolian activities began at least 200K years ago and terminated around

13,000 years B.P. (Singhivi *et al.*, 1983). The vast alluvial plain of Haryana and Punjab was formed out of sediments deposited by the rivers flowing from the Shivaliks. During arid phase this alluvium was reworked by aeolian activity and resulted in the formation of sand dunes and sand plains (Sidhu and Sehgal, 1978).

The cold arid region occupies 7.0 m ha area covering Ladakh, Kargil districts in Jammu and Kashmir and Lahul Spiti district in Himachal Pradesh. The region is characterized with mild summer and annual rainfall of less than 150 mm. The soils occur on summits and ridge tops, mountain and valley glacier, glacio-fluvial valleys and fluvial valleys of greater Himalayas. Soils are skeletal and calcareous with alkaline in reaction and low to medium in organic matter content (Pratap Narain, 2008).

The Soils

The distribution of soils in the arid region of India is shown in Table 1 (Shyampura *et al.*, 2002). The soils of this tract have been mapped in Entisols, Aridisols and Alfisols soil orders. The Entisols cover maximum 17134.26 thousand hectares (54.21%), followed by Aridisols and Alfisols. The area of latter two is 14254.32 and 213.10 thousand hectares, comprising 45.1 and 0.67% of hot arid India. Haplocalcids, Haplocambids, Haplosalids, Petrocalcids and Haplogypsids constitute Aridisols at the great group level, while Torripsamments, Torriorthents and Torrifluents are the part and parcel of Entisols. The Natrargids, Pleargids and Haplargids are the great groups mapped in Alfisols. The spatial distribution of these great groups is shown in Fig.1. Haplocambids dominantly occur in the arid part of Haryana, Gujarat and Punjab, covering around 77, 42 and 39.6% of delineated area in their respective state. Torripsamments dominantly mapped in 47.1% area of western Rajasthan, while the share of these soils to the marked area is around 43,14.3 and 9.7% in Punjab, Haryana and Gujarat, respectively. Haplocalcids are the second dominant soils of Gujarat after Haplocambids with 11.1% of allocated area under arid land. Petrocalcds and Haplocalcids together constitute 8.4% area of western Rajasthan. The contribution of Haplosalids to the delineated arid land is higher in Gujarat than Rajasthan. Torriorthents, the shallow skeletal soils associated with hills are mapped in 7.8 and 4.3% area of arid part of Rajasthan and Gujarat, respectively. Torrifluents fine textured deep soils along the course of river constitute around 2% area of arid zone both in Rajasthan and Gujarat. Haplogypsids and Haploargids represent relict soils in Rajasthan and Gujarat, while Natrargids and Pleargids are the paleosols mapable only in the latter (Shyampura *et al.,* 2002).

Table 1. Dominant soil of arid region of India (000, ha).

Order/Great Group	Area	Rajasthan	Gujarat	Harayana	Punjab
Alfisol	213.10 (0.67)				
Natrargids		-	43.32 (0.14)		
Pleagragids		-	28.45 (0.09)		
Haplargids		136.27 (0.43)	5.00 (0.01)		
Aridisol	14254.32 (45.10)				
Haplosalids		96.23 (0.30)	49.04 (0.15)		
Petrocalcids		1349.20 (4.27)	-		
Haplogypsids		287.28 (0.90)	-		
Haplocalcids		996.28 (3.15)	651.50 (2.06)	1155.44 (3.65)	594.82 (1.8)
Haplocambids		6706.7 (21.22)	2366.81 (7.48)		
Entisol	17134.26 (54.21)				
Torripsamments		13198.9 (41.76)	568.56, (1.8)	214.50 (0.67)	720.00 (2.3)
Torrifluvents		639.63 (2.02)	127.98 (0.40)		
Torriorthents		1207.77 (3.82)	456.88 (1.44)		

The soils on summits and ridge tops of greater Himalayas are shallow to medium deep, excessively drained, sandy-skeletal to loamy skeletal, highly calcareous and severely eroded with low organic carbon and available water capacity (Sidhu *et al.*, 2007). While, the soils of Mountain and valley glacier are similar in characteristics except they are covered with snow for a longer period. These soils were classified as Lithic Cryorthents and Typic Cryorthents. The glacio-fluvial valleys and fluvial valleys soils of greater Himalayas are medium deep to deep, well to excessively drained, loamy skeletal to coarse loamy and fine loamy soils with slightly acidic to neutral with medium to high contents of organic carbon. Some soils are highly calcareous and slightly to moderately alkaline have been classified as Typic Udorthents/Udifluvents, and Dystric Eutrudepts great group, respectively (Sidhu *et al.*, 1997).

Physical Properties

Soils under Entisols are generally found in those parts of arid regions where high aeolian or fluvial activities are observed. The average soil depth of this type of soil is 118 cm. Average bulk density of these soils is 1.58 Mg m^{-3}. Surface horizon is rich in sand content in comparison to subsurface horizons. Soil texture is sandy with average sand content of 89%. In the extreme arid part at Jaisalmer, Bikaner, and Barmer sand content is > 90% for most of the places. Soil color is mainly yellowish brown. The hue of the soil is 10YR, value ranges from 5-6, and chroma ranges from 3-4. Surface as well as subsurface soils are single fine grain in structure. Soils are mainly loose, non-sticky and non plastic in consistency. Most of the soils are well drained and fall under very rapid (>25.4 cm hr^{-1}) class of O'Neals permeability class. Water retention at 1/3 bar (field capacity) on an average is 6.69% (0.07 cm^{-3} cm^{-3} or 70 mm ha^{-1} of soil depth). Similarly, the water retention at 15 bar (permanent wilting point) is also very low (2.62%)

In contrast to Entisols, Aridisols are dominant in those parts of arid regions where aeolian activity is comparatively less. The average soil depth of this type of soil is 100 cm with well demarcated horizons. Concretions of calcite below the soil profile are a common feature of these soils. Average bulk density of these soils is 1.43 Mg m^{-3}. Average sand content of Aridisols is lesser than Entisols and is around 70%. Soil color is mainly yellowish brown to dark brown or pale brown. The hue of the soil is 10YR, value ranges from 5-6, and chroma ranges from 4-5. Surface as well as subsurface soils are single fine grain in structure. At few places, fine weak subangular blocky structure is found at subsurface soil layers. Soils are mainly loose, non-sticky and non plastic in consistency. At few places, presence of high clay and organic carbon at subsurface layers make the soil massive, friable, and slightly sticky. Most of the soils are well drained and fall under either rapid (12.5-25.4 cm hr^{-1}) or very rapid (>25.4 cm hr^{-1}) class of O'Neals permeability class. Water retention at field capacity (FC) and permanent wilting point (PWP) in Aridisols are comparatively higher than Entisols and are 13% and 5%, respectively.

Soils under Alfisols are found in few places of arid regions of India. In comparison to Entisols or Aridisols, these soils are comparatively rich in clay content (36%). Organic carbon content of Alfisols is also higher (3.7 g kg^{-1}) than Entisols (1.5 g kg^{-1}) and Aridisols (1 g kg^{-1}). Average permeability of these soils are moderately slow. Due to presence of high amount of clay, water retention at both FC and PWP are high (23% and 10%, respectively).

Nutrient Status of Arid Region Soils

Characteristically these soils are very low in organic matter/ humus and most of the nutrients reserve is present in un-weathered mineral forms. These soils have low clay and silt, and therefore nutrient adsorption and retention by these soils are very low. Soils are generally alkaline in nature and high in soluble salts and calcium contents.

Organic matter and Nitrogen

Arid zone soils are low in organic matter because of low vegetation cover, high temperature and coarse texture. Organic carbon content in soils below 300 mm rainfall zone ranges between 0.05-.2% in coarse textured soils 0.2-0.3% in medium textured and 0.3-0.4% in fine textured soils. Dhir (1977) has shown that even in low range of organic carbon (>0.5%) increase in clay content is associated with rise in organic carbon. With increase in clay content there is increase in organic carbon content. Joshi (1990a) has reported that bulk of organic carbon (67-89%) is present in non humic form followed by fulvic and humic form and mean value of HA-carbon/FA carbon increased with increase in silt+clay. Aggarwal and Lahiri (1977), Aggarwal *et al.*, (1993) reported build up of organic carbon and nitrogen and C:N ratio (10:1) under vegetation cover. C:N ratio ranged between 5.1 and 6.9 and 3.9 and 10.1, respectively, in surface and sub-surface soil.

Nitrogen in soils is present as organic (95-98%) and inorganic but in arid region soils, the inorganic form constitutes about 5 to 18% of the total N. Aggarwal and Lahiri (1981) reported 46 to 67% N as inorganic or mineralized in unstabilized sand dunes of western Rajasthan. Lower organic carbon and available nitrogen have also been reported in the soils of aeolian plains than in other landforms. Total N content of arid soils varied widely, as coarse textured Cirai, Pal, etc. contained 0.028% to 0.050%, medium textured Pipar and Soila (0.042 to 0.056%) and fine textured Asop contained 0.060 to 0.065% N. Aggarwal *et al.*, 1975 reported relatively highest concentration amino acid bound N amongst the various forms in arid soils of Rajasthan.

Phosphorus

Phosphorus present in soils as organic and inorganic forms but organic form constitute hardly 10-20% of the total phosphorus. Total phosphorus content in soils ranges between 300-1500 $\mu g\ g^{-1}$ (Mehta *et al.*, 1971; Deo and Ruhal, 1972; Choudhari *et al.*, 1979) and about 80% of the inorganic P remain bound with Ca. Al-P was higher, generally higher than Fe-P. Total and inorganic phosphorus were irregularly distributed in the soil profile of arid soils, but organic phosphorus decreased with depth (Pareek and Mathur, 1969; Talati *et al.*, 1975). 15-20% (97-110 kg ha^{-1}) of the total P is present in organic form as phytin, lecithin, phospholipids and other unidentified compounds (Tarafdar *et al.*, 1989). The available phosphorus content varies widely in different soils and is about 2.4 to 3.9% of total P and the mean content in different soil series is less than 10 µg g^{-1} (Mathur *et al.*, 2006). Even though soils are often medium to low in available P, response of P-fertilization in arid soils is generally observed only in good rainfall years (Aggarwal *et al.*, 1989).

Microbial mobilization of soil phosphorus

An extensive survey through arid zones revealed that the population of P-solubilizing micro-organisms is relatively low and varied from one place to place (Venkateswarlu *et al.*, 1984). Bacteria were the dominant group in all the soils followed by fungi. But isolation of actinomycetes especially Streptomyces spp. which can solubilise inorganic phosphates, from arid soil was reported (Rao *et al.*, 1982). However, P-solubilzers isolated from arid soils could not perform satisfactorily in the field because of lack of competition with the native flora. Organic P-compounds must be hydrolyzed by phosphatases of either plant or microbial origin, into plant available form. Tarafdar *et al.* (1989) reported that activity of phosphatases in different arid soils varied with landuse pattern. High activity of acid and alkaline phosphatases were observed in the rhizosphere of legumes (Tarafdar and Rao, 1990). Tarafdar *et al.* (1988) isolated a number of phosphatase producing fungi (PPF) belonging to Penicillium and Aspergilus from arid soils and their field application enhanced dry matter production and grain yields of clusterbean and mung bean (Tarafdar *et al.*, 1992, 1995).

Arid soils contain 7 to 80 spores of VA-mycorrhizal fungi (Glomus, Gigaspora and Acaulospora genera) 100 g^{-1} soil. Almost all plants growing in desert including xerophytes do carry VAMF infections on their roots (Kiran Bala *et al.*, 1989) and the infection varied from plant to plant. In general the Young plants mostly carry mycelium with a small number of vesicles while and spores were common on mature roots. Population of VAM fungi decline during fallow. Crops sown after long periods of fallow have poorly developed mycorrhizal systems and suffer from P-deficiency. VAMF infection on roots of neem was observed up to 250 cm depth, but the intensity of VAMF infection was inversely proportional to the availability of water. VAM-fungi also enhance nodulation and N_2-ase activity in legumes (Tarafdar and Rao, 1997). Positive and a significant interaction between *Rhizobium*-VAM fungi was also observed.

Available potassium

The arid soils are well provided with available potassium (70-890 kg ha^{-1}). The total K content in arid region soils ranged between 980-1890 mg 100 g^{-1} with an average value of 1489 mg 100 g^{-1} soil. Major proportion of total potassium in arid soil is present as mineral form followed by interlayer, non-exchangeable and water-soluble form. These forms beside related to each other are correlated with sand and silt fraction and K resistance to depletion (Choudhari and Pareek, 1976).

Arid soils of Rajasthan contain (30 to 1270 mg kg^{-1}) HNO_3-soluble and (20 to 1120 mg kg^{-1}) fixed potassium. Some dune and interdunal soils show negative K fixation (Aggarwal *et al.*, 1979; Joshi *et al.*, 1982a). The K fixation capacity was related with the clay content, K-saturation and weathered K-bearing minerals (Talati *et al.*, 1974; Joshi 1986a; Mathur *et al.*, 1981 and Dutta and Joshi, 1993). Kalyansundaram *et al.* (1993) reported only 5.4% soils of north Gujarat as low, 55.2% medium and 38.5% high in available potassium. In the irrigated north-west plain soils of Rajasthan Mathur *et al.* (2006) reported wide variation of potassium content within the soil group i.e. 277 to 488 kg K_2O ha^{-1} in Torrifluvent, 215 to 389 kg K_2O ha^{-1} in Torripsamment and 200 to 374 kg K_2O ha^{-1} in Calciorthid soil group. Reserve K constituted 8 to 15% of the total K. K fixing capacity of arid zone soils are lower than of adjoining areas (Choudhari and Jain, 1979).

The activity ratio for different arid soils was in the range of 3-21 x 10^3 mol L^{-1}. Labile potassium, potassium adsorbed on specific and non specific sites, potassium buffering capacities and K potential were generally lower in dune inter-dune and sandy – plain soils than in the medium fine textured alluvial soils (Dutta and Joshi, 1990, 1992; Joshi 1992, 1993). In the soils of Saurastra region water soluble (0.003-0.21 m.e 100 g^{-1}), exchangeable (0.03-2.0 m.e 100 g^{-1}), non exchangeable (0.32-21.7 m.e 100 g^{-1}) and total (1.1-20.3 m.e 100 g^{-1}) forms of potassium were observed (Patel *et al.*, 1993). Increase in $CaCO_3$ content beyond 30% enhanced the K fixation. Different K parameters, decreased with increase in clay content (Patel *et al.*, 1993).

Secondary Nutrients (Calcium, Magnesium and Sulphur)

Calcium is an essential element present in varying amount 0.1 to 5.2% in the arid soil. However, higher amount 15-20% (as CaO) is present in some lower layers of many soils. The exchangeable calcium which is indicator of availability, ranged between 1.5 to 20 m.e. 100 g^{-1} soil. Fine textured Aridisols of Pipar and Pali contain 15 to 20 m.eq 100 g^{-1} whereas dune and coarse textured contain between 1.5 to 4.0 and 2.2 to 4.0 m.eq 100 g^{-1} soil. Magnesium is present in various forms in arid region soil with mineral forms as dominant fraction (32 to 87% of total Mg). These are followed by dilute acid soluble, exchangeable, organic bound and water soluble. Total sulphur content in arid region vary between 280-500 µg g^{-1} of which 50 to 80% remains in inorganic forms. This is in contrast to most other regions where organic bound sulphur predominates. Sulphate sulphur dominates in surface soils whereas non sulphate sulphur dominated the lower horizon of arid region soils. Reverse pattern is true for other soils (Joshi *et al.,* 1973). Calcium, magnesium and sulphur contents in most arid zone soils are generally adequate for plant growth.

Micronutrients

Micronutrients in soils are derived almost entirely from the parent material. Each of the four micro-elements (Zn, Mn, Fe and Cu) occurs in variety of minerals in both igneous and metamorphic rocks, with Fe being by far the most abundant and Cu is least. Soils rich in ferromagnesian minerals contained higher amount of total iron (Joshi and Dhir, 1982) and the soils associated with augite and hornblende is associated with higher amount of total Zn (Lal and Biswas, 1973; Singh and Singh, 1981). In arid region of western Rajasthan, the variety of soils reported (Dhir, 1977) have been found to be associated with their physiographic occurrence (Roy *et al.*, 1967; Lodha *et al.*, 1982). The soils of the alluvial plain of the mid-west of Rajasthan contained comparatively greater amount of HCl soluble and DTPA extractable Mn and Fe than sandy arid plains (Typic Torripsamment), Ghaggar plain (Calciorthid) and plains of interior drainage (Torripsamment). Dune soils occurring in better rainfall zones (400-450 mm) contained higher amount of HCl soluble and free iron (Joshi and Dhir, 1983a). Free and reducible Mn was lower in dunes with low rainfall areas as compared to the dunes with high rainfall (Joshi and Dhir, 1983a). Free iron and exchangeable Fe were higher in interdune soils. Among the four micronutrients, Zn, Mn and Fe appeared marginal in their deficiencies in arid soils of Bikaner (Soni *et al.*, 2006).

Iron

Iron content in desert soils is comparable with hilly, red loam, brown and grayish brown soils of the Rajasthan (Choudhari *et al.*, 1979). DTPA extractable Fe constitutes about 3.71 to 4.17% of total Fe. Other exchangeable forms (ferrous 6-10 µg g^{-1} and ferric 12-16 µg g^{-1}), reducible (ferrous 10-25 µg g^{-1} and ferric15-35 µg g^{-1}) and free form varied between 0.45-0.55%. Joshi *et al.* (1981), however, reported that in extreme arid parts exchangeable Fe was 2.2-5.6 µg g^{-1} in different arid soils. In the arid soils of

Punjab reducible and exchangeable Fe were in ferrous forms, whereas in Rajashthan and Haryana soils it was in ferric form (Shukla and Singh, 1973).

In the arid soils of Rajasthan about 40% soil samples contained 2-5 ppm and 54% samples had 5 to 10 ppm DTPA-Fe (Joshi and Dhir, 1983b). In Haryana soils of Mahendragarh district were well provided, whereas 25% in Sirsa and 51.6% in Hisar district were deficient in iron (Shukla *et al.*, 1975). Iron deficiency reported in Bhatinda (38%), Faridkot (40%) and Sangrur (11%) districts of Punjab. In Jamnagar, Kachchh, Banaskantha and Mehsana districts of Gujarat 8-23% soils were deficient and 45-65% samples marginal in available iron (Dangarwala *et al.*, 1983).

Manganese

Total manganese content in arid soils ranged between 250-875 µg g^{-1}. Reducible and active forms varied between 3 to 123 on 4 to 128 µg g^{-1}, respectively (Johri *et al.*, 1978). However, lower contents were reported for Jaisalmer and Barmer soils (Joshi and Dhir, 1982). DTPA extractable Mn in arid soils of Rajasthan varied from 1.1 to 25 µg g^{-1} (Dhir *et al.*, 1983). These values were comparable with similar soils of Punjab (Arora and Sekhon, 1981) but the Haryana soils contain higher amount of Mn (6.4-73.8 ppm; Shukla *et al.*, 1975). DTPA extractable Mn in the arid soils of Gujarat showed wide range (0.8-104.4 µg g^{-1}) and only <5% samples were deficient (Dangarwala *et al.*, 1983; Dangarwala and Patel, 1996). In arid Rajashthan 23% samples were below the critical limit, most of which were from the dune and interdune soils (Joshi and Dhir, 1983b). Available manganese was deficient in 29% samples of Hisar and marginal in 40% samples of Sirsa district. The soils of Mahendragarh district were adequate in available manganese.

Zinc

Content of zinc in arid region soils often ranged from 41 to 130 µg g^{-1}. Further, the dune field soils showed higher content compared to Chirai, Khajwana, Gajsinghpur and Pipar soils. Arid soils of Rajasthan are in general well provided with available zinc while deficiency could be encountered only in 13.5 and 9.6 samples in Barmer and Jailsalmer districts, respectively. Wide variations in the contents of exchangeable (0.24-1.28 µg g^{-1}) and DTPA soluble (0.27-2.36 µg g^{-1}) have been reported (Joshi *et al.*, 1982b; Sharma *et al.*, 1983. The exchangeable and DTPA soluble forms were not associated with clay, silt and organic carbon. Exchangeable and DTPA soluble forms of zinc showed irregular distribution with depth (Joshi and

Dhir, 1981). Sharma and Kolarkar (1983) observed slightly higher values of DTPA Zn (0.83-1.97 µg g^{-1}) in Jamnagar soils. Dangarwala *et al.* (1983) reported zinc deficiency in 44, 39 and 13% samples in Banaskantha, Jamnagar and Kachchh districts, respectively. The studies revealed that about 80% samples of Hisar, Mahendragarh and Bhiwani districts of Haryana and 25% samples of similar soils in Punjab are deficient in zinc (Anonymous, 1982-83, Arora and Sekhon, 1981). The Zn adsorption by sandy soils follwed the Langmuir adsorption equation. The quantity of Zn adsorbed by sandy soils was much less than the medium fine textured soils (Joshi *et al.*, 1983b, Joshi and Sharma, 1986). Significant relationships between the quantity, intensity and supply parameters indicated that sandy soils could maintain higher level of available Zn. However, the calcareous soils had low adsorption maxima and high bonding energy constants than the non calcareous soils. Strong affinity of Zn with $CaCO_3$ indicated low availability of Zn in these soils (Joshi, 1996).

Copper

Contents is arid soils varies from 30 to 94 µg g^{-1} and medium to fine textured Pipar and Pali contained higher amounts than coarse textured Chirai and dune soils. Most of the arid soils of Rajasthan, Punjab and Haryana appeared sufficient in Cu (Dhir *et al.,* 1983; Singh, 1983). However, Takkar *et al.* (1976) reported 22 and 25% samples deficient in Cu in Sangrur and Gurudaspur district respectively. In the Banaskaantha district of Gujarat 22% deficient samples (Dangarwala *et al.*, 1983). The exchangeable (0.23-1.56 µg g^{-1}) DTPA extractable forms of copper showed wide variations in different arid soils (0.28-1.25 µg g^{-1}) (Joshi *et al.*, 1982b; Sharma *et al.*, 1985; Dangarwala *et al.*, 1983).

Micronutrient transformations and their relationship with soil properties

The transformation of micronutrients in soils depends upon soil pH, soil texture, type of clay mineral, organic matter, salinity/ alkalinity, quality of irrigation water, soil moisture and temperature. In arid soils, the DTPA extractable Fe was significantly and positively correlated with clay, silt and organic carbon and negatively with soil pH (Sharma *et al.*, 1983) and $CaCO_3$ (Joshi *et al.*, 1983b). Most of the Fe deficiency in arid soil is associated with high $CaCO_3$. Total Mn was not related with any of the soil parameters, but HCl soluble Mn was significantly related with clay, silt and organic carbon. The reducible Mn was not governed by pH and $CaCO_3$ as by clay and organic carbon (Joshi *et al.*, 1981). Free Mn was negatively related with pH and $CaCO_3$ and positively with organic carbon. The mean values of reducible, exchangeable and DTPA soluble Mn decreased with increase in soil pH, $CaCO_3$, organic matter (Joshi and Dhir, 1983a) and finer fraction of soils (Joshi and Dhir, 1983b, Lal and Biswas, 1973). However, for Zn, only HCl soluble fraction was associated with clay, silt and organic carbon, but exchangeable and DTPA soluble forms were not related with any of the soil parameters (Joshi *et al.*, 1982b; Sharma *et al.*, 1983). The HCl soluble Cu was significantly related with clay, silt, organic carbon and $CaCO_3$ content of soils. Available Cu was significantly related positively with clay, silt and organic carbon and negatively with pH. Exchangeable Cu was critical in arid brown and marginal in sierozem soils of Punjab and Haryana, respectively (Grewal *et al.*, 1969; Singh and Shukla, 1984; Singh *et al.*, 1988). Medium textured soils contained slightly higher amounts of DTPA soluble Cu than dune, interdune and sandy plain soils.

There was marked effect of saline/high RSC irrigation water on availability of micronutrients in soils. Soils irrigated with saline and high RSC waters were low in available micronutrients (Joshi, 1988, 1990b). The contents of HCl soluble, free and reducible forms of Mn in salt affected soils were comparable with the associated non saline soils, but their predictability was much reduced (Joshi *et al.*, 1988a). However, little difference was observed in HCl-Fe and free Fe in salt affected and associated non saline soils. Due to the effects of different soil parameters in salt affected soils, the HCl-Fe was better predictable but free Fe had low predictability (Joshi *et al.*, 1988a). Exchangeable Fe in salt affected and associated non saline soils were comparable. The salt affected and associated non saline soils did not differ in various forms of Zn, but high salinity appears to vitiate their predictability (Joshi *et al.*, 1988b). Though there was no difference in the contents of HCl soluble and exchangeable Cu in salt affected soils and the associated non-saline soils, but their predictability was considerably low (Joshi *et al.*, 1988b).

Adsorption/desorption behaviour of micronutrients in arid soils

The adsorption of Zn and Cu in arid soils followed Langmuir adsorption equation. Because of the low clay/organic matter, low cation exchange capacity, high base saturation and calcareous nature of sandy soils, they have characteristic adsorption and release behaviour for these nutrients. The quantity of Zn adsorbed by sandy soils was much less than medium/fine textured soils (Joshi *et al.*, 1983b; Joshi and Sharma, 1986). Significant relationship between quantity, intensity and supply parameters indicated that sandy soils could maintain higher level of available Zn. Strong affinity of Zn with $CaCO_3$ indicated low availability of this nutrient in such soils (Joshi, 1996). However, Cu could be adsorbed at low concentration but with increasing addition, there was precipitation of Cu rather than multilayer adsorption (Joshi, 1995). The adsorption of Cu was less in fine sandy than loamy soils (Joshi, 1986b).

Micronutrients in plants and their recycling in arid soils

It is possible to estimate the extent to which the micronutrient cations are recycled through the decomposition of plant materials from assumptions about the dead materials and the concentration of cations. Rainfed crops and grasses/shrubs of arid region have higher amount of micronutrient content as compared to irrigated crops. Among grasses, substantial higher amount of copper was observed in bharut (*Cenchrus biflorus*) and sewan (*Lasiurus sindicus*) grass. Zn was found deficient in irrigated crops (groundnut, wheat, and mustard), but was not the case with rainfed crops (Soni *et al.*, 2003). Among the perennial components, the return of Fe is maximum through trees (Total Fe=381 ppm) followed by shrubs (Total Fe=251 ppm) and grasses (Total Fe=235 ppm) of arid region (Sharma *et al.,* 1985). As regards Mn, arid zone grasses have highest concentration of Mn followed by tree species. Grasses have also significantly higher values of Zn and Cu as compared to trees and grasses (Sharma *et al.*, 1984). Fleming (1973) and Dhir *et al.* (1985) also stated that arid zone grasses are significantly low in Mn and quite high in Zn and Cu.

Various soil degradation processes viz., Aeolian hazards, water erosion including floods have detrimental effect on micronutrient availability (Raina and Joshi, 1994).The soils under natural pasture were low in available micronutrients than the soils under sown ungrazed pastures (Raina and Joshi, 1991). Comparatively higher amount of micronutrient was observed in natural rangelands followed by arable rain fed cropping and minimum in irrigated conditions (Soni *et al.*, 2006). Considering the status of natural rangelands as ideal, the percent losses of Fe, Zn, Cu and Mn showed that reduction in available micronutrients was more in irrigated lands as compared to rain fed cultivated lands. On an average, Fe, Zn, Mn and Cu were reduced by 32.4, 24.0, 23.8 and 12.0% in irrigated and 9.2, 8.4, 10.4 and 6.8% in rain fed cultivated soils over natural rangeland systems, respectively (Soni *et al.*, 2006). Build up of all the four micronutrients (Mn, Zn, Cu and Fe) was more in medium and fine textured soils under *Oran* system as compared to cultivated lands.

Nutrient Management in Arid Soils

Nutrient use efficiency is evaluated using metrics that reflect crop uptake of fertilizer added in the current growing season. The problem of low nutrient use efficiency is conventionally viewed as a consequence of temporal asynchrony and spatial separation between applied nutrients and the crop. As a result, efforts to improve nutrient utilization efficiencies have emphasized on improved delivery of nutrients to the root zone during the period of crop uptake through modifications such as banding, fertigation, split fertilizer applications, etc. To increase crop access to N fertilizer, a variety of additives have been developed that inhibit urease activity, nitrification and denitrification. These approaches have been extremely successful in terms of increasing nutrient use efficiency and maximizing yields; however, their utilization on mass scale has met with limited success. Despite more than 30 years of concentrated effort, mass balances indicate that annual N and P inputs consistently exceed harvested exports by 40 to >100% resulting in substantial losses of these nutrients to the environment. Thus, it is evident that global challenge of meeting increased food demand and protecting environmental quality will be won or lost in cropping systems (Cassman *et al.*, 2002). Major limitation of most of the approaches tried in past three decades is lack of their applicability on large scale on small farm holdings. Only two approaches hold promise for application on mass scale to increase nutrient use efficiency (1) application of optimum quantity and (2) internal nutrients circulation.

Application of optimum quantity

One of the first step necessary for achieving higher fertilizer use efficiency (FUE) is to apply the right amount of fertilizer. But the long term estimations of N requirement of crops under rain-fed conditions may be very difficult as the yield levels vary from zero to three times of average yield. Using average yields in arid regions is too conservative and may actually result in lowering average yields with time because of insufficient nutrient availability for the very favourable years and on contrary, use of relatively high yield goals results in excess N applications in most years and can greatly reduce profit. The current concern over the potential for excess N to degrade the environment also makes this alternative unacceptable. Tucker (1988) presented three ground rules to arrive at logical yield goals. These include choosing yield goals based upon: (1) highest yield within the past 5 years with good crop management (2) yield goal set a 1.5 times of long term average, and (3) yield goal based on soil capabilities as defined in Standard

Soil Surveys, using yields of highest yield obtaining farmer's in the vicinity on the same kind of soil.

Uncertainties in soil nitrogen (N) supply in rainfed agriculture and crop N demand present a challenge to scientists in deciding on N fertilizer rates. Number of field studies have documented that the improvements in N use efficiency is possible with site-specific N management approaches. Lobell (2007) has presented a general model of N rate decision-making which computes the optimal N rate that maximizes expected profit given uncertainties in N supply and demand. The cost of uncertainty is measured as the difference in N rate when soil N supply and crop N demand are unknown versus known perfectly. Eliminating uncertainty in soil N supply (but not crop demand) reduces average N rates by 5–40% in different crops while perfect knowledge of potential crop N demand (but not soil supply) reduces rates by 3-10%. Simultaneous knowledge of both factors reduced N rates by significantly more than the sum of their individual effects. This approach is very different from most extension services in India which provide a single, standard fertilizer recommendation for an entire district or region. Farmers apparently have few guidelines for adjusting N-fertilizer amount to account for the large differences in the indigenous N supply, indicating the need for a 'field-specific' approach to N management. Field-specific N management could lead to substantial reductions of N rates without yield loss in a wide range of cropping systems, thereby improving profitability and environmental quality.

Internal nutrient circulation

The approach comprises of various conventional practices like recycling of crop residues, either through direct application or as manure and cultivation of legumes often referred as integrated nutrient management in past. The practice of effective use of inorganic and organic sources of nutrients together in a proper proportion not only reduces the requirement of inorganic fertilizers, but also improves physical conditions of soil, enhances water retention capacity and its availability in the soil. Apart from this, the biological properties of soil are also improved considerably (Sharma *et al.*, 2005, 2008, 2009) and fertilizer use efficiency is also increased. The results of several studies have shown that the combined use of fertilizer and farm yard manure (FYM) is very much essential in rainfed areas for sustaining moderate to high yields and achieving higher nutrient use efficiencies. Besides, application of FYM and composted organic wastes and other organics improve yield stability in rainfed areas (Aggarwal and Venkateswarlu, 1989; Venkateswarlu and Hegde, 1992; Singh *et al.*, 2000).

Singh *et al.* (1981) observed that under arid conditions of Jodhpur continuous application of sheep manure in general gave substantially higher yields than the application urea alone. Rao and Singh (1993) showed that substitution of 50% of fertilizer requirement by FYM resulted in yield levels nearly similar to those obtained with complete fertilization. Aggarwal and Praveen-Kumar (1996) on the basis of a seven year study on arid soils showed not only a beneficial effect of FYM application but also a synergistic effect of simultaneous application of FYM and inorganic fertilizers on crop yield. FYM application increases the utilization efficiency of fertilizer N, however, improvement in soil fertility after FYM application is a very slow process.

Nutrient content of pearl millet, sorghum stover is relatively low, stover can contribute to the productivity of the soil. Such residues must be managed carefully, however, because N can be immobilized at the time of peak maize N requirements, resulting in poor crop growth. In rainfed areas, cereal stover is often fed to livestock, and manure is applied in field. This way of recycling the residues is more beneficial for crop than their direct application in field. Losses of N from such systems are often high. Cattle manure is applied in a dried, aerobically decomposed form, often with a high sand content and N content that is frequently around 1% or less. Research shows that the most efficient use of manure is to combine it with some inorganic fertilizer. Ladd and Amato (1985) and Snapp and Silim (2002) showed that the most promising route to improving inorganic fertilizer efficiency in cropping systems is by adding small amounts of high-quality organic matter (possessing a narrow C/N ratio and a low percentage of lignin) to soils. It provides readily available N, energy (carbon), and nutrients to the soil ecosystem, and improve structure, and increase soil microbial activity and nutrient cycling and reduce nutrient losses from leaching and denitrification (De-Ruiter *et al.*, 1998). Soil microbes are valuable not only because they supply nutrients directly, but because they enhance the synchrony of plant nutrient demand with soil supply by reducing large pools of free nutrients (and consequent nutrient losses from the system). Thus, microbes maintain a buffered, actively cycled nutrient supply.

Incorporation of crop residues and natural vegetation in soil improve microbial activity during decomposition. Also adhesive action of decomposed products improves soil aggregation, hydraulic conductivity and moisture retention (Venkateswarlu, 1984, 1987, Gupta, 1984; Gupta and Gupta, 1986). Leaving the crop residues in soil generally have a positive effect on grain yield (Aggarwal *et al.*, 1996). Crop residues are also efficient source of nutrient like other organics viz., cattle manure and compost. However, Aggarwal *et al.* (1996) did not find any significant change in the yield of succeeding crop of pearl millet after addition of crop residues with wide C:N ratio, whereas it was significant after incorporation of residues with narrow C:N ratio.

Legume rotations are an important practice for restoring soil fertility on larger land holdings. The amount of N returned from legume rotations depends on whether the legume is harvested for seed, used for forage, or incorporated as a green manure. Estimated net N return of 23-110 kg ha^{-1} from pigeon pea, 23-50 kg ha^{-1} from dolichos beans, and 25-60 kg ha^{-1} from groundnuts has been reported by Giri and De (1980).

Mishra (1971), Mann and Singh (1977), Singh (1980) and Singh *et al.* (1985) also reported that in arid soils pearl millet-cluster bean rotation gave higher yield than of continuous cultivation of pearl millet due to improved soil fertility (Praveen-Kumar *et al.*, 1996). Singh *et al.* (1985) in a long-term study found an increase soil organic carbon by 12% and available soil P by 25% after legume cultivation. Singh and Singh (1977) on the basis of a long-term study reported that cultivation of green-gram in rotation with pearl millet supplied with 20 kg N ha^{-1} gave similar yield as with application of 40 kg fertilizer N ha^{-1}. Singh *et al.* (1985) observed that rotation of pearl millet with green gram or clusterbean was better than its rotation with moth bean. Praveen-Kumar *et al.* (1996) reported that higher yield of pearl millet when it was preceded by clusterbean cultivation than green gram. Beneficial effect of legumes to pearl millet also depends on the number of seasons of their cultivation prior to pearl millet. The intercropping of pearl millet and legumes in arid soils has also shown promising results (Mishra, 1971; Singh and Joshi, 1980; Singh *et al.*, 1978).

Major quantity of N i.e, upto 70% of total N uptake, can be taken up by the pearl millet within first 30 days of growth. Though it slows down thereafter, but continues gradually till the grain filling stage. This high N demand cannot be met from the soil and thus pearl millet respond favorably to the N addition (Aggarwal and Vekateswarlu, 1989), which ranged from 7.0 to 18.0 kg grain kg^{-1} N with higher values in good rainfall years. Singh *et al.* (1981) have reported that the yield of pearl millet doubled with the application of 40 kg N ha^{-1}. Similar results have also been reported by Singh *et al.* (1981). Aggarwal and Praveen-Kumar (1996) on the basis of a seven year long study reported significant response to application 80 kg N ha^{-1} only in the years of good rainfall. Comparison of different N fertilizers showed that, maximum yields were recorded with ammonium sulphate. But due to high cost of ammonium sulphate, urea has become the major source of N in arid regions even though utilization efficiency of N from urea by pearl millet is very low. Various studies in CAZRI Jodhpur have revealed that the mixing of elemental S with urea (Aggarwal *et al.*, 1987) or application of small quantity of ammonium sulphate before the application of urea (Praveen-Kumar and Aggarwal, 1988) increases its efficiency. Praveen-Kumar and Aggarwal (unpublished data) also showed that NH_4 : NO_3 ratio in a N fertilizer also effect its utilization efficiency and observed maximum yield levels and highest utilization efficiency from the applied N fertilizer when NH_4 : NO_3 ratio in the fertilizers was 3:1. Besides ammonia volatilization denitrification is now being considered an important pathway of N loss (Peterjohn, 1991). Due to different loss mechanisms major part of N applied, if not used by crop is lost from soil. As a result residual effect of fertilizer N is generally not observed (Aggawal and Praveen-Kumar, 1996). Praveen-Kumar and Aggarwal (Unpublished data) demonstrated this in a field experiment wherein 20, 40, 60 and 80 kg N ha^{-1} was applied in different plots at the time of sowing and the crop was harvested after 20, 40 and 60 days of growth symbolizing complete crop mortality at early, medium and late stage of drought, respectively. Next year pearl millet was again grown in these plots without addition of N fertilizer to study the residual effect. The residual effect was compared with the yield in some other plots where fetilizer @ 0, 20 and 40 kg N ha^{-1} was added. Results indicated comparable grain yield in most plots where residual effect was studied to those in control plots where no fertilizer was added. This suggested that fertilizer N applied previous year did not show significant residual at any level of fertilizer application and stage of crop harvest. Since droughts occur frequently in arid regions because of which crop often fails, therefore, farmers consider application of N fertilizers a risky input and hence the need for its better management.

Split application of N fertilizers is therefore, considered a risk avoiding strategy which results in the higher yield as compared to their one time application, increased utilization efficiency and lower risk. Praveen-Kumar and Aggarwal (1997, 1998) observed basal application of fertilizer N may be avoided if clusterbean has preceded the pearl millet.

Biodiversity in Soils

Soil biodiversity is an important resource that provides ecosystem processes essential to the functioning of natural and global systems. Biota occupy remarkably different habitats within profile of arid soils with some species living on decaying biological matter, some in the rich organic matter horizon, and some in deeper layers and the species composition may vary even at millimeter scale depending on type and amount of vegetation and soil texture. Soil organisms moderate numerous ecosystem processes (e.g., decomposition, C and N transformation, hydrologic cycles). Changes in land-use, climate and atmospheric can alter species composition within the soil community, and may impact ecosystem function.

Current priorities in the study of soil biodiversity include: (1) understanding the functions of rarely sampled fauna so that species estimates and global distributions are based on an accurate and current database; (2) determining which habitats are most vulnerable for soil biodiversity loss, e.g., where the 'hot spots' of biodiversity are, and which habitats and what time frames are most amenable to restoration; (3) synthesizing data and determining which invertebrate and microbial 'species' are key to ecosystem processes; (4) identifying gaps in knowledge of multispecies interactions and their influence on ecosystem functioning; (5) collaborating on long-term (more than 3 years) experiments to examine effects of global changes on aboveground-below-ground biodiversity linkages and ecosystem functioning; and (6) determining, based on natural history information, which species are more likely to be invasive if introduced, and using this potentially to reduce spread and to identify threats to other species.

Macro-fauna

The arid soils are home to diverse life forms adapted to hot and dry milieu. Soil organisms contribute in formation of organic matter and nutrient cycling. The burrowing invertebrates create macropores that allow rapid flow of water into or through soil. The tiny arthropods produce fecal pellets that are mixtures of soil and organic matter. These become stable soil aggregates. The arid soil meso and macro fauna are constituted largely by insects, mites, earthworms and millipedes. Predators in the soil food web include scorpions, centipedes, spiders, mites, some ants and beetles. They check the population of many soil biota. The reptiles and rodents represent the soil dwelling vertebrates, the former play a predatory role while the latter thrive on a variety of food resources.

Soil compaction, low vegetation or plant litter reduces the number of soil arthropods. Their level of activity depends on micro-environmental conditions including temperature, moisture, aeration, pH, pore size, and types of food sources.

Earthworms move soil from lower strata up to the surface and move organic matter from the soil surface to lower layers. Suthar (2002) studied the earthworm resources of arid Rajasthan and their utilization in vermitechnology. Suthar (2009) recorded occurrence of nine species of earthworms from Jodhpur district. These included *Pontoscolex corethrurus, Amynthas morrisi, Metaphire posthuma, Lampito mauritii, Perionyx sansibaricus, Ocnerodrilus occidentalis, Dichogaster bolaui, Ramiella bishambari* and *Octochaetana paliensis*. Diversity and abundances of earthworms in conventional, integrated and organic agro-ecosystems was also measured. Maximum numbers of earthworm were found in integrated farming system and abundance of earthworms in arable system was directly related to the management practices (Suthar, 2009).

There have been but few studies on the soil macro faunal associations in different production systems of the arid regions and their contribution to soil fertility. Tripathi *et al.* (2005) reported that Acari, Myriapoda, Coleoptera, Isoptera and Collembola arthropods as the major soil faunal groups in silvipastoral systems of arid zone. Relative densities of Acari, Myriapoda and other arthropods were highest in silvopastoral systems and those of Coleoptera, Isoptera and Collembola were highest in pure grass plots. Termites are another important arthropods in the soil.

Termites aid in crop residue breakdown, enhance the porosity of soil, increase the soil's infiltration capacity and affect nutrient cycling by concentrating organic matter in the nests. However, their beneficial role is shadowed by the damage they cause to the cultivated plants. All the known species in the arid regions are subterranean. This group of arthropods has been studied fairly well owing to their economic importance in all fields. Nearly two scores of termite species have been recorded from the arid region (Rathore, 1996). Parihar (1981) collated the available information about termites and their management. The known termite fauna of the arid parts of Rajasthan, Gujarat, Haryana and Punjab are represented by the following species: *Amitermes belli, Anacanthotermes macrocephalus, Angulitermes jodhpurensis, Coptotermes heimi, C. kishori, Eremotermes fletcheri, E. neoparadoxalis, E. paradoxalis, Heterotermes indicola, Incisitermes didwanaensis, Microcerotermes cameroni, M. heimi, M. laxmi, M. palestinensis, M. raja, M. sakesarensis, M. tenuignathus, Microtermes mycophagus, M. obesi, M. unicolor, Odontotermes assmuthi, O. bellahunisensis, O. brunneus, O. dehraduni, O. distans, O. feae, O. giriensis, O. girnarensis, O. guptai, O. gurdaspurensis, O. latiguloides, O. microdentatus, O. obesus, O. paralatiguloides, O. redemanni, O. sasangirensis, O. O. wallonensis, O. lokanandi, O. indicus, Psammotermes rajasthanicus, Speculitermes cyclops, S. sinhalensis, Synhamitermes quadriceps, Trinervitermes biformis* and *T. fletcheri.*

Ants also modify soil properties through their nesting and foraging activities. While most of the ants found in arid regions are foragers, a few are predatory and some tend sucking insects. Still there have not been extensive studies about the foraging by ants in the arid regions. The available information is mostly restricted to documentation of the occurrence of ants in the arid tracts (Tak and Rathore, 1996; Tak, 2008), which include *Acantholepis frauenfeldi, Anochetus punctiventris, A. sedilloti*, *Camponotus angusticollis, C. compressus, C. irritans, C. mitis, C. taylori, Cataglyphis bicolor setipes, Crematogaster brunnea contemta, Dorylus labiatus*, *D. orientalis*, *Meranoplus bicolor, Messor barbarus humalayana, Monomorium atomus, M. criniceps, M. destructor, M. glaber, M. indicum, M. pharaonis, M. scabriceps, M. wroughtoni, M. gracillimum, M. latinode, Pheidole sulcaticeps, P. wroughtoni, Sima rufonigra* and *Tapinoma melanocephalum.*

Coleoptera is another important order of insects associated with soil. The grubs of most beetles are inhabitants of soil, plant roots or decaying matter. Some of these are also predators of injurious insects. Being of agricultural importance, beetles and weevils have received attention of researchers. However, there is no account of their benign contribution in enriching the soil. Pal (1977) had given an account of the white grubs prevalent in the arid regions. Tripathi *et al.* (2008) studied the diversity and abundance of beetles in some silvipastoral systems. The more common Scarabaeids in the arid region are species of the genera *Lachnosterna* (*Holotrichia*), *Anomala*, *Adoretus, Rhinyptia, Schizonycha,* and *Onthophagus. Bembidion luniferum, Asaphidion triste, Leitus indus* and *Scaritus* species are more common Carabids. There is a large number of other beetles whose grubs inhabit the arid soil.

The grubs and adults of dung beetles contribute profusely in decomposing the organic matter in arid soils. The beetles process large amounts of animal dung into nodules or balls, and roll these into subterraneous chambers or tunnels where they are degraded, thereby increasing soil fertility. They also prevent the use of decaying materials by other pest insects. Eighty-five species of these beetles have been documented from the arid regions belonging to *Onthophagus, Caccobius, Onitis, Copris, Scarabaeus, Catharsius, Gymnopleurus, Oniticellus, Phallops, Drepanocerus, Heliocopris* and *Chironitis* genera (Ram-Sewak, 2009).

The Collembolan insects contribute significantly in litter decomposition. The majority of springtails feed on fungal hyphae or decaying plant material. But not enough information is available about them from the Indian arid soils. Seven species of Collembola including *Xenylla obscura* and *Isotomodes dagamae* were recorded from Sriganganagar district by Faisal and Ahmad (2005). Their existence and establishment has been attributed to the change in land use pattern due to the development of canal irrigation.

Although a large number of species of soil mites exist in the arid regions, there have not been any systematic attempts to study these organisms. Sanyal (1996) while giving an account of the soil mite fauna from Rajasthan has listed only three species *viz*.; *Eugamasus* sp, *Galumna flebellifera* and *Microsmaris pinnata* collected from the drier tracts.

There have been many studies on rodents in the arid regions, their damage and control strategies, but no precise estimates are available about their contribution to soil fertility, if at all. The soil inhabiting rodents in the arid zones include *Bandicoota bengalensis, Gerbillus gleadowi, G. nanus, Meriones hurrianae, Mus booduga, M. cervicolor, M. musculus, M. platythrix, Nesokia indica, Rattus gleadowi, R. meltada pallidior* and *Tatera indica.*

There is a need to generate more information about the soil meso and macro fauna that influence soil fertility under arid conditions and the ways to enhance their activities.

Soil microorganisms

Microbial activity in desert soil is highly dependent on characteristics such as temperature, moisture and the availability of organic carbon (Parkar *et al.*, 1984; Rao and Tarafdar, 1998). Of these, moisture availability is the major factor affecting microbial diversity, community structure and activity. Populations of aerobic bacteria in deserts across the world are reported to vary from <10 in Atacama desert to 1.6×10^7 g^{-1} in soils of Nevada (Skujnis, 1984). Populations in Indian arid zone reported to have relatively smaller (1.5×10^2-5×10^4 g^{-1} soil) (Venkateswarulu and Rao, 1981; Kathuria, 1998). Gram-positive spore formers are dominant and the populations do not decline significantly even during summers (Rao and Venkateswarlu, 1983). Actinomycetes may constitute ~ 50% of the total microbial bacterial population in desert soils. Dominant microflora of desert soils is made up of coryneforms, i.e. *Archangium*, *Cystobacter*, *Myxococcus*, *Polyangium*, *Sorangium* and *Stigmatella*; sub-dominant forms comprise *Acinetobacter*, *Bacillus*, *Micrococcus*, *Proteus* and *Pseudomonas*. Cynobacteria also contribute significantly (0.02 to 2.63×10^4 g^{-1} soil) to the biota of hot arid regions in terms of primary productivity and nitrogen fixation (Bhatnagar *et al.*, 2003). The dominant cynobacterial forms of Thar desert are *Chroococcus minutus*, *Oscillatoria pseudogeminata* and *Phormidium tenue*; *Nostoc* sp. dominates amongst heterocystous forms. Fungal populations as viable propagules range from 0.5 to 14.7×10^3. The dominant genera include *Aspergillus*, *Curvularia*, *Fusarium*, *Mucor*, *Penicillium*, *Paecilomyces*, *Phoma* and *Stemphylium*. Xeric mushrooms such as *Coprinus*, *Fomes*, *Terfezia* and *Teramania* and arbuscular mycorrhizal fungi such as genera *Glomus*, *Gigaspora* and *Sclerocystis* have also been reported from desert (Trappe 1981; Pande and Tarafdar, 2004).

Rhizosphere is an important site of microbial activity in desert soils, since it provides ample carbon substrate in an otherwise organic matter poor arid soil. Generally R:S (Rhizosphere : soil) ratio is high in arid soils for nearly all metabolic types of bacteria (viz. heterotrophs, dizotrophs, cellulites and nitrifiers) and fungi in most plants studied (Kathuria, 1998; Singh and Tarafdar, 2002). The soil zone penetrated by fine roots and held together by mucilage is called the rhizosheath. *Bacillus polymyxa* and the fungus *Olpidium* are found associated with rhizosheaths. *Ancalomicrobium* and *Hypho-microbium*- like organisms are also present (Wullstein and Pratt, 1981). Rhizosheaths are important because of the associated diazotrophs and enhanced water retention and nutrient uptake (Watt *et al.*, 1994).

In the rhizosphere of desert plants mycorrhiza play a very significant role in plant nutrition and stabilization (Tarafdar and Rao, 1997, 2002; Tarafdar and Gharu, 2006). Most species in families of *Asteraceae*, *Fabaceae*, *Poaceae*, *Rosaceae* and *Solanaceae* usually form endomycorrhizal associations in arid habitats (Skujins, 1984). Trappe (1981) listed 264 plant species from arid and semi-arid environments that had mycorrhizal-based root colonization and approximately 25% species exhibited specific associations with endomycorrhizal fungi. *Glomus deserticola* is indigenous to many desert soils (Bhatnagar *et al.*, 2003). Kiran Bala *et al.* (1989) reported >50% infection by vesicular-arbuscular mycorrhizal (VAM) fungi in 17 tree species of the Indian desert, with genera *Glomus* and *Gigaspora* being dominant. *Opunitia* and *Euphorbia* showed considerable root infection. In desert, incidence of arbuscular mycorrhiza (AM) infection varies with the availability of water (Tarafdar, 1995) and with composition of plant community (Kiran Bala *et al.*, 1989). Mycorrhiza also help in desert reclamation and soil stabilization. They link soil particles to each other and to the roots in part by producing glomalin, an important glue that holds aggregates together. Panwar and Vyas (2002) reported beneficial effects of *Acaulospora mellea*, *Gigaspora margarita*, *G. gigantean*, *Glomus deserticola*, *G. fasciculatum*, *Sclerocystis rubiformis*, *Scutellospora calospora* and *S. nigra* on *Moringa concanensis* and proposed use of such AM fungi in conservation of this endangered multipurpose tree species in Indian desert.

Crusts on soils are formed by microorganisms and microphytes. These are variously called as cryptogannic/cryptobiotic/biological/cynobacterial/ microphytic crusts (West, 1990). A consortium of green algae, cyanobacteria, lichen, fungi, bacteria, diatoms, mosses and liverworts form cryptobiotic crusts. Mosses and liverworts seem to favour the comparatively more mesic sites. Cynobacteria favours the harshest sites, and lichens dominate in intermediate sites. Cynobacterial crusts generally dominate poor sandy soils. Lichens increase proportionately with carbonates, gypsum and silt content of the substrate (Gracia-Pichel *et al.*, 2001; Budel, 2002). *Microcoleus chthonoplastes* is dominant in saline sand crusts (Gracia-Pichel *et al.*, 2001). The most common genera are *Microcleus* (*M. Chthonoplastes*, *M. paludosus*, *M. sociatus* and *M. vaginatus*) and *Nostoc* sp. Other forms are *Calothrix*, *Lyngbya*, *Oscillatoria*, *Phormidium*, *Scytonema* and *Tolypothrix*. Common green algae of soil crusts are *Chlorella*, *Chlorococcum*, *Coccomyxa* and *Klebsormidium*. Dominant fungal genera in crusts are *Alternaria*, *Fusarium* and *Phialomyces* whereas in non-crusted soils, *Alternaria* and *Penicillium* dominate followed by *Fusarium*. Approximately 90% of the aerobic bacterial population of cryptobiotic crusts consists of corneform bacteria (Skujins, 1984).

Diversity status of cryptobiotic crusts at Thar desert in India showed 43 morphotypes of diazotrophs in BG11-N enrichment and 71 of algae and cyanobacteria in the same medium supplemented with nitrogen (Bhatnagar *et al.*, 2003). Most frequent form was *Phormidium tenue*. In the case of diazotrophs the most frequent forms were *Nostoc punctiforme*, *Nostoc commune* and *Nostoc polludosum*. Cynobacteria presence was influenced by their plant partners. *Alternaria* sp. was the dominant fungus in these crusts.

Microorganisms in soil are poorly characterized. It has been established that the genetic diversity of soil has an estimated 6400 to 38000 prokaryotic species per gram. On the other hand, less than 0.3% of the microorganisms present are culturable by standard techniques (Pettit, 2004). Only a handful of studies have looked at microorganisms in tropical soils. Microbiological properties of these soils also varied depending on the type of land use patterns. Grasslands, in general, supported higher number of micro-organisms than tree plantations, cultivated fields or barren land. Stabilization of shifting and sand dunes introduction of vegetation has markedly increased the soil microflora. In general, the low organic matter content and poor moisture availability of desert soils were the major factors limiting optimum microbial activity.

Fungi like *Fusarium*, *Gliocladiu*, *Penicillium* and *Trichoderma* are stress tolerant. Majority of fungi are mesophiles with maximum growth between 25 and 30°C (*Mucor mucedo*, *Mortierella*, *Penicillium chrysogenium*), however, *Cylindrocarpon* sp. *Candida scotti* are cold tolerant (psychrotolerant) and can grow near 0°C; others are thermotolerant and grow above 40°C (*Rhizomucor*, *Thermomyces*, *Talaromyces*). Xerotolerant fungi can grow on dry material (*Aspergillus*, *Pencillium*) with low matric potential (a_w) while osmotolerants grow at very low osmotic potential (*Pichia* sp.). Dung of herbivorous mammals harbors a large number of fungi, termed coprophiles, of while *Pilobolous*, *Ascobolus* and *Basidiobolus* are famous for their special shot-gun dispersal mechanism !

An interesting ecological group of fungi captures and grows parasitically on nematodes, their cysts and eggs (nematophagous); over 150 species are reported (Gray, 1998) within the genera *Catenaria*, *Dactyela*, *Harposporium*, *Monacrosporium*, *Nematophthora*, *Rhopalomyces* and *Stylopage*. Such fungi are good trapping agents in the biological control of nematodes.

Potentials of the Arid Zone Soils

Soils in the drier regions have low reserves of soil organic matter. Singh *et al.* (2007) reported 2.13 Pg carbon stock in the 0-100 cm depth of which 1.23 Pg as soil organic carbon and 0.90 Pg as soil inorganic carbon, in the arid and semi arid regions of Rajasthan. They had studied the same under different soil types. Per year 4200- 4600 kg km^{-2} soil organic carbon can be sequestered in the untilled soils of arid Rajasthan, if they are put under canopy cover round the year. The desert and saline soils in the Kutch peninsula is reported to have a current total carbon stock of 0.8 Pg with an estimated potentials of 1.3 Pg carbon. Uncertainties persist in the estimation of net flux of CO_2 from the soils of tropical areas due to inconsistency in land use/ land cover pattern (Chapin and Ruess, 2001; Jones *et al.*, 1998). The studies conducted at RRS, Kukma indicated soil organic carbon stock of 35.13 t ha^{-1} under the silvipastoral system involving *Neem* and *Cenchrus ciliaris,* 31.9 t ha^{-1} under Acacia and *Cenchrus ciliaris,* in the 100 cm soil depth.

The carbon sequestration in soil is strongly affected by the root production (Matamala *et al.*, 2003). The trees in the arid zones put forth a large volume of below ground biomass in the form of roots. The tree roots play an important role in adding organic matter to the soil. About 25% of the total living biomass of trees is in roots which continuously add organic matter to soil by death and decay of roots. It is more important in arid zone where climax tree species like *Prosopis cineraria* that have very deep root system which can reach upto 70 m depth. Thus in arid zones large volume of carbon gets sequestered in lower layers, that have high resilience. Narain (2008) reported planting trees and grasses in the degraded lands of arid zone can help to increase the soil carbon stock from 24.3 Pg to 34.9 Pg. The studies conducted at RRS, Kukma indicated a total below ground carbon stock of 1.61 t ha^{-1} that constituted 23.4% of total carbon stock under silvipastural system involving *Acacia tortilis* and *Cenchrus setegerus* and 27.6% contribution by below ground portions to the total carbon stock under *Acacia tortilis* and *Cenchrus ciliaris*.

The intentional controlled burning of biomass can produce charcoal or black carbon that can contribute to carbon sequestration (Goldberg, 1985). The activated charcoal, apart from locking carbon in the soil for centuries, can attribute positively to the cation exchange capacity, physical, chemical and biological properties of soil.

References

Aggarwal, R.K. and Lahiri, A.N. 1977. Influence of vegetation on the status of the organic matter and nitrogen of the desert soils. *Science and Culture* 43: 533-534.

Aggarwal, R.K. and Lahiri, A.N. 1981. Evaluation of fertility status of stabilized and unstabilized dunes of Indian desert. *Agrochemica* 25: 54-60.

Aggarwal, R.K. and Praveen-Kumar 1996. Integrated use of farm yard manure and fertilizer N for sustained yield of pearl millet (*Pennisetum glaucum*) in arid region. *Annals of Arid Zone* 35: 29-35.

Aggarwal, R.K. and Venkateswarlu J. 1989. Long term effect of manures and fertilizers on important cropping systems of arid region. *Fertilizer News* 34: 67-70.

Aggarwal, R.K. and Venkateswarlu, J. 1989. Long-term effect of manures and fertilizers on important cropping systems of arid region. *Fertilizer News* 34: 67-70

Aggarwal, R.K., Dhir, R.P., Bhola, S.N. and Kaul, P. 1975. Distribution of nitrogen fractions in Jodhpur soils. *Annals of Arid Zone* 14: 183-190.

Aggarwal, R.K., Praveen-Kumar and Power, J.F. 1996. Use of crop residue and manure to conserve water and enhance nutrient availability and pearl millet yield in an arid tropical region. *Soil and Tillage Research* 41:43-51.

Aggarwal, R.K., Praveen-Kumar and Raina, P. 1993. Nutrient availability from sandy soilsunderneath *Prosopis cineraria* compared to adjacent open site in an arid environment. *Indian Forester* 119: 321-325.

Aggarwal, R.K., Raina, P. and Praveen-Kumar l987. Ammonia volatiliation losses from urea and their possible management for increasing nitrogen use efficiency in an arid region. *Journal of Arid Environment* l3: l63-l68.

Aggarwal, R.K., Sharma, V.K. and Dhir, R.P. 1979. Studies on potassium fixation and its relationship with chemical characteristics of some desert soils of western Rajasthan. *Annals of Arid Zone* 18: 174-180.

Anonymous 1982-83. All India co-ordinated scheme on micro-nutrient in soils and plants. Annual Report, ICAR, New Delhi.

Arora, C.L. and Sekhon, G.S. 1981. Influence of soil characteristics on DTPA extractable micronutrient cations in some soil series of Punjab. *Journal of Indian Society of Soil Science* 29: 453-461.

Bhatnagar, A., Bhatnagar, M., Makandar, Md.B. and Garg, M.K. 2003. Satellite Centre for Microalgal Biodiversity in Arid Zones of Rajasthan. Project completion report, funded by Department of Biotechnology, New Delhi.

Budel, B. 2002. Diversity and ecology of biological crusts. In *Progress in Botany* (Eds. K. Esser, U. Luttge, W. Beyschlag, and F. Hellwig), pp. 386-404. Springer-Verlag, Berlin.

Cassman, K.G., Dobermann, A. and Walters, D.T. 2002. Agroecosystems, Nitrogen-use Efficiency and Nitrogen Management. *AMBIO* 31(2): 132-140.

Chapin-III, F.S. and Ruess, R.W. 2001, The roots of the matter. *Nature* 411: 749-752.

Choudhari, J.S. and Jain, S.V., Mathur C.M. 1979. Phosphorus fractions in some soil orders of Rajasthan and their sequence of weathering stage. *Annals of Arid Zone* 18: 260-268.

Choudhari, J.S. and Pareek, B.L. 1976. Exchangeable reserve potassium in soils of Rajasthan. *Journal of Indian Society of Soil Science* 24: 57-61.

Choudhari, J.S., Pareek, B.L. and Jain, S.V. 1979. Distribution of different forms of iron in major soil groups of Rajasthan. *Indian Journal of Agricultural Sciences* 27: 338-340.

Dangarawala, R.T. and Patel, K.P. 1996. Micronutrient research in Gujarat. In *Soil Research in Gujarat-A Compendium* (Eds. G.R. Patel *et al.*), pp.65-76.

Dangarwala, R.T., Trivedi, B.S., Patel, M.S. and Mehta, P.M. 1983. Micronutrient research in Gujarat, pp. 137. GAU, Anand.

Deo, R. and Ruhal, D.S. 1972. Status and availability of phosphorus in calcareous soils of Rajasthan. *Indian Journal of Agricultural Science* 42: 316-320.

De-Ruiter, P.C., Anje-Margriet, Neutel and Moore, J.C. 1998. Biodiversity in soil ecosystems: the role of energy flow and community stability. *Applied Soil Ecology* 10: 217-228.

Dhir, R.P. 1977. Western Rajasthan soils: their characteristics and properties. In *Desertification and its Control* (Eds. P.L. Jaiswal), pp. 102-105. ICAR, New Delhi.

Dhir, R.P. 1989. Paleopedology and geochronology. *Journal of the Indian Society of Soil Science* 37: 612-619.

Dhir, R.P., Rajaguru, S.N. and Singhvi, A.K. 1994. Desert quaternary formations and their morphostratigraphy: implications for the evolutionary history of the Thar. *Journal Geological Society of India* 43: 435-447.

Dhir, R.P., Sharma, B.K. and Joshi, D.C. 1983. Availability of iron, manganese, zinc and copper in some soils of western Rajasthan. *Annals of Arid Zone* 22: 343-349.

Dhir, R.P., Sharma, B.K., Dutta, B.K. and Saxena, S.K. 1985. Concentrations of mineral elements in some arid zone species from a common habitat: 2. Grass species. *Indian Journal of Ecology* 12: 205-208.

Dutta, B.K. and Joshi, D.C. 1990. Quantity-intensity parameters of potassium and their relationship with available forms and soil properties in dune and interdune soils. *Journal of Indian Society of soil Science* 38: 404-409.

Dutta, B.K. and Joshi, D.C. 1992. Quantity-intensity parameters of potassium and their relationship with available forms in salt affected soils. *Journal of Potassium Research* 5: 61-69.

Dutta, B.K. and Joshi, D.C. 1993. Studies on potassium fixation and release in arid soils of Rajasthan. *Transactions of Indian Society of Desert Technology* 18: 191-199.

Faisal, M. and Ahmad, M. 2005. Collembola diversity in changing agricultural landscapes of the Thar Desert: A case study in Sriganganagar district of Rajasthan, India. *Journal of Arid Environment* 63(4): 717-724.

Fleming, G.A. 1973. Mineral composition of herbage. In *Chemistry and Biology of herbage* Vol.I., pp. 529-563. Academic Press, London.

Garcia-Pichel, F., Lopez-Cortes, A. and Nubel, U. 2001. Phylogenetic and morphological diversity of cyanobacteria in soil desert crusts from the Colorado plateau. *Applied Environmental Microbiology* 67: 1902-1910.

Giri, G. and De, R. 1980. Effect of preceding grain legumes on growth and nitrogen uptake of dryland pearl millet. *Plant and Soil* 56: 459-464.

Goldberg, E.D, 1985.Black carbon in the environment properties and distribution. John Wiley and sons. New York.

Gray, N.F. 1988. Fungi attacking vermiform nematodes. In *Diseases of Nematodes* (Eds. G.O. Poinar and H.B. Jansson), pp. 3-37. CRC Press, Boca Raton.

Grewal, J.S., Bhumbla, D.R. and Randhawa, N.S. 1969. Available micronutrient status of Punjab, Haryana and Himachal soils. *Journal of Indian Society of Soil Science* 17: 23-31.

Gupta, J.P. 1984. Effect of mulches on hydrothermal regimes of soil and crop yield. Annual Report, pp. 143. Central Arid Zone Research Institute, Jodhpur.

Gupta, J.P. and Gupta, G.K. 1986. Effect of tillage and mulching on soil environment and cowpea seedling growth under arid conditions. *Soil Tillage Research* 7: 233-240.

Gupta, J.P., Joshi, D.C. and Singh, G.B. 2000. Management of Arid Agro-ecosystem. In *Natural Resource Management for Agricultural Production in India* (Eds. J.S.P. Yadav and G.B. Singh), pp.551-668. International Conference on Managing Natural Resources for Sustainable Agricultural Production in the 21st Century hold on Feb. 14-18, 2000, New Delhi, India.

Johari, S.N., Joshi, D.C. and Sharma, V.C. 1978. Study on the manganese status of some soils of western Rajasthan. *Annals of Arid Zone* 17: 133-135.

Jones, T.H. et al. 1998. Impacts of rising atmospheric carbon dioxide concentrations on model terrestrial ecosystems. *Science* 280: 441-443.

Joshi, D.C. 1986a. Potassium release behaviour of some arid soils. *Journal of Indian Society of Soil Science* 34: 56-63.

Joshi, D.C. 1986b. Studies on the adsorption and availability of copper in some arid soils. *Plant and Soil* 94: 357-367.

Joshi, D.C. 1988. Changes in the available micronutrient status during amelioration of soils irrigated with high RSC/saline water. *Annals of Arid Zone* 27: 87-94.

Joshi, D.C. 1990a. Composition and nature of humus in typical aridisols of Rajasthan. *Annals of Arid Zone* 29: 93-97.

Joshi, D.C. 1990b. Available micronutrient status of soils degraded due to irrigation with residual sodium carbonate/saline water. *Annals of Arid Zone* 29: 9-13.

Joshi, D.C. 1992. Relationship between the quantity and intensity parameters of potassium in Aridisols of Indian desert. *Journal of the Indian Society of Soil Science* 41: 430-437.

Joshi, D.C. 1993. Soil resources of Rajasthan. In *Natural and Human Resources of Rajasthan* (Ed. T.S. Chouhan), pp. 77-92. Scientific Publishers, Jodhpur.

Joshi, D.C. 1995. Adsorption and desorption of copper by calcareous arid soils. *Annals of Arid Zone* 34: 253-257.

Joshi, D.C. 1996. Adsorption and desorption of Zn by calcareous Aridisols. *Annals of Arid Zone* 35: 319-324.

Joshi, D.C. and Dhir, R.P. 1981. Distribution of different forms of copper and zinc in the soils of extremely arid part of western Rajasthan. *Journal of the Indian Society of Soil Science* 29: 379-381.

Joshi, D.C. and Dhir, R.P. 1982. Distribution of different forms of manganese and iron in soils of extremely arid part of western Rajasthan. *Annals of Arid Zone* 21: 1-8.

Joshi, D.C. and Dhir, R.P. 1983a. Distribution of micronutrient forms along duny landscape. *Annals of Arid Zone* 22: 135-141.

Joshi, D.C. and Dhir, R.P. 1983b. Available forms of manganese and iron in some arid soils and their relation with soil properties. *Annals of Arid Zone* 22: 7-14.

Joshi, D.C. and Sharma, B.K. 1986. Adsorption and desorption of zinc by sandy soils of arid Rajasthan. *Journal of Indian Society of Soil Science* 34: 257-263.

Joshi, D.C., Choudhari, J.S. and Jain, S.V. 1973. Distribution of sulphur fractions in relation to forms of phosphorus in soils of Rajasthan. *Journal of Indian Society of soil Science* 21: 289-294.

Joshi, D.C., Dhir, R.P and. Gupta, B.S. 1982b. Distribution of different forms of Cu and Zn in some soils of arid Rajasthan. *Journal of Indian Society of Soil Science* 30: 547-549.

Joshi, D.C., Dhir, R.P. and Gupta, B.S. 1981.Forms of iron and manganese in some soils of arid Rajasthan. *Journal of Indian Society of Soil Science* 29: 462-468.

Joshi, D.C., Dhir, R.P. and Gupta, B.S. 1983a. Influence of soil parameters on DTPA extractable micronutrients in arid soils. *Plant and Soil* 72: 31-38.

Joshi, D.C., Gupta, B.S. and Dutta, B.K. 1982a. Soil factors affecting forms of potassium and potassium fixation capacity. *Annals of Arid Zone* 21: 199-205.

Joshi, D.C., Sharma, B.K. and Dhir, R.P. 1983b. Studies on the adsorption of Zn by fine textured alluvial soils of arid Rajasthan. *Clay Research* 2: 39-45.

Joshi, D.C., Singh, N. And Kolarkar, A.S. 1988b. Influence of salinity and associated soil properties on status of available zinc and copper in salt affected soils of the Guhiya catchment Rajasthan. *Journal of Indian Society of Soil Science* 36: 833-836.

Joshi, D.C., Singh, N. And Kolarkar, A.S. 1988a. Forms of iron and manganese and their availability in salt affected soils of the Guhiya catchment of the upper Luni basin of Rajasthan. *Tropical Agriculture* 65: 41-48.

Kalyansunderam, N.K., Patil, R.G., Karelia, G.N. and Patel, S.H. 1993. Studies on soil and fertilizer potassium in north Gujrat region. In: *Potassium in Gujrat Agriculture,* pp. 128-138. Gujarat Agricultural University, Sardar Krushinagar.

Khathuria, N. 1998. *Rhizosphere microbiology of desert*, M.Sc. dissertation, pp. 52. Department of Microbiology, Maharshi Dayanand Saraswati University, Ajmer , Rajasthan.

Kiran Bala, Rao, A.V. and Tarafdar, J.C. 1989. Occurrence of VAM associations in different plant species of the Indian desert. *Arid Soil Research and Rehabilitation* 3: 391-396.

Kolarkar, A.S., Singh, N., Gupta, B.S. and Abichandani, C.T. 1974. Water stable aggregates, texture and organic matter in medium textured range soils of western Rajasthan. *Journal of Indian Society of Soil Science* 22: 1-5.

Ladd, J.N. and Amato, M. 1985. Nitrogen cycling in legume cereal rotations. In *Nitrogen Management in Farming Systems in Humid and Sub-humid Tropics* (Eds. B.T. Kang and J. Van der Heide), pp. 105-127. Haren, The Netherlands, Institute for Soil Fertility (IB), and Ibadan, Nigeria, International Institute for Tropical Agriculture.

Lal, F. and Biswas, T.D. 1973. Factors affecting the distribution and availability of micronutrient elements in major soil groups of Rajasthan. *Journal of Indian Society of Soil Science* 21: 455-466.

Lobell, D.B. 2007. The cost of uncertainty for nitrogen fertilizer management: A sensitivity analysis. *Field Crop Research* 100: 210-217.

Lodha, B.K., Joshi, D.C. and Jain, S.V. 1982. Physiography and soil association in Rajasthan. *Journal of Indian Society of Soil Science* 30: 326-333.

Mann, H.S. and Singh, R.P. l977. Crop production in Indian Arid Zone. In *Desesrtification and its Control*, pp. 215-334. ICAR, New Delhi.

Matamala, R., Gozaler-Meler, M.A., Jastrow, J.D., Norby, R.J and Sclesinger, W.H., 2003. Impacts of fine roots turnover on forest NPP and soil carbon sequestration potential. *Science* 302: 1385-1387.

Mathur, G.M., Ram Deo and Yadav, B.S. 2006. Status of Zinc in irrigated North-West plain soils of Rajasthan. *Journal of Indian Society of Soil Science* 54(3): 359-361.

Mathur, S.K., Goswamy, N.K. and Talati, N.R. 1981. Fixation of potassium in north-west Rajasthan soils. *Transactions of Indian Society of Desert Technology* 6: 29-32.

Mehta, P.C., Puntamkar, S.S. and Seth, S.P. 1971. Vertical distribution of phosphorus in the soils of western Rajasthan. *Journal of Indian Society of soil Science* 19: 389-394.

Mishra, D.K. 1971. Agronomic investigations in arid zone. *Proceedings Symposium on Problems of Indian Arid Zone*, pp. 165-169. Central Arid Zone Research Institute, Jodhpur.

Narain, P. 2008. Dryland management in arid ecosystem. *Journal of the Indian Society of Soil Science* 56: 337-347.

Pal, S.K. 1977. *White Grubs and Their Management,* Bulletin No. 5. Central Arid Zone Research Institute, Jodhpur, 86 pp.

Pande, M. and Tarafdar, J.C. 2004. Arbuscular mycorrhizal fungal diversity in neem-based agroforestry systems in Rajasthan. *Applied Soil Ecology* 26: 233-241.

Panwar, J. and Vyas, A. 2002. A biological approach towards conservation of endangered plants in Thar desert, India. *Current Science* 82: 576-578.

Pareek, B.L. and Mathur, C.M. 1969. Available and total phosphorus status in soils of Rajasthan. *Journal of Indian Society of soil Science* 17: 147-149.

Parihar, D.R. 1981. Termite pests of vegetation in Rajasthan and their management. Bulletin No. 16. Central Arid Zone Research Institute, Jodhpur, 31 pp.

Parker, L.W., Frechman, D.W., Steinberger,Y., Driggers, L. and Whitford, W.G. 1984. Effects of simulated rainfall and litter quantities on desert soil biota: soil respiration, microflora and protozoa. *Pedobiologia* 27: 185-195.

Patel, M.S., Patel, K.A., Kalyansundaram, N.K. and Patil, R.K. 1993. Potassium in Gujarat Soils. Gujarat Agricultural University, Sardarkrushinagar, 154 pp.

Peterjohn, W.T. 1991. Denitrification: Enzyme content and activity in desert soils. *Soil Biology and Biochemistry* 23: 845-855.

Pettit, R.K. 2004. Soil DNA libraries for anticancer drug discovery. *Cancer Chemotherapy Pharmacology* 54: 1-6.

Praveen-Kumar and Aggarwal, R.K. 1997. Nitrogen in arid soils: availability and integrated management for increased pearl millet production. In *From Research Station to Framer's field: Nutrient Management Research for Millet Based Cropping Systems for Western Rajasthan* (Eds. B. Seeling, and N.L. Joshi), pp. 25-42. International Crop Research Institute for Semi-Arid Tropics, Hyderabad.

Praveen-Kumar and Aggarwal, R.K. 1998. Interdependence of ammonia volatilization and nitrification in arid soils. *Nutrient Cycling in Agroecosystem* 51: 201-207.

Praveen-Kumar and Aggarwal, R.K. l988. Reducing ammonia volatilization from urea by rapid nitrification. *Arid Soil Research and Rehabilitation* 2: l3l-l38.

Praveen-Kumar, Aggarwal, R.K. and Power, J.F. 1996. Cropping systems: Effect on soil quality indicators and yield of pearl millet in arid Rajasthan. *American Journal of Alternative Agriculture* 14: 178-184.

Raina, P. and Joshi, D.C. 1991. Influence of grazing on the fertility status of sown and natural pasture in arid region. *Annals of Arid Zone* 30: 197-201.

Raina, P. and Joshi, D.C. 1994. Desertification and soil health hazard in Indian arid zone. *Current Agriculture* 18: 55-64.

Ram-Sewak 2009. Dung beetles (Coleoptera: Scarabaeidae: Coprinae) of the Thar Desert of Rajasthan and Gujarat. In *Faunal Ecology and Conservation of the Great Indian Desert* (Eds. C. Sivaperuman, Q. H. Baqri, G. Ramaswamy and M. Naseema), pp. 25-39. Springer Berlin Heidelberg.

Rao, A.V. and Tarafdar, J.C. 1998. Significance of micro-organisms in afforestation programmes in arid zone. *Annals of Arid Zone* 37: 337-346.

Rao, A.V. and Venkateswarlu, B. 1983. Microbial ecology of the soils of Indian desert. *Agricultural Ecosystem and Environment* 10: 361-369.

Rao, A.V., Venkateswarlu, B. and Kaul, P. 1982. Isolation of a phosphate dissolving soil actionmycete. *Current Science* 51: 1117-1118.

Rao, V.M.B. and Singh, S.P. 1993. Crop responses to organic sources of nutrients in dryland conditions. In *Advances in Dryland Agrilculture* (Ed. L.L. Somani), pp. 287-304. Scientific Publishers, Jodhpur.

Rathore, N.S. 1996. Termites (Isoptera) of the Thar desert. In *Faunal Diversity in the Thar Desert: Gaps in Research* (Eds. A.K. Ghosh, Q.H. Baqri and I. Prakash), pp. 171-183. Scientific Publishers, Jodhpur.

Roy, B.B., Ghose, B. and Pandey, S. 1967. Landscape-soil relationships in Chhotan block in Barmer district of western Rajasthan. *Journal of Indian Society of Soil Science* 15: 53-58.

Sanyal, A.K. 1996. Soil mite (Acarina) fauna in the Thar desert. In *Faunal Diversity in the Thar Desert: Gaps in Research* (Eds. A.K. Ghosh, Q.H. Baqri and I. Prakash), pp. 89-92. Scientific Publishers, Jodhpur.

Sharma, B.K. and Kolarkar, A.S. 1983. Available major and micronutrients in arid soils of Jamnagar district of Gujarat. *Annals of Arid Zone* 22: 1-5.

Sharma, B.K., Dhir, R.P. and Dutta, B.K. 1985a. Mineral nutrient elements in natural vegetations of arid Rajasthan. *Annals of Arid Zone* 23: 235-241.

Sharma, B.K., Dhir, R.P. and Joshi, D.C. 1985. Available micronutrient status of some soils of arid zone. *Journal of Indian Society of Soil Science* 33: 50-55.

Sharma, B.K., Joshi, D.C., Gupta, B.S. and Raina, P. 1983. Influence of physiography soil association on the vertical distribution of different forms of copper and zinc in some soils of Rajasthan. *Current Agriculture* 7: 174-180.

Sharma, B.K., Raikhy, N.P., Gupta, B.S. and Joshi, D.C. 1984. Influence of landscape soil relationship on the forms of manganese and iron in arid soils of Rajasthan. *Tropical Agriculture* 61: 221-225.

Sharma, K.L., Kusuma Grace, J., Srinivas, K., Ramakrishna, Y.S., Korwar, G.R., Maruthi Sankar, G., Uttam Kumar Mandal, Ramesh, V., Hima Bindu, V., Madhavi, M., and Pravin N. Gajbhiye 2009. Influence of tillage and nutrient sources on yield sustainability and soil quality under sorghum-mung bean system in rainfed semi-arid tropics. *Communications in Soil Science and Plant Analysis* 40: 2579-2602.

Sharma, K.L., Kusuma, G.J., Mandal, U.K., Gajbhiye, P.N., Srinivas, K., Korwar, G. R., Hima Bindu, V., Ramesh, V., Ramachandran, K. and Yadav, S.K. 2008.

Evaluation of long-term soil management practices using key indicators and soil quality indices in a semi-arid tropical Alfisol. *Australian Journal of Soil Research* 46: 368-377.

Sharma, K.L., Mandal, U.K., Srinivas, K., Vittal, K.P.R., Ramesh, V. and Kusuma, G.J. 2005. Long-term soil management effects on crop yields and soil quality in dryland Alfisols. *Soil and Tillage Research* 83: 246--259

Shukla, U.C. and Singh, R. 1973. Forms and distribution of iron in some eierozem soils of Haryana. *Journal of the Indian Society of Soil Science* 21: 35-40.

Shukla, U.C., Gupta, B.L. and Singh, R. 1975. Available and potentially available forms of iron and manganese in surface arid brown soils. *Journal of Indian Society of Soil Science* 23: 484-488.

Shyampura, R.L., Singh, S.K., Singh, R.S., Jain, B.L. and Gajbhiye, K.S. 2002. Soil series of Rajasthan, National Buerau of Soil Survey and Land Use Planning publication No. 95 NBSS& LUP, Nagpur, 364 pp.

Sidhu, G.S., Rana, K.P.C., Sehgal, J. and Velayuthum, M. 1997. Soils of Himachal Pradesh for Optimizing Land Use. National Buerau of Soil Survey and Land Use Planning Publication No. 57b. (Soil Series of India), Nagpur, 44 pp.

Sidhu, P.S. and Sehgal, J. 1978. Geology, geomorphology and sediment mineralogy and geochemistry of the Indus basin. In *Land and Water Management in the Indus Basin India,* Vol.1, pp. 276-286. Indian Ecological Society, Ludhiana

Sidhu, P.S., Rana, K.P.C., Tarsem Lal, Mahapatra, S.K., Verma, T.P., Rao, R.V.S., Jagat Ram, Singh, S.K. and Singh, S.P. 2007. Soils of Himachal Pradesh: Inventory for land use planning. *Journal of the Indian Society of Soil Science* 55: 203-208.

Singh R.P., Singh, H.P., Daulay, H.S. and Singh, K.C. 1981. Fertilization of rainfed greengram-pearl millet sequence. *Indian Journal of Agricultural Science* 59: 498-503.

Singh, G. 1977. Climatic changes in the Indian desert. In *Desertification and Control.* pp. 25-32. Central Arid Zone Research Institute, Jodhpur.

Singh, H.P., Venkateshwarlu, B., Vittal, K.P.R. and Ramachandran, K. 2000. Management of rainfed agro-ecosystem. In *Natural Resource Management for Agricultural Production in India* (Eds. J.S.P. Yadav and G.B. Singh), pp. 668-774. International Conference on Managing Natural Resources for Sustainable Agricultural Production in the 21st Century, New Delhi

Singh, J.P. and Tarafdar, J.C. 2002. Rhizospheric microflora as influenced by sulphur application, herbicide and *Rhizobium* inoculation in summer mung bean (*Vigna radiata* L.). *Journal of the Indian Society of Soil Science* 50: 127-129.

Singh, K. and Shukla, U.C. 1984. Copper status of some sierozem soils of Haryana. *Journal of Indian Society of Soil Science* 32: 368-370.

Singh, K.C. and Singh, R.P. 1977. Inter cropping of annual grain legumes with sunflowers. *Indian Journal of Agricultural Science* 47: 563-567.

Singh, K. 1983. Available copper status and the relationship with some characteristics of the tropical arid brown soils of Haryana. *Transactions of*

Indian Society of Desert Technology and University Centre of Desert Studies 8: 84-88.

Singh, K., Shukla, U.C., Rajhans and Karwasra, S.P.S. 1988. Distribution of different forms of copper in some soils of Haryana. *Journal of Indian Society of Soil Science* 36: 176-179.

Singh, Megh and Singh, K.S. 1981. Zinc and copper status of soils of Rajasthan. *Annals of Arid Zone* 20: 77-85.

Singh, P. and Joshi N.L. 1980. Intercropping of pearl millet in arid areas. *Indian Journal of Agricultural science* 50: 338-341.

Singh, R.P. 1980. Cropping systems for drylands of Indian Arid Zone. *Annals of Arid Zone* l9: 443-447.

Singh, R.P., Daulay, H.S. and Singh, K.C. 1978. Response of mustard to different levels of nitrogen and row spacing field under limited moisture supply. *Indian Journal of Agricultural Sciences* 48: 234-239.

Singh, R.P., Singh, H.P., Daulay, H.S. and Singh, K.C. 1981. Effect of periodical application of nitrogen inorganic and organic form on yield of rainfed pearl millet. *Indian Journal of Agricultural Science* 51: 409-416.

Singh, S.D., Bhandari, R.C. and Aggarwal, R.K. 1985. Long term effects of phosphate fertilizers on soil fertility and yield of pearl millet grown in rotation with grain legume. *Indian Journal of Agricultural Science* 55: 274-278.

Singh, S.K., Singh, A.K., Sharma, B.K. and Tarafdar, J.C. 2007, Carbon stock and organic carbon dynamics in soils of Rajasthan, India. *Journal of Arid Environments* 68: 408-421.

Singhvi, A.K. Sharma, Y.P. and Agarwal, D.P. 1983. Thermoluminescence dating of dune sands: some refinements. PACT Third specialist seminar on TL and ESR dating, 26-31 July, 1982, Strasburg.

Skujins, J. 1984. Microbial ecology of desert soils. *Advanced Microbial Ecology* 7: 49-91.

Snapp, S.S. and Silim, S.N. 2002. Farmer preferences and legume intensification for low nutrient environments. *Plant and Soil* 245: 181-192.

Soni, M.L., Beniwal, R.K., Mondal, B.C. and Yadava, N.D. 2006. Micronutrient status of arid soils under three predominant land use systems in arid zone. *Current Agriculture* 30: 53-56.

Soni, M.L., Mondal , B.C. and Beniwal , R.K. 2003. Micro minerals in plant animal systems in arid zone of Rajasthan. In: *Seventh International Conference on Desert Technology* , Jodhpur. pp.33.

Suthar, S.S., 2002. Earthworm resources and their utilization in vermitechnology in desert region of Rajasthan. *Ph.D. Thesis*. J.N.V. University, Jodhpur, India, 287 pp.

Suthar, Surindra 2009. Earthworm communities a bioindicator of arable land management practices: A case study in semiarid region of India. *Ecological Indicators* 9: 588-594.

Tak, Neena. 2008. *Ants of arid zone of Rajasthan*. Zoological Survey of India, Kolkata, 46 p.

Tak, Neena and Rathore, N.S. 1996. Ant (Formicidae) fauna of the Thar Desert. In *Faunal Diversity in the Thar Desert: Gaps in Research* (Eds. A.K. Ghosh, Q.H. Baqri and I. Prakash), pp. 271-276. Scientific Publishers, Jodhpur.

Takkar, P.N., Bansal, R.L., Mann, M.S. and Randhawa, N.S. 1976. Micronutrient status of soils and wheat crop of Punjab. *Fertilizer News* 21: 47-51.

Talati, N.R., Mathur, S.K. and Attri, S.C. 1974. Behaviour of available and non exchangeable potassium in soils and its uptake in wheat crop. *Journal of Indian Society of soil Science* 22: 139-144.

Talati, N.R.; Mathur, G.S. and Attri, S.C. 1975. Distribution of various forms of phosphorus in north-west Rajasthan soils. *Journal of Indian Society of soil Science* 23: 202-206.

Tarafdar, J.C. 1995. Role of VA mycorrhizal fungus on growth and water relations in wheat in presence of organic and inorganic phosphates. *Journal of the Indian Society of Soil Science* 43: 200-204.

Tarafdar, J. C. and Rao, A.V. 2002. Possible role of arbuscular mycorrhizal fungi in development of soil structure. In *Arbuscular Mycorrhizae: Interactions in Plant, Rhizosphere and Soils* (Eds. A.K. Sharma and B.N. Johri), pp. 189-206. Oxford & IBH Publishing Co. Pvt. Ltd.

Tarafdar, J.C. and Gharu, A. 2006. Mobilization of organic and poorly soluble phosphates by *Chaetomium globosum*. *Applied Soil Ecology* 32: 273-283.

Tarafdar, J.C. and Rao, A.V. 1990. Rhizosphere effect on phosphatases under different vegetable crops grown in saline sodic soils of western Rajasthan. *Journal of the Indian Society of Soil Science* 38: 753-755.

Tarafdar, J.C. and Rao, A.V. 1997. Mycorrhizal colonization and nutrient concentration of naturally grown plants on gypsum mine-spoils in India. *Agriculture Ecosystems and Environments* 61: 13-18.

Tarafdar, J.C., Kiran Bala and Rao, A.V. 1989. Phosphatase activity and distribution of phosphorus in arid soil profiles under different land use patterns. *Journal of Arid Environments* 16: 29-34.

Tarafdar, J.C., Rao, A.V. and Kiran Bala 1988. Production of phosphatases by the fungi isolated from desert soils. *Folia Microbiology* 33: 453-457.

Tarafdar, J.C., Rao, A.V. and Praveen-Kumar 1992. Effect of different phosphatase producing fungi on growth and nutrition of mung bean (*Vigna radiata* (L.) Wilczek) in arid soil. *Biology and Fertility of Soils* 13: 35-38.

Tarafdar, J.C., Rao, A.V. and Praveen-Kumar 1995. Role of phosphatase producing fungi on growth and nutrition of clusterbean (*Cyamopsis tetragonoloba* (L.) Taub). *Journal of Arid Environments* 29: 331-337.

Trappe, J.M. 1981. Mycorrhizae and productivity of arid and semi arid range lands. In *Advances in Food Production System for Arid and Semi Arid Lands* (Eds. J.J. Manassha, and E.J. Briskey), pp. 581-599. Academic Press, New York.

Tripathi, G., Ram, S., Sharma, B.M. and Singh, G. 2005. Soil faunal biodiversity and nutrient status in silvopastoral systems of Indian desert. *Environmental conservation* 32: 178-188.

Tripathi, G., Deora, R. and Sharma, B.M. 2008. Diversity and abundance of beetles in silvipasturelands of Thar Desert. *Tiger paper* 35: 1-7 pp.

Tucker, B.B. 1988. Soil fertility assessment and management and management strategies in dry land system. In *Challenges in Dry Land Agriculture: A Global Perspective* (Eds. P.W. Unger, T.V. Sneed, W.R. Jordan and R. Jesen), pp 361-366. Proceedings International Conference on dryland farming, Texas Agricultural Experiment Station College, Amarillo, Bushland.

Venkateswarlu, B., Rao, A.V. and Raina, P. 1984. Evaluation of phosphorus solubilization by microorganisms isolated from Aridisols. *Journal of the Indian Society of Soil Science* 32: 273-277.

Venkateswarlu, J. 1984. Nutrient management in semi-arid red soils. Part II, Project Bulletin No. 8 AICRPDA, Hyderabad.

Venkateswarlu, J. 1987. Efficient resource management for drylands of India. *Advances in Soil Science* 7: l65-22l.

Venkateswarlu, J. and Hegde, B.R. 1992. Nutrient management for sustainable production in coarse textured soils. In *Nutrient management for sustained productivity*, pp. 188-194. Proceedings International Symposium Punjab Agricultural University, Ludhiana.

Venkateswarulu, B. and Rao, A.V. 1981. Distribution of microorganisms in stabilized and unstabilised sand dunes of Indian desert. *Journal of Arid Environment* 4: 203-208.

Watt, M., McCully, M.E. and Canny, M.J. 1994. Formation and stabilization of rhizosheaths of *Zea mays* L. (Effect of soil water content*). Plant Physiol.*, 106: 179-186.

West, N.E. 1990. Structure and function of microphytic soil crusts in wild wind ecosystems of arid to semi-arid regions. *Advanced Ecological Research* 20: 179-223.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur,113-150 pp.

Surface and Groundwater Resources of Arid Zone of India: Assessment and Management

R.K. Goyal[1], Dorjey Angchok[2], Tsering Stobdan[2], Shashi Bala Singh[2] and Hitesh Kumar[2]

[1]*Central Arid Zone Research Institute, Jodhpur*

[2]*Defence Institute of High Altitude Research, Leh-Ladakh*

Water is a precious resource that is currently in need of long-term planning for storage and judicious use for the survival of mankind. Excessive exploitation of water without any systematic conservation programme can lead to depletion of the resource beyond recovery, as is being currently experienced in the arid regions. This chapter discusses the water resources of the two most problematic arid areas in the country, the hot arid areas of western Rajasthan and the cold arid areas of Ladakh district in Jammu and Kashmir.

Water Resources of Arid Western Rajasthan

Western part of Rajasthan state is the most problematic area within the hot arid zone. The average annual rainfall here is 318 mm, as compared to 531 mm in Rajasthan state. Due to low and erratic rainfall, replenishment of exploited water is also very poor. During the Twentieth Century, different parts of western Rajasthan experienced agricultural drought once in three years to every alternate year. The overall probability of drought for the state is 47%. The weather condition even in average years for most part of the year remains too dry and inhospitable for successful growth of crops. Under such conditions of uncertainty, conventional cropping is risky and has necessitated widespread use of groundwater for irrigated cropping. Although the whole of Rajasthan state is categorized as water-scarce (having per capita water availability below 1000 m^3 $year^{-1}$ Narain *et al.*, 2006a), the condition in western Rajasthan is more precarious. The west-central part of western Rajasthan is devoid of any drainage network and has meager surface water resources, which adds to the problem (Fig. 1). Rapid urbanization and industrialization, increasing pollution of the water sources by the industrial units and over-extraction of water from deep wells has led

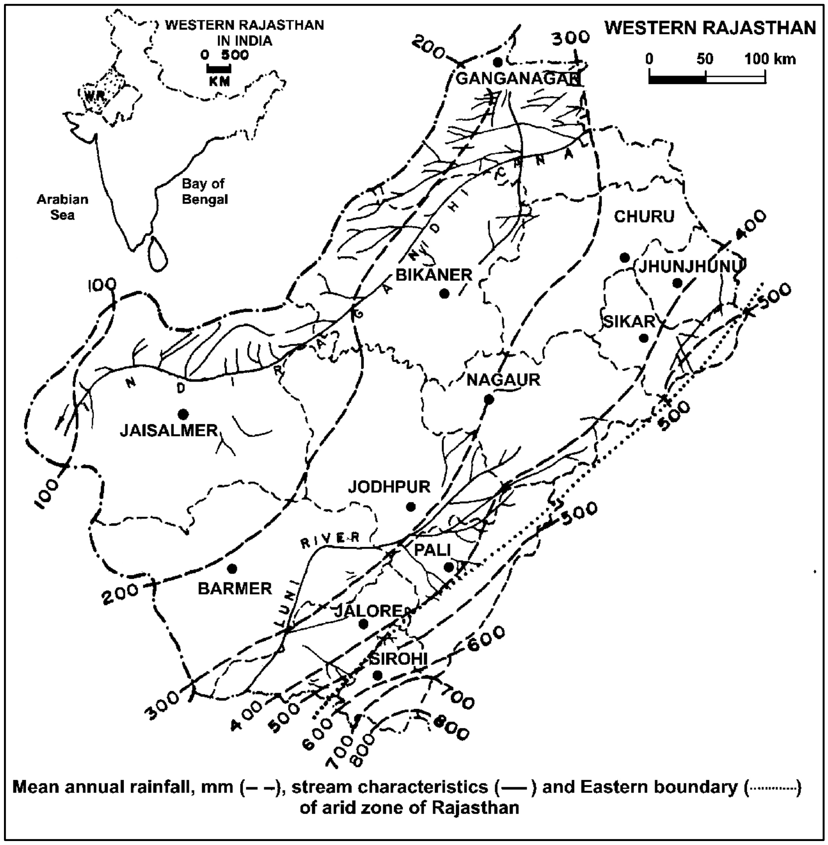


Fig. 1. Rainfall and stream characteristics of arid zone in Rajasthan.

to water quality problems. Despite climatic adversity, this is one of the most densely populated deserts of the world.

Long-term statistical analysis of rainfall data of the region indicates an asymmetric average storm intensity profile for storms of short duration, with the highest intensities falling in the first part of the storm. Occurrence of water flow in the watercourses is unpredictable, of short duration and high variability. The instantaneous discharge-duration curve shows very high and irregular peaks indicating the problems of controlling runoff. Regulation of sporadic discharge by means of surface reservoir presents many problems, especially the high ratio of storage to mean annual runoff volume required to produce the degree of control necessary for economical agricultural development (Goyal and Vittal, 2008).

Hydrological zones

Hydrologically western Rajasthan has been divided into three broad zones (Venkateswarlu *et al.*, 1990).

Zone – I : Region with major input of surface water from more humid region, frequently with extensive irrigated agriculture. About 60% area of Ganganagar district in the north and 50% area of Bikaner district and 25% area of Jaisalmer district in the northwest lie in this zone. This is the main canal irrigated zone in arid Rajasthan.

Zone-II: Plain lands with a primitive or no stream network. The region has a system of repetitive micro-hydrology. Churu, Jhunjhunu, Sikar, Nagaur, Jodhpur and parts of Bikaner, Jaisalmer and Barmer districts come under this category. This zone occupies 52% area of arid Rajasthan.

Zone-III: Sloping region with an integrated stream network. The Luni basin, occupying the districts of Pali, Jalore, part of Jodhpur and Barmer districts, lie in this zone.

Surface water resources

The inherent surface water resources of the western Rajasthan are scarce and because of low and erratic rainfall, replenishment of these water resources is also very poor. Due to high atmospheric temperature and low humidity, a large part of the rainwater is lost as evapotranspiration. Except in canal command area in north, surface water potential is very low in the central, western and southern parts. More than 50% area of northwest Indian arid zone comprises of sandy plains, dune systems, eroded rocky/gravely surfaces and isolated hillocks. In central and western parts, the run-off generated in response to some high-magnitude rainstorms gets lost in sandy terrain. As per initial estimate approximately 280 x 10^6 m^3 surface water is available annually for utilization in this part (Jain, 1968). Mehta and Kashyap (1970) estimated the surface water potential of this region as 200 x 10^6 m^3, out of which 130 x 10^6 m^3 is utilisable resource. Sharma and Vangani (1992) estimated the surface water potential of this region as 1360 x 10^6 m^3 out of which 47% was utilized till 1988 (Table 1).

Nearly 33% area of the zone is occupied by the Luni Basin, the Sahibi Basin and a few smaller river basins. These are ephemeral drainage systems and convey runoff only in response to torrential rainfall during the monsoon season. The estimates of surface water resources for Luni basin ranges from 518 x 10^6 m^3 (Dhir and Krishnamurthy, 1952), to 571 x 10^6 m^3 (Dhruvanarayana *et al.*, 1964), to 868 x10^6 m^3 (Mehta, 1970), to 939 x 10^6 m^3 (Mehta and Kashyap, 1970), to 858 x 10^6 m^3 (Anon., 1980), to 1130 x 10^6 m^3 (Sharma, 1991). Large numbers of tanks, reservoirs, minor irrigation dams and check dams have been constructed at different locations in Luni basin and other areas to store runoff water during monsoon. About 550 storage tanks in the capacity ranging from less than 1.51 to 208 x 10^6 m^3 are functional with total utilizable capacity of nearly 1169.28 x 10^6 m^3 for providing irrigation to 0.102 x 10^6 ha land (Khan, 1997). Out of these, six reservoirs viz. Jaswantsagar, Sardar Samand, Jawai, Hemawas, Ora and Bankali, are the major irrigation tanks with capacity of irrigation of more than 4000 ha each. Jawai is the main source of drinking water supply to many towns and villages (Source: Irrigation Department, Govt. of Rajasthan).

Table 1. Surface water resources (mcm) in arid Rajasthan

District	Zone-I	Zone -II	Zone-III	Total
Ganganagar	6.49	11.19	–	17.68
Bikaner	7.14	26.16	–	33.3
Churu	–	22.82	–	22.82
Jhunjhunu	–	8.04	96	104.04
Sikar	–	10.48	96	106.48
Jaisalmer	5.03	38.38	–	43.41
Jodhpur	–	20.66	–	20.66
Nagaur	–	53.18	–	53.18
Pali	-	–	869	869
Barmer	–	19.64	–	19.64
Jalore	–	–	71	71
Total	18.66	210.55	1132	1361.21

* including Hanumangarh.

About 15% area in the north-west arid zone of India receives major input of water through an extensive canal network. This region comprises of the arid districts within the states of Haryana and Punjab and the north-western part of Rajasthan. The canal systems in this region are the Gang Canal, the Bhakra Canal and the Indira Gandhi Canal bringing water by diverting the flows of the Sutlej, the Beas and the Ravi in Punjab. The estimated designed capacity of these canals varies from 314 to 524 cumec (Murthy and Gulati, 1978; Uppal, 1978; Gupta, 1987; Kapoor and Rajvanshi, 1977). On the basis of average flow from 1982 to 1996 the canal water available in the four districts of Ganganagar, Hanumangarh, Bikaner and Jaisalmer is at the rate of 0.90 m ha^{-1} (Anon., 1988; 1996), far more than the stipulated mean value of 0.51 m ha^{-1}.

Indira Gandhi Nahar Pariyojna (IGNP)

The Indira Gandhi Nahar Pariyojna (IGNP) receives its supplies from the Indian share of waters of Indus river basin as per Indus Water Treaty of September 1960 between India and Pakistan. The three eastern rivers of the basin (namely Ravi, Beas and Sutlej) have been harnessed since then through several facilities dams, reservoirs, links and canals. Although water resources development of the Indus waters dates back to centuries, major activities started in the Tenth Century and continued to meet with the growing needs of the agricultural community. The Gang canal system built during 1922-1929 utilizes 1.11 million acre feet (MAF) of water which constitute the pre-partition share of India, drawn from the Sutlej river near Ferozpur Head Works. RD 45 of the Gang canal was linked with Harike Barrage constructed in the upstream at a later date. The inter-state agreement for sharing waters of the Ravi-Beas rivers came into being in the year 1955 between erstwhile State of Punjab, Jammu and Kashmir (J&K) and Rajasthan, followed by Bhakra Nangal agreement in 1950. Agreements were later revised and finally as per 1981 agreement total share of water for Rajasthan in Ravi-Beas waters was 9.71 MAF. This quantum of water was further allocated by the Government of Rajasthan to IGNP stage I and II, 3.59 MAF(inclusive of 0.22 MAF for drinking and other uses) and 4.00 MAF (inclusive of 0.65 MAF for drinking and other uses), respectively. The remaining water was given to Gang Canal 1.44 MAF (1.11+0.33), additional water for Bhakra system from Ravi-Beas waters 0.21 MAF and Sidhmukh/Nohar Project 0.47 MAF.

Stage I consists of a 204 km long feeder canal, having a headworks discharge capacity of 460 m^3 sec^{-1}, which starts from Harike Barrage. 170 km of the feeder canal lie in Punjab and Haryana and 34 km in Rajasthan. The Stage-I also consists of 189 km long main canal and 3454 km long distribution system, which are concrete lined, and serve 553 kha of culturable command area, out of which 46 kha are served by pumping to a 60 m lift, through four pumping stations. IGNP Stage II comprises construction of a 256 km long main canal and 5,606 km of a lined distribution system, and will serve 1,410 kha of CCA (873577 ha area in flow and 537018 ha under lift), utilising 4,930 Mm^3 yr^{-1} of water. The main canal in the entire length was completed in the year 1986. The irrigation intensity initially planned for Stage I and Stage II was 110% and 80%, respectively (GOR, 1999). The canal system was initially designed at a water allowance of 5.23, 3.0 and 2.0 cusecs/1000 acres for Stage I, Stage II flow area and Stage II lift areas, respectively (which works out to 0.36, 0.21 and 0.14 cumecs per 1000 hectares).

Irrigation in canal command area needs proper management to avoid water logging, soil salinity, etc. More than 60% of canal command area has sandy soils with poor water holding capacity. Nearly 50% of additional water applied in form of irrigation goes as deep percolation and joins groundwater.

The problem of water logging is more apparent in recent years. The mean rate of water table rise varies from 1.1 m year^{-1} in Stage-I to 0.81 to 0.85 m year^{-1} in Ghaggar plain and Bhakra command, respectively, and 0.64 m year^{-1} in Gang canal command area. On the basis of annual rise in water table, it has been found that an area of 1456 km^2 has already turned critical (water table within 6 m of land surface). However, a far more serious water logging problem awaits Stage-II, owing to an underground hard substratum of gypsum within 10 m depth. In about 34% area (1205 km^2) of the gross command area of 3544 km^2, water collected in low lying areas does not seep down (Rahmani and Soni, 1997). Due to capillary action, the water comes to the surface with dissolved salts and evaporates, leaving the salt behind, thus making the land saline. According to one study (Chouhan, 1988), if surface drainage is not introduced in the waterlogged area, thousands of hectares of land will be submerged and salinised in 25 to 30 years.

In the adjoining Haryana state, Sirsa and Hisar districts have 148 km^2 (3.0%) and 266 km^2 (4.0%) area, respectively, within the influence of high water table (Rao *et al.*, 1986); the rate of water table rise is in the range of 0.14 to 1.0 m year^{-1}. In addition to salts contributed by groundwater nearly 2.0 x 10^6 t of salts are added annually through canal irrigation. In Punjab state nearly 1.05 x 10^6 ha area is irrigated through canals in the arid districts of Faridkot, Firozpur and Bhatinda (Sidhu *et al.*, 1991). As a result about 80% of the total salt affected and waterlogged area of the state occurs in these districts; the water table is rising @ 0.52 to 0.75 m year^{-1}.

Groundwater Resources of Arid Rajasthan

Groundwater resources of this region are very poor in terms of quantity and quality. Groundwater in this region is not sufficient even for drinking purposes. Over and above insufficient quantity, the groundwater is moderately to highly saline over large area. A dominantly sandy terrain and disorganized drainage network (drainage density is as low as 0.3 km km^{-2}), and recurring droughts constantly exert pressure on already meager groundwater resources. The stage of groundwater development has exceeded 100% in Barmer, Jalore, Jhunjhunu, Jodhpur, Nagaur, and Sikar districts. Number of Safe blocks has been significantly reduced because of meager rainfall and over exploitation of groundwater resources mainly for irrigation (Fig. 2). Summary of groundwater status in year 2004 along with status of groundwater blocks is presented in Table 2. Groundwater resources of arid Rajasthan as in year 2001 is presented in Table 3.

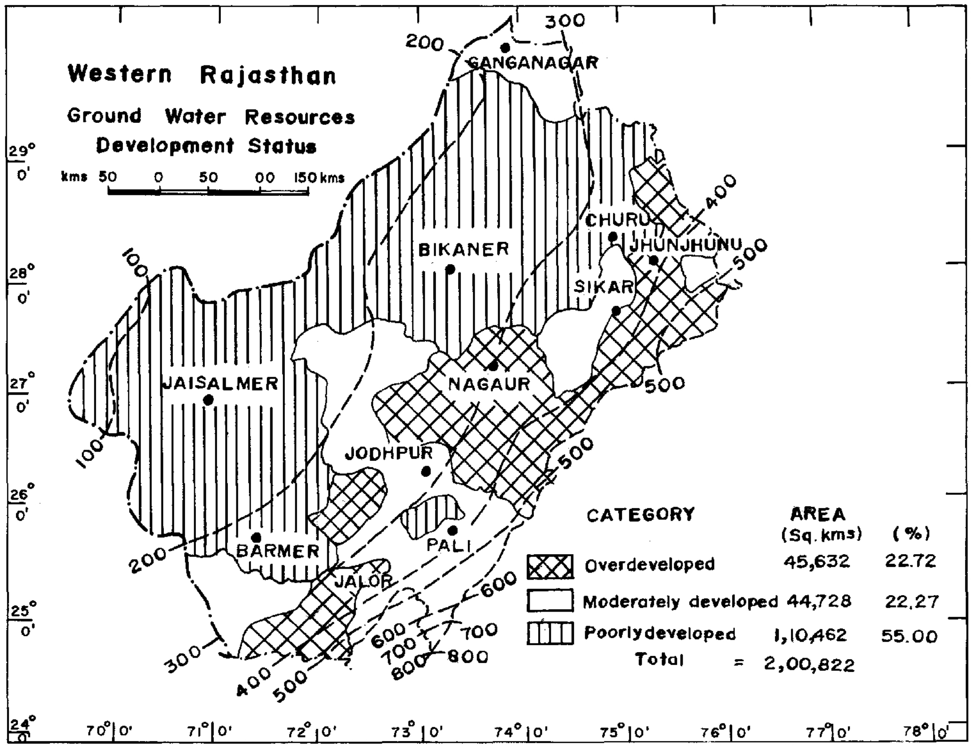


Fig. 2. Status of groundwater development in Western Rajasthan.

Table 2. Summary of Groundwater resources (mcm) in arid zone of Rajasthan

Ground water status		2001	2004
Groundwater recharge/availability		3519	3323
Groundwater draft	Irrigation	3741	3996
	Domestic & industrial	541	600
	Gross	4282	4596
Groundwater balance		(-)763	(-)1273
Stage of development (%)		121.68	138.30
No. of blocks	Total	84	84
	Safe	19	19
	Semi-critical	5	5
	Critical	23	23
	Over-exploited	37	37

Source: G.W.D. Rajasthan.

Table 3. Cropped area and stage of groundwater development (2001) for arid Rajasthan

District	Total area (km^2)	Total cropped area (km^2)	Total irrigated area (km^2)	Net annual groundwater availability (mcm)	Existing gross groundwater draft (mcm)	Stage of groundwater development (%)
Barmer	28173	16504	1505	250	256	102
Bikaner	30356	14653	2284	198	145	73
Churu	13859	11408	581	198	117	59
Ganganagar	10930	9068	7869	199	134	67
Hanumangarh	9703	8827	5499	195	165	85
Jaisalmer	38392	4674	907	53	40	75
Jalore	10566	7409	2022	424	827	195
Jhunjhunu	5917	6097	2426	243	420	173
Jodhpur	22564	12278	1766	393	661	168
Nagaur	17644	13654	2948	628	842	134
Pali	12331	5829	1121	413	330	80
Sikar	7742	6716	2719	325	345	106
Total	208177	117117	31647	3519	4282	121.6

Groundwater depletion

Due to over mining groundwater levels are declining in 9 out of 12 districts of arid Rajasthan since 1984. Groundwater table in Jalore and Pali districts shows a decline rate of more than 0.50 m $year^{-1}$. In Jodhpur, Jhunjhunu, Nagaur and Sikar districts groundwater decline rate is 0.44-0.48 m $year^{-1}$. In Barmer, Churu and Jaisalmer districts the rate of decline is less than 0.20 m $year^{-1}$. In Bikaner, Ganganagar and Hanumangarh districts water level shows a rising trend due to IGNP (Table 4).

Future groundwater scenario

Future projection of groundwater utilization has been worked out for the year 2010, 2015, 2020 and 2025 considering the average growth rate @ 3.20% compounded annually, though the present actual growth rate is higher (Table 5). The data on utilizable recharge are considered constant which is for 2001.

Table 4. Groundwater fluctuation during 1984-2003 in arid zone of Rajasthan

District	Average annul fluctuation in groundwater table (m year^{-1})	Total decline/increase in water level (m)
Barmer	-0.17	-3.18
Bikaner	+0.05	+0.86
Churu	-0.05	-0.98
Ganganagar	+0.31	+5.79
Hanumangarh	+0.24	+4.60
Jaisalmer	-0.01	-0.18
Jalore	-0.54	-10.17
Jhujhunu	-0.48	-9.14
Jodhpur	-0.48	-9.08
Nagaur	-0.46	-8.68
Pali	-0.53	-10.11
Sikar	-0.44	-8.39

"- decline, "+"rise in water level.

Table 5. Projected groundwater scenario for arid Rajasthan

Projection	Year					
	2001	2005	2010	2015	2020	2025
Utilizable groundwater recharge (mcm)	3519	3519	3519	3519	3519	3519
Net groundwater utilized (mcm)	4282	4856.97	5685.43	6655.22	7790.42	9119.25
Balance groundwater (mcm)	-763	-1337.97	-2166.43	-3136.22	-4271.42	-5600.26
Groundwater development stage (%)	121.7	138.02	161.56	189.12	221.38	259.14

The projection presents a grim situation even when the numbers are on a lower side. The stage of development is likely to reach 161.6, 189.1, 221.4 and 259.1% in the year 2010, 2015, 2020 and 2025, respectively. Arid Rajasthan has to face the adverse effects of overexploitation.

Strategies for Water Resource Management in Arid Zone

Rain is the principal source of water in this region, which augments soil moisture, groundwater and surface flows. Agriculture and several other economic activities in arid areas depend on rain. Of the total water use about 85% of water is used for irrigation and remaining 15% is used for drinking, industrial and other purposes. About 65% of irrigation water and 30-40% of drinking water is subjected to serious losses. Hence, increasing water use efficiency, coupled with increasing availability of water through rainwater harvesting and management, is key to survival on sustainable basis. Rainwater harvesting, its conservation and efficient utilization can solve problem of water scarcity to a greater extent. Rainwater harvesting in small ponds (*nadis*), underground tanks (*tankas*), *Khadins* (Low lying areas) etc., is an age-old tradition here. These traditional structures vary in design, shape and size. These structures are now partially or sometimes totally neglected because of increased dependence on tubewell, tankers, canal water supply, etc. The traditional methods require revival and improvement for being more economical and efficient.

Rainwater harvesting in Nadis and Ponds

The people of rural arid areas live in scattered settlements called *dhani's* distributed over sand dunes, interdunal plains and undulating landforms. Under such conditions it is inconceivable that organized water supply will be feasible to fully meet the demand of thirsty land, human and livestock. Rainwater harvesting in *Nadi* and farm pond for groups of farm families or community are the most viable proposition. *Nadi* is a dugout pond used for storing runoff water from adjoining natural catchment during rainy season. High evaporation and seepage losses through porous sides and bottom, heavy sedimentation due to biotic interference in the catchment and contamination are its major bottlenecks. Complete control of seepage and evaporation losses is very costly and not foolproof. Nadi can play a significant role in preventing complete crop failure (Mann and Singh, 1977; Singh, 1983). Singh (1986) reported better utilization of nadi water for raising nurseries, orchards and to support the initial establishment of trees observed instead of watering field crops. Chatterji *et al.* (1985) reported pollution of nadi water due to free access of human and livestock, leading to the growth of many harmful bacteria and other water-borne diseases and therefore, not safe for human consumption in Nagaur district. Sedimentation in pond is another major problem. Shankarnarayan and Singh (1979) observed reduction in water surface area and drainage basin area up to 1.8 to 2.4 and 6 to 8 times, respectively, due to biotic interference. To overcome these problems CAZRI has developed designed *Nadis* with LDPE lining on sides and bottom keeping surface to volume ratio 0.28 and provision of silt trap at inlet (Khan, 1989). *Nadis* also help in recharging groundwater aquifers although their effect varies depending on the underlying soils and rocks.

Where the substrate is rocky, it is estimated that they contribute a depth of 0.06 metres of water a year compared to 1.58 metres in sandy plains. A study of a 2.25-hectare *nadi* with a storage capacity of 15,000 cubic metres in the north Gujarat alluvial area calculated that the pond contributed as much as 10,000 cubic metres of water to the groundwater aquifer in one rainy season.

Farm Pond is an improved version of *nadi* with treated catchment and surplusing arrangement for removal of excess water. A farm pond of 20,000 m^3 capacity was constructed at Kukma watershed at Bhuj in Gujarat by CAZRI in year 2004. Construction of farm pond resulted in assured availability of 20,000 m^3 water even in during 150 mm rainfall (Narain *et al.,* 2006 b). The collected water was used to provide irrigation to Datepalm, ber, aonla and other fruits plants in nearby area. Construction of large number of rainwater harvesting nadis and farm ponds can solve the problem of uncertainty of occurrence of rainfall and can store water during heavy rainfall for non-monsoon period for human, livestock and crops on sustainable basis. Therefore, construction/renovation and desilting of nadis/farm ponds during drought relief measures by state government and NGO's can be beneficial.

Rainwater harvesting in Khadin for crop production

Recurring droughts and long dry spells are regular feature of arid zone of Rajasthan, which result in crop failure or severe reduction in crop growth and yield. A traditional practice of *khadin* farming in arid Jaisalmer district ensures better moisture conservation and cropping. The system is very effective even where annual average rainfall is less than 200 mm.

Khadin farms were first constructed by Paliwal Brahmin of Jaisalmer district in the Fifteenth Century (Sehgal, 1973). The Paliwals connected most of the local catchments into well-knit system of *khadin* farms for assured crop production even under low rainfall. Kolarkar *et al.* (1983) observed 2 to 16 times lower electrical conductivity (EC) of Khadin soils compared to outside farms. The reduction in EC has been attributed to leaching of salts through seepage water in khadin. The *khadin* soils hold soil moisture to last up to growing season. The average yield of 20 to 30 q ha^{-1} for wheat and 13 to 25 q ha^{-1} for chick pea without any specific agronomical practices and fertilizers were also reported under khadin. Tiwari (1988) has linked the *khadin* cultivation with the farming system of Kalibanga and Rang Mahal cultures of the Indian desert, which are presumed to be of Harappan age (3000 BC).

CAZRI has evolved a design package and guidelines for construction of khadins (Khan, 1992 a). Improved khadin has been constructed by CAZRI near village Danta in Barmer district. The catchment area of the khadin is 137 ha with 6.88 ha submergence. Provision of 40 m bed bar in 450 m long earthen embankment was provided for spilling over excess water in khadin bed. The total water storage capacity of khadin is 54.2 x 10^4 m^3 and beneficiaries are four farm families (Khan, 1998 a). A Khadin of 20 ha area was developed in Baorali-Bambore watershed with surplussing arrangement. Before construction of Khadin, uncontrolled runoff from upper catchment used to wash away seeds, fertilizers, and standing crops, besides loss of valuable water. After construction of Khadin, farmers could take excellent Kharif and Rabi crops (Narain and Goyal, 2005). Collecting water in a khadin aids the continuous recharge of groundwater aquifers. Studies of groundwater recharge through khadins in different morphological settings suggest that 11 to 48% of the stored water contributed to groundwater in a single season. This replenishment of aquifers means that subsurface water can be extracted through bore wells dug downstream of the khadin. The average water-level rise in wells bored into sandstone and deep alluvium was 0.8 metres and 1.1 metres, respectively. There were 500 such *khadins* covering an area of 12,140 ha in Jaisalmer and the crop production from such areas was adequate to feed the people of Jaisalmer district. Large-scale development of *khadin* farms at suitable locations in western Rajasthan can enhance land productivity.

Rainwater harvesting from constructed catchment

Under this system, catchments are constructed in such a way that runoff is directed to a desired destination instead of spreading here and there. The desired destination may be crop/tree to supplement the soil moisture or a reservoir for storage and subsequent utilization. Inter-row, inter-plot and micro-catchment are some of the constructed catchments, which can be used to enhance the availability of water. Runoff from micro-catchments was generally found to depend upon rainfall and catchment characteristics. The results of seven years' field studies showed that micro-catchments produced 13 to 32% of rainfall as runoff at 0.5% slope; and even higher amounts at 5% (36 to 45%) and 10% (26 to 44%) slopes. Runoff generally increased with decreasing slope length; runoff for 5 and 10% slope were nearly equal but greater than for 0.5% slope (Sharma, 1986). Apparently, there is a critical slope beyond which runoff is not affected by slope increases. A large part of the rainfall is absorbed by the sandy soil of the catchment, thereby reducing the total amount of harvested water. Various surface covers and sealants were experimented to increase runoff.

Plastic covered catchments were found to generate 95% runoff while Janta emulsion (asphalt), pond sediment and compacted catchments yielded 91%, 88% and 66% runoff, respectively (Sharma *et al*., 1986). The results of studies at farmer's field in Kalyanpur (Barmer district) showed very high efficiency of moisture conservation with stone and sand filled polythene bags with associated improvement in growth and establishment of Ziziphus mauritiana (ber) seedlings (Ojasvi *et al*., 1999).

Inter-row water harvesting using ridge-furrow has also been found useful in raising dryland crops. Under this technique, 50-60 cm wide ridges alternated with 30-40 cm inside furrows (15 cm deep) are constructed using ridger equipment. Crops are planted in furrows, adopting a paired row design. Ridges yield runoff to the furrows, thus enhancing the moisture regime in the root zone. Singh *et al.* (1973) reported 210% increase in the yield of pearl millet with this system. They concluded that ridge-furrow technique has better adaptability for small holders, as no area of the field is lost to catchment construction. Singh (1982) suggested maintaining the furrows and ridges as permanent structures. Thus, if the tillage is restricted to furrows only, the energy input can be substantially reduced.

Rainwater harvesting for groundwater recharge

As per groundwater estimates of Rajasthan for year 2001, total annual groundwater availability is 11,159 mcm as against total annual water demand (draft) of 11,626 mcm. The overall stage of groundwater development for Rajasthan state is 104%, which is categorized as 'overexploited'. Presently out of total 32 districts, 14 districts are in the category of overexploited, 4 in critical zone, 8 in semi-critical zone and remaining 6 are considered in safe category. With increasing demand for water, more and more blocks are likely to be in the category of overexploited and need immediate attention for recharge of groundwater.

Percolation tanks, pondage in stock tanks with infiltration galleries, sand filled dam, anicuts across stream, sub-surface barriers, etc., are used for groundwater recharge (Ojasvi *et al*., 1996; Goyal, 1999). Sub-surface barriers constructed across ephemeral streams trap sub-surface flow to recharge groundwater aquifer (Khan, 1998 b). Construction of two sub-surface barriers of 10 m length each within 300 m from water supply well was found enough to store runoff water required for a village having a population of 500 (Anon., 1974). Singh *et al.* (1989) reported that soil conservation practices have increased recharge to the extent of 14.02 to 19.52% of rainfall in Udaipur region. Adoption of conservation measures like anicuts, loose stone check dams, brushwood check dam, etc., in Jhanwar watershed (Jodhpur district) resulted in recharge/increase of groundwater level @ 0.33 m-.75 m year^{-1} (Bhati *et al.,* 1997; Goyal *et al.*, 2007). In another watershed at Osian-Bigmi (1991-96), conservation measures like loose stone check dams, vegetative barriers and anicuts resulted in rise in water table by 1.1 m, indicating the effectiveness of conservation measures for recharge of groundwater (Gupta *et al.*, 2002).

Rainwater harvesting through tanka for potable water

Good quality potable water is a global issue, particularly in developing world because 80% of the diseases in the world is due to poor quality drinking water. The problem of poor quality groundwater used for drinking is more acute in Rajasthan (Table 6). Concentration of fluoride ranges from 0.4 to 90 mg l^{-1} leading to various diseases like dental fluorosis, skeletal fluorosis and, non-skeletal manifestation etc.

Table 6. Comparison of groundwater quality in Rajasthan and rest of India

Particulars	India	Rajasthan			
		Villages	Habitations	Total	% of country
Multiple quality problems	25092	9572	9067	18639	74
Only fluoride	31306	4477	4515	8992	29
Only salinity	23495	3235	2193	5428	23
Only nitrate	13958	4211	3671	7882	56.5
Only iron	118088	79	52	131	0.1
Only arsenic	5029	-	-	-	-
TOTAL	216968	21574	19498	41072	

Source: Report of expert committee on integrated development of water resources, June 2005.

Rainwater is the purest form of water. Appropriate harvesting of rainwater from roof top and open and its utilization can alleviate problem of fluoride to great extent. Studies conducted at CAZRI have revealed that roof made of different materials can generate 50- 80% runoff that can be stored in underground cistern (*tanka*) which could provide excellent drinking water round the year. Rainwater can also be harvested in tanka using artificially prepared catchment. Collection and storage of excess rainwater in tankas is an age-old tradition for meeting domestic water requirements. Till today most villages depend on these structures as source of drinking water. Traditional *tankas,* constructed with lime plaster, typically have a life span of three to four years. They suffer from seepage and evaporation losses and in the absence of proper silt traps and pollutant-free inlets, the quality of the conserved water deteriorates over time, making it unsafe for drinking. In many situations, degradation of the catchment area means that it does not yield the quantity of water required to continuously replenish the structure.

CAZRI has designed improved *tankas* for individual family to community with capacities of 5,000 to 600,000 litres. Vangani *et al.* (1988) have observed that an individual family tanka is better managed than a community tanka. The improved *tankas* include silt traps at the inlets to prevent pollutants from entering the *tanka*. The improved designs have a lifespan of more than 20 years. Planting of suitable tree species around the periphery of the catchment area of a *tanka* is recommended to improve the local environment (Khan, 1992b; Bhati *et al.,* 1997). CAZRI has constructed 17 improved *tankas* at Kalyanpur and Baorali-Bambore under National Wasteland Development Board and National Agricultural Technology Projects (1998-2003). The improved *tanka* design developed by CAZRI has wide acceptability in the region, and has been widely replicated under Rajeev Gandhi National Drinking Water Mission. The number of improved tankas in different capacity ranges constructed in the region is 11,469 with a total storage capacity of 475200 cubic meters. These are sufficient to meet the drinking and cooking water requirements for a population of 132000 throughout the year (Khan and Venkateswarlu, 1993). *Tanka* is highly economical compared to hauling of water from long distances. The most economical size of tanka is 50,000 liters with Rs. 1.5 per liter cost of construction.

Rainwater harvesting for supplemental/life saving irrigation

Studies conducted at CAZRI and elsewhere show that application of water at critical stages of tree/crop growth increases the yield substantially. Complete drought or long dry spells within a season are very common in this region. Harvested rainwater can be used to provide supplemental/life saving irrigation, particularly to trees and crops. Khan (1995) observed that with supplemental irrigation (60 litres irrigation^{-1} plant^{-1}) the fruit yield of *ber* (*Ziziphus mauritiana*) and pomegranate increased substantially. In comparison to no irrigation, increase in fruit yield with 2, 4 and 6 irrigations for ber was 46.4, 80.3 and 124%, respectively, whereas in the case of pomegranate it was 69.8, 112.5 and 191.7%, respectively. At Jhanwar watershed harvested rainwater from a farm pond (271 m^3 capacity) was used to grow *ber* plantation and subsequently to provide supplemental irrigation, which resulted in increased fruit yield of ber (8 q ha^{-1}) with 1.67: 1 benefit: cost ratio (Goyal *et al.*, 1995). Katiyar *et al.* (1999) reported a benefit to cost ratio of 2.5:1 with supplemental irrigation to wheat, mustard and gram with farm pond. The system of rainwater harvesting by way of farm ponds and subsequently its recycling for life saving irrigation can provide an effective check against dry spells and drought for economic yields (Goyal *et al.*, 1997; Goyal and Sharma, 2000).

Increasing water productivity by reduction in water losses

Evaporation accounts for over two third of water losses from surface water bodies in hot arid regions. Reducing surface area by increasing storage depth can appreciably reduce water losses. The surface area can also be reduced by storing the water in a compartmented reservoir, and pumping the water from one compartment to another as the water is used, so that there are some full compartments and some empty, instead of a single shallow sheet when the reservoir is partly used. Covering the field with any kind of mulch also helps in reduction of evaporation losses from the surface. Evaporation loss can also be minimized by reducing wind velocity through shelter-belts of suitable tree species around water bodies or by artificially shading of water surfaces. Studies on artificial shading of water surface have shown encouraging results in controlling evaporation losses. Shading of water surface with polyethylene sheet successfully reduced evaporation by 91%. Evaporation reduction with floating materials ranged from 37% for *Saccharum munja* to 82% for polystyrene sheet. Foamed rubber sheet, polyethylene sheet and bamboo reduced evaporation by 74%, 66% and 53%, respectively. The floating polystyrene sheet and polyethylene covers were the most economical (Khan *et al.*, 1990). The micro-irrigation systems like drip and sprinkler economize both water and fertilizers. These systems could be popularized to increase the productivity of limited rainwater.

Flash flood management

Although most parts of arid Rajasthan are drought-prone, flash floods are not uncommon in this region. Since rainfall in this region is of convective nature and usually occurs at a very high intensity for shorter duration creating flash flood, particularly in urban areas where buildings and roads generate very high runoff even for little rainfall. During 1979 large parts of state witnessed flash flood due to very heavy downpour of more than 500 mm in just 3-5 days which cut off the state from rest of the country for several days. Between 1901 and 2003 western Rajasthan witnessed nine moderate and 19 severe floods. Although floods are considered a natural calamity, however, if the excess flood water or its part can be managed and utilized for rejuvenating the depleted aquifers as well as improving surface water resources the problem of water scarcity during droughts can be solved.

Harvesting and conservation of floodwater to rejuvenate the depleted aquifers by adopting artificial recharge techniques will remarkably improve the water availability for growing population. Out of 12 district of arid Rajasthan, Bikaner, Hanumangarh and Ganganagar districts have reported a rise of groundwater table due to canal irrigation and remaining 9 districts have recharge potential of 30.3×10^9 cum based on groundwater depletion taken between 1984-2003 (Table 7).

Table 7. Groundwater recharge potential of arid Rajasthan (base year 2004)

District*	Potential area (Km^2)	Average groundwater depletion (m) (1984- 2003)	Unsaturated volume (mcm)	Weighted specific yield (%)	Potential recharge volume (mcm)
Barmer	12734.65	-3.18	40496.2	5.3	2147.4
Churu	7895.62	-0.98	7737.7	6.0	466.8
Jaisalmer	9868.30	-0.18	1776.3	5.0	90.4
Jalore	8228.10	-10.17	83679.8	6.0	5050.1
Jhunjhunu	5273.69	-9.14	48201.5	5.4	2636.6
Jodhpur	18867.92	-9.08	171320.7	4.3	7513.7
Nagaur	16378.50	-8.68	142165.4	4.7	6805.8
Pali	7362.54	-10.11	74435.3	3.1	2315.5
Sikar	7263.46	-8.39	60940.4	5.3	3273.6
Total	107595.51		630753.3		30299.9

* Bikaner, Hanumangarh and Ganganagar districts have reported a rise of ground-water table due to canal irrigation, so these districts have not been considered for groundwater recharge.

Narain *et al.* (2006 a) have estimated a potential of 5.9×10^9 cum of flash flood for western Rajasthan. A part of flash flood can be used to recharge groundwater of these districts. Bilara limestone, Lathi Sandstone, Jodhpur Sandstone and Alluvium aquifers are most suitable for groundwater recharge.

Watershed Management for Soil and Water Conservation

Initial approach of conservation programs was based on particular land problem and individual holdings. In this approach often the upper reaches of the fields were left untreated and runoff from uplands used to damage the conservation work laid out in the individual holdings at downlands. The watershed approach helps in an integrated development of different parts of the watershed in accordance with their nature, problems and potential with best amount of interference. The integrated watershed management principles have accordingly been adopted for holistic development of drought prone and rainfed areas.

In areas where there is no defined drainage system and internal drainage is choked in sand dune complex, the 'Index Catchment Approach' was considered for taking development activities. Index catchment is demarcated by considering the crest line of sand dunes or eroded rocky outcrops from the line of water divide (Vangani *et al.,* 1998).

Focused efforts on watershed management were started after 1983 when Govt. of India (GOI) launched model watershed projects with involvement of Indian Council of Agricultural Research. Under this program 47 model watersheds were identified in different agro-climatic zones all over the country. Rajasthan got its first model watershed during 1986-87 as Jhanwar model watershed near Jodhpur. Later on, to cover large areas of dryland, the National Watershed Development Program for Rainfed Area (NWDPRA) was launched in 1990-91 by GOI. This scheme covered blocks with less than 30% area under irrigation. Under this scheme Rajasthan initiated development in 204 watersheds in 190 Panchayat Samities. To involve large segments of the rural community in this venture, new guidelines for watershed development were adopted from 1st April 1995, and subsequently revised in August 2001. In 2008 National Rainfed Area Authority issued common guidelines for watershed management that became effective from 1st April 2008.

Lessons learnt in watershed management

In Rajasthan out of 26.5 million ha (rainfed) requiring natural resource management through watershed development and alternative income generation activities so far only 4.6 million ha has been treated under various schemes. Area available for watershed treatment in western Rajasthan is 2.0 million ha, whereas so far only 0.274 million ha has been treated under various schemes (Govt of Rajasthan, 2006). One of the examples of the benefits of watershed development in degraded arid fringe is in the degraded Aravallis at Siha, Rewari (in Haryana), where the number of electrified wells have increased from 67 to 205, sprinkler set from 2 to 70 and irrigated area from 260 to 420 ha. The livestock population increased from 882 to 1396. Consequently, milk production increased from 2997 to 5724 liters day^{-1} and overall income increased by 400 to 500% (Singh *et al*., 1996). With proper soil and water conservation measures in watershed in the Aravallis, soil loss was reduced from 150 t ha^{-1} to less than 5 t ha^{-1}. Development of water resources resulted in the increase of net irrigated area to 28 ha and cropping intensity from 128 to 210%. Food grain and fodder production also increased substantially (Bhardwaj and Dogra, 1997).

Likewise, adoption of graded bunds, gully control structures, contour cultivation, intercropping, use of cover crop in rotation along with other improved package of practices proved sustainable in the semi-arid region of Rajasthan. Graded bund has reduced the run-off from 20 to 4.8% and soil loss from 24 to 4.12 t ha^{-1} y^{-1}. Besides other benefits, intercropping on contour resulted in 48% higher grain yield (Singh *et al*., 1997). By adoption of various development activities in Osian index catchment during a five-year period, cropping intensity increased by 31.4% and forage yield by 1.97 t ha^{-1}. Construction of water harvesting structures helped to increase the groundwater recharge as indicated by rise in static water level. Sediment deposition against loose stone check dam was 3.86 m/ha/yr (Vangani *et al.,* 1998).

CAZRI has developed more than 6000 ha area under Jhanwar, Sar, Baorali-Bambore, Kalyanpur and Kukma watersheds. For rainwater management, CAZRI designed underground *tanka* of 10 - 600 m^3 capacities for different rainfall and catchment conditions. These *tankas* were successfully constructed at Jhanwar, Sar, and Baorali-Bambore watersheds (Bhati *et al.,* 1997). Harvested water of these tankas has been used to provide life saving irrigation to plants. The benefit cost ratio of tanka ranged from 1.25 to 1.40 under different uses (Goyal *et al*., 1995, 1997; Goyal and Sharma, 2000).

About 60 ha area was covered under contour bunding in Jhanwar and Baorali-Bambore watersheds. Bunding helped to increase the yield of pearl millet by 40% over control (3 q ha^{-1}) in Jhanwar watershed. Contour vegetative barriers of perennial grasses or shrubs were constructed for conserving soil and water in sloping lands. Rooted slips of local eight species of perennial grasses (*Cenchrus ciliaris, C. setigerus, Cymbopogon jwarancusa, Lasiurus sindicus, Panicum antidotale, P. turgidum, Saccharum bengalenses* and *Vetiveria zizanioides*) and seedling of six species of shrubs (*Agave americana, Aloe barbadensis, Barleria prionitis, Euphorbia antisyphylitica, Ipomoea carnea* and *Leptadenia pyrotechnica*) were transplanted at 1 m vertical interval on contours across the slope. Result indicated that perennial grass species performed the best and formed effective barrier against soil erosion. Runoff volume and specific peak discharge were reduced by 28-97% and 22-96%, respectively (Sharma *et al.,* 1999). In another study conducted at Kalyanpur during 1998, vegetative barrier of *L. sindicus, Saccharum munja* and *Cassia angustifolia* were established at horizontal interval of 30 m. The moisture data revealed 36.5%, 72% and 54.2% higher moisture storage as compared to control in *C.*

angustifolia, *L. sindicus* and *S. munja*, respectively (Gupta and Rathore, 2002).

Under *ex-situ* rainwater management a *Khadin* of 20 ha areas was developed in Baorali-Bambore watershed with surplussing arrangements. Before construction of the *Khadin*, uncontrolled runoff from upper catchment used to wash away seeds, fertilizers, and standing crops besides valuable water. After construction of the *Khadin*, farmers could take excellent Kharif and Rabi crops.

For *in-situ* rainwater management circular micro-catchment of 5% inward slope with LDPE lining was successfully demonstrated in watershed area for establishment of *Ber* and other trees. For severely eroded and gullied catchment loose stone check dams (LSCD) were constructed at 1 m V.I. in Jhanwar watershed on 17 gullies, which proved very effective in controlling further extension of gullies and stabilized all the gullies (Goyal *et al.,* 2007). For channel treatment three masonry anicuts and two loose stone anicuts were constructed on the main streams at Jhanwar and Baorali-Bambore watersheds, respectively, which resulted in substantial reduction in water velocity and erosion downstream. Temporary inundation upstream helped in regeneration of vegetation beside recharging of groundwater. In Sar watershed, artificial recharge of groundwater was superimposed in a 2.8 ha m pond with three infiltration wells to improve water availability for conjunctive uses. For moisture conservation soil, straw and plastic mulch were tried in Baorali-Bambore watershed. The grain yield of pearl millet was 32.67% and 28.12% higher for plastic and straw mulch, respectively, over no mulch.

In alternative land use system various systems like agro-horticulture with pearl millet/mung/moth + Ber/Aonla/pomegranate, silvi-pastoral system with *C. ciliaris* + *Prosopis cineraria/ Colophospermum mopane/Harwickia binata* were successfully established in watershed areas. Ditch-cum-mound fencing and cut and carry system was adopted for pasture development in Jhanwar watershed (Bhati and Goyal, 1997). For wastelands alternative crops like *Cassia angustifolia* and *Lawsonia alba* were successfully raised at appropriate locations in the watershed. For arable farming improved varieties of pearl millet, clusterbean, mung bean, moth bean, etc., were introduced.

Water demand under global warming

As per general circulation models (GCMs) with different scenarios of greenhouse gas emission, the globally averaged surface temperature is projected to increase by 1.4 to 5.8°C between 1990 and 2100. The possible change in temperature due to global warming will have serious implications for the present ecosystem. The greatest threat will be increase in evaporative losses and water demands caused by higher temperature (Minitzer, 1993). Globally evapotranspiration trends are projected for +5% to +10% increase due to increased temperature by +2°C to +5°C under equivalent doubling of atmospheric CO_2 from pre-industrial level (Schneider *et al.*, 1990). Wetherald and Manabe (1981) found that global evaporation changes by 3% when temperature changes by 1°C. Similarly, Budyko (1982) suggested 5% increase in evapotranspiration demand for each degree Celsius rise in temperature. Enhanced evapotranspiration would be primarily a consequence of higher air and land surface temperature. Even in tropics, where temperature increases are expected to be smaller than elsewhere, the increased rate of moisture loss from plants and soil could be considerable (Rind *et al*., 1989; Parry, 1990). Lal and Chander (1993) suggested a rise in annual mean surface temperature by 2.0-3.5°C over the Indian subcontinent by the year 2090. According to them warming would be most pronounced over northwestern India. The normal average annual evapotranspiration of Rajasthan is estimated as 1701 mm. A small increase of 1% in temperature (≤0.42°C based on normal maximum temperature of Rajasthan) will enhance the evapotranspiration demand by 11.7 mm on annual basis. It will cause an additional annual water demand of 718 mcm and 2250 mcm for the whole state based on net irrigated area (61345 Km^2) and total cropped area (192302 Km^2), respectively (Goyal, 2004). Total available utilizable groundwater for Rajasthan is 11159 mcm and the increase of 1% in temperature will put additional stress of 6.43% to 20.16% on existing groundwater resources and will reduce the number of safe districts from 6 to 3, bringing additional districts in the category of 'critical' and 'overexploited'. An increase in temperature by 2-3% from normal (i.e. 0.82-1.24°C) will leave only 1 district in the category of 'safe' zone. The remaining 31 districts will be mostly in the category of 'overexploited'. The satellite data of Rajasthan shows a total wetland area of 3450 Km^2 which includes 1239 Km^2 ha as natural and 2210 Km^2 as man-made. Increase in evaporation due to global warming will cause additional annual water loss of 40.4, 80.7 and 121 mcm for 1, 2 and 3% increase in temperature, respectively. Globally, projected increase in temperature/evapotranspiration demand is coupled with increase in precipitation by almost same magnitude. However, it is projected that shift will be more towards extreme events. The area with higher rainfall will likely have more rainfall and areas with less rainfall will have lesser rainfall. Since this state is not blessed with good perennial river systems, any increase in water demand requires careful planning for future water resource development. More emphasis is needed on development of technologies for reducing water losses in reservoirs, conservation of rainwater and development of such crop varieties that require less water.

Water Resources of Ladakh[1]

In India the risk-prone high altitude areas include the easternmost trans-Himalayan part of Ladakh and Zanskar range (Jammu and Kashmir) and some parts of Lahoul-Spiti (Himachal Pradesh). Truly described as cold desert with low population density, Ladakh constitutes the easternmost trans-Himalayan part of Jammu and Kashmir State of India comprising of Leh and Kargil districts, bordering Pakistan and China (Fig. 4). Leh covers an area of 82665 Km^2 and 51358 ha of reporting area, situated along the valleys of the Indus River with an estimated population of 117232 (Table 8). Leh is India's highest district, and one of its most arid, coldest and sparsely populated parts (Humbert-Droz, 2004). The district is sandwiched between two Himalayan ranges, Zanskar in west and Ladakh in east. Across the eastern range are the great highlands of Leh district, Chang Thang, which extends along the south of Ladakh and west, over the Indian-Chinese border into Tibet. To the north of Leh district is the district of Kargil and beyond it is the Karakoram Range. The Indus River runs through Leh district from south to north, collecting the water of melting glaciers and straddling several high-lying villages along its banks. Geo-ecologically Leh district is divided into almost two halves- a cold arid desert with minimal precipitation in the northern half, and high altitude grassland (Chang Thang) with perennial grasses in the southern half.

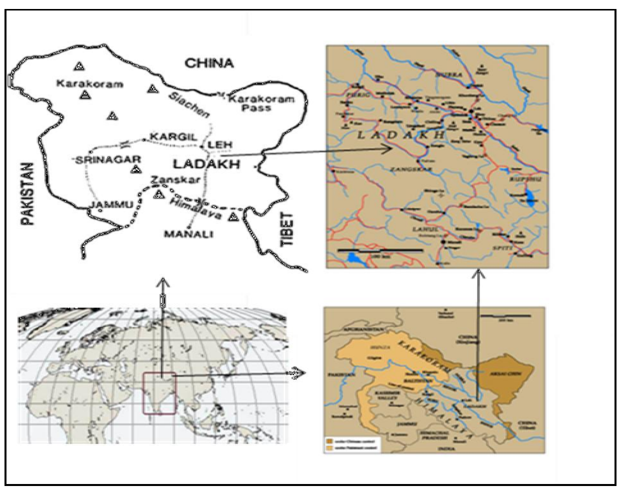


Fig. 4. Location of Ladakh district.

[1] This section is based on contribution from Dorjey Angchok, Tsering Stobdan, Shashi Bala Singh and Hitesh Kumar

Table 8. Leh district at a glance

Geographical area	Reference year	82665 km^2
Reporting area	2007-08	51358 ha
Number of tehsils	2007-08	03 No.
Number of blocks	2007-08	09 No.
Number of villages	1981 Census	114 No.
Population	2001 Census	117232 No.
Households	2001 Census	24147 No.
Average household size	2001 Census	05 No/Hh
Cultivators	2001	22149 No.
Net area sown	2007-08	10193 ha
Net area irrigated	2007-08	10193 ha
Gross area irrigated	2007-08	10599 ha

Source: Statistical Hand Book, Ladakh Autonomous Hill Development Council, Leh, 2007-08.

The cold desert region of Ladakh, lying at an elevation of 2600 to 5030 m above MSL, is characterized by low relative humidity (20-40%), low atmospheric pressure (493 mm Hg), low partial pressure of oxygen, high wind velocity (8-10 km hr^{-1}), very low annual precipitation (80-300 mm), and sub-zero temperature (up to -40°C) during winter months. Intense sunlight, high evaporation rate, strong winds and fluctuating temperature (30 to -40°C) characterize the general climate. It is generally said that a man sitting in the sun with his feet in the shade can have sunstroke and frostbite at the same time.

With sparse vegetation there is little moisture in the atmosphere. Rains are very rare, though it may even snow during July-August, the hottest months. Because of high mountains all round, the area remains landlocked to the outside world for nearly six months in a year.

Irrigation Technology

Despite the mountains being global storehouse of fresh water (in the form of glaciers), the communities residing in them have to struggle with a severe shortage of water, both potable, as well as for irrigation. Nowhere does this cause greater hardship for habitation and livelihood than in the cold desert regions of the Himalayas. The reasons vary from climatic to geographic to human-induced ones. Depleting water resources are manifest in the form of thinning/retreating glaciers, sedimentation of water harvesting structures, etc. In the Trans-Himalayan region, the main form of precipitation is snow, but barely 250 mm or less per year. The economy of these regions is based primarily on agriculture, but the cultivation period is very short as the land is snow-covered for about 6 months. Water for irrigation comes almost from glacial melt, transported over long distances through small channels that are locally called canals/*kuhls.* In view of the prevailing arid conditions in the district, agriculture is possible only where water for irrigation is available; much of irrigation in the district is through canals/khuls (Tables 9, 10).

Table 9. Source of irrigation (area in ha)

Year	Net area irrigated		Gross area irrigated	
	Canals/ Khuls	Total	Canals/ Khuls	Total
2000-01	8476	8476	10493	10493
2001-02	8496	8496	10523	10523
2002-03	8460	8460	10478	10478
2003-04	8416	8416	10424	10424
2004-05	10117	10117	10428	10428
2005-06	10189	10189	10585	10585
2006-07	10554	10554	10585	10585
2007-08	10193	10193	10599	10599

Source: Statistical Hand Book, Ladakh Autonomous Hill Development Council, Leh, 2007-08.

Irrigation technology in Ladakh was transferred from neighbouring regions (Osmaston, 1985). The farmers have partly transformed the barren semi-desert into green croplands through skilful irrigated cropping that goes back to at least Tenth Century A.D., when it is said to have been introduced by the scholar saint, Atisa (Bell, 1928).

The major source of water in Ladakh and other similarly cold arid areas is the glacial melt water through streams. Other sources are the natural springs, which are generally the outlet point of various watersheds, and whose discharge is controlled by groundwater from various glacial-melt streams. More often the streams run some distance away from the cultivable land, or are incised deeply below it, so that a long canal is necessary to bring water to the desired place. It is not easy to lay the canal avoiding the natural obstructions, or to maintain a uniform gradient. It requires considerable traditional expertise. The skillfully engineered work sometimes gives rise to an optical illusion that it is flowing up-hill. The canal bed is often made of very porous material, loose stones and boulders, so there is considerable loss from seepage. The bushes and trees growing around the channels confirm that these losses take place. The Stongde Gompa (in Zangskar valley of

Ladakh) canal loses nine/tenths of the initial flow of 0.01 m^3/sec before reaching the Gompa (Crook and Osmaston, 1994). Wherever it is possible, farmers have skilfully diverted the water through construction of long canals, some of them running for few kilometres traversing through rocky mountains. These canals were constructed during early stage of the history of the region.

Table 10. Area irrigated (ha)

Year	Area Irrigated under							
	Wheat	Grim	Other millets	Pulses	Total food grains	Fruits & veg	Oil-seeds	Fodder
2000-01	2550	4772	286	259	8029	338	70	2056
2001-02	2604	4734	436	270	8044	338	73	2068
2002-03	2653	4702	377	272	8004	331	73	2070
2003-04	2894	4504	349	249	7996	331	73	2027
2004-05	2894	4480	384	249	8007	334	67	2020
2005-06	2973	4463	375	272	8083	348	65	2089
2006-07	2756	4682	355	251	8044	285	67	2078
2007-08	2968	4452	359	286	8065	352	74	2089

Source: Statistical Hand Book, Ladakh Autonomous Hill Development Council, Leh, 2007-08.

The glacial melt waters form various rivulets called *kangs-chhu* (ice water) which join together to form a *togpo* (stream). Togpo water is discharged/diverted to a valley touching many villages, in which the main canal, called *ma-yur* (mother channel), is constructed. It is built along a mountainside that forms its retaining wall, and is lined with clay to hold the water. This may be termed the Ladakhi version of a dyke. Water from the *ma-yur* is further diverted into *yu-ra* (small canal), which irrigates the fields. The point from where togpo water is diverted into *ma-yur*, and *ma-yur* water into a *yu-ra* is called yurgo. Ska is the point from where *yu-ra* water is diverted to the field. Water in the ska is further guided through channels known as *snang*, which carry the water throughout the field. The cultivated fields are generally on terraces and irrigation is through gravity gradient. Therefore, immense skill is required of the farmer to maintain the gradient of the field. The gradient should be such that it is neither steep nor flat, rather a gradient that allows smooth flow of water with enough seepage into the soil with negligible erosion.

The water distribution through a system of channels is quite complex with different sizes of channels distinguished by various names (Table 11). There may be some regional differences in the phonetics of the names. Moreover, it is similar in whole of Ladakh (Crook and Osmaston, 1994).

Table 11. Local name for irrigation channel system in Leh

Main channel	*ma-yur*
Intermediate channel	*yu-ra*
Channel to field	*nang-yur*
Channel along top and sides of the fields	*yi-hu*
Channel down middle of a large field	*star*
Small near-contour bunds across field	*nang*
Gaps on lower side of *nang*	*tomik*
Control sluice by field	*ha (rKa)*
Stone for blocking sluice	*hardo (rKarDo*)
Sod or earth blocking sluice	*fang (sPang)*

Ponds

In some villages, water from the *togpo* through *ma-yur* is stored in rdzing (pond). The water from this is then diverted into a *yu-ra* that carries it to the field. Individual families rarely construct their own pond. Every year in the beginning of spit (spring), ponds are cleared of silts. The villagers collectively undertake the cleaning operation. Usually the silts are piled up into *lut-pung* (small mounds), on the edge of the pond to hold the water, as this silt is used to prepare manures it is stored in dry lavatories. Usually a pond gets water supply from the village stream through the *ma-yur*. In some villages like Phey, a-Yu and Ska-ra ponds are also supplied water from *chhu-mig* (spring water). This is possible because they are situated at a lower level, and because the springs in these villages are well endowed.

Irrigation water management

Irrigation water is a critical source of food and wealth in any high altitude cold desert. One might expect to find a complex politics of distribution and exploitation. Distribution is certainly complicated, but exploitation is rare (Gutschow, 1993). There are inevitable abuses and conflicts in the distribution of water. Villagers are continually being watched at the same time that they are watching out for their neighbours, thus creating a reciprocal check on activities. It is difficult to evade signs of cheating, a moist field when all the surrounding fields are dry.

The combination of an effective social organization with technical expertise suited to the local environment has enabled the farmers of cold desert to convert a few patches of their semi-desert to a very intensive and highly productive agriculture. This adaptation by the Ladakh farmers to a high altitude cold desert is the foundation of human settlement in such an inhospitable environment. The farmers in large villages are divided into groups commonly known as *Schhu-cho,* and each group gets right to water according to the traditional distribution system. The groups and the distribution pattern of water are recorded in the land records, stored at the patwari's office, whose duty includes maintenance of an official register of these water rights or on a silk document in the village itself, generally referred to as *bandabas* by local people. The documentation suggests that these disputes could be taken to the court. While such cases are beginning to be witnessed in some rare cases, mostly villagers still prefer to negotiate their disputes at the village level itself.

Distribution of water for irrigation is in accordance with the rotational system. The rotational system is largely determined by the village topography, total village acreage, relative exposure to sun, average temperature, size of glacier, soil type and seepage in the irrigation channel, among other factors (Gutschow, 1993). The amount of acreage and the number of irrigation channels in any given village seems to determine which kind of rotational scheme is used. If the village is small and the irrigation channels few, rotational system of water distribution is pegged to the household, rather than the channels. For example in Leh and Sakti, water distribution is arranged by channels. In Phey (small village of forty-three household), water distribution is pegged to the household. This is because in small villages it is fairly easy to arrange and anticipate whose field will get water according to the rotational system. In a village where distribution is arranged by channels, the field lying along the given channel is irrigated in order, which may belong to a large variety of households. These predetermined rotational schemes between households, are in accordance to *bandabas*.

Chhur-pon

The word *chhur-pon* means Lord of the water, derived from *chhu* meaning water and *spon* meaning Lord. Water supply to individual families for irrigation is supervised by a *chhur-pon*. The *chhur-pon* is an official selected by the villagers, who is in charge of water distribution for irrigation and is perhaps the most important functionary in this regard (Koshal, 2001). This functionary used to be selected by consensus in earlier times. Nowadays rotation system is prevalent in most villages. The office of the *chhur-pon* has been in existence ever since people can remember, except in villages where water is available in abundance. In some villages the word *chhur-pon* is also assigned as individual house name (in Ladakh every house has a name). This is a clear indication of the importance of *chhur-pon* in these villages.

If water is available in abundance then a *chhur-pon* is not required, as in the case of Hunder village of Nubra block. Even in villages where there are *chhur-pons*, his task is reduced to a great extent when water is in abundance. If the scarcity of water in a village is acute, then more than one *chhur-pon* is required, even if the village is small in size. In return for their service a *chhur-pon* is given *so-nyom* (one man load of cereal crop) after the harvest but nowadays this has been taken over in monetary terms, and the amount differs among villages. The *chhur-pon* has thus quite difficult duties to perform. As a customary respect for water, while stopping or releasing water from *ma-yur* to the *yu-ra* the *chhur-pon* has to keep his *gon-cha* (long overcoat) at ankle length and can not tuck it into his belt as is often done while working.

It is expected of the *chhur-pon* to distribute water according to the rota system, and monitor the activities of other farmers. At the operational level he is not much seen in the picture. Members of the village monitor each other's activities, and this system is inbuilt, as all the members are aware of how much and at what time water has to be diverted into their *yu-ra*. The farmer receiving water first monitors that the water is not diverted earlier than the decided time, and the farmer who receives later, monitors that his turn for water is not delayed.

The first watering of the field occurs soon after the *sa-ka* ceremony is performed. Sa-ka is a festive-auspicious occasion. The day for *sa-ka* is decided by the village *onpo* (astrologer). On this day, all the work concerning cultivation, including construction of *ma-yur, yu-ra*, their repair work, etc., as well as the order in which it is to be done, is decided, and appropriate persons from the village are selected for various jobs. Only after making all the arrangements the agricultural work at the village level gets started. The *sa-ka* is performed in each village, or sometimes a group of villages performs it jointly. Its time varies from valley to valley or even from one sub-valley to another. It was customary to celebrate *sa-ka* ceremony on *gya-pe ma-zying*[2] (the mother field of the king), who possessed land in every village. After the conquest of Ladakh by the general Zoravar Singh, *sa-ka* was held in the *ma-zying* (mother field) of the aristocratic family. In villages where there is no aristocratic mansion, it is performed in the main field of the monastery. Besides, each family performs *sa-ka* on their own *ma-zying*.

The amount of winter snow determines the anticipated supply of water during summer, which further determines whether marginal fields should be sown or not in spring. The weather in spring determines whether the irrigation water supply will start early or late, since cool cloudy weather delays the snowmelt. This affects the ploughing and sowing time and the sequence in which the crops are sown.

The application of sufficient but not excessive irrigation water is one of the most important farmer's skills. Insufficient water will result in poor growth, reduction in yield and possible risk of salinization. Excess can be dangerous to newly germinated crop, leach nutrients and waste of water. To avoid this situation when the crops are tender, only the skilled persons, especially the elders, are involved in irrigation of the field (mostly the first two irrigations, after the seeds are sowed). Later, when the crops are established well in the field, the less experienced younger people provide irrigation. Fields are irrigated for the last time in autumn after the soil is ploughed when harvesting of crop has been done. This practice causes the water to freeze in the soil, and prevents it from being flow out. The water is available again when the spring thaw occurs, and the soil gets moist for ploughing.

Watering a field

First watering (*tha-chus*): Once the field is irrigated it is left for 3-15 days depending on the quality of the soil. The moist earth is called ser (gold), more precisely *chhu-ser* (literally *chhu* means water) i.e. earth is gold when it is supplied with right quantity of water. Soil with the right moisture is best suited for sowing and is referred to as *ser- phar- tog* (gold is ready); if it is too damp, then it is *ser-lchin-te dug* (gold is heavy). A snowfall in winter is a source of great satisfaction, for when it melts the earth absorbs the water and remains moist till ploughing and sowing begins. This kind of moist soil is called *kha-ser* (earth made gold by the snow). This saves farmers from first watering of the field and also the drudgery of waiting for their turn.

Second watering (*dol-chhu*): After the field has been ploughed and sown, the second irrigation is given. Around 15-20 days of gap exist between the first and the second irrigation. The second irrigation is most important and is a delicate task because by this time the seeds have just sprouted: *dol* (to sprout), *chhu* (water), i.e. watering the tiny budding shoots. A skilled and knowledgeable person takes the responsibility of irrigating the field at this stage. Usually second irrigation needs more than one person. Insufficient or excess watering may lead the tender plants to get *tshik-ches* (burnt) or *shi-ches* (die). The *khyem* (spade) used for irrigation also serves as a measuring rod.

Third watering (*sak-chhu*): It is given 15-20 days after the second irrigation. It is generally a light irrigation, otherwise the crop will die. By this time the crop grows up to a height of about five inches (~13 cm). If denied irrigation at the right time, the upper portion of the crop dries up. In case someone's field is in great need of water, but his turn to irrigate is far away, then he requests someone irrigating the field to release one *sha-gu-gang-ngi* or *nang gang-ngi chhu* (a channel-full water).

Fourth watering (*non-chhu*): It is given 10-15 days after the third watering. By this time the crop grows strong enough to stand a little excess or slightly inadequate supply of water. Anyone can look after the watering because it does not entail any specific knowledge. At the time of *non* (all the crop has grown to the same level) *chhu* (water) it is easier to find out which plants have withered away and which would survive. In other words, the condition of the field becomes clear. From now onwards the crop has to be watered regularly, about once a week depending on the moisture in the soil and weather condition. No special care is required for these watering except to see that the water is let in and then closed. These are generally undertaken by the less experienced younger people. These continue for about six times before the last watering, which is called *do-chhu*.

Last watering (*do-chhu*): Application of *do-chhu* is very important. If the field is not watered now the ears of the crop get dry and start falling. *Do-chhu* means watering of fully-grown crop field. The shoots are of equal height and ready to be reaped. By this time some members of the family water the crop for the last time, while other members are busy harvesting the *ol* (alfalfa).

Global Warming: Ladakh Perspective

The evidence of global warming is becoming abundantly clear with newly appearing reports on climate change. One of the major consequences of rising global temperature is that the glaciers and ice-shelves are receding. This is true for the cold desert of Ladakh also (Jogesh, 2008). With diminishing glacial resources and increasing variations in climatic and ecological conditions, impacts like flash floods and frequent locust attacks are increasing. The Leh's inhabitants are, therefore, trying to adjust to the new threats to their traditional livelihoods and sustenance.

The Tsomoriri lake in the eastern Changthang valley is glacier fed so anything that happens to the glaciers will impact the lake. The locals say that there are signs to suggest that the water level of the lake has increased over the last couple of years. Trekking along the Tsomoriri wetlands to a small island in the lake is a place that was once a breeding ground for the highly endangered black-necked crane. Today, with rising water levels, the island is almost fully under water and the last crane was spotted here seven years ago. Only 60 black necked cranes exist in India and experts say, that if global temperature continues to rise, more than 100 million species will be at the risk of extinction. Ladakh appears to be at the starting point of the climate crisis in the region, which if continues, will threaten not just the biodiversity of the whole region but also most of its water resources (Jogesh, 2008).

According to Behera and Rahul (2008) ecologically fragile geographical areas like Ladakh are most likely to be adversely impacted by climate changes, which can rightly be considered as global commons, often inhabited by traditional communities dependent on scarce natural resources for their livelihoods, which are often at subsistence or near-subsistence level. Hence, an understanding of these communities' perceptions and responses to climate change are essential to constructing effective sustainable development strategies that mitigate adverse impacts of climate change. They found that the perceptions of climate change are widespread and include observations of rise in temperature and heavy snow melt, less snow fall, heavy and untimely rainfall, biodiversity loss, etc. These changes have severely affected the use and management of natural resources and hence the livelihoods of the local people (Table 12).

Table. 12. Household perception of climate change compared to the last one or two decades

Block	Number of Households	Percentage		
		Yes	No	Don't know
Leh	6299	65.87	32.75	1.38
Kharu	1341	96.77	2.70	0.53
Khalatse	2245	94.22	3.81	1.97
Nyoma	1176	85.86	8.34	5.80
Durbuk	725	88.10	11.76	0.14
Nubra	2917	90.71	8.23	1.06
Leh District	14703	80.59	17.80	1.61

Source: Gyurja Project - Ladakh Autonomous Hill Development Council Household Survey 2006.

Leh district receives about 20 mm rainfall in a year, which has risen to nearly ten times in the past few years (Sethi, 2007). As evident from Table 16, more than 73% of the surveyed households in Leh district have perceived the increasing intensity of rainfall. This heavy and untimely rain in recent years has caused widespread damage to private and public property through landslides and flash floods. The flash flood of August 2006 in Leh destroyed homes, bridges and roads, cutting off villages from sources of communication and assistance, and inundated the fertile fields with rock debris and sand, rendering the land unsuitable for further cultivation. Inhabitants of Leh district feel that climatic change has affected their livelihood in some way. According to surveyed households despite a well functioning *Chhurpon* system, their villages face severe water scarcity, which is attributed to heavy runoff of water from faster snow melt, and erratic nature of sunshine hours causing unpredictable flow of glacial melt water into the streams. It is important to note that the run off water enters the Indus River and flows downstream. Ladakhis have traditionally not relied on the Indus for irrigation (except for few villages like Shey, Thiksey, Choglamsar, etc.) due to its shallow depth and difficulty in lifting water from its levels without the use of less efficient mechanized pumps that also pollute the environment. The altitude and climate of Ladakh pose major mechanical challenges that are often not experienced in any permanently inhabited part of the world (Behera *et al.*, 2008).

The disappearance of snow from the surrounding mountains has led to reduced grass yields important for grazing. As a result, the pastoralist groups now move more frequently from one place to other in search of grazing lands as compared to a decade earlier. This has further impacted the regenerative ability of the highlands. Another impact of climatic changes has been the increase in the frequency and intensity of pest attacks. The recent (2006) devastating invasion by locusts, both in magnitude and duration in Nyoma and Durbuk blocks is perceived by inhabitants of villages such as Anlay, Rongo, and Kuyul in these blocks as a consequence of the rise in temperatures in the region. It has been noted by the agricultural extension office and the Defence Institute of High Altitude Research (DRDO) at Leh that the frequency of such pest attacks can be attributed to warmer temperatures which is conducive to the increase in the geographical range and the duration of infestation of such agricultural pests.

Conclusion

Management of water resources in arid areas is a real challenge. The challenge becomes tougher in view of recent observation on global warming and consequently per capita more water requirement to maintain present level of production. Ever increasing population coupled with rapid industrialization is also posing a serious threat to available water resources. Therefore a multi-point strategy is needed for management of water resources. On one hand continuous technological advancement/refinement is needed for the better understanding of hydrology of this region and on other hand developed technologies needs to be popularizes and percolated at extreme down end. For hot arid areas traditional rainwater harvesting structures like *tanka*, *nadi, baori, talab* etc needs renovation on continuous basis. Efforts should be made by the government for timely desilting of traditional rainwater harvesting structures. Since rainfall in this region is convective nature and occurs generally with high intensity for a shorter duration. The nature of this of rainfall not only causes flash flood situation but also leads loss of huge quantity of runoff water particularly in urban areas. So special efforts are needed to harvest flash floodwater for the lean period by construction of large storage structures at appropriate sites. Efforts are also needed to control the indiscriminate extraction of groundwater by the private tubewell owners by law and recharge of groundwater should be made mandatory.

The entire Himalayan region suffers from the problem of technology inadequacy. Despite the difficulties for plants, animals, and humans to live in desert regions, they are increasingly being utilized because of pressure from population growth. This problem is expressed in the expansion of agricultural activities onto desert lands as well as by the formation and rapid growth of urban and industrial canters. Under the given the ecological heterogeneity there is no way standard solutions that could be replicated over large areas. The need for action research in generating viable options through collaborative thinking is necessary. People's knowledge about natural resources and various conservation measures needs to be supplemented with modern science and technology in an experimental manner so that limits of both the knowledge system - formal and informal - become opportunities for innovation rather than constraints. Large scale efforts in restoration of productivity of eroded regions have to be appreciated without ignoring the fact that spreading resources thinly may give political advantage but would not generate any durable change in the resource management situation (Gupta, 1995).

Despite the existence of indigenous water management techniques these have become grossly inadequate for present needs. A lot more needs to be done in terms of technology development, field level testing and refinement, transfer and adoption by the clients in light of meeting the future needs and challenges posed by environmental degradation and integrated catchment resource management.

References

Anonymous 1974. More Water for Arid Lands: Promising Technologies and Research Opportunity. National Academy of Science, Washington, D.C., 56 p.

Anonymous 1980. Annual Report. Central Arid Zone Research Institute, Jodhpur, pp. 17-18.

Anonymous 1988. Report of the Working Group on Arid Zone Research. Department of Science and Technology, New Delhi, 128 p.

Anonymous 1996. Monitoring of Water Table and Drainage Trial and Demonstration. Groundwater Board, Bikaner, 35 p.

Jogesh, A. 2008. Ladakh Experiences Signs of Global Warming. Sci-Tech Section, CNN-IBN, May 30, 15:58 hrs.

Behera, B., and Rahul, T.V. 2008. Understanding the Relationship between Global and Local Commons: A Study of Household Perceptions of Climate Change in Leh, India. *Presented at 12th Biennial Conference of the International Association for the Study of Commons*, Cheltenham, England, July 14-18.

Bell, C. 1928. *The People of Tibet*. The Clarendon Press, Oxford.

Bhardwaj, S.P. and Dogra, P. 1997. Watershed Management models for Himalayas, Shivaliks and Aravallies Indian. *Journal of Soil Conservation* 25(1): 1-8.

Bhati, T.K. and Goyal, R.K. 1997. Conservation of plant genetic resources through watershed approach in Indian arid zone - A case study. In *Recent Advances in Management of Arid Eco-system* (Eds. S. Kathju, R.K. Abhichandani, Amal Kar and N.L. Joshi). Scientific Publishers, Jodhpur, p. 126.

Bhati, T.K., Goyal, R.K. and Daulay, H.S. 1997. Development of dryland agriculture on watershed basis in hot arid tropics of India - A case study. *Annals of Arid Zone* 36: 115-121.

Budyko, M.I. 1982. The Earth's climate: past and future. International Geophysics Series, New York, Academic Press, 29:307

Chatterji, P.C., Vangani, N.S. and Sharma, M.L. 1985. Unmanaged drinking water source in arid areas of Rajasthan. A case study of Nagaur district. *Annals of Arid Zone* 24(1): 47-55.

Chouhan, T.S. 1988. Integrated Area Development of Indian Desert. Geo-Environ Academia, Jodhpur, 230 p.

Crook, J.H. and Osmaston, H.A. 1994. Himalayan Buddhist Villages: Environment, Resources, Society and Religious Life in Zangskar, Ladakh. Motilal Banarsidass Publication, Delhi.

Dhir, R.D. and Krishnamurthy, K.V. 1952. The hydrology of the Rajasthan desert. In Proceedings of the Symposium on Rajasthan Desert. *Bulletin of the National Institute of Sciences of India* 1: 211-216.

Dhruvanarayan, V.V., Sriniwas and Murthy, K.N.K. 1964. Efficient use of water resources in Indian arid zone. In *Proceedings of Symposium on Problems of Indian Arid Zone*, pp. 25-27. New Delhi.

GOR 1999. IGNP Studies for State of Rajasthan. Final Report, Annexure-B Irrigation Performance. Government of Rajasthan, March 1999.

Goyal, R.K. 2004. Sensitivity of Evapotranspiration to Global Warming: A Case Study of Arid Zone Of Rajasthan (India). Agricultural Water Management 69(1): 1-11.

Goyal, R.K. 1999. Localized groundwater recharge system. In *Proceedings of the Brainstorming Session on Groundwater Modeling* (Ed. K.D. Sharma), pp. 170-173. CAZRI, Jodhpur.

Goyal, R.K. and Sharma, A.K. 2000. Farm pond: A well of wealth for the dryland dwellers. *Intensive Agriculture* 38(5-6): 12-14 and 26.

Goyal, R.K. and Vittal, K.P.R. 2008. Water resource management in hot arid zone of India. *Journal of Hydrological Research and Development* 23:38-54.

Goyal, R.K., Ojasvi, P.R. and Gupta, J.P. 1997. Farm ponds: A key to survival in arid areas. *Asian Watmanet*, newsletter. No. 11, pp.12-13.

Goyal, R.K., Ojasvi, P.R. and Gupta, J.P. 1997. Rainwater management for sustainable production in Indian arid zone. In *Proceedings, 8th International Conference on Rainwater Catchment* (Eds. B. Aminipouri and J. Ghoddoussi), pp. 1060-1063.Tehran.

Goyal, R.K., Ojasvi, P.R. and Bhati, T.K. 1995. Economic evaluation of water harvesting pond under arid conditions. *Indian Journal of Soil Conservation* 23(1): 74-76.

Goyal, R.K., Bhati, T.K. and Ojasvi, P.R. 2007. Performance evaluation of some soil and water conservation measures in hot arid zone of India. *Indian Journal of Soil Conservation* 35(1): 58-63.

Gupta, A.K. 1995. Rethinking policy options for watershed management by local communities: Combining equity, efficiency and ecological-economic viability. *Indian Farming* 44(10): 3-14.

Gupta, J.P. and Rathore, S.S. 2002. *Biomass Production and Rehabilitation of Degraded Lands in Arid Zone*. CAZRI, 20 p.

Gupta, M.C. 1987. Possibilities for mixing of brackish and saline groundwater with fresh water in canal and water courses. In *Studies for the Use of Saline Water in the Command Areas of Irrigation Projects*, pp. 47-59. Hisar.

Gupta, V.P., Sharma, R.P. and Goyal, R.K. 2002. Impact assessment of conservation measures in arid areas: a case study of Osian-Bigmi (Jodhpur) watershed. Proceedings of International Conference on Integrated Water Resource Management for Sustainable Development, New Delhi, pp. 1012-1019.

Gutschow, K. 1993. Lords of the fort, Lords of the water, and no Lords at all: The position of irrigation in three Tibetan societies. Proceedings of the Sixth International Colloquium on Ladakh. Leh, p. 105.

Humbert-Droz and Dawa, S. (Eds.) 2004. Biodiversity of Ladakh: Strategy and Action Plan, Sampark, New Delhi.

Minitzer, I.M. 1993. Confronting Climate Change: Risk, Implications and Responses. Cambridge University Press, 382 p.

Jain. J.K. 1968. Resources and Potentialities of Rajasthan. *Ph.D. Thesis*, University of Jodhpur, Jodhpur. 278 p.

Kapoor, A.S. and Rajvanshi, B.S. 1977. The Rajasthan Canal Project. In Desertification and its Control, Indian Council of Agricultural Research, New Delhi, pp. 121-129.

Katiyar, V.S., Singh, A.K. and Singh, S.V. 1999. Impact of water harvesting and recycling in south eastern Rajasthan. *Indian Journal of Soil Conservation* 27(1): 22-25.

Khan, M.A. and Venkateswarlu, J. 1993. Rainwater harvesting for increasing water availability in arid Rajasthan. *Journal of Institution of Engineers* 6: 18-26.

Khan, M.A. 1989. Upgraded village pond - nadi to ensure improved water supplies in arid zone. *Water and Irrigation Review* 9(2): 20-23.

Khan, M.A. 1992a. Development and management of surface water resources for its optimum utilization. Proceedings of VIII Congress of Asia and Pacific Regional Division. IAHR, Pune, pp. 191-200.

Khan, M.A. 1992b. Development of surface water resources. In *Rehabilitation of Degraded Arid Ecosystem* pp. 136-143.. Scientific Publishers, Jodhpur.

Khan, M.A. 1995. Importance of water resources management in arid Rajasthan. *Journal of Natural Heritage Institute* 4: 53-59.

Khan, M.A. 1997. Water resources of Indian arid zone. In *Desertification Control in the Arid Ecosystems of India for Sustainable Development* (Eds. Surendra Singh and Amal Kar), pp. 58-70. Agro Botanical Publishers (India), Bikaner.

Khan, M.A. 1998a. Design package and guide lines for Khadin constructions. Report Submitted to Govt. of Rajasthan. 20p.

Khan, M.A. 1998b. Rainwater management. In *Fifty Years of Arid Zone Research* (Eds. A.S. Faroda and Manjeet Singh), pp. 167-174. CAZRI, Jodhpur.

Khan, M.A. and Issac, V.C. 1990. Evaporation reduction in stock tanks for increasing water supplies. *Journal of Hydrology* 119: 21-29.

Kolarkar, A.S., Murthy, K.N.K. and Singh, N. 1983. Khadin - A method for harvesting water for agriculture in the Thar Desert. *Journal of Arid Environment* 6: 59-66

Koshal, S. 2001. Ploughshares of God Ladakh: Land, Agriculture and Folk Tradition. Om Publications, New Delhi, 288p.

Lal, M. and Chander, S. 1993. Potential impacts of greenhouse warming on the water resources of the Indian subcontinent. *Journal of Environmental Hydrology* 1(3): 3-13.

Mann, H.S. and Singh, R.P. 1977. Crop production in the Indian arid zone. In *Desertification and its Control*, pp. 215-224. ICAR, New Delhi.

Mehta, H.S. and Kashyap, S. 1970. Water potential of Rajasthan. In *A Search for Water*, pp. 109-114. Sarjana Prakashan, Jaipur.

Mehta, H.S. 1970. The Luni Basin. In *A Search for Water*, pp. 29-36.. Sarjana Prakashan, Jaipur,

Murthy, V.V.N. and Gulati, H.S. 1978. Optimal use of canal waters in the Indus Basin. In *Proceedings of National Symposium on Land and Water Management in the Indus Basin*, pp. 156-166. Ludhiana.

Narain, P., Khan, M. A. and Singh, G. 2006a. Potential for water conservation and harvesting against drought in Rajasthan. Working paper No. 104, Drought Series: Paper 7. IWMI, 23p.

Narain, P. and Goyal, R.K. 2005. Rainwater Harvesting for Increasing Water Productivity in Arid zones. *Journal of Water Management* 13(2): 132-136.

Narain, P., Goyal, R.K. and Khan, M.A. 2006b. Watershed management in hot arid zone of India. *Soil and Water Conservation Today* 1(2): 2-5.

Singh, N.J., Sharma, A.K. and Yadav, K.S. 1996. All round development through watershed management - A success story. *Indian Journal of Soil Conservation* 24(2): 160-164.

Ojasvi, P.R., Goyal, R.K. and Gupta, J.P. 1996. Hydrological aspects of a localized groundwater recharge system. In *Proceedings of the Symposium on New Strategies of Water Resource Management for 21st Century* pp. 36-45. J.N.V. University, Jodhpur.

Ojasvi, P.R., Goyal, R.K. and Gupta, J.P. 1999. The micro-catchment water harvesting techniques for the plantation of Jujube (*Zizyphus mauritania*) in an agroforestry system under arid conditions. *Agricultural Water Management* 41: 139-147.

Osmaston, H.A. 1985. The productivity of the agricultural and pastoral system in Zangskar. Second Ladakh Colloquium. University of Pau, Acta Biological Montana 5: 75.

Parry, M.L. 1990. *Climate Change and World Agriculture*. Earthscan, London, 165p.

Rahmani, A.R. and Soni, R.G. 1997. Avifaunal changes in the Indian Thar Desert. *Journal of Arid Environments* 36: 687-703.

Rao, K.V.G.K., Singh, O.P., Gupta, R.K., Kamra, S.K., Pandey, R.S., Kumbhare, P.S. and Abrol, I.P. 1986. *Drainage Investigations for Salinity Control in Haryana*. Central Soil Salinity Research Institute, Karnal, 95 p.

Rind, D., Goldberg, R. and Ruedy, R. 1989. Change in climate variability in 21st Century. *Climate Change* 14: 5-37.

Schneider, S.H., Gleick, P.H. and Mearns, L.O. 1990. Prospects for climate change. In *Climate Change and US Water Resources* (Ed. P.E. Waggoner), pp.41-47. John Wiley and Sons, New York.

Sehgal, K.K. 1973. Rajasthan District Gazetteers – Jaisalmer. Government of Rajasthan, pp. 82-121.

Sethi, A. 2007. India's heritage feels the heat too. Times of India, June 13, Kolkata.

Shankamarayan, K.A. and Singh, S. 1979. Application of Landsat data for Natural Resource Inventory and Monitoring of Desertification. SDSU-RSI-79-17, Remote Sensing Institute, Brookings, South Dakota, 136 p.

Sharma, K.D. 1986. Runoff behavior of water harvesting micro-catchments. *Agricultural Water Management* 11: 137-144.

Sharma, K.D., Joshi, N.L., Singh, H.P., Bohra, D.N., Kalla, A.K. and Joshi, P.K. 1999. Study on the performance of contour vegetative barriers in an arid region using numerical models. *Agricultural Water Management* 41: 41-56.

Sharma, K.D., Pareek, O.P. and Singh, H.P. 1986. Microcatchment water harvesting for raising Jujuba orchard in an arid climate. *Transaction of the ASAE* 29:112-118.

Sharma, K.D. 1991. Water resources - An overview of the world deserts. *Annals of Arid Zone* 30: 283-300.

Sharma, K.D. and Vangani, N.S. 1992. Surface water resources in the Thar Desert and adjoining arid areas of India. In *Perspectives on the Thar and the Karakum* (Eds. A. Kar, R.K. Abichandani, K. Anantharam and D.C. Joshi), pp. 130-140. Department of Science and Technology, New Delhi,

Sidhu, P.S., Sharma, P.K. and Bajwa, M.S. 1991. Characteristic, distribution and genesis of salt-affected sods in Punjab. *Journal of the Indian Society of Remote Sensing* 19(2): 269-276.

Singh, A.K., Kumar, A.K., Katiyar, V.S., Singh, K.D. and Singh, U.S. 1997. Soil and water conservation measures in semi-arid regions of south-eastern Rajasthan. *Indian Journal of Soil Conservation* 25(3): 186-189.

Singh, A.K., Singh, J. and Mahnot, S.C. 1989. Effect of soil conservation measures on groundwater recharge. In *Proceedings, Silver Jubilee Convention of Indian Society of Agricultural Engineering*, Rajasthan Agricultural University, Udaipur, pp.148-155.

Singh, H.P. 1982. Management of desert soils. In *Proceedings of the 11th International Congress of Soil Science,* pp. 676-687. New Delhi.

Singh, H.P. 1986. Problems and principles of management of desert soils. In *Monograph on Science and Engineering of Desert Soils* (Eds. Alam Singh and M.L. Christian). Geo-Environmental Academy, Jodhpur, 123 p.

Singh, R.P. 1983. Runoff collection and recycling. *Farm Ponds Bulletin* 6, CRIDA, Hyderabad, 4 p.

Singh, S.D., Daulay, H.S. and Muthana, K.D. 1973. Runoff farming making the best of available water. *Indian Farming* July, pp. 7-8.

Tiwari, A.K. 1988. Revival of water harvesting methods in the Indian desert. *Arid Lands Newsletter, University of Arizona* 26: 3-8.

Uppal, H.L. 1978. Hydrological balance of the Indus Basin. In *Proceedings of National Symposium on Land and Water Management in the Indus Basin*, pp. 1-50. Ludhiana.

Vangani, N.S., Sharma, K.D. and Chatterji, P.C. 1988. Tanka - A reliable system of rainwater harvesting in the Indian desert. CAZRJ Bulletin No. 33, CAZRI, Jodhpur, 16 p.

Vangani, N.S., Singh, S and Sharma, R.P. 1998. Index catchment - a new concept for sustainable integrated development. *Annals of Arid Zone* 37: 133-137.

Wetherald, R.T. and Manabe, S. 1981. Influence of seasonal variation upon the sensitivity of a model climate. *Journal of Geophysical Research* 86 (C2): 1194-1204.

Venkateswarlu, J., Sen, A.K., Dubey, J.C., Joshi, N.L., Kar, A., Kolarkar, A.S., Purohit, M.L., Ramakrishna, Y.S., Rao, A.S., Sharma, K.D., Singh, Y.V. and Yadav, M.S. 1990. *Water 2000 AD: The Scenario for Arid Rajasthan*. Central Arid Zone Research Institute, Jodhpur, 49 p.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 151-179 pp.

Plant Diversity Conservation for Sustainability

Suresh Kumar[1], G. Singh[2], P.J. Parmar[3], R.P. Pandey[3], S.C. Sharma[4], S. Sundarmoorthy[5], J.P. Singh[1], Pawan Kasera[5], Chandan Singh Purohit[1] and David N. Sen[5]

[1]*Central Arid Zone Research Institute, Jodhpur,*

[2]*Arid Forestry Research Institute, Jodhpur,*

[3]*Botanical Survey of India, Arid Zone Circle, Jodhpur,*

[4]*Dungar College, Bikaner,*

[5]*Jai Narain Vyas University, Jodhpur.*

Conservation of plant diversity for its sustainability is enshrined in Article 7 of Convention of Biodiversity (CBD) (UNEP, 1992). It implies making inventories of organisms within each country for proper use. This assumes importance in view of the fact that anthropogenic and development induced changes, compounded by climate change and global warming would also be adversely affecting thus enhancing the process of habitat and species loss. In Indian arid zone, earliest attempts on systematic exploration of phytodiversity dates back to 1859 when King traveled Rajputana desert and published sketch of the flora of Rajputana (1879). Since then a large number of researchers have generated information on botanical diversity at ecosystem, species and gene level. While focus of this review is on species and landscape level diversity, details on relevant intra species variability have been provided. Diversity in life cycle processes and their interaction with soil nutrient processes are also discussed. Thrust areas of future research are outlined. Role of people participation in biodiversity conservation has been highlighted at the end.

Floristic diversity

Floristic elements of different habitats in Jodhpur, north-west Rajasthan and Bikaner were described in a series of papers by Blatter and Hallberg (1918-21), Mulay and Ranam (1950), Ramachandran (1950) and Sarup (1952, 1953, 1957, 1958a, b). Agharkar (1952) mentioned plant species occurring on sand, gravel, rock, ruderal and in water. All these studies along with many others on floristics (Biswas, 1952; Santapau, 1958; Rao and Kanodia, 1962,1962a,1963; Rao, 1970) have been reviewed and upgraded in the form of a book, the "Flora of the Indian Desert" (Bhandari, 1978, 1990) and included in the enlarged Flora of Rajasthan (Shetty and Singh, 1987-93). It emerged from this study that the Indian desert has 682 species belonging to 352 genera and 87 families of flowering plants. Of these 9 families, 37 genera and 63 species are introduced. Poaceae and Leguminosae are the largest families amongst monocotyledons and dicotyledons, respectively. Incidentally, Poaceae is the largest family of 57 genera and 111 species. Phytogeographically, 37% of the botanical species represent African elements, 20.6% Oriental elements, 14% species being tropical and 10.3% cosmopolitan and 9.7% Australian. Nearly 9.4% species are endemic to this region (Bhandari, 1990). "Flora of Ganganagar" by Dhillon and Bajwa (1969); "Rare and threatened Plants" by Pandey *et al.* (1983); "Flora of Pali" by Pandey and Shetty (1984); "Vegetation of Bikaner" by Parmer *et al.* (1985); "Flora of Desert National Park" by Pandey *et al.* (1985a); "Flora of Alwar" by Parmar (1987); "Existing Flora of Ranthambhore Tiger National Park" by Das and Singh *et al.* (1995); Flora of Keoladeo National Park by Prasad (1996), "Flora of Churu" by Singh *et al*. (1997); "Biodiversity of Desert National Park, Rajasthan" by Singh and Singh (2006) are other notable contributions. Sharma and Aggarwal (2008) reported 53 grasses of Nagaur district, 17 being of medicinal value (Sharma *et al*., 2006) and a new variety of grass *Acrache racemosa* var. *sumanensis* (Aggarwal and Purohit, 2007). Sharma, Purohit and Kantiya (2007) worked on the grasses of Bikaner and Sriganganagar districts and reported additional 30 grasses in Bikaner and 12 in Sriganganagar district. Purohit and Sharma (2007) reported a new record, *Polypogon fugax* Nees ex Steud from Sri-ganganagar. Other new records are *Calamogrostis pseudophragmites* (Hall.f.) Koeler var. *tartarica* (Hook.f.) Bor; *Enteropogon monostachyos* (Vahl) K. Schum. ex Engl. and *Poa supina* Schard. by Sharma *et al.* (2008a,b,c), *Bothriochloa insculpta* (Hochst.) A. Camus by Purohit and Sharma (2008) from Sri-ganganagar. This Himalayan grass introduced with water by Indira Gandhi Canal has aromatic spikes of potential value in perfumery. Relationship between vegetation and socio-economic status in Bikaner by Singh *et al.* (2008) revealed that the area having low floral diversity predominantly supported livestock rearing for livelihood.

Status of Rare, Endangered and Threatened (RET) Taxa

Threatened plants and habitats in India were listed by Jain and Shastry (1980). Following this, concerted efforts on the subject were made in 1980-1985, through a program "Project on Study, Survey and Conservation of Endangered Species of Flora" by Botanical Survey of India. This provided valuable base-line data of about 1,000 threatened and endangered plants of India. Pandey *et al.* (1983) reported 41 and Sharma (1983) reported 106 RET taxa from Rajasthan. Pandey and Shetty (1985) listed RET taxa and Singh

(1985) dealt with "threatened taxa and their scope of conservation". The present flora of Rajasthan has 2090 species belonging to 819 genera under 159 families of vascular plants (Shetty and Singh, 1987-1993). This included 63 RET taxa, reasons for their depletion and strategies for conservation as well as 45 species of crop and other cultivated plants having 66 species of their wild relatives. However, various researchers are working on under explored areas in search of new species and re-defining the status of RET species.

Diversity at species and subspecies level

The arid plants not only show taxonomic diversity in respect of number of genera and species but also exhibit considerable inter and intra-specific diversity with respect to size, morphology, growth, phenology, chemical constituents and reproductive behavior. For instance, Jindal *et al.* (2005) recorded considerable variation in morphology and seed traits in natural population of *Commiphora wightii* (Arn.) Bhandari at Beriganga Jodhpur. The results of an extensive survey to assess the variability of *Capparis decidua* (Forsk.) Edgew. showed vast variation in morphological as well as fruit and seed related characteristics (Singh *et al.*, 2007). Brick red is the common flower colour in *C. decidua*, however, yellow flowered plants were also reported in Indian desert (Mertia, 2001). Enormous variability in morphological characters of *Aloe vera* (L.) Burm. f. is documented by Kumar *et al.* (2005b).

Haloxylon salicornicum (Moq.) Bunge ex Boiss., *Acacia jacquemontii* Benth. and *Calligonum polygonoides* L. exhibited enormous variation in morphological and growth traits. In *H. salicornicum*, range of perianth colour and size viz., creamy white, light pinkish white, light pink, pink, pinkish white with large, medium and small type of perianth was recorded. Seeds of *Haloxylon recurvum* (Moq.) Bunge ex Boiss. also showed perianth of distinct colour i.e. creamy white, light pink and dark pink. The plant height in *A. jacquemontii* varied from 17.7 to 78, 33.0-128.3 and 50-171.7 cm after 1, 3 and 5 years of planting, respectively. The plant height in *H. salicornicum* ranged from 30.5-100.0 cm after first year of planting to 36.0-125.0 cm after five years of planting. In case of *C. polygonoides* the height varied from 23.3-110.0 cm after first year of planting to 50.0-196.7 cm after five year of planting. Mertia and Prasad (2005) gave account of variability of pod and seed characteristics of *Acacia jacquemontii* in Jaisalmer District. Prakash and Sen (1987) reported the erect/bushy and sub-erect spreading forms of *Crotalaria burhia* Buch.-Ham. ex Benth. The erect bushy form survives throughout the year and sub-erect spreading form dries completely during summer season.

Such polymorphic adaptations found in desert plants also include deep or extensive root system, marked development of hard, fibrous tissues, and small leaves which are often grey-green in colour and hairy in texture, with a thick cuticle. An increasing fasciation and flattening of stem has been commonly observed in arid zone plants such as *Crotalaria burhia, Convolvulus microphyllus, Euphorbia caducifolia, Leptadenia pyrotechnica*, etc. Fleshiness is more or less a rule in plants of saline habitats (*Suaeda fruticosa, Haloxylon salicornicum, Zygophyllum simplex, Trianthema triquetra*, etc.).

Morphological variability at different phenophases

Foliage characteristics in arid plants such as shape, size and orientation often change with time and environment. The size and structure of leaves vary with location on the plant body and variations also occur between juvenile and adult leaves, and early and late leaves.

Intense solar radiation causes a variety of adaptive responses in plants such as leaf orientation (folding, curvature, twisting and curling, Sen and Lekhak 1984). Leaves in most species are held vertically or in any direction other than right angle to incident radiation so that minimum of their surface area is exposed to sun rays. Such active orientation of leaves in response to solar radiation has been termed as parahelionastic movement by Begg and Torssell (1974).Variability in leaf size is also introduced due to seasonal changes,e.g. Large leaves are produced during rains which either reduce very much in size or are shed during the drought in a great majority of plants. *Borreria articularis, Dicoma tomentosa, Trianthema portulacastrum*, *Aerva persica, Convolvulus microphyllus, Crotalaria burhia* and *Fagonia indica* show much seasonal variations in leaf size and shape. The leaves of all these species attained maximum size in the rainy season and 3-5 times reduction was noted in winter season. Further drastic reduction was noted in all the species in the summer season with the onset of the harsh climatic conditions and depletion of soil moisture. In contrast uniformity in leaves is maintained in plants like *Calotropis procera* ,*Salvadora persica, S. oleoides, Prosopis juliflora* and *P. cineraria.*

In *Fagonia indica*, seedling leaves are petiolate and trifoliate, which became bifoliate and ultimately unifoliate with the advancement of the dry season. Two lateral leaflets dropped out at an early stage of the leaf development so that the new leaves produced during late winter and summer, were unifoliate, sessile and small from the very beginning due to degeneration of lateral leaflets at the ontogenic stage (Sen and Lekhak, 1984; Sen and Mohammed, 1987).

Variation in colours of the flowers observed may have an adaptation in arid conditions. In *Euphorbia caducifolia*, red and green cyathia were reported by Sen (1982). Evidently the coloured inflorescence is better adapted, as self-pollination in this plant is minimized or completely eliminated. This crossing may be responsible for a variety of seed coat colours and their patterns found in this species. The floral colour variations are also noted in *Convolvulus microphyllus* (pink and white), *Tephrosia purpurea* (pinkish-red and white), *Solanum virginianum* (purple and white), *Evolvulus alsinoides* (white, pink and violet) and *Calotrpis procera* (mauve and white).

Seed polymorphism is a common feature in plants of Indian desert. This includes production of viable seeds different in size, shape, weight, seed coat pattern, dormancy, germination requirements, etc. (Sen, 1977; Bansal and Sen, 1981). Seeds produced on the same plant may vary in shape or colour and these variations may be associated with different germination responses. Seed size, shape and colour are frequently changed by the conditions under which the mother plant grows. Thus, the preconditioning environment appears to be the major cause of seed polymorphism (Baskin and Baskin, 2005).

Mishra and Sen (1984) reported polymorphic seeds in *Indigofera hochstetteri*. *Ipomoea pes-tigridis* possesses nine forms of seeds (A-I) ranging from yellow, yellowish-brown and brownish-black to black. These seeds have either very long hairs, very short hairs or no hairs at all. There are also great differences in their weights (Bhati and Sen, 1978). *Cucumis callosus* produces fruits of two sizes in the rainy season with differences in the number of seeds per fruit, and in their seed size and weight. In December, small fruits are not produced, while those of large size are smaller in all dimensions (Sen *et al*., 1995). In *Chenopodium album* and *C. murale* two types of seeds, i.e. black and brown have been observed. Two types of seeds, i.e. yellow and yellow-mottled were reported in *Indigofera hochstetteri*; black and grey in *Asphodelus tenuifolius*; and brown and whitish-brown in *Plantago ovata* (Sen and Kasera, 1990, 1994). In *Triantema triquetra* polymorphic seeds were recorded by Mohammed and Sen (1991), which distinctly differ in their weight, size, viability and germination behaviour. Based on the distinct colour variation, the seeds of *Crotalaria burhia* were separated into four categories: A-yellow, B-brown, C-grayish-back, and D-black by Prakash and Sen (1988). The shape of these seeds ranged from round, semi-lunar to compressed. Mishra and Sen (1986) reported two forms in *Tephrosia purpurea* having L and S populations, the former having four and the later with three different types of seeds.

Shukla *et al*. (2000) and Prakash *et al*. (2001) reported variability in various seed parameters such as weight, shape, size and viability in *Prosopis* *cineraria* and *Salvadora persica*, respectively. Saharan *et al*. (2001) reported polymorphic seeds in *Evovulus alsinoides*, which differ significantly in their weight and viability. Kasera and Prakash (2005) observed bilobed, sometimes trilobed and rarely tetralobed fruits/seeds in *Commiphora wightii* and their colour varied from yellowish-white to black. The yellowish-white ones did not germinate due to absence of embryo, while black seeds germinated. The seeds have two lobes and each may have one, two or no embryo. The rudimentary/fleshy embryo is present in black seeds. Kedia (2006) recorded polymorphic seeds in *Eclipta alba*, which varied in colour, i.e. light brown (A), dark brown (B) and black (C). The significant differences were observed in their weight and size. All these have significance especially in the desert and hence it may be a preliminary step towards evolution (Stebbins, 1976). A most striking feature of adaptation and continuance of race has been seen in wild forms of til (*Sesamum mulayanum*), guar (*Cyamopsis tetragonoloba*), moth (*Phaseolus trilobus*). In fact Sen (1982) has proposed that sort of microevolution is taking place in this desert, as those species which are well adapted and strong in competitive ability both interspecific and intraspecific will be able to survive in days to come.

Diversity in life cycle processes

The scholars in the Ecology Lab of the Department of Botany, JNV University have studied (Chawan, 1995) nearly hundred desert plants for seed morphology and germination behavior that includes grasses (17), herbs (46), shrubs (17), trees (16), climers (3) and sedge (1). The analysis of morphological diversity revealed that oval or ovoid shape is predominant (26) followed by round shape (12) and the least being spatulate (*Cryptotegia grandiflora*) and trigonus (*Sida cordifolia*). *Polycarpaea corymbosa* produced smallest seeds while *Balanites aegyptiaca,* the largest. The annuals and perennials are nearly 50:50 among the studied plants.

Trends in Seed Viability

The viability of seeds in many arid zone species is very high, thus enabling them to withstand uncongenial conditions. Seeds of *Cenchrus setigerus*, *Dictyloctenium aegyptium, Indigofera cordifolia, Lathyrus indica, Heliotropium marifolium, Arnebia hispidissima, Citrullus colocynthis* and *Cucumis callosus* can remain viable for periods ranging from 1-15 years. Wild legumes such *I. hochstetteri, I. oblongifolia, Tephrosia purpurea* and cucurbit like *Citrullus lanatus* exhibited viability after 9, 13, 7 and 12 years of storage, repectively (Sen *et al*., 1988). Interestingly seasonal seeds of *C. lanatus* retained viability for longer periods (<12 years) than off-season (summer season) seeds.

Diverse processes in dormancy

Hard seed coat dormancy is most prevalent among the members belonging to families such as Fabaceae, Mimosaceae, Convolvulace, Malvaceae and Tiliaceae. Stored seeds of *Alysicarpus vaginalis* after acid scarification revealed improved germination than fresh seeds, as they required after ripening period for full development of embryo (Bhandari, 1977 and Bansal, 1978). *Borreria articularis* germination was inhibited by chemicals in the seed coat: seasonal seeds possessed lesser inhibitors than off season seeds (Sundaramoorthy and Sen, 1993). *Lasiurus sindicus* husk inhibited germination as de-husked seeds revealed improved germination. In the later stage of maturation, maximum germination was observed with high moisture loss. In still advanced stages, the water loss decreased together with the percent germination.

Diversity in germination

Sen and Chatterji (1968) studied germination in 47 arid zone plants. Some seeds did not respond to germination, other germinated poorly and there were still others that registered good germination under laboratory conditions. Sen *et al*. (1968) stated that water shortage in deserts would probably act as a 'mater limiting factor' on germination of seeds of desert plants. Sharma and Sen (1974) observed hundred percent germination upto 55 and 47% moisture in *Merremia aegyptia* and *M. dissecta,* respectively. With seed maturation, the moisture content decreased and ultimately a stage was reached where no germination occurred and a secondary dormancy due to hard seed coat developed. In *Crotalaria burhia* and *Convolvulus microphyllus*, the water loss was maximum at the early stages when the seeds were not fully mature with no germination or poor germination percent was registered.

Diversity in Plant Communities: Typification Studies

Eight different schools of vegetation ecology in the past century have followed five different approaches based on (1) Clements climax concept, (2) Braun Blanquets methods (3) Physiognomic and life form studies (4) dominance indices and (5) multivariate approaches (Kumar, 1998). Champion (1936) classified forest types of India and recognized four major types in Indian desert and later enlarged to six types (Champion and Seth, 1968). Desert Thorn Forest 6B/C_1 and Desert Dune Scrub (6/1S1) are the two major types. *Salvadora* Scrub (6/E4) and *Acacia senegal* (6E2) are edaphic types. *Ziziphus* scrub (6B/DS1) and *Euphorbia* scrub (6B/DS2) are degradational types. Composition of plants in each type was described based an actual dominance. This is the most widely followed classification by foresters in India. Two other systems of classification of vegetation viz. five formations by Puri (1952) and Mathur (1960) are of historical and academic interest and are not as popular as that of Champion and Seth (1968).

Braun-Blanquet's approach to study desert vegetation has been followed by two researchers namely Sen (1966) and Bharucha (1975). All elements of flora are considered to define an association. Sen (1966) described 44 associations in 15 alliances and eight orders for the vegetation in and around Jodhpur. Associations were grouped into alliances, orders and finally classes. It was at 'order' level that was correlated to specific edaphic conditions and information on ecological amplitude was provided. Studies of Bharucha (1975) focused on entire Rajasthan wherein he recognized 13 associations along with characteristic species and their habitat affiliations, facies species, species of alliances, order, companions and escapes.

From the Pilani school have emerged work on plant ecology of Bikaner (Joshi, 1956), sand dune vegetation of Pilani (Joshi, 1958; Nair and Joshi, 1956; Bakshi, 1954,1957), vegetation of Aravalli (Nair and Nathawat, 1957), vegetation of Jhunjhunu (Nair, 1961) scrub communities of Churu (Sharma, 1961), structure and composition of plant communities at Churu (Sharma, 1965) and phytosociology of sand dunes of Sikar (Sharma, 1972). Almost all of this work has been concentrated in the easternmost boundary of the Indian desert. Raheja (1965) described present vegetation and floristics of arid zone of India in relation to microclimate. Gaussen *et al.* (1971) classified and mapped vegetation of Rajasthan into 12 types representing formations- halophytic, humid and dry conditions. In the arid zone, halophytes and dry types are predominant. Salt marshes, saline bogs and halophytic pseudosteppe constituted halophytic vegetation. The dry type is constituted by thorny and deciduous types. The thorny type is composed of three series viz., *Calligonum polygonoides* series, *Prosopis-Capparis-Ziziphus* series and *Acacia-Capparis* series. These series have been subdivided on the basis of physiognomy of vegetation into spiny thicket, discontinuous thicket, bushy savanna, scattered under shrub, scattered shrubs and trees in cultivated areas. Gupta (1975) distinguishes these types on specific landform types:

1. Spinous formations of thorn forest on medium and low altitude,
2. Mixed Xeromorphic thorn forests on graded alluvial plains or desert plains,
3. Mixed Xeromorphic thorn forests and riverain forest on flood plains,
4. Riverain thorn forest on graded flood plains,
5. Psammophytic desert scrub on sand dunes, and
6. Halophytic/scrub desert on shallow saline depressions.

Vegetation Classification Based on Dominance Indices

By and large, two indices i.e. cover and Important Value Index (IVI) (Curtis and Mcintosh, 1950) have been used to identify dominant and codominant species in the vegetation of the arid region. Satyanarayan (1963) used cover as a measure of dominance for typication of vegetation in the Central Luni Basin and recognized five formations viz., 1. Mixed Xeromorphic thorn forest, 2. Mixed Xeromorphic woodland, 3. Dwarf semi-shrub desert, 4. Psammophytic scrub desert and 5. succulent halophytic desert. In another study of desert vegetation, Satyanarayan (1964) correlated the recognized communities with different habitats and established their successional trends. Subsequently dune vegetation was also typified on the basis for cover dominance (Shankaranarayan *et al.*, 1965; Satyanarayan *et al.*, 1966). Temporal phyto-sociological changes during monsoon were studied using this index on rocky habitat (Gaur and Satyanarayan, 1967); alluvial plains (Satyanarayan and Gaur, 1967); semi-rocky habitats (Satyanarayan and Gaur, 1968); and vegetation surveys of different areas viz. Chohatan (Anonymous, 1963), Saila block (Anonymous, 1965), Ahor block (Anonymous, 1966), Jalore block (Anonymous, 1967), Luni block (Anonymous, 1969) and Chohatan Block (Anonymous, 1970).

During this period (1960-1975), grassland types were named after dominants and codominants based on cover from line intercept data (Shankarnarayan and Satyanarayan, 1964; Nanda and Gupta, 1968; Gupta and Saxena, 1966; Gupta, 1971; Gupta and Saxena, 1971, 1972; and Gupta, 1975). A comprehensive summary of these studies has been provided by Pandeya (1968) in his paper on the range resources of Rajasthan.

The year 1975 witnessed a major shift in approach: the dominance index based on Importance Value Index was used for the first time by Shankar and Saxena (1975 a, b) in studying ground vegetation under different tree canopies and in comparing vagetational changes on rocky habitats under protection. The IVI has been extensively used since then by Shankar and his associates in a large number of studies on desert vegetation and its phytosociology. Notable among these are phytosociology studies pertaining to the UNESCO's MAB project on Productivity of Arid Grazing Ecosystem (Anonymous, 1976, 1977, 1978), ecological studies on arid shrublands of western Rajasthan (Shankar and Bhati, 1977), study on changes in dune vegetation due to protection (Shankar and Dadhich, 1977) and in ecological survey of vegetation in the Guhiya and the Bandi catchments (Shankar and Kumar, 1980, 1981a, 1982), Jaisalmer, Jalore, Barmer, Kutch, Sikar and Jamnagar district (Shankar and Kumar, 1987; Kumar and Shankar, 1987b; Saxena, 1989; Saxena, 1996). In classifying the vegetation of the Guhiya and the Bandi catchments, the dominants and co-dominants in grasslands were determined on the basis of RIV (Relative Importance Value= IVI divided by 3) and a total of seven grassland types were established (Kumar and Shankar, 1986 a). Within each grassland type, tree-shrub dominants and co-dominants were listed according to land form, soil texture and soil depth (Kumar and Shankar, 1985). Efficacy of this system of classification and mapping vegetation was corroborated by diversity-dominance relations of perennials in different types of grasslands (Kumar and Shankar, 1986b. 1987a). However, some studies based on transects continued, such as the one by Rajpurohit *et al.* (1979) wherein vegetation communities were delineated along decreasing salinity at the margin of an abandoned salt pit at Pachpadra salt basin. Pandeya *et al.* (1967) devised a method of classification of Narmada forest which has been suitably modified by workers at Rajkot to describe coastal desertic vegetation of Kutch (Pandya and Sidha, 1985). This method combines density, cover and height along with the coefficient of variation to arrive at Relative Growth Value Index (RGVI). Jain (1968) described the vegetation and its succession in Kutch area while grasses and grasslands of Kutch were detailed by Kanodia and Nanda (1966).

Looking back, majority of work has been qualitative or semi-quantitative. The community characterization even after using quantitative dominance index has been on the basis of landforms (Saxena, 1977a, b; Shankar, 1978), landform and precipitation (Gupta and Sharma, 1971), climate and landform (Nanda and Gupta, 1968) besides the purely qualitative and subjective characterization combined with landform types (Sarup and Puri, 1960; Prakash and Nanda, 1961; Joshi, 1956, 1958; Nair and Joshi, 1956, 1957; Nair, 1961; Sharma, 1965). Because of this reason alone, the number of plant communities recognized by different workers in the Indian desert has varied. Even the same group of workers classified grasslands into nine (Gupta, 1971), seven (Gupta and Saxena, 1972), four (Gupta and Sharma, 1971) and again seven types (Gupta, 1975). In fact, in their book on “Environmental analysis of Thar Desert”, Gupta and Prakash (1975) described five types of vegetation classification wherein 7 to 12 plant communities have been recognized. In two publications appearing in the same year, the same author has recognized in western Rajasthan, six vegetation types in one paper (Saxena, 1977a) and nine in another paper (Saxena, 1977b). The six major formations recognized by Satyanarayan (1964) still continue to be most widely accepted. Most work of Plant Ecology Unit can be summarized into these six formations (Shankar and Kumar, 1988). Besides basic composition in different rainfall zones, variations in these formations have also been given.

Temporal Studies in Biodiversity

Changes in species composition over time have been monitored by many workers (Kumar, 1998) but the one which recognized temporal limits to vegetation development on various habitats by Shankar (1983) deserve special mention. Duration of enclosure required by each habitat to attain climax status was deduced from empirical observations. Richness, evenness and dominance diversity change during 3-5 years of rehabilitation of rocky catchments (Kumar, 1997), gypsum mine spoils (Kumar *et al*.,1998) as well as grazing induced impacts (Narita *et al*., 1997). Temporal changes have also been analyzed using multivariate analysis (Kumar *et al*., 1998) but these have yet to be modeled to understand and predict the impact of degradation, conservation and finally climate change.

Phytodiversity Mapping

In a chronological review of researches on mapping of vegetation using both ground and remotely sensed data, Kumar (1998) concluded that vegetation maps of future will have to be a standardized computer based vegetation resource information system. For this refinements in analytical techniques and satellite sensors are essential prerequisites. Last two decades have seen a number of publications adopting newer approaches to digital image analysis of desert landscapes and some of them have also proved useful in Indian Thar desert (Kumar *et al*., 2006). Nevertheless, traditional mapping through visual interpretation of satellite data have continued in all the natural resources appraisal reports of various districts by CAZRI and other organizations e.g. grassland mapping of Jamnagar (Kumar *et al.,* 2006). Recently nation wide mapping of vegetation carbon pool by NRSA that includes western Rajasthan is in progress to model vegetation composition and biomass in various climate change scenarios. Regional estimates of biomass using succinct estimator and satellite data are still required on seasonal basis to prepare contingency plans in surplus and scarcity situations, well in advance.

Diversity in relation to soil nutrients

Biodiversity and soil are strongly related– soil provides nutrients and is the medium for a large variety of organisms and interacts closely with the biosphere; conversely, biological activity is a primary factor in the physical and chemical formation of soils (Bardgett, 2005). Thus the factors influencing soil health i.e., physical and chemical properties as well as nutrients availability, also influence biological diversity and ecosystem functioning. Plant species richness does not necessarily enhance ecosystem processes, but it identifies two types of factors that could generate such an effect: (*i*) complementarity among species in the space they occupy below ground and (*ii*) positive correlation between mean resource-use intensity and diversity. In this, plant biomass, primary productivity, and nutrient retention all increase with diversity (Loreau, 1998), but the effect of species richness on productivity or other ecosystem processes is masked by the effects of physical environmental parameters on these processes. The relationship between plant diversity and mineral nutrient concentrations in soil and soil solution vary among sampling dates. This indicates a synchrony between the soil and the diversity of life, either above or below ground. Thus, it is not surprising that soil management has a direct impact on biodiversity including practices that influence soil volume, structure, biological and chemical characteristics, though soil also exhibits adverse effects like changes in fertility and physical and chemical conditions (Baskin, 1997). The correlation of biodiversity and soil can be observed spatially – for example, both natural and agricultural vegetation boundaries correspond closely to soil boundaries, even at continental and global scales (Young and Young, 2001). To sustain life forms there is a need to maintain soil health and fertility in all of its dimensions. These includes at least 20 essential mineral nutrients (i. e., C, H, O, N, P, S, K, Ca, Mg, Si, Fe, Mn, Cu, Mo, Zn, B, Cl, Co, V and Ni), which differ in molecular size, valance, oxidation state and mobility within the soil. Competition for limited resources may determine the presence, absence or abundance of species in a community and determine their spatial arrangement and structure depending upon climatic conditions and resource availability. Depending on the management and environmental and physiological factors that control plant growth, and function, one or more species will gain at the expense of another, causing one species to be either a winner (strong competitor) or a loser (weak competitor) (Van Noordwijk *et al*., 1996). The winners are assured continued survival, while the losers face suppression and/or elimination.

A number of field experiments have been conducted to investigate the effect of a loss of biodiversity on ecosystem processes such as N cycling (Schmid *et al*., 2002; Spehn *et al*. 2005). Because plants are major players in the cycling of N, most studies in which plant diversity was manipulated have addressed the effects of a loss in plant species richness on N pools (Loreau *et al*., 2001; Scherer-Lorenzen *et al*., 2003). David *et al*. (2001) examined the effects of erosion in four wadis in the central Negev desert and observed significant negative effects of erosion on soil organic carbon, nitrate nitrogen and water-holding capacity, but not on soil phosphorus, conductivity or pH. But, erosion resulted in an increase in plant species richness and significantly altered plant community structure in eroded areas. Increased plant species richness in eroded sites is consistent with the intermediate disturbance hypothesis of plant community structure.

But studies of arid habitats have revealed that total species richness or alpha diversity declines upon severe degradation (Kumar, 1994). Species richness has been found to be a reflex of interaction of factors like soil texture, depth, moisture and pH besides biotic pressure (Kumar, 1992). The species composition varies so much so that no two habitats have similar composition. Consequently, beta diversity is high (Kumar, 1996) indicating that process of habitat diversification is quite active providing suitable niches. Hence, in order to conserve different species, their in *situ* conservation in designated habitat is foremost requirement. This assumes significance in view of the fact that much of these natural habitats are now threatened due to mining, oil exploration, industrialization, urbanization, irrigated cropping and even military actions.

Effect of tree canopy on soil nutrients and diversity

Under the tree canopy, species composition of the herbaceous layer changes along gradients extending from bole to canopy drip-line and into adjoining inter-tree zone. In general, C_3 grasses and herbaceous dicots occur primarily beneath tree canopies, whereas C_4 grasses dominate the patches beyond the canopy (Pieper, 1990), though evidences of growing *Amaranthus* spp., a C_4 plant under tree canopy can also be seen under field conditions. Differences in species composition under and away from savanna trees are more distinct in low than in high rainfall zones suggesting that environmental gradients are stronger in habitats, where effects of the radiant energy regime or root competition have a greater influence on species interactions (Belsky *et al.,* 1993).

Increased herbaceous production beneath *Acacia albida* canopy is associated with lower soil temperature, lower plant water stress, but greater soil organic matter concentration, mineralizable nitrogen and microbial biomass compared to those of adjacent grassland away from tree canopies. Relatively greater production of *Cenchrus ciliaris* and *Cassia angustifolia* (a species that remains green during summer when maximum sand drift takes place) with *Calligonum polygonoides* than *Acacia tortilis* and *P. juliflora* showed that *C. polygonoides* is the best species for regeneration and production of not only *Cassia angustifolia* but also facilitates regeneration of indigenous flora and thus beneficial in effective stabilization of sand dunes (Singh *et al*., 2003; Singh, 2004). Browsing of trees with low, dense, evergreen canopies can enhance morning and afternoon light levels, facilitating establishment of unique grasses, and increases total herbaceous biomass beneath the tree canopy (Fuhlendorf *et al*., 1997).

The enhanced soil nutrient conditions under the canopies influence forage productivity and quality. Herbaceous species also take advantage of heterogeneity in several ecological properties between canopies and inter canopy patches and increase herbaceous diversity (Breshears, 2006). In Indian desert, herbage population of 76.9 and 61.5 individual m^{-2} and diversity of 1.7 and 1.4 with retained canopy of *Azadirachta indica* and *Prosopis juliflora* as compared to 43.4 and 33.5 individual m^{-2} population and 1.4 and 1.2 diversity with respective tree species without canopy (Upadhyay, 2008) indicate that canopy restructuring offers good potential for improving understorey vegetation.

Excavation of trench around *Prospis juliflora*/*Azadirachta indica* in Indian Desert minimized tree root competition indicated by enhanced soil nutrients and herbage diversity. In this herbage diversity were 1.60 and 1.55 with *A. indica* and; 1.30 and 1.29 with *P. juliflora* under trench and without trench treatment, respectively (Upadhyay, 2008). Evidently, reduction in competitive effects favored species richness/diversity. In fact increased number of species, population and diversity indicated that effect of diversity on productivity increased with fertility (Fridley, 2002). Exponential increase in species richness and species diversity with soil available NH_4-N concentration suggested the importance of nutrients in increasing biological diversity (Singh, 2008). Contrary to the reports that soil fertility reduces species richness, greater diversity maintains higher nutrient status. Dybzinski *et al*. (2008) observed that seedlings of *Echinacea purpurea* grown in soil collected from experimental communities containing 16 plant species produced 70% more biomass than seedlings grown in soil collected beneath monocultures. This increase was likely attributable to greater soil N availability, which had increased communities diversity over the 10-years-duration.

Increasing species richness results in decrease in plant-available nitrogen in soil after functional group richness. Similar to mineral N concentrations in the soil, organic and total N concentrations in soil are also controlled by the presence of legumes or grasses and species richness. Thus, relation between biodiversity and soil available nutrients is intimate and complex. These both should be protected and conserved for long term sustainability of the life. Conservation of soil and water facilitates soil water storage and nutrient retention enhancing herbage diversity and productivity. Organic farming may be propagated for maintaining both diversity and sustainability. Loss of trees from pastureland/rangelands, as is currently occurring worldwide, could significantly reduce the nutritional quality and diversity and should be halted for diversity and long term sustainability.

Economic Importance of Phytodiversity

Economic importance of plants found in this region has long been recognized and documented in a series of papers from CAZRI. Gupta and Saxena (1968) assessed the potential of *Salvadora oleoides* and *S. persica* for non edible oil in western Rajasthan. Plant foods, part used, season of availability were listed by Saxena (1979) and was further enlarged to include fuel, fodder, gums, oilseed yielding plants in another publication by Saxena (1981,1988). It has been documented that 40 species belonging to 21 families yield leaves that can be used as vegetables. 27 species coming from 10 families yield edible fruits; 8 species yield fiber; 3 crude rope; 8 oils and 7 gums or resins. Besides, many of these are source of medicines. (Saxena, 1979, 1981). Singh *et al*. (2005, 2006, 2008b, 2009) documented economic importance of shrubs. Eleven grasses of fodder value were described by Oza (1972) from Kutch area of Guajarat. Many of these plants have medicinal value also (Saxena, 1984). Grasses of medicinal value were described from Nagaur by Sharma *et al*. (2006). This information has been updated in the form of a database (Kumar and Praveen, 2000) in order to prioritise families needing search for newer medicinal plants. In a series of publications, medicinally important species and their uses have been detailed by Kumar *et al.* (2003, 2004a,b,c, 2005 a, b, 2007) Kumar and Praveen (2000a,b) and Sharma *et al.* (2006).

Priorities in Conservation

Land use pattern in 12 arid districts of arid Rajasthan clearly indicates that over 70% of the area supports culturable wastes, crop fallows and open community grazing lands (Faroda, 1996), all supporting rich biodiversity and yet much less understood. There is considerable information on vegetation types and their successional trends on different habitats in Rajasthan desert (Shankar and Kumar, 1988). Information also exists on temporal limit to natural regeneration upon protection of degraded habitats on different landforms (Shankar, 1983). Some patterns of biodiversity in grazing lands upon degradation and along edaphic and moisture gradients are also studied (Kumar, 1994). It is therefore necessary to strengthen this activity further so that need based conservation options could be evolved in the form of technology capsules. This will involve multidisciplinary set of recommendations for habitat development and regeneration, which has been accepted by IUCN as the only way for *in situ* conservation, so that minimum viable population of endangered species is maintained. This is more so because biodiversity is perceived now in ecosystem perspective which can be best studied by its systematic survey and monitoring.

Thrust Areas

Since plant resources are depleting in Rajasthan (Singh and Pandey, 1997) survey of existing phytodiversity, their monitoring to assess status at different intervals and arriving at their conservation and utilization strategies should be, therefore, main guiding principles. Further, preparation of concentration and sparseness map of phytodiversity should enable select priority areas for conservation on one hand and know biodiversity rich areas for exploitation by future generations.

Efforts are also needed to (1) Study the species diversity patterns in different land uses on variety of landforms in three major rainfall regions of the Indian desert, including ecotones and along gradients of degradation; (2) Integrate land resource information with diversity in GIS perspective for preparing biodiversity maps.

Secondly, there is also an urgent need for intensive monitoring of biodiversity on selected habitats in each edaphoclimatic condition. Repetitive record of biodiversity is essential for understanding its trends for taking mid term appraisal and corrective measures for conservation. It will be required to develop monitoring network befitting overall national and international goals and criteria, especially in climate change scenario.

The major aim could be to monitor species diversity of the selected biotopes and protected areas in desert (e.g. Desert National Park) at different intervals using functional groups or guilds as well as Participatory Resources Appraisal (PRA). It could be endeavored to record changes in the number and distribution of invasive species and rarities (such as endemics, endangered, rare and threatened species) and investigate into causes of the declining species. Rapid assessment criteria of diversity through censuses of indicator/keystone species as well as site monitoring using Remote Sensing and GIS should be developed.

While survey and monitoring of biodiversity can continue, concurrent efforts on standardization of conservation techniques for sustainable utilization of biodiversity are needed to save those species at the brink of extinction. Here, the major emphasis could be:

1. To investigate biology and habitat requirements of selected endangered/threatened/rare species after prioritizing them.
2. To study dynamics of reintroduction of species in wild habitats after multiplying them in controlled conditions.
3. To study feasibility of different species in cryo-preservation.
4. To determine safe utilization, biomass/seed extraction levels affording effective survivals.
5. To document, verify and utilize the local indigenous knowledge, in developing resource rehabilitation modules to revive biodiversity in different human impacted systems.

Some of the above aspects are being investigated in the Desert Botanical Garden, CAZRI in a research programme sponsored by Ministry of Environment and Forests, New Delhi. Strong linkage will be needed with state owned forest reserves/national parks for conducting and fulfilling above activities.

Peoples's Participation in Conservation of Diversity

Historically, Indian arid zone has been an agrarianpasturalist system which was "ecologically self contained", "economically safe producing" and "socially complete" till the dawn of monarchy followed by the British (Damodaran, 1992). It is now widely believed that the underlying heterogeneity that sustained it ecologically and economically has been systematically destroyed by way of centralizing power, more expeditiously since British Raj. A system of collecting land revenue was developed. A new centre of power for collecting tax at district level, named as collector was imposed on a flourishing socio-economic-ecological system. The district collector's subjects were not "communities" but tax paying fiscal land units. Thus, little attention was paid to socio-economic fabric, and all efforts were directed to meet the ruler's need. In order to collect more tax, the centralized (state owned) surveys demarcated boundaries of villages, tehsils and districts, not based on ecological determinants but based on ease in collecting the maximum land revenue. And this system still prevails. Local panchayats which are to carry out state run programmes, thus, are ill prepared to carry out biodiversity conservation. This is evident by the fact that there is not a single example of Panchayat run improvement programme of village commons, which are natural repositories of adapted genes in diverse agroclimatic situations. On the contrary, popular/socio-religious movements like Chipko or those of "Bishnois" in Rajasthan have been geared to meet conservation efforts. It becomes clear that while administrative machinery at village level is ill equipped to do biodiversity conservation, there are strong socio-religious ethos that encourage it. Efforts must be to initiate action which strengthens conservation programme capitilising these ethos so as to ensure community participation. This way only conservation can be taken up in both grazing lands and agroecosystem (Kaul, 1993) in order to save precious diversity in the desert.

References

Aggarwal, R.K. and Purohit, C.S. 2007. A new variety of Acrachne racemosa (Heyne ex Roem. and Schult.) Ohwi from Nagaur district in Rajasthan. *J. Econ. Taxon. Bot.* 31(2): 245-246.

Agharkar, S.P. 1952. Plant ecology of the Rajputana Desert. *Bulletin of the National Institute of Sciences in India* 1: 246-247.

Anonymous 1963. Land transforming plan of Central Luni Basin in West Rajasthan. *Divisional Report.* Division of Basic Resources Studies, CAZRI, Jodhpur Imimeo.), pp. 160.

Anonymous 1965. Land transforming plan-Saila block Wersten Rajasthan. *Divisional Report* No 65/1, CAZRI, Jodhpur, (Mimeo), pp. 98

Anonymous 1966. Land transformation plan of Ahor block in western Rajasthan. *Divisional Report,* No. 66/1 CAZRI, Jodhpur, (Mimeo), pp. 106.

Anonymous 1967. Land transformation plan-Jalore block in Jodhpur district, western Rajasthan. *Divisional Report,* No. 67/1 CAZRI, Jodhpur, (Mimeo), pp. 122.

Anonymous, 1969. Land transformation plan of Luni block in Jodhpur district, western Rajasthan. *Divisional Report,* No. 69/1 CAZRI, Jodhpur, (Mimeo), pp. 138.

Anonymous 1970. Land transformation plan of Chohatan panchyat samiti block in Barmer district, western Rajasthan. *Divisional Report,* CAZRI, Jodhpur, (Mimeo), pp. 45.

Anonymous 1976. Productivity of grazing land ecosystem. *First Annual Progress Report,* CAZRI, Jodhpur, (Mimeo), pp. 110.

Anonymous, 1977. Productivity of arid grazing land ecosystem. *Second Annual Progress Report,* CAZRI, Jodhpur, (Mimeo), pp. 98.

Anonymous 1978. Productivity of arid grazing land ecosystem. *Third Annual Progress Report,* CAZRI, Jodhpur, (Mimeo), pp. 91.

Bakshi, T.S. 1954. The vegetation of Pilani and its neighbourhood. *J. Bom. Nat. Hist. Soc.* 52: 484-514.

Bansal, R.P. 1978. Seed reserves in the soils of cultivated fields and their ecological variability in relation to crops in arid zone*. Ph.D. Thesis*, University of Jodhpur, Jodhpur, India.

Bansal, R.P. and Sen, D.N. 1981. Bizzare seed patterns in plants of the Indian arid zone. *Desert Plants* 3: 31-38.

Bardgett, R.D. 2005. *The Biology of Soil: A Community and Ecosystem Approach,* Oxford University Press Inc, New York.

Baskin, C.C. and Baskin, J.M. 2005. *Seeds: Ecology, Biogeography and Evolution of Dormancy and Germination* (5th ed.). Academic Press, USA, pp. 666.

Baskin, Y. 1997. The work of nature, The Scientific Community on Problems of the Environment (SCOPE), Island Press, Washington, DC.

Begg, J.E. and Torssell, W.B.R. 1974. Diaphotonastic and parahelionastic leaf movements in *Stylosanthes humilis* H.B.K. (Townsvilloustylo). *Bull. R. Soc. N. Z.* 12: 277-283.

Belsky, A.J., Mwonga, S.M., Amundon, R.G., Duxbury, J.M. and Ali, A.R. 1993. Comparative effects of isolated trees on their under canopy environment in high and low rainfall Savanna. *Journal of Applied Ecology* 30: 143-155.

Bhandari, D.C. 1977. Studies on arid zone legumes with special reference to *Indigifera* species. Their ecology, nitrogen metabolism and role in crop ecosystem. *Ph.D. Thesis*, University of Jodhpur, Jodhpur, India

Bhandari, M.M. 1978. *Flora of the Indian Desert*, Scientific Publishers, Jodhpur pp. 471

Bhandari, M.M. 1990. *Flora of the Indian Desert*, MPS Repros, Jodhpur.

Bharucha, F.R. 1975. Plant association in western Rajasthan. In *Environmental Analysis of the Thar Desert* (Eds. R.K. Gupta and I. Prakash), pp. 273-297. English Book Depot. Dehradun

Bhati, P.R. and Sen, D.N. 1978. Adaptive polymorphism in *Ipomoea pes-tigridis* (Convolvulaceae), a common rainy season weed of the Indian arid zone. *Pl. Syst. Evol.* 129: 111-117.

Biswas, K. 1952. Desert vegetation. *Bull. Nat. Inst. Sci. India.* 1: 247.

Blatter, E. and Hallberg, F. 1918-21. The Flora of the Indian Desert (Jodhpur and Jaisalmer). *J. Bom. Nat. Hist. Soc.* 26: 218-246, 525-551, 811-818, 968-987; 27: 40-47, 270-279, 506-519.

Breshears, D.D. 2006. The grassland-forest continuum: trends in ecosystem properties for woody plant mosaics. *Frontiers in Ecology and Environment* 4: 96-104.

Champion, H.G. 1936. A preliminary survey of the forest types of Indian and Burma. *India Forest Research* (n.s.). Vol. I., 286, p.

Champion, H.G., Seth, S.K. 1968. *A Revised Survey of the Forest Types of India.* Manager of Publications, Govt. of India, New Delhi, 404 p.

Chawan, D.D. 1995. *Environment and Adaptive Biology*, Scientific Publishers, Jodhpur.

Curtis, J.T. and Mcintosh, R.P. 1950. The interrelationship of certain analytic and synthetic phytosociological characters. *Ecology* 31: 434-455.

Damodaran, A. 1992. Local self-government and geometry of biodiversity conservation: Roots of imcompatibility. *Economic and Political Weekly* (Feb. 22, 1992 issue): 419-424.

Das, S.N. and Singh, V. 1995. A study on the Ranthambhore Tiger Reserve National Park Rajasthan with reference to its existing Flora. *J. Econ. Taxon. Bot.* 19(1): 27-46.

David, W., Kayla, F. and Yoav, A. 2001. The effects of loess erosion on soil nutrients, plant diversity and plant quality in Negev desert wadis. *J. Arid Environment* 48: 461-473.

Dhillon, K.B.S. and Bajwa, P.S. 1969. A contribution towards the flora of Ganganagar district. *Bull. Bot. Surv. India*. 21: 234-244.

Dybzinski, R., Fargione, J.E., Zak, D.R., Fornara, D. and Tilman, D. 2008. Soil fertility increases with plant species diversity in a long-term biodiversity experiment. *Oecologia* 158: 85-93.

Faroda, A.S. 1996. Perspective Plan – 1996-2020 of CAZRI. P-55 (Mimeo.) CAZRI, Jodhpur.

Fridley, J.D. 2002. Resource availability dominates and alters the relationship between species diversity and ecosystem productivity in experimental plant communities. *Oecologia* 132: 271-277.

Fuhlendorf, S.D., Smeins, F.F. and Taylor, C.A. 1997. Browsing and tree size influences on Ashe Juniper understory. *Journal of Range Management* 50: 507-512.

Gaur, Y.D. and Satyanarayan, K.A. 1967. Phytosociological studies of the monsoon vegetational of rocky habitat. *Indian Forester* 93(12): 806-814.

Gaussen, H., Meher-Homji, V.M., Legris, P., Balsco, F., Delacourt, A., Gupta, R.K. and Troy, J.P. 1971. International map of vegetation and environment conditions. *Sheet Rajaputana.* Publication No. 17, ICAR, New Delhi and Inst. Fr., Pondicherry, India.

Gupta R.K. and Prakash. I. (Eds.) 1975. *Environment Analysis of Thar Desert.* English Book Depot. Dehradun, 484 p.

Gupta, R.K. 1971. Ecology of pastoral areas in the arid zone of Rajasthan. *Annals of Arid Zone* 10(2and3): 136-157.

Gupta, R.K. 1975. Plant life in the Thar. In *Environmental Analysis of Thar Desert* (Eds. R.K. Gupta and I. Prakash), pp 202-236. English Book Depot, Dehradun.

Gupta, R.K. and Saxena, S.K. 1966. Habitat, grassland types and forage potential of Jalore district in western Rajasthan. *Annals of Arid Zone* 5(2): 189-203.

Gupta, R.K. and Saxena, S.K. 1968. Resource survey *Salvadora oleoides* Decne and *S. persica* Linn. for non-edible oil in western Rajasthan. *Tropical Ecology* 9(2): 140-150.

Gupta, R.K. and Saxena, S.K. 1971b. Ecological studies on the protected and overgrazed rangelands in the arid zone of west Rajasthan. *Journal of Indian Botanical Society* 50 IV:2189-300.

Gupta, R.K. and Saxena, S.K. 1972. Potential grasslands types and their ecological succession in Rajasthan. *Annals of Arid Zone* 11: 198-218.

Gupta, R.K. and Sharma, S.K. 1971. Grasses of the rangeland in the arid Rajasthan. *Journ. de Agri. Tropicals et de Botanique Appliques* 18(1, 2and3): 50-99.

Jain, S.K. and Shastry, A.R.K. 1980. *Threatened Plants of India: A State of the Art Report.* Botanical survey of India, Kolkatta.

Jain, S.K. 1968. The vegetation and succession of plant communities in Kutch Gujarat State. In *Proceedings of Symposium on Recent Advances in Tropical Ecology,* pp. 426-433. Varanasi, India.

Jindal, S.K., Singh, Manjit and Singh, Deepa. 2005. Guggal-A therapeutic shrub. In *Shrubs of Indian Arid Zone* (Eds. P. Narain, M. Singh, M.S. Khan and Suresh Kumar), pp. 55-60. Central Arid Zone Research Institute, Jodhpur.

Joshi, M.C. 1956. Plant ecology of Bikaner and its adjacent areas in comparison with rest of western Rajasthan. *Journal of Indian Botanical Society* 35: 237-246.

Joshi, M.C. 1958. Preliminary survey of the sand dune vegetation of Pilani and its neighbourhood. *Journal of Indian Botanical Society.* 37: 309-327.

Kanodia, K.C. and Nanda, P.C. 1966. On the grasses and grasslands of Kutch. *Annals of Arid Zone* 5(s): 173-188.

Kasera, P.K. and Prakash, J. 2005. Ecology and cultivation practices of guggal (*Commiphora wightii*): an endangered medicinal plant of the Thar desert in

India. In *Recent Progress in Medicinal Plants.* Vol. 9. *Plant Bioactives in Traditional Medicin* (Eds. D.K. Majumdar, J.N. Govil, V.K. Singh and R.K. Sharma), pp. 403-423. Stadium Press LLC, USA.

Kaul, R.N. 1993. Strategies for conservation of biodiversity in the that desert. In *Biodiversity Conservation: Forests, Wetlands and Deserts* (Eds. B. Frame, J. Victor and Y. Joshi), pp. 91-103. Tata Energy Research Institute, New Delhi.

Kedia, S. 2006. Ecological studies of some medicinal plants in Indian arid zone. *Ph.D. Thesis*, J.N. Vyas University, Jodhpur.

King, G. 1879. Sketch of the Flora of Rajputana. *Indian Forester* 4: 206-236.

Kumar, S. 1992. Comparing classification and different ordination of vegetation in the Thar desert of India with implication in resource management. *Tropical Ecology* 33: 110-131.

Kumar, S. 1994. Ecology of degraded vegetation and its recovery in the Indian Arid Zone. *JIRCAS International Series* 1: 27-37.

Kumar, S. 1996. Trends in structural compositional attributes of dune interdune vegetation and their edaphic relations in the Indian Desert *Vegetatio* 124: 73-93.

Kumar, S. 1998. Vegetation resources in the Indian arid zone. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and Manjit Singh), pp: 89-119. CAZRI Jodhpur.

Kumar, S. and Parveen, F. 2000 A. Floristic diversity as a source of household traditional and commercialized remedies in arid western Rajasthan India. *J. Econ. Taxon. Bot*. 24(2): 495-505

Kumar, S. and Parveen, F. 2000B . Potential medicinal plants for diversifying crop base in the Indian arid zone-Issues of their trade versus conservation *Current Agriculture* 24: 65-68

Kumar, S. and Shankar, V. 1985. Vegetation ecology of the Guhiya catchment of the Upper Luni Basin. *Tropical Ecology* 26(1): 1-11.

Kumar, S. and Shankar, V. 1986a. Grass cover of the Guhiya catchment of the Upper Luni Basin. I. Present and Potential herbage production and carrying capacity. *Indian Journal of Forestry* 9(2): 126-131.

Kumar, S. and Shankar, V. 1986b. Vegetation ecology of the Bandi catchment in the Upper Luni Basin, western Rajasthan (Abstract). In *Proceedings of Seminar of Society for Green Vegetation Research and CAS.* Department of Botany, Banaras Hindu University, Varanasi.

Kumar, S. and Shankar, V. 1987a. Vegetation ecology of the Bandi catchment in the Upper Luni Basin, western Rajasthan. *Tropical Ecology* 28: 246-258.

Kumar, S. and Shankar, V. 1987b. Vegetatoin In *Integrated Natural and Human Resources appraisal for sustainable development of Jalore District* (Eds. S. Singh, K.D. Sharma and D.C. Joshi), pp. 26-35. CAZRI, Jodhpur.

Kumar, S., Sharma, K.D., Sharma, B.K. and Gough, L.P. 1998. Richness diversity and evenness of vegetation upon rehabilitation of gypsum spoiled lands in the Indian arid zone *Annals of Arid Zone* 37(2): 139-145

Kumar, S., Goyal, S. and Parveen, F. 2003. Ethno-medico-botany of household remedies of Kolayat tehsil in Bikaner district, Rajasthan. *Indian Journal of Traditional Knowledge* 2(4): 357-365.

Kumar, S., Goyal Sangeeta, Parveen, F. 2004 a. Ethno veterinary Plants in the Indian Arid Zone. *Ethnobotany* 16:91-95.

Kumar, S., Parveen, F. and Azam, M.M. 2004b. Potential medicinal herbs for agroforestry systems on drylands : Growth and yield of Apamarg (*Achyranthes aspera* Linn.) under canopies of tree species. *Range Mgmt. and Agroforestry* 25(2): 129-133.

Kumar, S., Parveen, F. and Goyal, S. 2004c. Ethno-veterinary plants in the Indian arid Zone. *Ethnobotany* 16: 91-95.

Kumar, S. Parveen, F., Goyal, S., and Chauhan, A. 2005A. Trading of Ethnomedicinal plants in the Indian Arid Zone, *Indian Forester*. 131(3) (March Issue): 371-378.

Kumar, Suresh, Azam, M.M. and Parveen, F. 2005b. *Aloe vera* in the Indian arid zone. In *Shrubs of Indian Arid Zone* (Eds. P. Narain, M. Singh, M.S. Khan and Suresh Kumar), pp. 73-78. Central Arid Zone Research Institute, Jodhpur.

Kumar, S., Mathur, M., Thakkar, P.S. and Jadhav, R.N. 2006. Spatial distribution of grasslands through remote sensing in a coastal region of India. *Range Management and Agroforestry* 27(1): 35-39

Kumar, S., Bastin, G., Friedel, M., Narain, P., Saha, D.K., Ahuja, U.R. and Mathur, B.K. 2006. Performance of different vegetation indices in assessing degradation of community grazing lands in Indian Arid Zone. In *Agriculture and Hydrology Applications of Remote Sensing* (Eds. R.J. Kuligowski, J.S. Parihar and G. Saito) (Vo. 6411).

Loreau, M. 1998. Biodiversity and ecosystem functioning: A mechanistic model. *PNAS*, 95: 5632-5636.

Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J.P., Hector, A., Hooper, D.U., Huston, M.A., Raffaelli, D., Schmid, B., Tilman, D. and Wardle, D.A. 2001. Biodiversity and ecosystem functioning: Current knowledge and future challenges. *Science* 294: 804-808.

Mathur, C.M. 1960. Forest types of Rajastha. *India Forester* 86(12): 734-739.

Mertia, R.S. 2001. A new record of yellow flowered *Capparis decidua* (Forsk.) Edgew. from Jaisalmer. *Annals of Arid Zone* 40: 219-220.

Mertia, R.S., and Prasad, R. 2005. *Acacia jacquemontii* Benth. A potential multipurpose shrub. In *Shrubs of Indian Arid Zone* (Eds. P. Narain, M. Singh, M.S. Khan and Suresh Kumar), pp 105-110. Central Arid Zone Research Institute, Jodhpur.

Mishra, R.K. and Sen, D.N. 1984. A report on germination behaviour on dimorphic seeds of *Indigofera hochstetteri* Baker, in Indian arid zone. *Curr. Sci.* 53: 380-381.

Mishra, R.K. and Sen, D.N. 1986. Polymorphism in populations of *Tephrosia purpurea* Pers. in Indian desert ecosystem. *Flora* 178: 183-190.

Mohammed, S. and Sen, D.N. 1991. Polymorphism as an adaptation in seeds of halophytes in Indian desert. In *Marvels of Seed. Proc. Intern. Seed Symposium* (Eds. D.N. Sen and S. Mohammed), pp. 207-212. Jodhpur University Press, Jodhpur.

Mulay, B.N. and Ratnam, B.V. 1950. The vegetation found around about Pilani. *Proc. 38th Indian Sci. Cong.* IV: 64-65.

Nair, N.C. 1961. Vegetation of Jhunjhunu, Manderala and the neighbouring places. *Journal of Bombay Natural History Society* 58(2): 433-440.

Nair, N.C. and Joshi, M.C. 1956. Sand dune vegetation of Pilani and its neighbouring. *Journal of Indian Botanica Society* 54(2): 281-301.

Nair, N.C. and Nathawat, G.S. 1957. vegetation of Harshnath aravai, Hills. *Journal of Bombay Natural History Society* 54(2): 281-301.

Nair, N.C. and Malhotra, S.K. 1961. A study of the vegetation of Lohargal and its neighbourhood. *Bull. Bot. Sur. of India* 3: 139-151.

Nanda, P.C. and Gupta, K.M. 1968. Grasses and grasslands: their distribution and utilization in Rajasthan. In *The Natural Resources of Rajasthan* (Eds. M.L. Roonwal), Vol. I, pp. 137-150. University of Jodhpur, Jodhpur.

Narita, K., Mertia, R.S., Kumar, S., Ichikawa, S. and Furukawa, A. 1997. Effect of different grazing intensities of sheep on arid grasslands in the Thar desert, India. *Trpics* 7(1-2): 105-114.

Oza, G.M. 1972. Note on fodder grasses for Gujarat cattle. *Annals of Arid Zone.* 11(1and2): 128-131.

Pandey, R.P., Shetty, B.V. and Verma, M.P. 1985a. A check list to the flora of the Desert National Park in Western Rajasthan. *J. Econ. Taxon. Bot.* 6(1): 45-60.

Pandey, R.P. and Shetty, B.V. 1985. Rare and threatened plants of Rajasthan. *Proc. Nat. Symp. Evaluate Environ.* Zoology Deptt. J.N. Vyas University, Jodhpur. *GEOBIOS* 238-241.

Pandey, R.P. and Shetty, B.V. 1984. A contribution to the flora of Pali district, Rajasthan. *Journ. Econ. Taxon. Bot.* 5: 335-378.

Pandey, R.P., Shetty, B.V. and Malhotra, S.K. 1983. A preliminary census of rare and threatened plants of Rajasthan. In *An Assessment of Threatened Plants of India* (Eds. S.K. Jain and R.R. Rao), pp. 52-62. BSI, Howrah.

Pandeya, S.C., Pandeya, S.M., Murthy, M.S. and Kuruvilla, K. 1967. "Forest Ecosystem" classification of forest vegetation with reference to forests in the river Narmada catchment area. *Journal of Indian Botanical Society* 47: 412-427.

Pandeya, S.C. 1968. Range resources of Rajasthan. *In The Natural Resources of Rajasthan* (Eds. M.L. Roonwal), Vol. I., pp. 105-134. University of Jodhpur, Jodhpur.

Pandeya, S.M. and Sidha, V.K. 1985. Structure and composition of forest vegetation of Kutch (Gujarat State) *Indian Forester* 111(8): 583-595.

Parmar, P.J. 1987. A contribution to the flora of Sariska Tiger Reserve, Alwar district, Rajasthan. *J. Econ. Taxon. Bot.* 27: 29-40.

Parmar, P.J., Pandey, R.P. and Roy, G.P. 1985. *Studies on the vegetation of Bikaner district in Rajasthan. J. Econ. Taxon. Bot.* 7(1): 55-67.

Pieper, R.D. 1990. Overstory-understory relationship in pinyon Juniper woodlands in New Maxico. *Journal of Range Management* 43: 413-415.

Prakash, B.S.V. and Sen, D.N. 1987. Adaptive features of *Crotalaria burhia* Buch.-Ham. in Indian desert. *Annals of Arid Zone* 26: 203-207.

Prakash, B.S.V. and Sen, D.N. 1988. A report on seed polymorphism in *Crotalaria burhia* Buch. Ham. in Indian desert. *Curr. Sci.* 57: 340-341.

Prakash, M. and Nanda, P.C. 1961. Ecological distribution of natural fodder grasses in western Rajasthan. *Indian Forester* 87(1): 10-19.

Prasad, V.P., Mason, D., Marburger, J.E. and Kumar, C.R.A. 1996. Illustrated flora of Keoladeo National Park, Bharatpur, Rajasthan. *Bom. Nat. Hist. Soc. Mumbai.* pp. 435.

Puri, G.S. 1952. The present position of the plant ecology of the Desert of Rajasthan and Saurashtra. *Bulletin of the National Institute of Science in India* 1: 233-240.

Purohit, C.S. and Sharma, S.C. 2008. Bothriochloa insculpta (Hochst.) A. Camus (Poaceae) A new record for Rajasthan. *J. Bomb. Nat. Hist. Soc.* 105(1): 111-112.

Purohit, C.S. and Sharma, S.C. 2007. Polypogon fugax Nees ex Steud – A new record for Rajasthan. *J. Econ. Taxon. Bot.* 31(2): 453-454.

Raheja, P.C. 1965. Influence of climatic changes on the vegetation of the arid zone of India. *Annals of Arid Zone* 4(1): 64-73.

Rajpurohit, K.S., Charan, A.K. and Sen, D.N. 1979. Micro-distribution of plants in an abandoned salt pit at Pachpadra salt basin. *Annals of Arid Zone* 18(1and2): 122-126.

Ramachandran, K.R. 1950. The grasses found round about Pilani (Rajasthan). *Proc. Indian Sci. Congr.* III: 65-66 (Abstract).

Rao, R.S. 1970. Studies on the flora of Kutch, Gujarat State, India and their utility in the economic development in the semi arid region. *Annals of Arid Zone* 9(2): 125-142.

Rao, R.S. and Kanodia, K.C. 1962. Studies on the vegetation and flora of Jodhpur division. *Annals of Arid Zone* (1): 16-46.

Rao, R.S. and Kanodia, K.C. 1962a. Studies on ecology and vegetation of interior parts of Barmer and Jaisalmer district in Rajasthan. *Proc. Indian. Sci. Cong.* III: 321-322.

Rao, R.S. and Kanodia, K.C. 1963. Studies on the vegetation and flora of Jodhpur division, Rajasthan State. *Annals of Arid Zone* 2(1): 35-60.

Saharan, P., Kasera, P.K. and Chawan, D.D. 2001. Seed polymorphism and germination behaviour of shankhpushpi (*Evolvulus alsinoides*). *Annals Arid Zone* 40: 97-99.

Santapau, H. 1958. History of Botanical Researches in India, Burma and Ceylon. Part II. *Systematics Botany of Angiosperms,* Publ. by IBS, Banglore.

Sarup, S. 1952. Plant ecology of Jodhpur and its neighbourhood. A contribution to the ecology of northwest Rajasthan. *Bulletin Institute of Sciences, India* 1: 223-232.

Sarup, S. 1953. Plant ecology of the north-western Rajasthan. *Proceedings of International Symposium on Desert Research, Jerusalem.* Special Publication Research Council, Israel 2: 335-345.

Sarup, S. 1957. A brief note on the vegetation of Rajasthan. *Dungar College Magazine* 18: 1-8.

Sarup, S. 1958a. The halophytes of the Indian desert. *Rajasthan University Studies Bot.* 3: 55-60.

Sarup, S. 1958b. A list of some common plants of Jaisalmer and its neighbourhood, Jaipur (mimeo.), pp. 1-15.

Sarup, S. and Puri, G.S. 1960. The vegetation types of the Indian desert. *Journal University of Rajasthan Studies (Bot. section)* 4: 57-85..

Satyanarayan, Y. 1963. Ecology of Central Luni Basin, Rajasthan. *Annals of Arid Zone* 2(1): 82-97.

Satyanarayan, Y. 1964. Habitats and plant communities of the Indian desert. In *Proceedings of Symposium on Problem of Indian Arid Zone*, pp. 59-67.Govt. of India, Ministry of Education, New Delhi.

Satyanarayan, Y. and Gaur, Y.D. 1967. Phytosociological variations in floristic composition of the vegetation in the arid zone. I. Monsoonal vegetation of the alluvial plains. *Annals of Arid Zone* 6(2): 178-199.

Satyanarayan, Y. and Gaur Y.D. 1968. Phytosociological changes of monsoon vegetation in semi rocky habitats. *Journal of Indian Botanical Societ* XLVII(3and4): 371-381.

Satyanarayan, Y. Saxena, S.K. and Gaur, Y.D. 1966. Studies in dune ecology:1. Vegetation of stabilized dunes. *Tropical Ecology* 7: 163-170

Saxena S.K. 1977a. Vegetation and its succession in the Indian desert. In *Desertification and its Control*, pp. 176-192. ICAR, New Delhi.

Saxena, S.K. 1977b. Vegetation of the Indian desert biome. In *Desert Ecosystem and its Improvement* (Eds. H.S. Mann), pp. 144-165. CAZRI, Monograph No. I, CAZRI, Jodhpur.

Saxena, S.K. 1979. Plant foods of western Rajasthan. *Man and Environment* 3: 34-43.

Saxena, S.K. 1984. Medicinal plants of Arid Zone- Possibility of their exploitation on commercial scale. In *Proceedings of Summer Institute on Recent Advances in Arid Horticulture*, CAZRI, Jodhpur.

Saxena, S.K. 1988. 'Lasu' an exclusive top feed for camels during drought. *Indian-Farming* 1988, 38(9): 19-20.

Saxena, S.K. 1989. Vegetation. In *Integrated Natural and Human Resources Appraisal, Barmer District* (Eds. P.C. Chattrji and D.C. Joshi), pp. 31-38. CAZRI, Jodhpur.

Saxena, S.K. 1996a. Vegetation. In *Integrated Natural and Human Resources Appraisal for Sustainable Development of Kachchh District* (Eds. Surendra Singh and Amal Kar), pp. 50-55. CAZRI, Jodhpur, 165 p.

Scherer-Lorenzen, M., Palmborg, C., Prinz, A. and Schulze, E.-D. 2003. The role of plant diversity and composition for nitrate leaching in grasslands. *Ecology* 84:1539–1552.

Schmid, B., Joshi, J. and Schläpfer, F. 2002. Empirical evidence for biodiversity-ecosystem functioning relationships. In *Functional Consequences of Biodiversity: Experimental Progress and Theoretical Extensions* (Eds. A. Kinzig *et al*.), pp. 120-150. Monogr. in Popul. Biol. 33. Princeton Univ. Press, Princeton, NJ.

Sen D.N. and Kasera P.K. 1990. Polymorphism and germination ecology of weed seed in Indian arid zone. In *Proceedings of National Seminar on Advances in Seed Science and Technology* (Eds. H.S. Shetty and H.S. Prakash), pp. 23-29. G.H. Krishnamurthy Mysore Printing and Publ. House, Mysore.

Sen, D.N., Chawan, D.D. and Chatterji, U.N. 1968. Diversity in germination of seeds in *Calotropis procera* R. Br. populations. *Osterr. Bot. Zeit*., 115: 6-17.

Sen, D.N. 1966. Ecology of the Indian Desert 1. On the phytosociological associations of the vegetation of Jodhpur *Tropical Ecology* 7: 136-152.

Sen, D.N. 1977. Environment and seed germination of Indian plants. The Chronica Botanica Co., New Delhi.

Sen, D.N. 1982. Environment and plant life in Indian Desert. *Geobios International, Jodhpur, India.*

Sen, D.N. and Chatterji, U.N. 1968. Ecology of desert plants and observations on their seedlings. I. Germination behavior of seeds. *Bull. Bot. Soc. Bengal* 22: 251-258.

Sen, D.N. and Kasera, P.K. 1994. Weed biology and chemical weed control in the Indian arid zone. In S*ustainable Development of the Indian Arid Zone - A Research Perspective* (Eds. R.P. Singh and S. Singh), pp. 303-318. Scientific Publishers, Jodhpur.

Sen, D.N. and Lekhak, H.D. 1984. Leaf response under drought. *Indian Rev. Life Sci.* 4: 279-311.

Sen, D.N. and Mohammed, S. 1987. Eco-physiological studies of *Fagonia cretica* L. in Indian desert. In *Environmental Issues and Researches in India* (Eds. S.K. Agarwal and R.K. Garg), pp. 61-83. Himanshu Publications, Udaipur.

Sen, D.N., Kasera, P.K. and Mohammed, S. 1988. Report on weed seed longevity in arid zone. A test of seed bank. *Geobios New Reports* 7: 98-100.

Sen, D.N., Mohammed, S. and Kasera, P.K. 1995. Some ecological observations on plants of Indian desert. In: *J. Indian bot. Soc. Platinum Jubilee Volume,* 74A, (Eds. C.M. Govil, K.S. Bilgrami and D. Singh), pp. 539-554. Agrawal Printers, Meerut.

Shankar, V. 1978. Ecology of the past and present vegetation of the Indian desert, vegetational indicators and use of score cards for measuring desertifications.

In *Glimpes of Ecology* (Eds. J.P. Singh and B. Gopal), pp. 269-283. Interantional Scientific Publishers, Jaipur, India.

Shankar, V. 1983. *Depleted Vegetatio of the Desertic Habitats: Studies on its Natural Regeneration.* Pub. No. 21. CAZRI, Jodhpur.

Shankar, V. and Bhati, N.S. 1977. Ecological studies on arid shrublands of western Rajasthan. In *Annual Progress Report.* CAZRI, Jodhpur, p. 32.

Shankar, V. and Dadhich, N.K. 1977. Effect of long term exclosure on changes in dune vegetation. *Annals of Arid Zone* 16(3): 381-386.

Shankar, V. and Kumar, S. 1980. Ecological survey of vegetation of Guhiya catchment of Upper Luni Basin. In *Annual Progress Report,* CAZRI, Jodhpur.

Shankar, V. and Kumar, S. 1981a. Ecological survey of vegetation of Bandi catchment of Upper Luni Basin, In *Annual Progress Report,* CAZRI, Jodhpur.

Shankar, V. and Kumar, S. 1982. Plant Resources. In *Report on Baxic and Human Resources Survey of Guhiya Catchment in the Upper Luni Basin* (Eds. K.A. Shankanarayan), pp. 193-212. CAZRI, Jodhpur.

Shankar, V. and Kumar, S. 1987a. *Grazing resources of Jaisalmer: Ecology and Development Planning with Special Reference to Sewan Grazinglands,* CAZRI Monograph No. 28., CAZRI, Jodhpur, pp. 91.

Shankar, V. and Kumar, S. 1988. Vegetation ecology of the Indian Thar Desert *International Journal of Ecology Environment Sciences* 14: 131-155.

Shankar, V. and Saxena, S.K. 1975a. Study of ground vegetation under various tree canopies. In *Annual Progress Report,* CAZRI, Jodhpur, p. 63-65.

Shankar, V. and Saxena, S.K. 1975b. Effect of long term closures on vegetation changes on rocky habitat at Kailana. In *Annual Progress Report,* CAZRI, Jodhpur, p. 63.

Shankarnarayan, K.A., Cherian, A. and Gaur, Y.D. 1965. Ecology of dune vegetation at Osian (Rajasthan). *Journal of Indian Botanical Society.* XLIV(1): 37-50.

Shankarnarayan, K.A. and Satyanarayan, Y. 1964. Grazing resources of Rajasthan 1. Grassland types of the alluvial plains. *Indian Forester* 90 970: 436-441

Sharma, B.M. 1961. Studies on the vegetation of arid zone of India- Composition of some scrub communities of Churu, Rajasthan. In *Proceedings of National Academy of Science, India* 32b: 157-168.

Sharma, B.M. 1965. Composition and structure of plant communities of Churu, Rajasthan. *Tropical Ecology* 6: 106-123.

Sharma, B.M. 1972. Phytosociological studies on the vegetation of sand dunes of Sikar, Rajasthan. *Indian Forester* 98(4): 240-243.

Sharma, S. 1983. A Census of rare and endemic flora of S. E. Rajasthan. *An Assessment of Threatened Plants of India* (Eds. S.K. Jain and A.R.K. Shastry), pp. 63-70.

Sharma, S.C. and Aggarwal, R.K. 2008. Study of Phytobiodiversity of Nagaur district in Rajasthan. *J. Eco.Taxon. Bot*. 32(2): 359-373.

Sharma, S.C., Aggarwal R.K. and Purohit C.S. 2006. Grasses of Medicinal value in Nagaur district of Rajasthan. *GEOBIOS* 33:336-337.

Sharma, S.C., Kantiya, J. and Purohit, C.S. 2008a. *Calamogrostis pseudophragmites* (Hall.f.) Koeler var. tartarica (Hook.f.) Bor (Poaceae) – A New Record of Rajasthan, *J. Bomb. Nat. Hist. Soc.,* 105(2): 227.

Sharma, S.C., Purohit, C.S. and Bhatiya, R. K. 2008,b. *Poa supina* Schard. (Poaceae) A new record for Rajasthan, *J. Bomb. Nat. Hist. Soc.* 105(1): 113.

Sharma, S.C., Purohit, C.S. and Kantiya, J. 2007. Addition to the grasses of Bikaner and Sriganganagar district, Rajasthan. *GEOBIOS* 34(4): 295-296.

Sharma, S.C., Purohit, C.S. and Kantiya, J. 2008c. *Enteropogon monostachyos (Vahl) K.* Schum. ex Engl. (Poaceae) A new record for Rajasthan, *J. Bomb. Nat. Hist. Soc.,* 105(1): 112.

Sharma, S.S. and Sen, D.N. 1974. A new report on secondary dormancy in certain arid zone seeds. *Curr. Sci.* 43: 386.

Shetty, B.V. and Singh, V. 1987-1993. Flora of Rajasthan. (Vol. 1-3), BSI, Calcutta.

Shukla, J.K., Chauhan, A., Kasera, P.K., Mohammed, S. and Chawan, D.D. 2000. Seed variability in *Prosopis cineraria* collected from different localities of Indian desert. *Sci. and Cult.* 66: 163-164.

Singh, B.P., Kalra, P. and Romana, H.S. 1997. An analysis of the Flora of Churu (North Rajasthan). *J. Econ. Taxon. Bot.* 2(3): 697-701.

Singh, G. 2004. Influence of soil moisture and nutrient gradient on growth and biomass production of *Calligonum polygonoides* in Indian desert affected by surface vegetation. *Journal of Arid Environment*s 56: 541-558.

Singh, G. 2008. Efficacy and economics of rain harvesting devices in controlling run-off losses and enhancing biomass production in Aravalli range. Report submitted to State Forest Department, Rajasthan.

Singh, G., Bala, N., Kuppuswamy, V. and Rathod, T.R. 2003. Adaptability and productivity of *Cassia angustifolia* in sandy soil of Indian desert. *Indian Forester* 213-223.

Singh, G., Chouhan, S. and Rathod, T.R. 2008. Vegetation diversity and socio-economic profile relations in some selected villages of India desert. *Indian Forester* 134(6): 744-756.

Singh, J.P, Soni, M.L. and Rathore, V.S. 2008b. Role of shrubs in rehabilitation of degraded lands in hot arid region. In *Natural Resources Management for Sustainable Development in Western India* (Eds. S.N. Prasad, R.K. Singh, Ashok Kumar, A.K. Parandiyal, Shakir Ali, J. Somasundaram, B.K. Sethy and V.N. Sharda), pp. 169-170. Allied Publishers, Pvt. Ltd. Delhi.

Singh, J.P., Mathur, B.K. and Rathore, V.S. 2009. Fodder potential of Lana (*Haloxylon salicornicum*) in hot arid region. *Range Management and Agroforestry* 30: 34-37.

Singh, J.P., Rathore, V.S. and Beniwal, R.K. 2006. Perennial medicinal plants for rainfed farming system in arid region. *Indian Journal of Arid Horticulture* 1: 8-14.

Singh, J.P., Rathore, V.S. and. Beniwal, R.K. 2007. Kheep (*Leptadenia pyrotechnica*): Potential rangeland shrubs of western Rajasthan, India. *Journal of Plant Genetic Resources* 20 (30): 199-203.

Singh, J.P., Soni, M.L and Rathore, V.S. 2005. Halophytic Chenopods Shrubs of Arid Zone. In *Shrubs of Indiana Arid Zone* (Eds. Pratap Narain, Manjit Singh, M.S. Khan and Suresh Kumar), pp 27-32. Arid Agro-ecosystem Directorate, Central Arid Zone Research Institute, Jodhpur.

Singh, Manjit, Jindal, S.K. and Sivadasan, Rekha 2007. *In situ* variability in morphological and fruit related traits of *Capparis decidua* (Forsk) Edgew. in arid and semi arid tracts of Rajasthan and Haryana. *Annals of Arid Zone* 46: 83-90

Singh, N.P. and Pandey, R.P. 1997. Depleting plants resources in the Rajasthan desert. *Bull. Bot. Surv. India* 36: 47-60.

Singh, V. and Monika Singh. 2006. *Biodiversity of Desert National Park, Rajasthan.* Botanical Survey of India Publ., Howrah.

Singh, V. 1985. Threatened taxa and scope for conservation in Rajasthan. *J. Econ. Tax. Bot.* 7: 573-577.

Spehn, E.M., Hector, A., Joshi, J., Scherer-Lorenzen, M., Schmid, B., Bazeley-White, E. *et al*., 2005. Ecosystem effects of biodiversity manipulations in European grasslands. *Ecological Monograph* 75:37–63.

Sundaramoorthy, S. and Sen, D.N. 1993. Ecological studies on seed germination of *Borreria articularis* (Linn.) F.N. Will. *Jour. Phytological Res.,* 6: 25-28.

UNEP 1992. Convention on Biodiversity *Nairabi, Kenya.* UNEP Environmental lawa and Institutions Programme Activity Center.

Upadhyay, S. 2008. Effect of resource manipulation on vegetation pattern and biomass production in arid environment. *Doctoral Thesis*. FRI, Univeristy, Dehra Dun.

Van Noordwijk, M.G., Lawson, Soumare A., Groot, J.J.R and Harriah, K. 1996. Root distribution of trees and crops: Competition and/or complementary. In *Tree-crop interaction: A Physiological Approach*, (Eds. C.K. Ong and P. Huxley), pp 319- 364, CAB International; Wallingford. UK

Young, A. and Young, R. 2001. *Soils in the Australian Landscape*. Oxford University Press, Melbourne

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 180-209 pp.

Improvement of Livestock Productivity in Arid Region

N.V. Patil[1], B.K. Mathur[1], M.S. Khan[1], H.C. Bohra[1], A.K. Patel[1], M. Patidar[1], P.P. Rohilla[1], D.K. Saha[1], Khem Chand[1], A.C. Mathur[1], S. Kachhawaha[1], S.K. Kaushish[1], S.A. Karim[2], A.K. Shinde[2], K.M.L. Pathak[3] and Champak Lal[3]

[1]*Central Arid Zone Research Institute, Jodhpur*

[2]*Central Sheep and Wool Research Institute, Avikanagar*

[3]*National Research Centre on Camel, Bikaner*

Indian hot arid zone covering landmass of 0.32 million km^2 and the cold arid area of 8.4 million ha with drought occurrence frequency of 47% in the last century in the hot desert makes this area difficult for agriculture. With poor soil conditions, higher evapotranspiration and higher wind velocity resulting in soil erosion and adversely affecting agricultural production, livestock husbandry assumes great importance as an effective drought management measure. The hot arid zone of Rajasthan distributed in 12 districts of the state have livestock population of 29.08 million, which is about 50% of the total population of the state. Of the total species wise livestock population available in Rajasthan, arid regions have 40.46% cattle, 29.77% buffaloes, 70.37% sheep, 53.80% goats and 82.14% camel. Except in the districts of Hanumangarh and Sriganganagar, where large ruminant production system of cattle and buffalo is dominant, in all other districts the small ruminant production system is prevalent, accounting for 55 to 77.5% of total livestock population. The camels represent about 80% of the total population of state (Livestock census, 2008).

Livestock Farming as a Drought Proofing Measure

Agriculture is more prone to drought compared to livestock rearing. Under drought years agriculture production may ebb as low as 10% of the normal year, whereas livestock production may still remain more than 50% under same conditions. In years with less than 25% of average rainfall, as much as 20% of the livestock are wiped out; while in years with less than 50% rainfall, the livestock population is reduced by about 10% in the arid region. Livestock farming has, therefore, been recognized as an instrument of drought proofing. The major components of Drought Prone Area Programme are sheep and goat development for wool, mutton and dairy development (Narain *et al.*, 2000). Livestock farming contributes significantly to the economy of the arid region, but involves much more intensive use of labour as compared to crop farming. Dairy enterprises involve still more intensive use of labour as compared to sheep and goat rearing. On an average 5.5 man hours per household per day are utilized in dairying during monsoon, while only 1 man-hour is utilized per adult cow unit. Thus at the present level of production with cattle, dairying alone may provide employment for 10 million man-hours a day. An equivalent amount of employment is estimated to be available from sheep, goat and camel farming. The goat dairying is affected to a lesser degree than cattle dairying during droughts, particularly when the land is affected by salinity and wind erosion.

Livestock Production and Constitution in Arid Regions

As per Livestock Census of Rajasthan State 2007, the sizable population of livestock in the arid region contribute significant share of production in terms of milk (41.77%), wool (76.01) and meat (53.44%) in the total production in the state. Of the total cow and goat milk produced in the state the share from arid region cows and goats remain to be 55.80 and 60.88%, respectively, whereas arid region buffaloes contribute 31.61% of the total buffalo milk production of the state. Within the arid area, however, major milk production comes from buffaloes (45.66%), followed by cows (38.21) and goats (16.13%).

In Rajasthan 53.46% share of meat production comes from arid region. Sheep, goat and buffaloes population of the arid region contribute 77.36, 52.60 and 34.71%, respectively of state meat production (Livestock Census, 2003). Within the arid region, goats contribute maximum 52.94% followed by sheep (32.80%), buffaloes (9.5) and pigs (5.02%) of the total meat production. Majority of wool production of the state comes from arid region (76.01%).

The arid livestock have better productivity compared to overall state. The breeds of cows, buffaloes and goats in arid region have better adaptability, which reflects in better average milk yield per head of 4.13, 5.60 and 0.87 kg day^{-1}, respectively compared to overall animal productivity of 3.53, 5.25 and 0.68 kg day^{-1}, respectively in the state. The buffaloes have been important part of livestock population in recent years and although it is about 11.81% of total livestock population, the share of buffaloes in the milk production has been to the tune of 45.16% of total milk production for arid region. The rainy and winter seasons are favorable for milk production. The wool productivity from the arid region sheep was also found better (1.79 kg head^{-1} year^{-1}) than the overall state average of 1.6 kg head^{-1} year^{-1} (Livestock Census, 2003).

Despite significant contribution of arid livestock to production in the state of Rajasthan, there is concern about the productivity of animals in this region. Though this livestock has the potential, limited resource availability, traditional rearing methods, difficulty in implementation of breeding policy and poor production management are major constraints for improvement of the livestock productivity.

Prevalent breeds of the region

The arid region is the home tract of Tharparkar, Kankrej and Rathi breed of cattle recognized for their milk production and efficiency. The Nagauri bullocks are well known as draught animals. Murrah, Mehsana, Jaffarabadi and Surti buffalo breeds are reared in the arid areas. The medium fine wool sheep breed Chokla and carpet wool producers Nali, Magra, Marwari, Jaisalmeri and Pugal also belong to this region. Sonadi and Malpura are good meat producers. Bikaneri and Jaisalmeri camels are inhabitants of this tract. Marwari and Kathiawari horses of the region are among the best racehorses of the country.

The Tharparkar breed of cattle once common in Jaisalmer, Jodhpur and Barmer is good milker (2500 litres) and is adapted to harsh climatic and poor management situations and is also resistant to common health disorders. The animals respond favourably to better feeding and management care. However, the Tharparkar pure blood is rare now, even in the home districts Jodhpur and Jaisalmer (Mathur *et al.*, 1991). Surveys showed that the advantage of crossbred cows over pure Tharparkar are greatly disturbed by the susceptibility of the crossbred to heat, high cost of management and health cover. The heat tolerance co-efficient value (88.88 ±1.92) of free grazing animals of this breed was equal to animals of Rathi breed (89.87±2.51).

Studies on the effect of improved management on the productivity of Tharparkar cattle showed that lactation milk yield, lactation length, dry period, inter-calving interval, milk fat, solids not fat (SNF) and total solids (TS) was better in cows maintained under scientific management, than those under traditional management (Patel *et al.*, 1994). The production and reproduction performance of the herd indicated that the age at first calving of Tharparkar cattle was 1340±75.8 days and lactating cows yielded 2038.2±98.1 l milk in a standard lactation period of 305-days and total

2225.4±128.2 l in a lactation period of 347.1+15.7 days. The peak yield of 10.30±0.28 l was observed at 55.5±6.71 days of lactation. The milk yield per day of lactation length (MY/LL) and per day of calving interval (MY/CI) indicating the efficiency of milk production against lactation length and calving interval traits were 6.41±0.28 and 4.40±0.31 l, respectively. No adverse effect of summer stress on the fertility was observed, as 80% cows conceived between April and August. The milk composition of Tharparkar cows was influenced by season, depending on feed/fodder availability. The highest milk fat content was found in winter season, followed by autumn, rainy and summer seasons. However, no seasonal effect was observed on milk fat under arid conditions (Patel *et al.*, 1997). The cows breed regularly despite harsh conditions of arid region. The average dry period and calving interval of the cows was 3.13±0.92 and 12.55±0.34 months.

Rathi cattle are native of Bikaner district. This breed is a milch type, brown in colour and of large size. The animals are traditionally reared in Bikaner, Ganganagar and Hanumangarh districts by the Rathis- a local tribe in the region. The cows are good milkers and have a standard lactation yield of 2500 l. The heifers mature at the average age of 3 years and attain weight between 208 to 302 kg. During pregnancy, animals gain around 50 kg body weight .The Rathi cattle attained highest (322.9 ±13.17 kg) and lowest body weight in October and August (246.31±1.90 kg), respectively. Animals started losing body weight after calving and it continued till 90 days after parturition (Kaushish *et al.*, 1998). The lactating cows have pendulous udder which make them prone to physical injuries. The animals have also been observed to suffer from the pre and postpartum uterine prolapse and resultant secondary uterine infections. Rearing these animals on the ranges is a concern for farmers of Bikaner district as most ranges are severely degraded in edible biomass and feeding in intensive system is not cost effective.

Kankrej breed of cattle native of Banaskantha district of Gujarat have wide distribution in Barmer and Jalore districts of western Rajasthan. Cows of this breed have milk-production capacity of 1,500-2,500 litres per lactation and bullocks are excellent draught animals. Studies at Livestock Research Station, Sardar Krushinagar indicated that the heifers well managed through individual feeding and proper housing can mature at an average age of 2 years with first calving at about 3 years. The reproduction performance in terms of calving interval and service period was optimum at 12-12.5 months and 65-68 days, respectively. The cows had a standard lactation yield of 2200 litres (Gujar, 1989). Studies conducted at Bikaner on Kankrej breed indicated that the animals can be maintained on *Lasiurus sindicus*-

dominated pasture at a stocking rate of 1 animal per 1.5 ha. During lean period in addition to grazing, animals given concentrate mixture pellets and *Lasiurus* grass hay gained average body weight up to 67 kg per animal in 18 months.

The buffaloes in Rajasthan are graded Murrah and Mehsana type breeds in the northern and southern parts of the desert, respectively. These animals yield an average 3000 litre of milk in a lactation period of 305 days. The buffaloes like to wallow in water, but have adapted to hot arid climate very well. During the past 40 years buffalo population in Rajasthan has increased from 3 million to 7.7 million. In the arid districts, there were 0.722 million buffaloes in 1951, which increased to 2.297 million in 2003 (Kaushish *et al.,* 1998). Banni breed of buffaloes in Gujarat produce about 2500 litres milk with high fat content. These animals thrive on local grazing vegetation of salt affected soils and provide economic sustenance to the livestock owners of the Kutch area of Gujarat. Buffaloes rearing in urban areas is more profitable than in rural because of the better marketing and sale price offered to the buffalo milk. However, the population of buffaloes is also increasing in the rural arid areas, as the animals have no social taboos towards sale of unproductive or surplus males.

Indian camel population is mainly confined to north-western states *viz*., Rajasthan, Gujarat, Haryana and Punjab which account for 93.12% of total Indian camel population with highest density (70.13%) in eleven arid districts of Rajasthan. The camel breeds in hot arid region are Bikaneri and Jaiselmeri. This animal possesses many unique qualities, which make it distinctly superior to other livestock. This “Ship of the desert” uses various adaptive mechanisms on hot arid sand dune. For instance cattle in the central desert of Australia with daily temperature of 40^{o}C are reported to have died without water in four days while camels in India survived for more than 15 days in the same environment. It has been estimated that a well-fed camel could carry some six month’s energy on it’s back while cattle are unlikely to have more than two-three months, if run out of food. Camels are able to sustain up to 20 to 22% of body weight loss during severe famine conditions whereas other livestock like cattle and buffalo cannot sustain beyond 10 to 12% loss in body weight. Camel population in India has declined from 1.03 million to 0.63 million within a decade. It is due to fast mechanization, increased irrigation and shrinkage of grazing/browsing land.

Camel can tolerate high temperature, solar radiation and water deprivation and subsists on poor quality, thorny, vegetation. Camel milk has comparatively better keeping quality and medicinal properties. In recent times, camel hide and bone have been used for making various types of consumer goods and fancy decorative items. Camel dung is good source of organic manure and fuel. Draught use of camel carting is profitable and advantageous over bullock carting for small farmers. Camel also has better utility as riding, racing, ploughing livestock and it has economic importance as meat, marketing and game animal.

Small Ruminant Production System of Arid Region

Sheep

The arid regions have a sizeable population of sheep. The important breeds of sheep in the desert region are Chokla, Magra, Marwari, Nali, Pugal and Jaisalmeri, with yearly wool production potential of 1.54, 1.80, 1.38, 2.12, 1.67 and 1.65 kg, respectively. On an average, 1.56 kg of wool per sheep per year is obtained in desert districts which is higher than the average wool obtained from other parts of the state (1.38 kg) and the country (0.88 kg). The best carpet-wool producing animals are found in the arid and semi-arid parts of India from which approximately 23 million kg wool is produced annually. The total wool production from cold arid Himalayan region is 3 million kg. The hot arid sheep breeds except Malpura and Sonadi produce medium to fine carpet wool. Marwari is one of the most popular breeds in arid region. Low income from the poor strains of sheep, unorganized markets for the produce and poor quality pastures are major constraints of sheep industry in the region. Shepherds follow age-old practices of sheep management, which not only affects the capacity to produce but also reduces the productive life span of the sheep (Kaushish *et al.,* 2006).

Goats

The important goat breeds of arid Rajasthan are Marwari, Parbatsar, Jhakrana, Sirohi and Shekhawati. Mehsana and Kachchhi breeds are found in the arid region of Gujarat. The goats are primarily raised for meat purpose. The Parbatsar and Jhakrana breeds are known for good milk and meat production. Marwari doe on an average yields 84 litres of milk in 180 days lactation period, whereas Parbatsar doe may yield up to 132 litres in 170 days lactation period (Patel *et al.*, 1999). The Marwari goat is extremely well adapted to the arid environment. However, due to lack of proper nutrition, genetic potential of these animals is not expressed to maximum (Mathur *et al*., 1999a). It grows and breeds faster, can tolerate higher salt loads, needs less water and survives on a wider variety of feeds including many weeds, as compared to the sheep. The studies on productivity and adaptability of various goat breeds viz., Marwari, Parbatsar, Shekhawati, Jhakrana, Kutchhi, Barbari and Jamunapari under desert conditions showed that these breeds were non seasonal in their reproductive behavior. The incidences of oestrus were very low in case of Jhakrana and Jamunapari goats (Mathur and Mittal, 1990).

The goat is mainly browser while the sheep is grazer. The goat is not necessarily the most important biotic factor involved in desertification. The deep-rooted bias against the goat may not be wholly justified on scientific grounds and its proper place in the agro-system of the desert needs to be redefined, particularly in view of the goat's potential to meet the protein gap in the country.

Research and Logistic Support

For breed conservation and improvement, Rajasthan Agricultural University (RAU), Maharana Pratap University of Agriculture and Technology (MPUAT), Central Sheep and Wool Research Institute (CSWRI), Central Arid Zone Research Institute (CAZRI), National Research Centre on Camel (NRCC), National Research Centre on Equines (NRCE), State Animal Husbandry departments and Department of Animal Husbandry, Government of India have their farms located in native tracts of arid breeds of livestock.

Research on Tharparkar cattle is being carried out at the Central Cattle Breeding Farm, Suratgarh, Livestock Research Station, Chandan and CAZRI, Jodhpur, the latter two also have Rathi breed in their mandate. The Livestock Research Station of MPUAT at Vallabhnagar in Udaipur district works for Surti buffaloes. The Rajasthan State Animal Husbandry Department’s Sheep Breeding Farm at Fatehpur in Sikar district, CSWRI, CAZRI and Wool Analysis Laboratory, Bikaner are engaged in research on sheep. Investigations on goats are carried out at Rajasthan state government’s Ramsar-Sirohi (Parbatsar) Farm, CAZRI and CSWRI. NRCC is devoted to research on camels and NRCE at Hisar and Bikaner work for equines.

Rajasthan State AH Department have semen processing facility for the cattle and buffaloes at Bassi, Jaipur and Narwa Khichian, Jodhpur with genetically superior male germplasm (bulls) maintained for semen collection and dissemination. In addition, the Rajasthan Cooperative Dairy Federation (RCDF) also has centres for semen collection and processing. The breeding farms are custodian of true to the type breeding animals and supply males and females for breed improvement programmes run by different institutes and/or animal breeders in the region.

To support the local breed improvement programme, grading up, crossbreeding and selective breeding is carried out through artificial insemination facility available at various state department centers, RCDF and Veterinary dispensaries in the region. Distribution of genetically superior males, castration of the local males having low genetic potential and registration of the progressive breeders are undertaken by state AH department.

Nutritional Insecurity: A Major Constraint

Grazing of livestock is common practice in arid zone of Rajasthan as about 53% of total area of western Rajasthan is available for grazing mainly for cow, sheep and goat. However, the availability of green forage from natural grazing lands/pasture to the grazing livestock is restricted to the monsoon and post monsoon months only. The traditional systems of grazing in western Rajasthan the Orans and Gochars, occupy about 62,000 ha. These lands attached to deities were considered sacred forests and were excellent source of biodiversity conservation. With passage of time encroachments on these lands began due to change in human values and these are on the path of degradation. Nearly one-third area of arid zone of Rajasthan is wasteland, of which 50% is grazing land and 45% sandy waste (Balak Ram *et al.* 2003). The production from the available grazing lands is hardly 300-400 kg ha^{-1} (Pratap Narain and Rajora, 2005).

Available Feed Resources for Livestock in Arid Region

Pasture and grass lands, communal and wayside grazing lands, crop byproducts and residues, fodder crops, non-conventional byproducts of agro industrial processing and feeds comprise various feed resources. Residues, straw and stover of wheat, barley, pearl millet, sorghum, mung, moth, gaur, cowpea and other legumes crops constitute a major part (60-70%) of feed resources for large ruminant. Areas available for grazing during monsoon period are 2-3 year fallow fields, reserve forest area, non-cultivable land or wasteland and the village grazing land (Oran).

In arid region *Cenchrus ciliaris*, *C. biflorus*, *C. setgerus*, *Lasiurus sindicus*, *Aristida* spp and *Eleusine* spp are dominant grasses available for grazing during monsoon period. Among trees/shrubs the dominant species are *Ziziphus nummularia*, *Prosopis cineraria*, *Acacia senagal*, *Accacia nilotica* etc. in low rainfall tract (200-250mm), shrub species like *Zizyphus numularia Capparis decidua, Calligonum polygonoides* and *Haloxylon salicornicum* serve as the top feed species. Other feed species are grasses like

Lapra (*Aristida funiculate*), Kuri (*Urocholoa panicoides*), Murat (*Brachiaria ramosa*), Ganthia (*Dactyloctenium aegypticum*), Chidi grass (*Eragrostis trenula*), Kagiyo (*Tetrapogan tenellus*), Dob (*Cynodon dactylon*), Ghumar (*Panicum antidotale*), Chira ka chanwala (*Sporobous indicus*), Makra (*Eluesine aegypticus*); weeds like Lolru (*Digera muricata*), Sathi (*Trianthema portulacastrum*), Bekaria (*Indigofera cordifolia*), Kanti (*Tribules terristris*), Antipada (*Achryanthes aspera*), Jhernia (*Digitaria marginata*), Kali bui (*Helotropium sabulatum*), Motha (*Cyperus rotundus*), Makhamal (*Celosia argentia*), Chandlia (*Amaranthus* spp); and trees/shrubs like Thor (*Euphorbia caducifolia*), Neem (*Azadirachita indica*), Gundi (*Cordia gharaj*), Vilayati babul (*Prosopis juliflora*), Nutan (*Dichrostachys nutan*), Kair (*Capparis deciduas*), Metha Jal (*Salvadora persica*), Aak (*Calotropis procera*), Anjan (*Hardwickia binnata*), Khimp (*Leptadenia pyrotechnica*), Ardu (*Ailanthus excelsa*) and Desibabul (*Acacia nilotica*).

Feed and Fodder Requirement and Availability

Estimates worked out on the requirement of feeds and fodders vary widely. The fodder demand was estimated to be 28.13 million tonnes for year 2000 on dry matter basis (Venkateswarlu *et al.* 1992). According to another estimate, the arid western Rajasthan harbours livestock equivalent to 10.96 ACU requiring 39,238 thousand tonnes dry matter annually. Dry roughages and green forage requirement will be 21,849 and 41,200 thousand tonnes, respectively. In addition, about 13 million tonnes of concentrate will be required annually to feed 23.96 million livestock in arid zone of Rajasthan (Patidar and Saxena, 2007). The availability of dry forages during normal and drought year is estimate to be 14,000 and 4,390 thousand t and of green forages 8,710 and 2,690 thousand tonnes, respectively, revealing the annual deficiency of 35.9% and 79.9%, respectively. Similarly, during these conditions, the green forages are deficient by 78.9% and 93.5%, respectively. The overall deficit of fodder ranges from 76% in western districts to 81% in the central districts and 82% in the eastern part (Pratap Narain and Kar, 2005).

Introduction of non-conventional/exotic species in silvipasture and in seeding mixture will help mitigate fodder scarcity during drought. Development silvipastures in non-arable or wasteland may be resorted to. Effective integration of native top feed species, pasture will reduce pressure on grasses and provide round the year availability of green feed to some extent.

Alternate Feed Resources for Arid Livestock

Arid regions have many feed resources in the form of agricultural produce, weeds, byproducts from agro-processing methods etc. Tumba (*Citrullus colocynthis*) seed cake a byproduct of the oil extraction industry is nutritionally rich as it contains 16- 22% crude protein. Inclusion of 25% tumba seed cake (TSC) in concentrate feed lowers the cost of animal feeding by 18-35% without any adverse effect on the production, general health and reproductive performance (Mathur *et al.*, 1989, Mathur, 1996, Mathur *et al.*, 2000). Salty shrub Lani (*Salsola baryosma*) at vegetative stage can be a good source of fodder to animals. The acceptability and palatability of fresh cut shoots showed that Lani is palatable (Mathur *et al.*, 2007). Lana (*Haloxylon salicornicum*) seeds having 18.60% crude protein could replace about 25% of the conventional sesamum cake in the concentrate for lactating cows (Anonymous, 2007). The powder of *Prosopis juliflora* pods can be used up to 35% in the concentrate of lactating goats with maintenance of milk production without having any detrimental effect on health (Mathur *et al.,* 2003). Similarly *P. juliflora* pod husk can be used up to 50% level in the concentrate along with tumba (*Citrullus colocynthis*) seed cake as low cost ration in the sheep without any adverse effect on animal health (Mathur *et al.*, 2002).

Fresh leaves of *Hardwickia binata* are palatable to goats and sole feeding supports the body weight growth of growing kids (Patil *et al.*, 2009). Feeding fresh leaves of *Colophospermum mopane* is not possible in goats but it can be fed at 35-40% of whole ration (Patil *et al.*, 2007). The palatability of dry *C. mopane* leaves was low and decreased with progress of feeding from 15 to 5% from 1st to 5th week and the traditional local *P. cineraria* leaves were better source of supplementation even in the dry form supporting the milk yield of goats. (Mathur *et al.*, 2006 b).

Thornless cactus *Opuntia ficus indica* introduced in Indian arid region has fodder value as a maintenance feed and was observed to reduce the water requirement if fed along with the dry roughages in goats, sheep and growing cattle. In addition, its high mineral content may reduce the mineral requirement, as arid animals often suffer from mineral imbalance (Mathur *et al.*, 2009).

The weeds in the rocky and sandy habitat of arid region have a distinct relative preference index for grazing sheep and goats. Patil *et al.* (2005) studied the preference of these animals to different weeds and found the same to be in the order: Kanti (*Tribulus terristris*), Kagio (*Tetrapogon tenellus*), Santo (*Trianthema protulacastrum*), Lolaru (*Digeria muricata*), Bekario (*Indigofera cordifolia*) and Gangan (*Grewia tanax*).

Top Feeds of the Indian Desert

The top feeds contribute about 60% of the total feed requirement of small ruminants in dry areas (Singh and Karim, 1997). Traditionally in dry arid areas these trees are heavily lopped, and are used for feeding mostly to grazing small ruminants. *Prosopis cineraria* is extensively lopped in winter, it can withstand recurrent lopping. A moderate sized mature tree of the species yields about 15 kg of leaf forage locally known as 'Loong'. *Z. numularia* locally known as 'bordi' is also heavily lopped in winter for its leaf fodder known as 'Pala'. Investigation at Pali and Jodhpur has shown that the species growing at medium density of 14% is optimum in natural grazing lands for maximum fodder production, which may yield about 125 kg of 'pala' per ha. Some suitable top feed species on rangelands with systematic lopping should be integrated for good pasture management. Trees can also be planted along the boundaries, inspection path and approach roads to serve dual role of windbreaks and source of fodder. A good pasture may have 30 to 35 such trees per hectare. The important top-feed-cum-shade trees for rangelands are *Acacia nilotica, Prosopis cineraria, Salvadora oleoides, Acacia senegal, Albizia lebbeck, Anogeissus rotundifolia, Anogeissus pendula, Azadirachta indica, Grewia tenax, G. spinosa, Techomella undulata* and *Hardwickia binata.* Shrubs like *Z. nummularia, Calligonum polygonoides, Haloxylon salicornicum, Capparis decidua* and *Acacia jacquemontii* are also relished by goats, camels and livestock.

Animal Performance on Desert Top Feeds

By and large, the consumption of *Z. nummularia* leaves is more than that of *P. cineraria* leaves, in both sheep and goats, the latter consuming considerably higher than the sheep (Ghosh and Bohra, 1984). The leaves of *A. excelsa, Z. nummularia* and *P. cineraria* are high in TDN and total digestible nutrients (64%, 50%, and 41.0% respectively), while the digestible crude protein (DCP) value of *A. excelsa* leaves is higher (16%) than the more palatable *P. cineraria* in sheep (3.1%) and goats (5.5%) (Bohra, 1980). The DCP of *Z. nummularia* in sheep and goats were 4.1 and 3.6%, respectively (Bohra, *et al.*, 1999). From the point of nutritive value, *A. excelsa* leaves can be considered the best feed among all desert tree leaves. However, this tree does not grow as extensively as *P. cineraria* or *Z. nummularia* in this region. On the basis of per unit of feed material in general, top feeds provide more energy than the grasses, as the digestibility of cellulose from desert grass *C. ciliaris* (Bohra and Ghosh, 1977) is higher than that of the tree leaves presumably because of the high lignin content of the top feeds.

The nutritive value in terms of digestible crude protein and total digestible nutrients of different feeds differ with animal species. *Z. nummularia* has high nutritive value for camel followed by the sheep and goats, while *P. cineraria* has the highest value for goats, followed by camel and the sheep. The browsing rams and grazing bucks reared under a silvipastoral system having *C. ciliaris* as a dominant grass and supplementaed with loppings of *Zizyphus rotundifolia* exhibited substantial body weight gains (Patil *et al.*, 2009). In the arid zone a substantial area is salt affected, where nothing can come up, except a few halophytic plants like *Salicornia bigelovii,* which can be cultivated under flood irrigation of brackish well water (Bohra *et al.*, 2009).

The desert top feeds, especially, *P. cineraria* and *Z. nummularia* leaves although have appreciable quantities of crude protein but their DCP value is very low because of tannins and lignin in these feeds. (Bohra *et al.*, 1999), which not only reduces the palatability, but also hinders utilization of dietary proteins by the animals as indicated by *in situ* degradability study of *P. cineraria* leaves in sheep rumen (Mathur *et al.,* 1998). Attempts have been made to improve the nutritive value of *Z. nummularia* leaves by treatment with dilute formaldehyde (Ghosh *et al.*, 1971) and *P. cineraria* leaves by treatment with ferric chloride (Gupta, 1967). For this purpose, over night soaking the leaves with 0.5N aqueous sodium carbonate solution, followed by washing with water, proved to be the best method for detanning *P. cineraria* leaves removing about 94% tannins of these leaves (Bohra and Goyal, 1986). Other desert plants also yield appreciable quantity of palatable pods. *P. juliflora* leaves are not relished by the animals, but its pods are highly palatable and relished by almost all the species of the livestock. Feeding of pods after suitable processing like crushing and grinding is possible. *A. tortilis* pods contain 5.7% DCP and 62% TDN and the *P. juliflora* pods, 7% DCP and 75% TDN (Mathur and Bohra, 1993). These pods contain appreciable quantity of micro-minerals, too.

Improvement of Livestock Productivity

Supplementary feed blocks

As the livestock in arid regions are mostly range managed except during monsoon, when dry grasses in the ranges and pastureland, and crop residues in the fallow lands are available, the animals suffer from deficiency of essential nutrients including fermentable energy, protein, minerals as well as carotene. There exist different means of supplementation of essential nutrients to the livestock. Appropriate formulations of multi-nutrient feed blocks (MNB) using locally available feed resources wheat bran, guar korma, *Bajra* husk and *Ardu* leaves, *Prosopis juliflora* ground pods, sugar cane molasses, urea, vitaminized mineral mixture, dolomite, common salt, deoiled soya bean meal have been developed. And as a binder locally available organic product-guar gum powder is being used as a binder. A proto-type solar dryer where the blocks can be dried has also been developed. A briquette machine to process all ingredients and manufacture the blocks has been developed at CAZRI. The supplementary feed blocks meant for the grazing ruminants have been tested in cattle, sheep and goats and were found to be economical source of nutrient supplementation to support the production functions of milk yield, body weight gain and wool yield. During 16 weeks feeding trial the MNB supplemented sheep group recorded 3.6% gain over the sheep maintained on roughage diet. The supplementary feed blocks were also found to improve the nutrient utilization in cattle. In a digestibility trial study on Rathi cows, the digestibility coefficient for DM and crude protein were found better (Mondal and Bohra, 2001). The supplementary feed blocks in the arid areas were found to improve the production performance of lactating animals especially cows, buffaloes and goats. The farmers also reported improvement in the conditions of Pica in the animals suffering from mineral deficiency along with increase in feed and water intake. In case of cattle and buffaloes, a 2 kg block offered as a lick lasted for about 7 and 5 days, respectively (Patel *et al.*, 2003). Feed block production units at farmers' places have been established following training to the farmers and rural youth about processing the feed ingredients using locally developed gadgets, providing rural employment.

Supplementary multi-nutrient mixture

For the small grazing ruminants that do not lick the above blocks, supplementary multi-nutrient mixture formulations were developed using the same ingredients. Feeding these mixtures to goats and sheep after grazing hours was found to improve body weights and milk yield appreciably (Rohilla *et al.*, 2009).

Complete feeds and feed/fodder banks for arid livestock

A low cost balanced diet has been formulated for ruminants, which does not require these animals to be sent for grazing in the rangelands. The alternate feeding diet for ruminants is based on crop residues and locally available agro-industrial products like straws, fallen tree leaves, by-products from other crops like cotton seeds, maize, groundnut, subabul, forest products like dry grass, pods, which can be blended to enable balanced supply of nutrients to the animals. The complete feed rations have been formulated area wise as per availability of various agricultural residues.

To improve the livestock productivity total mixed ration (TMR) or complete feed blocks (CFB) have been developed. In an evaluation trial, the lactating Tharparkar cows fed TMR prepared out of local fodder *Cenchrus Ciliaris* and concentrates available in the area were found to produce milk more economically compared to cows fed on local grass and supplemented with pelleted cattle feed (Mathur *et al.*, 2006). The results of trials conducted at Avikanagar under intensive feeding on 50:50 roughage and concentrate ratios of complete feed indicated that the feed efficiency was higher than 20% because of higher carcass fats. In this study, the crossbred weaner lambs maintained on these diets had higher ADG of 180 g compared to 127 ADG in native lambs. In another study the lambs fed intensively on 50:50 RC based complete feed attained 33.5 kg finishing weight with 11% feed efficiency at 6 months of age (Shinde *et al.*, 1995). In a study conducted on Marwari kids, Patil *et al.* (2006) observed that the kids weaned at 2 months age had comparatively better growth rate than the kids weaned at 3 and 4 months age when these were fed on complete feed diets having roughage to concentrate ratio 30:70 utilizing Khejri leaves and Masoor straw in equal proportion as a roughage source and local material in the concentrate mixture. The cost of feeding was economical for kids reared on CFB after weaning at 2 months age (Rs. 65.37 kg^{-1}) as compared to those weaned at 3 months (Rs. 70.40 kg^{-1}) and at 4 months (Rs.71.27 kg^{-1}). Similarly in the intensive management system the Marwari kids fed on CFB along with goat paneer whey gained higher body weight than the kids fed on CFB only. The results of the above studies indicate that goat and sheep can be reared intensively without sending the animals for grazing and it can achieve the targeted body weights during minimum possible time. It also helps to achieve the expanded use of crop residues and locally available agro-industrial byproducts by formulating complete rations.

The technology of complete feeds is appropriate for the arid region livestock encountering frequent droughts. In such situations advanced planning could be of great help to have enough stores of complete feeds as feed banks, which can be mobilized to places of deficiency.

Stress Management in Arid Livestock

Heat, drought, scarcity of water and feed, nomadism/migration and overstocking particularly due to the unproductive animals are the main problems of arid livestock. The arid region is characterized by high air temperature during summer up to 45-47°C, low relative humidity 12-18%, high wind velocity 13-14 km h^{-1}, scanty and erratic precipitation and a high rate of evapo-transpiration. The soil salinity is high at several patches within this region, the incidences of brackish water with total soluble salt content of around 3000 ppm is common here. All these factors lead to high stress conditions that result in poor productivity of livestock. Even though the animal breeds of arid environment have adapted to these situations very well, the extremes in environmental conditions have enormous effects on physiology and productivity of farm animals (Singh and Upadhyay, 2009). Studies indicated that the provision of proper shelter improved livestock performance through moderation of environmental factors (Patel *et al*., 2001, Singh *et al*., 2003 and Patel *et al*., 2007). The animals need to be protected from direct solar radiation during the hottest hours of the day to ameliorate the effect of heat stress (Shinde *et al.*, 2002).

Cattle adaptability

Livestock being homeotherms need to keep their body temperature within a moderately narrow range to work efficiently. Tharparkar and Rathi breeds of cattle are well adapted to arid environment (Prasad *et al.*, 1999). The heat tolerance co-efficient values of free grazing animals of these breeds were found to be 88.88±1.92 and 89.87±2.51, respectively. An increase in pulse rate and respiration rate during summer season was observed as an adaptation index and these parameters were found to be the highest in June and lowest in January. The daily water consumption per 100 kg live weight was also higher (13.27 L) during May and lowest (5.62 L) during December (Anon., 1990). Similarly the physiological norms of Rathi cattle at weekly interval indicated that the highest 39.7^{0}C and lowest 37.1^{0}C rectal temperature was recorded in June afternoon and January morning, respectively. The diurnal variations were observed in rectal temperature, pulse rate and respiration rate, the magnitude of these traits was higher from April to September (Anon., 1994). Rathi cattle had significantly higher percent packed cell volume, haemoglobin and total body water in comparison to Tharparkar cattle, suggesting better adaptability of Rathi cattle in arid environment of Bikaner region.

Adaptability of small ruminants

The long-term effect of heat and water stress in sheep physiology studied at CAZRI indicated an unusual ability of the desert breed to maintain circulation even when faced with considerable haemoconcentration. When water was reduced to below 75% of normal daily requirement, there was a steady decline in the body water stores. On an average, there was an

18% loss in body weight after remaining without water for 3 days during winter and 25% during summer. Interestingly, the digestibility of crude fibres increased in water restricted sheep while nitrogen balance was not affected due to water stress. The rate of passage of feed was slow in water-restricted sheep in comparison to normally hydrated animals.

During water restriction, water lost from the body of an animal is drawn from various body water compartments and the degree to which these compartments are depleted during dehydration differs from species to species. In Marwari breed of goat 4-days of water deprivation during summer lowered the plasma volume (PV) by 13% of normal. In Marwari sheep, on the other hand, PV was reduced by 43% under similar conditions. The Australian Merino sheep lost about 45% of PV after 5 days of absolute water deprivation. The mechanism involved in the retention of plasma water in goat and camel appears to be associated with the retention of plasma proteins, particularly albumin, in the vascular bed. Unlike Macfarlane's Merino and the Marwari sheep, which exhibited severe reduction in the SCN space at the end of dehydration regimes, the Marwari goat tends to conserve its SCN space somewhat more efficiently, there being a reduction of SCN space by only about 8% (Khan *et al.,* 1979b). In the Marwari goat the reduction in the cell and gut water is of the order of 41% at the end of 4-day dehydration regime, while in sheep it may be to the extent of 30% only. Cell and gut water is of special significance during periods of water stress in the Marwari goat because it is this water, which is mainly relied upon by the animal for maintaining its normal circulatory volume (Khan, *et al.,* 1979a). The cell and gut water may, thus, be considered as "Emergency Water Reservoir" which is used to avert the circulatory failure in the goat. The inability of sheep to use this water fully at times of water crisis and its primary dependence on circulatory water for evaporative cooling and other essential purposes, makes the sheep decisively less desert worthy than the goat.

Deprivation of drinking water for as long as 13 days during late winter to black Marwari goat showed an extraordinary ability to maintain its body weight, whereas Marwari sheep almost reached its limit of physiological tolerance by the end of this period. The desert donkey could, however, resist the dehydration due to water restriction only up to 9 days. The rate of body water loss in goat, sheep and donkey was 46, 87 and 99 ml^{-1} kg^{-1} day^{-1}, respectively, during the dehydration regime. During dehydration, the rank order in respect of maintenance of SCN space in these species was Marwari goat < Marwari sheep < Desert donkey. Of the total amount of body water lost, the cell and gut of the donkey contributed to the SCN space to the extent of 24% only in contrast to 80% in the goat (Khan *et al.,* 1979a) and the camel

(Macfarlane *et al.,* 1963). Interestingly, it is the interstitial water (IFW), which contributes about 70% to the depleting extra cellular fluid compartment. Camels reportedly survive for more than 15 days under approximately similar environmental conditions while sustaining, unlike sheep and donkeys, about 30% loss in body weight.

Body water turn over rate (BWTR) values provide an understanding of a variety of slow evolutionary processes of adaptation by which quite distantly related mammals survive in arid environments, such as the camel and the goat [black coloured] with great success and economy, while others such as cattle and man perform with difficulty and huge expenditure of water and energy. Among Indian desert livestock species, a significant rank order was observed in respect of water turn over rates in hydrated and re-hydrated sheep, goat and donkey. It was lowest in Marwari goats and highest in donkeys; Marwari sheep occupied a middle position. Positive correlation between BWTR and heat load has also been observed in sheep, goat and donkey of the Indian desert (Khan and Ghosh, 1983) BWTR estimates suggests that the Marwari sheep turned over nearly 17% more water per day than the Marwari goat (Khan and Ghosh, 1983). The Parbatsar goat behaved similar to the Marwari sheep in this respect.

In order to maintain homeostasis, animals lose water through surface evaporation (insensible means Sweating and Respiratory Mechanism like panting), and loss through feaces and urine. In hot environments, evaporative heat loss may provide the only channel through which an animal can dissipate its heat; the supply of water and the mode of evaporative cooling thus assume greater importance.

Water salinity tolerance levels

Salinity is a common feature of desert surface water. Mittal and Ghosh (1983) have reported that 4000 ppm soluble salts in drinking water is tolerated by both sheep and goats, although long term effects of this level of salinity on production status have not yet been assessed. Sheep and goats have been reported to tolerate up to 1000 ppm $NaNO_3$, 4000 ppm $MgSO_4$, 30 ppm NaF. Marwari goats can tolerate up to 1500 ppm NaCl. Further in their feeds, goats take in considerably more salts and proteins than the sheep, as top feeds are generally rich in mineral and proteins than the grasses. Hence, the overall salt tolerance is more in goats than in the sheep.

Response of Arid Livestock to Aridity

The hogget of native Nali, Chokla and their crosses with Rambouillet and Soviet Merino maintained in shade or exposed to sun during summer were exchanged. It was seen that the crossbreds had experienced higher stress than the local sheep breeds, recording higher respiration rate and lower rectal temperature. The physiological response viz. respiration rate and heart rate were lower in sheep provided shade and nutritionally restricted or fed *ad lib* in comparison to those animals exposed in sun (Hooda and Naqvi, 1990). In a physiological study to see the responses of sheep and goats to stress when sent for grazing under arid conditions, it was observed that Magra sheep and Marwari goats can safely be grazed within 8 km from their watering point without any ill effect on their health when the average atmospheric temperature is around 44°C (Kaushish and Mittal, 1994).

In a study to know the effect of dry climate on milk production performance of cows, it was observed that the productivity of cross-bred of exotic with indigenous breeds were not seriously affected by the hot dry climate in north western parts of Rajasthan. But hot humid coastal and eastern region of the country with heavy rainfall had a stressful effect in lowering the productivity. The milk yield decrease in dairy cows was found to be more when temperature rise was associated with increase in humidity (Shinde *et al.,* 1990; Dutta *et al.*, 1995). To explain the adaptability of local cows the effect of summer season on the productivity of Tharparkar cattle was not significantly influenced by season of calving in arid zone though the 305-days lactation was higher in winter season calvers (1438.8 litre) than summer season (1274.9 litre). However, the total lactation yield was more or less similar in both seasons due to one month longer lactation length in summer season calvers (Patel *et al.*, 2000).

Though the Marwari goat breed is well adapted to desert vagaries, the productivity of these animals is affected adversely due to extremes of climatic conditions. In a group of ewes exposed to thermal stress it has been observed that the occurrence of estrus was late (30.6+1.2 h) with shorter estrus period (31.7+3.6 h) in comparison to the ewes which were maintained under shed (Naqvi *et al.*, 2004). However, the thermal protected ewes exhibited estrus earlier (25.5+1.1 h) and the estrus period was longer (37.7+1.6 h). The reproductive performance of Tharparkar cattle in terms of dry period and calving interval was not significantly influenced by season of calving, but comparatively lower dry period (101.9+23.3 days) and calving interval (414.5+27.9 days) was observed in winter season calvers than summer and rainy season calvers (Patel *et al.*, 2000). On the other hand it was observed that buffaloes calving in rainy season had higher reproductive efficiency in terms of lower service period (198.4+15.1 days) and calving interval (501.4+15.3 days) (Patel and Tripathi, 1998). In Tharparkar cattle the milk production and reproduction efficiency was higher under arid conditions (Patel *et al.*, 2001).

The average age at puberty, first conception and first kidding in Kuchhi, Marwari and Beetal breeds of goats ranged from 311.2±5.43 to 560.0±6.52, 387.4±3.75 to 605.9±4.59 and 509.4±3.45 to 760.3±4.50 days, respectively. The average service period (157.00±1.30 days) and kidding interval (305±4.56 days) were shortest in Kuchhi. The post-partum interval and getting interval were shortest in Kuchhi and longest in Beetal. The tupping and concentration were higher in Kuchhi (Kaushish *et al.*, 1994). In a growth performance study the climatic stress particularly heat during growth period of animal was found to reduce the body weight gain. The month of birth of lambs also affects the body weights. The lambs born in January to February were heaviest at 6 months body weight (30.6+0.93 kg) with decreasing trend in lambs born in March to December time period (Poonia, 2004).

Shelter Management Approach to Overcome Thermal Stress

Three types of shelters for livestock are prevalent in the rural areas of the arid zone, viz. open housing system (barbed enclosure without any roof), kutcha (thatched roof house) and pucca housing system (Patel *et al.*, 2005). These structures are not very efficient in regulating the temperature. A model improved animal shelter with west-east orientation was developed at CAZRI to provide comfortable environment to goats. The maximum temperature in the model shelter was found lower during summer months and higher during the winters compared to the traditional structures (Mishra *et al.*, 2006). The effect of comfortable housing was studied in growing kids and lactating does. Higher body weight (9.52 kg) gain was observed in the 6 month old male kids of Marwari breed, when reared under closed type improved animal shelter during summer months compared to 7.52 kg in the traditional animal shelter during 6 months period of experiment (Patel *et al.*, 2007). Marwari goats housed in improved shelters had 22% more lactation yield during winter season due to protection from cold. Patel *et al.* (2001) observed lower lactation yield in Marwari goats housed in thatched roof animal shelter during winter in comparison to closed type pucca animal shelter where these goats yielded 38 lit more milk in a lactation period of 154 days with higher milk fat content of 4.77%.

Health Disorders in Arid Livestock and Preventive Measures

Epidemiological studies indicate prevalence of diseases like foot and mouth disease (FMD), rabies, ephemeral fever, sheep and goat pox, tuberculosis, Johne's disease, botulism, enterotoxaemia mycoplasmal infections, blood protozoa, coccidiosis, brucellosis, HS, BQ, anthrax, rickettsial and chlamydial diseases, nematode infestations, mange and pica among the livestock in arid regions (Kishore, 1998). High incidence of subclinical mastitis has also been reported from this area (Singh *et al.*, 1999). Conventional vaccination programmes in vogue in this zone do not cover whole of the population of the animals due to inadequate doses available. Also goat and camel are not usually covered under this programme. Therefore, this programme needs to be extended in whole of the susceptible population.

Parasitic diseases

Arid climate is not very conducive for some of the parasitic infestations like flukes and cestodes. With increased availability of water for irrigation and the prevalent animal husbandry practice being either migratory or of intensive type, it leads to hitherto unreported type of parasitism in animals. Preventive measures are usually the only practicable approach in such cases. Biannual deworming with broad-spectrum antihelmintics like albendazole, fenbendazole, tetramisole, levamisole, closantel, ivermectins etc. should be practiced for all types of animals for roundworms. For *Oestrus ovis* infestation in Sheep and goats ivermectins provides some degree of relief. Hydatidosis, a common problem in sheep, goats, camels, buffaloes and Gid (*Cerebral coeneurosis*) in goats need surgical corrective measures. Mange in all species needs local miticidal application using herbal/pyrethrins/pesticides as dust/spray + ivermectins parentally (Singh and Gahlot, 1999). Apart from prophylaxis with vaccines, drugs effective in prevention of certain diseases are also available. Such chemoprophylactics should be used as a routine health prophylaxis management and preventive measure should be taken against diseases like coccidiosis in kids, calves and lambs, trypanosomiasis in camels, cattle and buffaloes, mange in camels, disesease like shipping fever and helminthiasis in all animals, pica in all ruminants and ticks in cattle with use of the drugs available using it periodically as per the occurrence.

Non-infectious diseases

Non-infectious diseases of livestock are dependent on the management practices. Several nutritional deficiencies have been identified in the animals of arid zone (Dongre, 2000). Deficiency of Vitamins A and D (Fakhruddin, 1987), B1 (Tanwar *et al.*, 1983; 1994) calcium, phosphorus, zinc, iron are registering an upward trend, with increasing reproductive disorders, particularly anoestrus in arid region (Mathur *et al.*, 2001). Energy and protein deficiency results in to pica. Copper, cobalt, selenium, zinc (Singh *et a1.*, 1994), iron and iodine are some of the trace minerals resulting into general conditions like anemia, retarded growth, reproductive disorders, pica (Kishore, 1998) and certain specific conditions suggestive of deficiency. Apart from these, deficiencies of vitamins D3, E, B1 (Tanwar *et al.*, 1983, 1994) and C have also been identified.

Production diseases

Milk fever and ketosis in cattle, buffaloes and goats, post-parturient haemoglobinuria in buffaloes, downer's cow syndrome and mastitis are important production diseases of this area. Milk fever occurs mainly due to calcium deficiency without concurrent deficiency of magnesium. Therefore, the treatment of milk fever should constitute calcium boroguconate only. Most likely period of occurrence is within one week post-parturient. However, subacute calcium deficiency affecting production can occur during early lactation and late pregnancy. Ketosis occurs between 3-7 weeks post-parturient period. Diabetic ketoacidosis has also been recorded in cattle, buffalo and goat. Zinc insulin is to be administered with constant monitoring of blood and urine sugar levels. Pica in cattle, buffaloes, camels and goats in this area is another problem (Mathur *et al.*, 2005). Botulism because of pica in cattle has been recorded from this area (Kishore, 1998). Protein-energy, salt, phosphorus-calcium, vitamin A, D and E deficiencies, helminthiasis (mainly round worms) had been identified as the major causes of pica. Successful management of pica is being practiced on these lines (Gahlot, 2005).

Toxicity

Cyanide, sodium chloride, nitrate and nitrite poisoning have been reported to occur in this zone since long (Sharma and Gahlot, 1997). Newer toxicity includes those with pesticides/farm chemicals, feed additives, drugs, environmental pollutants etc. (Radostits *et al.,* 1994) and accordingly need awareness in farmers of the critical region and treatment assistance as per the occurrence.

Traditional Pastoralism

Transhumance pastoralism is one of the major sources of livelihood of a sizeable part of population inhabiting the arid region of Western

Rajasthan. One recent estimate suggests that there are six million graziers in Rajasthan, who mainly derive their livelihood through sheep, goat and camel rearing, and have socio-economic backwardness. The survival of sheep and goat depends on the common property resources and on migration. Livestock migration, especially of the sheep is a common phenomenon mainly due to scarce vegetation, lack of culturable wasteland and poor rainfall. Maximum concentration of sheep and goat population is in the western arid districts of Rajasthan. Hindus like *Raika/Rabari, Jat, Rajput* and *Meghwal* and *Sindhi* Muslims practice pastoralism. Unlike in other parts of the world, the pastoralists in arid western Rajasthan have permanent settlements. The migration of the sheep and goat flocks start in October-November towards the grazing resource rich areas of north, western or central Indian states, returning in the months of monsoon depending upon the rainfall in the arid region. Studies conducted (Saha *et al.*, 2004) in this region revealed that majority of *Raikas* own very meager agricultural land (< 1 hectare) with all other socio-economic backwardness like illiteracy, traditional beliefs and customs, lack of occupational diversity etc. Despite all hardship pastoralism would continue in view of widespread illiteracy, lack of diversified occupational base, poor land holding, biophysical characteristics of the region and for livelihood security. The major problems faced by the pastoralists during migration are denial of access to feed resources from CPRs, inadequate water points along the routes, forest laws inhibiting the entry and also capture of the animals, lack of veterinary and husbandry aid during routes. There is need of urgent policy decisions as this practice is to continue as a life support system. The National Policy for Farmers (2006) has also emphasized the need for securing pastoralists' forest grazing rights including those areas, which are declared as joint forest management, wildlife sanctuaries and national perks. But there is strong resistance against these policies becoming law, especially among the environmentalists.

Marketing of Livestock and Its Produce in Arid Regions

Efficient marketing of cattle and buffalo is an important factor for increasing milk availability in arid region. Beside state animal fairs, large numbers of animal fairs are organized by panchayats for trade of different livestock species. These fairs provide platforms for sale and purchase of livestock. The most common channels in trade of bovines are: Farmer-Farmer, Farmer-Trader-Farmer, Farmer-Trader-Commercial herds.

Milk producers of arid region market milk through four channels *viz*. private vendor, cooperative society; private dairy and direct sale to consumers. The most popular channel (used by 52.8% producers) is through cooperative societies supported by RCDF followed by direct sale to consumers. Organized private dairies are also coming up in the region.

Sheep breeders depend on middlemen to market live animals and wool (Singh and Rollefson, 2005). Suresh *et al.* 2007 reported sale of live sheep through village agents. In the case of wool, sheep breeders directly take it to nearest mandi and sell to the wholesalers at market rate. The marketing of Indian sheep wool is affected by imports from other countries. Kumar and Singh (2006) reported that commercial goat keepers sell goats and their produce on farm itself. Goat milk also has market in the region. Camel marketing mainly takes place through livestock fairs in Rajasthan. A few animals are also purchased by butchers.

References

Administrative Bulletin 2008-09. Directorate of Animal Husbandry, Govt. of Rajasthan Jaipur, Rajasthan.

Ahuja, L.D. 1980. Grass production under Khejri. In *Khejri in the India Desert its role in Agro Forestry* (Eds. H.S. Mann and S.K. Saxena), Monograph No. 11: pp. 28-30. CAZRI, Jodhpur.

Annual Report 2008. Central Arid Zone Research Institute, Jodhpur

Anonymous 1990. Responses of Rathi cattle fed on *Prosopis cineraria* (Khejri) leaves. *Annual Report*, CAZRI, 1989-90, 65 p.

Anonymous 1994. Performance of Rathi cows and calves under arid conditions *Annual Report*, CAZRI 1993-94 pp.90-91.

Anonymous 2007. Feeding Lana (*Haloxylon salicornicum*) and Saji (*Haloxylon recurvum*) to Lactating Rathi Cattle. *Annual Report*, CAZRI 2007 pp.101-102.

Balak Ram 2003. Impact of human activities on land use changes in arid Rajasthan: Retrospect and prospects. In *Human Impact on Desert environment* (Eds. Pratap Narain, S. Kathju, Amal Kar, M.P. Singh and Praveen Kumar), pp 44-59.Scientific Publishers, Jodhpur, India.

Bohra, H.C. 1980. Nutrient utilization of *Prosopis cineraria* (Khejri) leaves by desert sheep ad goats. *Annals of Arid Zone* 19: 73-81.

Bohra, H.C. and Ghosh, P.K. 1977. Effect of restricted water intake during summer on the digestibility of cell wall constituents, nitrogen retention and water excretion in Marwari sheep. *Journal of Agricultural Science* (Camb.) 89, 605-608.

Bohra, H.C. and Goyal, S.P. 1986. Chemical detaining of *Prosopis cineraria* leaves. Presented at the 5th Animal Nutrition Workers Conference, Udaipur. Karnal: Animal Nutrition Society of India, July 14-17, 1989.

Bohra H.C., Ghosh, P.K. and Goyal, S.P. 1999. Nutrient availability from *Ziziphus nummularis* leaves in desert sheep ad goats. *Journal of Eco-physiology* 2:129-134.

Bohra, H.C., Patel, A.K. and Kaushish, S.K. 2009. Palatability, digestibility of various constituents and nitrogen retention in Marwari sheep offered *Salicornia bigelovii* biomass and *Cenchrus ciliaris* straw mixed diet. *Indian Journal of Animal Sciences* (in press).

Census of Livestock 2003.Goverment of Rajasthan, Jaipur.

Census of Livestock 2007.Goverment of Rajasthan, Jaipur.

Dutta T., Taneja, V.K. and Singh, A. 1995. Effect of climatic variables on average daily milk production in crossbred cattle. *Indian Journal of Animal Sciences* 65(a): 1004-1007.

Fakhruddin, 1987. Mineral and vitamin deficiencies in livestock of western Rajasthan. Scientific programme and abstracts [1(c) 13], National Symposium on "Livestock production vis-a-vis fodder and pasture development in western Rajasthan", 2-3 March 1987, Livestock Research Station, Rajasthan Agricultural University, Chandan Jaisalmer (Raj.).

Gahlot, A.K. 2005. Animal health management in drought prone area. Seminar on “Sustainable livestock production in arid region”, March 22-23, 2005.College of Veterinary and Animal Science, Bikaner (Raj.).

Ghosh, P.K., Ratan, R. and Taneja, G.C. 1971. Effect of chemically protecting dietary protein from microbial degradation in the rumen on wool growth. *Indian Journal of Experimental Biology* 9: 109-110.

Ghosh, P.K. and Bohra, H.C. 1984. Palatability, digestibility and nutritive value of some important top feeds of arid and semi-arid regions of India. In *Agroforestry in Arid and Semi-arid Zones* (Ed. K.A. Shankarnarayan). Central Arid Zone Research Institute, Jodhpur.

Gujar B.V. 1989. *Ph.D thesis* submitted to the Gujarat Agril University, SK Nagar, Gujarat

Hooda, O.K. and Nagvi, S.M.K. 1990. Effect of thermal load and feed restriction on the relative adaptability of Malpura and Avikalin sheep in semi-arid region. *Indian Journal of Animal Sciences* 60(5): 608-611.

Kaushish, S.K and Mittal, J.P. 1994. Physiological responses of sheep and goats to exercise stress under arid conditions. *Indian Journal of Animal Sciences* 64: 423-424.

Kaushish, S.K. 2006. Sheep breeds of India and Their production. In *Strategies for Sustainable Livestock Production* (Ed. S.K. Kaushish, H.C. Bohra, B.K. Mathur, A.K. Patel, and A.C. Mathur). Kalyani Publishers Ludhiana. pp 323

Kaushish, S.K., Bohra, H.C., Mathur, B.K. and Patel, A.K. 1998. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and Manjeet Singh), pp.393-426. CAZRI, Jodhpur.

Khan, M.S. and Ghosh, P.K.1983. Body water turn overrate in Indian desert mammals. *Journal of Arid Environment* 6:173-175.

Khan, M.S., Sasidharan, T.O. and Ghosh, P.K. 1979a. Water regulation in BalTIler goat of the Rajasthan desert. *Experientia* 35: 1185-86.

Khan, M.S., Sasidharan, T.O. and Ghosh, P.K. 1979b. Glomerular filtration rate and blood and urinary urea concentration in BalTIler goats of the Rajasthan desert. *Journal of agricultural Sciences*. 93: 243-248.

Kishore, R. 1998. Clinico-haemato-biochemical and therapeutic studies on bovine suffering from allotriophagia. *M.V.Sc. Thesis* Rajasthan Agricultural University, Bikaner.

Kumar, Shalander and Singh, N.P. 2006. Status and Prospects of commercial goat farming in India. Status and prospects of commercial sheep farming in India, National workshop-cum-seminar on Commercial Goat and Sheep Farming and Marketing: Farmer-Industry-Researcher Interface, March 4-5, 2006, CIRG, Makhdoom, Farah, Mathura, U.P.

Macfarlane, W.V., Morris, R.H. and Howard, B. 1963. Turnover and distribution of water in desert camels, sheep, cattle and kangaroos. *Nature* (Lond), 197: 270-271.

Mathur, A.C., Mathur, B.K., Kaushish, S.K. and Patel, A.K. 2001. Effect of package of improved nutritional management practices on true anoestrous cases in buffaloes in rural arid Rajasthan. Paper presented at Ann. Conv. & Ntl. Symp. on 'Fertility management of farm animals under adverse agroclimatic conditions' 6-8 Oct 2001, Jodhpur (India) Souvenir & Abstracts p 39.

Mathur, B.K. 2003. Livestock: human need for sustainability in arid environment. In *Human Impact on Desert Environment* (Eds. Pratap Narain, S. Kathju, Amal Kar, M. P. Singh and Praveen- Kumar), pp. 506-514. Arid Zone Research Association of India and Scientific Publishers (India), Jodhpur, India.

Mathur, B.K. and Bohra, H.C. 1993. Nutritive value of *Prosopis juliflora* leaves and pods. Presented at the workshop on potential of *Prosopis* spp. for Arid and Semi Arid Regions of India, Jodhpur. Central Arid Zone Research Institute, Jodhpur. November 22-23, 1993.

Mathur, B.K., Patel, A.K. and Kaushish, S.K. 2000. Utilization of tumba (*Citrullus colocynthis*) seed cake of desert for goat production 70(4): 431-433.

Mathur, B.K, Bhati, T.K. and Tewari, J.C. 2006,b. Comparative palatability of *Prosopis cineraria* v/s *Colophospermum mopane* leaves in lactating Marwari goat in arid region. *In:* National Symposium on "*Livelihood Security and Diversified Farming Systems in Arid Region"*. January 14-16,2006 organized by Arid Zone Research Association of India, CAZRI, Jodhpur. No.3-2 pp.51-52.

Mathur, B.K, Mathur, A.C., Bohra, H.C. and Sharma, B.K. 2006a. Mineral Status in Anestrous Cattle and Buffaloes of Arid Region of Rajasthan. *In:* XII Animal Nutrition Conference on "*Technology Interventions in Animal Nutrition for Rural Prosperity"*,January 7-9,2006. Organized by ANSI and ICAR, at Anand Agricultural University, Anand.pp.78.

Mathur, B.K, Patil, N.V., Mathur, A.C. and Patel, A.K. 2005. Impaction of Rumen of desert buck due to Polythene bags- A case study. *Livestock International* 10(5):17-20.

Mathur, B.K. 1996. Effect of replacement of cotton (*Gossypium* spp.) seed cake from Tumba (*Citrullus colocynthus*) seed cake and sun dried poultry droppings on the performance of sheep. *Ph.D. Thesis* submitted to Rajasthan Agriculture University, Bikaner, Rajasthan.

Mathur, B.K. and Bohra, H.C. 1993a. Digestibility of straws of different varieties of bajra. In *Proceedings of the 6th Animal Nutrition Research Workers' Conference on Feeding Strategies of Livestock and Poultry in Relation to Available Feed Resources*, p., 158. University of Agriculture and Technology, Bhubneshwar, September 13-16, 1993.

Mathur, B.K. and Mittal, J.P. 1990. Production performance of various goat breeds on natural protected rangelands in arid region. In: National Seminar on *Philological Status of Indigenous Livestock, Its Contribution to World Rural Economy as Prospects,* held at Assam Agricultural Universities

Mathur, B.K., Abichandani, R.K. and Patel, A.K. 1999a. Higher incidences of twinning in Marwari goats by supplementary feeding in hot arid region. *In "Proceedings IX Animal Nutrition Conference",* 2-4th December 1999. Acharya N.G. Ranga Agricultural University, Rajendra Nagar, Hyderabad. Abstract No. 237. p 144.

Mathur, B.K., Bohra, H.C., Patel, A.K. and Kaushish, S.K. 1998. In situ Rumen degradability of Khejri (*Prosopis cineraria*) leaves in Marwari sheep. Presented at the Golden Jubilee Seminar on. "Sheep, Goat and Rabbit Production and Utilization for Maximizing Production Efficiency, pp. 27. "Indian Society for Sheep and Goat Production and Utilization. Jaipur: CSWRI, April 1998.

Mathur, B.K., Mittal, J.P. and Prasad, S. 1989. Effect of tumba cake (*Citrullus colocynthis*) feeding on cattle production in arid region. *Indian Journal of Animal Sciences* 59: 1464-1465.

Mathur, B.K., Mittal, J.P., Shiv Prasad and Mathur, A.C. 1991. Need of conserving Tharparkar breed of cattle in Indian desert. *Indian Farming* 41(3): 4-6.

Mathur, B.K., Patel, A.K., Mathur, A.C., Abichandani, K.K. and Kaushish, S.K. 2000. Wheat straw (untreated treated) consumption by tharparkar heifers during summer under stall fed conditions in "Third Biennial Conference of Animal Nutrition Association" on "Livestock feeding strategies in the new millennium", Nov. 7-9, 2000. CCSHAU, Hissar. No. 282 p.206.

Mathur, B.K., Patil, N.V., Mathur, A.C., Bohra, H.C., Bohra, R.C. and Sharma, K.L. 2009. Comparative Mineral Status of Jodhpur District Villagers' Cattle v/s Institute Farm Managed Tharparkar Cattle in Hot Arid Zone. Proceedings of Animal Nutrition World Conference, 14-17 Feb., New Delhi, India pp.61.

Mathur, B.K., Patil, N.V., Mathur, A.C., Bohra, H.C., Patel, A.K and Bohra, R.C. 2006. Effect of total mixed ration prepared from local feed resources on feed intake, milk production efficiency and blood profile of Tharparkar cattle in arid region. *In: VI Biennial Conference of Animal Nutrition Association on "Strenthening Animal Nutrition Research for Food Security, Environment Protection and Poverty Alleviation"* September15-17,2006. Sher-e-Kashmir University of Agricultural Sciences & Technology, Jammu, J & K pp.77.

Mathur, B.K., Shiv Prasad and Mittal, J.P. 1989. Effect of tumba cake (*Citrullus colocynllus*) feeding on cattle production in arid region. *Indian Journal of Animal Science* 59:1464-65.

Mathur, B.K., Singh, J.P., Beniwal, R.K. and Singh, N.P. 2007.Utilization of salty shrub-Lani (*Salsola baryosma*) of arid region as drought feed for goats.FR-55.In: International Tropical Animal Nutrition Conference, October 4-7, 2007 NDRI, Karnal pp.33.

Mathur, B.K., Siyak, S.R. and Bohra, H.C. 2003. Feeding of Vilayati babool (*Prosopis juliflora*) pods powder to Marwari Goats in Arid Region. *Current Agriculture* 27(1-2): 57-59.

Mathur, B.K., Siyak, S.R. and Paharia, Shailesh 2002. In corporation of *Prosipis juliflora* Pod husk as Ingredient of low cost ration for sheep in arid region. *Current Agriculture* 26(1-2): 95-98.

Mishra, Dinesh, Patel, A.K. and Singh, Harpal 2006. Development of Improved Animal Shelter for Arid Region. National Symposium on “Livelihood Security and Diversified Farming Systems in Arid Region”. January 14-16, 2006, CAZRI, Jodhpur. Pp. 59-60

Mittal, I.P. and Ghosh, P.K. 1983. Long telTII saline drinking water and female reproductive performance in Magra and Marwari sheep of the Indian desert. *Journal of agricultural Sciences* 101: 751-754.

Mondal, B.C. and Bohra, H.C. 2001. Effect of Multi-nutrient feed block supplementation on feed intake and nutrient utilization in Rathi heifers. Proceedings of X Animal Nutrition Conference on “Emerging Nutritional Technologies for Sustainable Animal Production and Environment Protection”, abst. No. 153, p. 95. N.D.R.I., Karnal, November 9-11, 2001 285 + vii p.

Naqvi, S.M.K., Maurya, V.P., Gullani, R., Joshi, A. and Mittal, J.P. 2004. The effect of thermal stress on supervolatory response and embryo production in Bharat Merio ewes. *Small Ruminant Research* 55(1-3): 57-63.

Narain, P., Sharma, K.D., Rao, A.S., Singh, D.V., Mathur, B.K. and Ahuja, Usha Rani 2000. *Strategy to combat Drought and Famine in the Indian Arid Zone*. Central Arid Zone Research Institute, Jodhpur, 65 p.

Narain, Pratap and Kar, Amal 2005. Drought in western Rajasthan impact, coping mechanism and management strategies, CAZRI, Jodhpur 45pp.

Narain, Pratap and Rajora, M.P. 2005. Managing drought stress for augmenting forage productivity in arid western Rajasthan. In *Livestock Feeding Strategies for Dry Regions* (Eds. P.S. Pathak and S.S. Kundu), pp. 41-56. International Book Distributing Co., Lucknow, India.

Nimbkar, C. and Nimbkar, B.V. 2006. Status and prospects of commercial sheep farming in India, National workshop- cum-seminar on Commercial Goat and Sheep Farming and Marketing: Farmer- Industry- Researcher Interface, March 4-5, 2006, CIRG, Makhdoom, Farah, Mathura, U.P.

Patel, A.K. and Tripathi, V.N. 1998. Effect of non genetic factors an economic traits of Surti buffalo. *Indian Journal of Animal Sciences* 68(6): 566-569.

Patel, A.K., Bohra, H.C. and. Kaushish, S.K. 1998. Effect of supplementation on comparative weight gain of certain goat breeds in arid zone. *Indian Journal of Small Ruminants* 4(2): 91-93.

Patel, A.K., Mathur, A.C. and Mittal, J.P. 1994. Factors affecting composition of milk in Tharparkar cows maintained under arid conditions. *Indian Journal Animal Production & Management* 10: 102-105.

Patel, A.K., Mathur, A.C., Mishra, Dinesh 2005. Traditional shelter management practices for livestock in arid region. National Conference on "Bridging Gap Between Ancient Technologies to Increase Agricultural productivity". December 16-18, 2005 CAZRI, Jodhpur. PP: 53-54

Patel, A.K., Mathur, B.K. and Kaushish, S.K. 2000. Effect of shelter management on body weight and milk yield of Marwari goats under arid condition. Int. Conference on Small Holder Livestock Production Systems in Developing Countries, Nov. 24-27, 2000, Thrissur, Kerala.

Patel, A.K., Paharia, Shailesh and Nagpaul, P.K. 2001. Productive performance of Marwari goats under different shelters in arid region. *Indian Journal Animal Production & Management* 17: 76-78.

Patel, A.K., Rohilla, P.P. and Mathur, A.C. 2007. Performance of Marwari kids and goats under improved and traditional animal shelter. *Indian Veterinary Journal* 84: 1069-1071.

Patidar, M. 2006. Strip cropping of grasses and legume in Silvipastoral system. In *Abstract of National Symposium on Livelihood Security and Diversified Farming System for Arid Region*. pp. 33. Jan. 14-17, 2006 CAZRI, Jodhpur.

Patidar, M. and Sexena, Anurag 2007. Paryavarn sarankshan ke liye chara utpadhan. *Kheti* 60(3): 18-22.

Patidar, M., Mathur, B.K., Rajora, M.P. and Mathur, D. 2008. Effect of grass – legume strip cropping and fertility levels on yield and quality of fodder in silvipastoral system under hot arid condition. *Indian Journal of Agricultural Sciences* 78: 394-398.

Patil, N.V., Mathur, B.K., Patel, A.K., Bohra, H.C. and Khan, M.S. 2006. Growth performance of arid breed kids weaned at different ages and received on complete feed block. Proceedings of Animal Nutrition Workers Association Conference, pp., 78. SKUAT, Jammu, September15-17, 2006.

Patil, N.V, Mathur, B.K, Bohra, H.C and Patel, A.K. 2005.Relative preference index for arid forages for goat and sheep. National Seminar on "*Conservation, Processing and Utilization of Monsoon Herbage for Augmenting Animal Production"*, December 17-18,2005. Organized by Indian Society for Sheep and Goat Production and Utilization, at RRS, CSWRI, Bikaner.pp.190.

Patil, N.V., Patel, A.K., Khan, M.S. and Bhati, T.K. 2009. Potential assessment of silivipasture system of arid Rajasthan based on its traditional use for rearing growing lambs and kids *Proceedings of world conference2009 on Animal nutrition Preparedness to combat challenges, New Delhi,* February 14-17, 2009 pp 278.

Prasad Shiv, Mathur, B.K. and Mittal J.P. 1999. Physiological adaptability of free grazing Tharparkar and Rathi heifers under arid conditions. *Journal of Eco Physiology* 2(2): 79-84

Radostits, O.M., Blood, D.C. and Gay, C.C. 1994. Veterinary Medicine, Eighth Ed., Bailliere Tindall. London (U.K.)

Rohilla, P.P., Patil, N.V, Bohra, H.C. and Patel, A.K. 2009. Effect of supplemental feeding of urea molasses mineral block (UMMB) on growth performance of Marwari lambs. *Proceeding of National Symposium on "Organic livestock farming- global issues, trends & challenges" W B University of Animal & Fishery Sciences, Kolkata,* February 26-28, 2009. pp 87.

Saha, D.K, Narian, Pratap and Patwa, F.C 2004. Socio-economic conditions of pastoral nomads-Raikas under changing agrarian situation in an arid district of Western Rajasthan, India. A study on dominant factors in a recent transformation of Livestock keeping in India. Nakasato Tsuguo (Ed). Fukuoka University of Education, Fukuoka, Japan: 145-175.

Sharma, S.K. and Diwakar, G.D. 1989. Economic evaluation of hortipastoral system in arid region of west Rajasthan. *Indian Journal of Range Management* 10: 119-122.

Sharma, S.N. and Gahlot, A.K. 1997. Veterinary, Jurisprudence, 4th ed., NBS Publishers, Bikaner (Raj).

Shinde, A.K., Bhatta, Raghavendra, Sankhyan, S.K. and Verma, D.L. 2002. Effect of season on thermoregulatory responses and energy expenditure of goats on semi-arid range in India. *The Journal of Agricultural Science* Cambridge University Press 139: 1:87-93

Shinde, A.K., Karim, S.A., Singh, N.P. and Patnayak, B.C.1995. Growth performance of weaner lambs and kids under intensive and semi intensive feeding management. *Indian Journal of Animal Sciences* 65: 630-633.

Shinde, S., Taneja, V.K. and Singh, N.P. 1990. Association of climatic variables and production and reproductive trait in crossbred. *Indian Journal of Animal Sciences* 60(1): 81-85.

Singh, A.P. and Gahlot, A.K. 1999. Studies on sarcoptes scabei infestation in dromedary. Abstracts, 17th International Conference of the World association for the advancement of Veterinary Parasitology, 15-19 August, 1999, Denis Centre for Experimental Parasitology, The Royal Veterinary and Agricultural University, Copenhagen (Denmark), pp: C.6.10.

Singh, A.P., Netra, P.R., Vashistha, M.S. and Sharma, S.N. 1994. Zinc deficiency in cattle. *Indian Journal of Animal Science* 64: 35-40.

Singh, Chakrawarti and Rollefson, I.K. 2005. Sheep pastoralism in Rajasthan- Still a viable livelihood option? Workshop report, LPPS, Sadri, Dist.-Pali, Rajasthan.

Singh, M., Tyagi, A.K., Mehla, R.K. and Singh, C. 2003. Milk production performance of cows under two different sets of management during summer. *Indian Journal of Animal Sciences* 73(6): 692-694.

Singh, S.V. and Upadhyay, R.C. 2009. Thermal stress on physiological functions, thermal balance and milk production in Karan fries and sahiwal cows. *The Indian Veterinary Journal* 86: 141-144.

Suresh, A., Gupta, D.C., Mann, J.S. and Singh, V.K. 2007. Sheep production in semi-arid zones-Management and Economics, CS&WRI, Avikanagar, Rajasthan

Tanwar, R.K., Kumar, A., Sharma, S.N., Yadav, J.S. and Mathur, P.D. 1983. Clinical findings and therapy of polioencephalomalacia in goats. *Indian .J. Vet. Med.* 3: 112-114.

Tanwar, R.K., Malik, K.S. and Gahlot, A.K. 1994. Polioencephalomalacia induced with amprolium in buffalo calves. Clinico-pathological findings. *Journal of Veterinary Medicine* 41: 396-404.

Varghese, K.A. and Varghese, N. 2002. Interregional and Temporal Dimensions of Livestock Sector in Rajasthan. In *Livestock in Different Farming Systems in India* (Eds. P.S. Birthal, A. Kumar and L. Tiwari). Advanced Publishing Concept, New Delhi. 93-104 pp.

Venkatateswarlu, J., Anantharam, K., Purohit, M.L., Khan, M.S., Bohra, H.C., Singh, K.C. and Mathur, B.K. 1992. *Forage 2000 AD The Scenario for Arid Rajasthan*. CAZRI, Jodhpur. 32 p.

Yadav, G.L. and Poonia, T.C. 2003. Production potential of grasses between existing stock of trees under Silvipastoral system in semi arid watershed area. In *National Symposium on Sustainability Advancement and Future Thrust Area of Research on Forage* pp 53. March 5-6, 2003. CCS, HAU, Hisar.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 210-237 pp.

Renewable Energy Spectrum in Arid Region

P.C. Pande, N.M.Nahar, PBL Chaurasia, Dinesh Mishra, J.C.Tewari and H.L. Kushwaha

Central Arid Zone Research Institute, Jodhpur

The consumption of energy is increasing due to fast growing population coupled rapid development and it is projected that world conventional energy sources will be exhausted in next 50 to 100 years. In this context, the situation in arid region is precarious where firewood, agricultural waste and cow dung cake are burnt for cooking food rather recycling to soils. There is insufficient electricity production leading to frequent power cuts and therefore villagers are unable to derive full benefits of electrical power. Kerosene oil is used for lighting and cooking and fast depleting diesel for running agricultural machinery including pumps. The burning of conventional fuel has created a concern for the environment due to emissions of green house gases, but it is essential to conserve energy for carrying out work. The availability of water is limited both for drinking and irrigation purposes. Hence, potable water needs to be arranged while for irrigation it should be used judiciously, preferably through drip and sprinkler systems. But again, this requires ensured source of energy. Moreover, there is a lot of spare time available with farmers after harvest of the crop, which can be utilized for income generation, if appropriate technology and energy resources are available. Since the development of any region is reflected in its energy consumption pattern, it is essential to seek for alternative sources of energy. In this context, renewable sources of energy like solar, wind power, biogas and efficient utilization of biomass offer considerable advantages to arid region for its sustainable development.

India occupies better position regarding solar energy potential. During winter from November to February most of the Indian stations receive 4.0 to 6.3 kWhm^{-2} day^{-1} solar irradiance, while in summer season this value ranges from 5.0 to 7.4 kWhm^{-2} day^{-1}. The arid and semi-arid parts of the country receive much more radiation as compared to rest of the country with 6.0 kWhm^{-2} day^{-1} mean annual daily solar radiation having 8.9 average sunshine hours a day at Jodhpur. Jaisalmer receives maximum radiation i.e., 6.27 kWhm^{-2} day^{-1}(Garg and Krishnan, 1973; Mani and Rangrajan, 1982). Considering this Jodhpur, Barmer and Jaisalmer districts are declared as solar enterprises zone suitable for setting up of solar power plants. The solar irradiance available in cold desert region, such as Leh, were observed to be 5.53 kWh m^{-2} day^{-1} on horizontal plane and 6.36 kWh m^{-2} day^{-1} at a 35 degree south facing tilt indicating an excellent potential of solar energy in high altitude cold desert (Jacobson, 2000). In nature, solar energy is utilized by plants and stored as biomass, which in turn can be used to provide energy. It is estimated that the existing potential of tree borne oilseeds in the country is 3.0-3.5 million tones, but only 0.50-0.69 million tones are being collected. Wind power is also a manifestation of solar energy. Wind potential has been assessed to be 45195 MW for the country while in Rajasthan it is some 5400 MW (Gupta, 2006; Anon., 2007). In addition, due to high cattle population there is a good potential of installing 915300 biogas plants in Rajasthan compared to 12 million family type biogas plants that can be installed in India (Anon., 2007). With such a high potential attempts to harness these renewable energy resources have been made and the work was reviewed (Pande and Garg, 1978; Mann *et al.*, 1980; Pande, 1988; Pande and Gupta, 1995; Pande *et al.*, 1998; Pande and Narain, 2006). It is now intended to present it with recent developments to enable one to formulate strategies for combating energy problems through technologies based on renewable and new sources of energy.

Solar Energy

Solar energy can be used as thermal energy for water heating, cooking, drying, distillation, space heating, cooling and power generation or it can be converted to electricity through photovoltaic cells, commonly known as solar cells. Flat plate collectors are used for low temperature applications (below 100°C) while concentrators are preferred for higher temperatures. As utilization of solar energy is important for arid region, both basic and applied researches have been carried out at different organizations such as Central Arid Zone Research Institute (CAZRI), Defence Laboratory (DLJ), MBM Engineering College and Jai Narain Vyas University (JNVU) at Jodhpur. Field Research Laboratory at Leh (renamed now as Defence Institute of High Altitude Research) has also been active in harnessing solar energy for cold desert (Rao, 1984).

In this context an important study revealed that width to length ratio should be three or more for collector reflector system to develop stationary solar devices (Pande *et al.*, 1978; Pande and Thanvi, 1988 a). On the other hand to reduce convective thermal losses with minimal shade effect in solar collector, the gap between absorber and cover glazing should be 40-50 mm (Nahar and Gupta, 1989). Transparent insulation material (TIM) generally used to reduce the convective heat losses in buildings was found to enhance the thermal efficiency in solar cooker and water heaters (Nahar *et al*., 1994b; Chaurasia and Twidell, 2001). Studies on mathematical modelling of flat plate collectors (Dhariwal and Mirdha, 2005) and cookers (Mirdha and Dhariwal, 2008) were also conducted. Earlier, Al_2O_3 -Co selective coatings on aluminium substrate and black nickel coatings on stainless steel were found effective (Nahar *et al*., 1989). In solar dryers dried pearl millet stalk was found to be a convenient insulation material (Thanvi and Pande, 1987, 1988). In solar stills basic design and operational parameters were optimised (Garg and Mann, 1976) and thermal losses were quantified (Thanvi and Pande, 1988b). It was observed that mirror boosters can enhance 20% distillate output in single sloped solar still (Thanvi and Pande, 1980). The effect of dust on the transmittance of glass and deterioration in specular reflectance of mirror at Mathania ranged from 24 to 50% (Nahar and Gupta, 1990; Gupta *et al*., 1994). The study indicated a need for regular cleaning of concentrators in solar thermal power plants.

In solar photovoltaics, although solar cell modules based on single crystal and multicrystalline silicon are more common and commercially available, other materials like CdTe, $CuInGaSe_2$, hydrogenated amorphous silicon have also been used for the fabrication of the modules. These photovoltaic technologies were reviewed earlier (Pande, 2002). Research carried out at CAZRI on the performance evaluation of PV modules under harsh arid conditions with high ambient temperature and dust, both factors affecting the performance adversely. The dust was reduced the current output of PV panels in open field to more than 30% (Pande, 1992a). Reflectors of extended length were found to enhance PV output by 17-20% with additional cost of 2-3% on reflector (Pande and Dave, 1999, 2007). These studies were used to design PV systems. On the other hand efforts were made to develop low cost solar cells. With the experience on fabrication, structural and opto-electronic characterization of various forms of CdS solar cells (Pande, 1984, 1990, 1992; Pande *et al*., 1984, 1985, 1988), successful attempt was made to electrophoretically prepare CdS-CdTe thin film devices using polar organic solvents as dispersion media and make it robust through laser induced recrytallization (Pande, 1994; Pande *et al*., 1996, 1997). Recently at JNV University and Defence Laboratory Jodhpur, organic semiconductors were explored and TiO_2 based thin film solar cells were attempted (Roy *et al*., 2008). While carrying out basic researches, efforts were made simultaneously on the applied aspects of both solar thermal and photovoltaic applications.

Solar Thermal Applications

Development of solar devices for different domestic, agricultural and rural based applications was given priority to provide convenient solar thermal devices for supplementing the energy needs. Some of these are discussed in the following sections.

Solar dryers

Fruit and vegetables, if dried, can be stored for a longer period enabling farmers to accrue higher profit by selling the dried product in off-season. Arid zones have low humidity and high irradiance and this makes the region most appropriate to use solar energy for drying fruit and vegetables. Solar dryer is a convenient and efficient device to dehydrate fruit, vegetables and industrial chemicals eliminating problems like dust contamination, insect infestation and spoilage due to rains when dried in the open. Among different solar dryers designed at CAZRI (Garg and Krishnan, 1974; Pande, *et al*.,1979, Garg *et al*., 1980; Pande 1980a, b; Pande and Thanvi, 1982; Thanvi and Pande, 1987; Thanvi and Pande, 1988a; Thanvi and Pande, 1989a,b; Thanvi and Pande, 1990; Pande and Thanvi 1991; Thanvi and Nahar, 2001), a low- cost tilted type solar dryer, costing about Rs. 2500 per m^2, has been extensively tested for drying onion, okra, carrot, garlic, tomato, chillies, ber, date, spinach, coriander, salt coated *aonwla*, magnesium carbonate, etc. Some of these solar dried materials like coriander can be powdered and stored for instant use as chutney. In eighties, solar cabinet dryers were used by local entrepreneurs for dehydrating catechu/sugar coated aniseeds and tobacco powder. Now inclined solar dryers of 10–100 kg capacity have been adopted and a scaled-up solar dryer of 1000 kg capacity installed in village Keru. CTAE Udaipur has developed solar tunnel dryers and installed for large scale drying (Rathore and Mathur, 2002). Solar dryers are finding increasing acceptability due to export potential of dried products. Such dryers can save about 290 to 300kWh/m^2 equivalent energy and farmers can accrue higher profits from solar dried products (Thanvi and Pande, 1989 b). Solar dryer -cum -water heater (Pande and Thanvi, 1991) is capable of dehydrating even at night. It efficiently dehydrated different grasses for making hay (Mali *et al*., 1999)

Solar desalination

In arid zone of India, there is acute shortage of potable water. Generally in summer season, villagers travel many miles to fetch fresh water. Sometimes villagers are forced to consume highly saline underground water containing nitrate and fluorides that leads to cause physical disorder of various kinds. Besides, distilled water is required in the laboratories and for battery maintenance. The solar energy can also be used to demineralise this water through solar stills. The distillate output of solar still is to be mixed with the available saline water in appropriate proportion to make it suitable for drinking purpose (Thanvi *et al*., 1987).

Low glass roof type solar stills were developed in seventies at CAZRI (Garg and Mann, 1976). A lot of work was also carried out at CSM&CRI, Bhavnagar. Large size solar still was installed at village Avania (Gujarat) and Bhaleri (Churu, Rajasthan) but maintenance remained a major problem. These solar stills were further improved with proper slope in distillation channel, supporting truss for ridge, windows for cleaning on two sides, better sealing and incorporation of a system to prevent algae and scale formations (Gupta *et al*., 1990). Thermal efficiency of such stills ranged from 20 to 34% from winter to summer with productivity ranging from1.0 to 3.3 Lm^{-2} day^{-1}. On the other hand in step basin tilted type solar stills (Thanvi, 1985, Thanvi and Pande, 1989c, 1990)) having capacity to produce 3 to 3.5 litres m^{-2} day^{-1} distilled water has potential to provide three to four times more distillate output in winter compared to that obtained from conventional solar still and it is independent of season due to its special design. Railways, electric grid stations, army units and schools have adopted such multibasin tilted type solar stills. It is estimated that the cost of solar still can be recovered in eighteen months. PV operated electrodialysis plants developed by Defence Laboratory, Jodhpur, were installed at Barmer to provide potable water to villagers. Recently a solar water pyramid of nine meters height having 30 m diameter, innovated by Martijn Nitzsche of Netherlands, has been installed at Roopaji Raja Beri in Barmer district by Jal Bhagirathi Foundation, Jodhpur. It produces distilled water like solar still, and also harvest rain water from the exterior side and daily can provide 1000 L safe drinking water (Sebastian, 2009).

Solar cookers

In rural India most of the energy required for cooking is met by firewood, agricultural waste and cow dung cake, the yearly consumption being about 150, 75 and 50 million tones, respectively. With the use of such cookers one can save about 30-40% of fuel requirement and seems to be a viable alternative for reducing the consumption of firewood. Solar cookers can be used for boiling rice, lentil, vegetables; roasting groundnut, potato etc., baking vegetables and cooking food and feed for animals. Simple hot box type solar cookers with single reflector are commercially available in market. BIS standards have also been made for solar cookers. However, the cooker requires orientation towards sun after every half of an hour. A simple solar hotbox cooker with masonry structure was in use during early nineties at SOS school, Leh. Some snow melting ovens were developed by DLJ. At CAZRI various types of solar cookers were developed and compared (Garg *et al.*, 1978a). Solar oven is better for cooking food for a family in a shorter time but requires tracking after every half of an hour. On the other hand double mirror box type solar cooker (Gupta and Purohit, 1986) requires tracking after only three hours, but stationary cooker (Pande and Thanvi, 1987, Pande and Thanvi, 1988a) with optimized width to length ratio can be used without sun tracking and utilises maximum solar energy due to its especial geometry. Subsequently more non-tracking solar cookers, both for domestic and community purposes, were developed (Nahar *et al*., 1993) at CAZRI and demonstrated.

In addition, efforts were made at CAZRI to develop a light sensitive solar tracker that can rotate solar cooker by sensing light through LDR and small PV cell and trigger circuit to mobilise tracking platform with cooker to capture maximum irradiance with the help of 12 volt DC motor, battery and mechanical drive. It facilitates the orientation of the cooker towards the sun enhancing 25% output compared to untracked cooker. But, the device that has got more attention and adopted by farmers is animal feed solar cooker, which can be used to prepare cattle feed by 3 pm, the time when the feed is required (Nahar *et al.*,1994a). These cookers are easy to fabricate by village artisans with locally available materials, enabling them to save firewood used for this purpose. Community cooking through concentrators has been successfully demonstrated at Brhmakumari Ashram, Mount Abu. Such Scheffler cookers (named after the German inventor) have also been installed at Tirupati and Sirdi temples. There have been a few demonstrations by private entrepreneur in arid region, but heavy wind loads, higher cost and effect of dust in arid region were the impediments. A solar cafetaria has been installed in Bhuj of Kutch region in Gujarat and reported to be working satisfactorily (Sharan and Mania, 2005).

Solar water heaters

Hot water in winter is an essential requirement for domestic uses such as bathing, cleaning of utensils and washing of clothes. In rural areas hot water is also required for softening of animal feed. Generally it is obtained by using firewood and cow dung cake in rural areas or using kerosene, liquid petroleum gas, coal or electricity in urban areas. The natural circulation type solar water heaters were studied extensively all over the world. It was found that flat plate collector using GI pipes header and riser and aluminium sheet as absorber save 30% cost while giving performance comparable to commercially available copper pipes and copper sheet flat plate collectors (Nahar, 1984, 1988, 1992; Nahar and Gupta, 1985). The heater can provide 100 L of hot water at 60-70^{o} C in the evening, which can be retained to 50-60^{o} till next day. Such water heaters of different capacities have been installed at Mt. Abu, CAZRI guest house, guest house of telecom department, Jodhpur and Rambagh Palace Hotel, Jaipur. These water heaters are also suitable for agro-based industries. On the other hand, collector-cum-storage solar water heater reduces the cost, to half of the conventional solar water heater, and provides 100 L hot water at 50-60^{o}C in the evenings and 40-45^{o}C the next morning (winter season) after covering the device with insulating cover (Garg, 1975). Such type of solar water heaters were studied in detail (Nahar and Gupta, 1988) and installed at villages for demonstration. The payback period of 100 L capacity natural circulation type and collector- cum- storage type solar water heater varies between 1.6 to 10.8 years and 1.1 to 6.5 years, respectively for different fuels like firewood, coal, electricity, LPG and kerosene. Studies on passive method by incorporating embedded pipes in cement concrete slabs indicated suitability of the system in providing hot water at moderate temperatures above 40^{o}C (Chaurasia, 2000).

BIS standards of flat plate collectors are available and standards for storage tanks are being developed. Tubular collectors are getting more popular due to lower cost. Use of large size solar water heaters have been demonstrated in dairy and textile industries in Maharashtra, Karnataka and Gujarat states.

Integrated solar device

It has been observed that solar water heaters are useful only during winter and solar cookers are not functional during monsoon months and intermittent days. Moreover solar dryers are useful during harvesting season only. With a view to using the same device throughout the year for one or other purpose, dual and multipurpose solar energy appliances have been developed. It includes solar water heater-cum-steam cooker (Garg *et al.,* 1979; Nahar *et al*., 1981), multipurpose solar device (Pande *et al.,* 1981; Nahar *et al.,* 1983), a step basin type solar water heater-cum-solar still (Thanvi and Pande, 1988b), solar cooker-cum-dryer (Pande and Thanvi, 1988a), solar water heater-cum-dryer (Pande and Thanvi, 1991), solar cooker-cum-water heater (Pande and Thanvi, 1988b; Nahar, 1988), solar cooker-cum-still (Pande 1997) and more recently three in one integrated devices (Pande, 2003, 2006, 2007).

The integrated solar device is a unique three- in -one system, which can be used throughout the year for different purposes. The geometry of the device permits cooking food without sun tracking. It can produce about 50 L hot water of 50-60°C utilizing the low altitude position of sun during winter and thus having energy gain both from top and front windows. The device can also be used for drying fruit and vegetables for their use in off- season. The novelty of the device is that the dehydration process continues even during the night through the heated water and thus is suitable for drying materials having high moisture content such as watermelon by using the device in cooking and drying modes in succession (Pande, 2009a). This novel diversified three in one solar device costing Rs. 6000 finds utility through out the year for one or the other purpose and makes the system more practical and economical.

Passive heating and cooled dwellings

Heating and cooling are required for comfort inside the houses and also to grow plants in poly houses. In cold desert region like Leh, generally kerosene fired *Bukharis* are used to heat the building. People keep the stalk on the roof to provide insulation in winter. DLJ and FRL were involved in developing space heating systems for such areas. Solar water heaters were used for space heating in Leh (Gupta and Chopra, 1976). However, anti freezing compounds were required to prevent bursting of pipes. Trombe wall structures with a blackened glazed south facing wall having vents with caps for air circulation are generally suitable for these places. One ITBP hospital near Leh was provided such a structure with improvements to keep it warm. The east-west direction, inclination of roof towards north, painting it white during summer, use of low-cost thermal insulation e.g. embedded air pockets in earthen bowls on the roof, advantage of low sub-soil temperature are some measures to reduce temperature inside room (Gupta *et al*., 1988). Two excellent solar passive houses have been constructed at the MBM Engineering College Jodhpur. The passive house building is partially sunk in the ground with exposed roof having an insulation of inverted earthen pots, a wind tower with built in evaporative cooling and provision to facilitate suction of air (Mathur, 1985). Among different treatments on the roof for cooling, evaporative cooling provided better results but it requires about 50 L/ m^2 water per day (Nahar *et al*., 2003). Pieces of white glazed tiles over roof can reduce the heat load from the roof and hence cool the environment inside building. This is getting popular in hot regions Efforts were also made for developing low -cost technique for cooling animal sheds at CAZRI, Jodhpur.

Solar poly-houses for growing plants

Green houses have a lot of potential for the off-season vegetable production. In cold desert, green houses have been used primarily for increasing the temperature and maintaining the humidity inside the chamber. In fact, the basic objective is to increase the temperature by using glass cover or PVC sheet or double glazing of two different materials. In hot arid region, the requirement is to reduce the temperature and maintain humidity. For this, a green house made of UV resistant polyethylene sheet with fan and pad systems for cooling is of great utility (Gupta *et al*., 1994). Experiments on the development of low cost cooling enclosure have recently been conducted at CAZRI. Some excellent experiments of earth tube cooled green houses have been conducted at Kutchh, Bhuj (Sharan and Jadhav, 2002; Annon., 2005). There is still a need for the development of a suitable low cost poly-house for hot region.

Cool Chamber for preservation of food materials

Maintenance of low temperature is a major problem particularly in desert region during summer season when the temperature is relatively very high and electricity is not assured or not available in rural areas. The high ambient temperature decreases shelf-life and spoils the vegetables, milk and milk products. A low- cost passive cool chamber based on the water evaporative cooling reduces temperature fluctuations and successfully preserve vegetables for short periods (Chaurasia *et al*., 2005). It lowers the maximum temperature by about 15°C and maintains humidity over 90%. The passive cool chamber can be used to preserve vegetables for a period of 3-5 days in summers and 4-7 days in winter. Shelf life of milk and milk products can also be extended for reasonable time. A small size cool chamber costs about Rs. 3000, which can preserve 30-50 kg vegetables fetching good market value of the vegetables besides reducing the spoilage. Skilled workers can easily fabricate cool chambers using local materials. Maintenance cost is negligible and electricity is not required.

Solar Devices for Income Generation

Farmers in this region have a lot of free time after the harvest. Solar stills and dryers enable them to earn profits by selling the products. A solar tea boiler can be used to provide 125-150 cups of tea per day (Nahar, 1987). Certain other solar devices developed at CAZRI can supplement the income.

A solar candle machine with 0.5 m^2 absorbing surface area can heat and melt paraffin wax to produce 10-16 kg candles during summer and 6-9 kg in winter (Chaurasia *et al*., 1982; Chaurasia and Gupta,1988; Chaurasia, 1991). The device can reduce labour requirement and vaporization losses of wax associated with conventional methods. With an initial investment of Rs. 12000, it can generate an average income of Rs. 1500 a month. NRDC, New Delhi has licensed the machine for commercialization through private entrepreneurs.

Another device is solar polish making machine (Pande, 1999: Pande 2003c), which provides a gainful engagement to villagers during off-season for preparing different types of wax-based polishes for leather goods, automobiles and floor having tremendous demand in the market. The solar polish making machine, comprising a cylindrical melting chamber has especially designed stirrer-cum-heat exchanger that can be operated with ease. The design is such that it could be operated in stationary mode, providing sufficient temperature to melt different waxes, facilitating the addition of ingredients from outside and mixing for getting the desired texture of the polish. The cost of this novel solar machine is about Rs. 6000 only. A person can earn Rs. 3000 a month by its use for making polishes of all kinds. Another solar device for making rose water has been developed that can provide 3.7 L of rose water in 3 days during winter (Thanvi and Pande, 1989d) . It is important to develop simple low-cost solar devices that can supplement the income of farmers.

Solar Thermal Power

Solar energy can also be used to generate high temperatures through series of tracking concentrators, which convert flowing water to steam enabling it for running turbine to produce electricity. A feasibility report for 30 MWe Solar Thermal Power Station at Mathania, Jodhpur was prepared by CAZRI (Gupta and Nahar, 1980). On the basis of that a 140 MWe hybrid solar thermal power station was proposed at Mathania to produce 35 MWe by solar energy and 105 MWe by other sources like naptha or gas to feed electric grid for supplementing the requirement of power in the region.

Solar Photovoltaic Applications

Photovoltaic systems are used for generation of electricity directly at the place of utility without the need of long network of electric grid causing a lot of transmission and distribution losses (Pande, 2003b). PV systems are useful in cold deserts like Leh and hilly terrains, where the extending of electric grid is difficult. PV lighting systems and a PV pump were installed there by CEL in eighties (Rao, 1984). The problem of freezing of electrolyte of battery in winter requires special care and design. IIT Delhi installed a tracking system for PV array at FRL, Leh to enhance the PV output. The performance of PV panels under harsh conditions of hot arid region was studied at CAZRI (Pande, 1990, 1992). The potential of solar PV was evaluated for pumping water in India (Rao and Pande, 1982). Subsequently following PV systems were developed for arid agriculture.

Solar PV pump-based drip system for growing orchards

Solar PV pump operated drip irrigation system, comprising 900Wp PV array with 800 W dc motor-pump mono-block and OLPC drippers, economizes the use of water and eliminates practically all the problems that are associated with flood irrigation and is suitable for growing orchards in arid region. The system is based on water requirement of horticultural plants, energy need and compensation of varying pressure due to change in solar radiation ensuring uniform application of water in the field (Pande *et al*., 2003). The system can command 4-5 ha pomegranate orchard with benefit cost ratio of more than 2 and may prove to be a boon in farms where water and land are available but the area is devoid of electrical power. However, the irrigation is not required through out the year and therefore the system remains idle for many days making no use of the costly PV array during this period. In view of utilizing the PV generated electricity to full extent either for some post-harvest or other relevant useful purposes and to make the system more cost effective, a compatible PV generator was developed.

PV Generator for Multiple Applications

The PV generator utilizes the power of solar photovoltaic pumping system comprising PV array of 900 Wp providing open circuit voltage from 60 to 80 V and short circuit current from 2-16 amp. A DC-DC voltage converter with air cooled fins is incorporated for charging 24 V battery bank with appropriate values of charging current and controlling it to threshold values for longer life of the system. A compatible inverter is provided having efficiency from 83% to 90% with output wattage at 240 W to 550 W. Especially designed two tier chamber has been fabricated for encasing DC-DC converter and inverter at the top and keeping batteries at the lower end. The system can be used either for running the pump or operating small machines, illuminating the farm building or for other agricultural activities (Pande *et al*., 2008).

Solar PV duster/sprayer

Solar PV duster is a novel device suitable for dusting insecticide and pesticides on crop. It essentially comprises a Photovoltaic panel carrier, storage battery and especially designed compatible dusting unit. The PV panel is carried over the head with the help of a lightweight PV panel carrier that provides shade to the worker and simultaneously charges battery to run duster (Pande 1998).

The average field capacity of PV duster comes to about 0.75 ha hr^{-1}. The same system can run ULV sprayer also (Pande, 1990; 1992b). In addition, it could be used to illuminate a compact fluorescent lamp for lighting. The device costing about Rs. 4500 can be used for lighting the house through out the year and for operating the duster/sprayer as and when required.

Since the capacity of earlier developed Photovoltaic ULV sprayer (Pande *et al*., 1990) was limited, a more versatile PV sprayer was fabricated. The device comprises a 6.5 Wp PV module connected to a 12V, 7 Ah maintenance free gel type battery through a diode. The battery is kept on a socket provided at the backside of the earlier developed panel holder, which acts as a headgear also, providing shade to the worker. A plastic tank to hold insecticide fluid is fixed on the rear side of the panel holder below the battery, which is connected to a DC motor-rotary pump mono-block. Provisions are made to carry the system with the help of slings to be slid on the shoulders and a belt to be fastened on to the waist of the worker. The pumped fluid is made to pass through a pipe to enter a spraying nozzle fixed at the head of a long aluminum tube, which is provided with a switch and holder. Initial results indicated that fluid could be sprayed with ease, the swath depending on the speed of the person.

PV winnower-cum-dryer

Solar PV winnower (Pande, 2003a) is a convenient device for winnowing grains, spices and other agricultural produce during the season after the harvest when there is lull in the natural wind and also for dehydrating fruit and vegetables under forced circulation of air. The system comprises PV modules, especially designed compatible winnower and drying cabinet (Pande, 2006). As a winnower 35 to 50 kg grain could be separated with in 1 to 1.5 hours from threshed materials. As a solar PV dryer 40-50 kg fruit and vegetables viz. water melon flakes, kachara (local cucumber) slices, grated carrot, ber, coriander leaves, chilies etc. could be dehydrated in less than half of the time required in open sun drying while retaining its colour and aroma. Initially two PV panels of 35 Wp were used, but after carrying out extensive studies on the effect of boosters on PV output a single panel with extended mirror reflector served the purpose (Pande and Dave, 2007).

The quality of the dried product is excellent due to desired temperature range inside the cabinet achieved by auto regulated PV run fan speed (Pande *et al*., 2008; Pande, 2009b). The system can be used for charging a battery for illumination of house. Thus it become more useful for domestic lighting and for agricultural purposes such as winnowing, cleaning of grains and dehydrating agricultural produce enabling farmer to get more benefits from the same system.

PV mobile unit

The PV mobile unit (Pande, 2009c) is a self-propelling device, which can be used on custom hire basis. It is a self sustained mobile power system to operate both AC and DC devices for contemplating various domestic, small agricultural and other rural applications such as operating churner for butter extraction in isolated cluster of houses (Dhanis) of arid region.

PV lighting and Power generation

There has been emphasis on the use of PV systems to provide electricity in arid region. Solar lantern and solar home lighting system with two compact fluorescent lamps, storage battery and PV panel are provided by the state nodal agency on subsidized rates to rural people. Such systems can be used for street lighting, parks illumination and use in rural areas (Swaroop, 2006). Several home lighting systems are in operation around Jodhpur. Small PV plants of 10 KW capacities have been installed in different villages of arid region to provide needful electricity for lighting and pumping. Rajasthan is considered to be a solar hub. There are several proposals and projects on the installation of solar PV plants of several MW capacities, which are in the pipeline. The generation of electricity through photovoltaics will supplement the power requirements without any need of water and help reduce the green house gas emissions, which take place otherwise in thermal power stations.

Wind Energy

Wind energy is the kinetic energy associated with the movement of atmospheric air. It has been used for thousands of years to propel boats and ships. There is evidence that the ancient Egyptians used windmills to pump water for irrigating arid fields and to grind food grains as early as 3600 BC.

But in recent years wind energy has been utilized more to generate electric power as it could provide energy at a cost 30% less than electricity from diesel pumps.

Wind Power Potential

At CAZRI wind power potential was assessed for arid region. Generally in this region, the wind blows towards north-east from October to March and towards south-west from April to September. Initial studies indicated Jaisalmer and Phalodi as potential sites for harnessing wind power (Krishnan and Garg, 1975). Subsequently attempts made to evaluate the wind power potential at different heights in Jodhpur revealed the annual average wind speed as 9.7 km hr^{-1} for 196 days at 3 m height, whereas at 10 m it exceeds 8 kmph (threshold value for low speed water lifting wind pumps) for 5780 hours in a year (Annon.1987). The wind speed data of Barli and Phalodi in Jodhpur District, Pachapadara, Bhadka and Derasar in Barmer district and Khodal and Jaisalmer in Jaisalmer District indicate annual mean wind speed (kmph) and average annual energy density (kWh/m^2/day) as 10.4 and 1.4 in Jodhpur, 14.9 and 2.8 in Barmer and 14.0 and 2.4 in Jaisalmer respectively. Maximum wind power potential in this region is available during March to September. By and large the western Rajasthan has 65 to 75% days in a year when wind speed is more than 8 km hr^{-1} (Annon., 1988).

Wind Pumps

In India, Dutch windmills were installed during seventies and eighties to pump water. Auroville multi-blade windmill with double-action pump increased water output by about 60% compared to the conventional single-action pumps. At CAZRI, Jodhpur, a sail wing wind mill was developed (Chowdhary and Krishnan, 1978) and its performance was evaluated (Chowdhary *et al*., 1980). Another vertical axis windmill (Savonius rotor) was also developed. An Apoly-12 PU 500 windmill was installed and tested for water lifting from an open dug well with total head of 7.5 m. The design of the pump was improved by modifying the piston and bottom plate, which enhanced the discharge by 10%. Depending on the wind speed the average discharge ranged from 45 to 330 cum day^{-1}. The rotor generated 0.91 to 1.03 hp at 16.7 kmph wind speed, which can be utilized to operate agricultural static machinery like grader, chaff cutter, etc. Twelve Apoly-12 PU 500 type and 19 deep well windmills were installed in Jodhpur and Churu district of Rajasthan in early nineties (Mehta, 1994). Somehow, the wind mills for lifting water have not got that much adoption due to deep water table and lull in winter when rabi crops need irrigation. More importance has been given to use wind power for electricity generation.

Wind Generators

Wind farms are successfully operating along costal area in Gujarat, Tamil Nadu and Andhra Pradesh where series of aero-generators generate electricity, which is fed to electric grid through proper inter-phasing. Considering this, efforts were made to analyze annual wind speed data at 20 to 25 meters height for seven places viz., Dhamotar, Devgarh, Harshnath, Jaisalmer, Khodal, Mohangarh and Phalodi by The Indian Institute of Tropical Meteorology. Mean annual wind speed at this height ranges from 4.31 to 5.73 m s^{-1} and mean annual availability of wind power density ranges from 117 to 206 W m^{-2}. Wind farms of 2.25 MW and 25 MW capacity were installed at Jaisalmer and 2.1 MW at Phalodi in the first phase by the state agency. A few private enterprises are now in arena to generate and sell it to state. The total installed capacity in Rajasthan has reached to a modest 670.97 MW by Nov. 2008 out of total 9587.14 MW in the country mainly spread across Tamil Nadu (4132.72 MW), Maharashtra (1837.85 MW), Karnataka (1184.45 MW), Gujarat (1432.71 MW), Andhra Pradesh (122.45 MW), Madhya Pradesh (187.69 MW), Kerala (23.00 MW), West Bengal (1.10 MW) and other states (3.20 MW) (Anon., 2008)). The capital cost of wind power projects ranges from Rs. 4.5-5.5 crore per MW and cost of generation is estimated to be Rs. 4-5 per kWh (depending upon the site). With the incentives provided by central and state governments, the future of wind power utilization seems to be promising. Hybrid systems need to be explored further for a comprehensive energy package.

Bio- Energy and New Technologies

Biomass

In nature, solar energy is utilized by plants converting it to biomass, however, scarcity of water in arid regions limits conversion of solar radiation into biomass. Prosopis juliflora, an extremely drought hardy, profuse coppicer plant has adapted well under harsh conditions. The biomass of this prolific tree can be used fruitfully as fuel directly or through conversion to coal. Prolific growth of Prosopis juliflora in Indian Thar desert offers vast scope of renewable energy (Pasiecznik *et al*., 2001). It is estimated that in arid western Rajasthan there is 668 million tonnes standing biomass (400 million tonnes dry wood) of P juliflora. Considering 4500 kCal kg^{-1} calorific values of this species, there is 2.8 x 10^{15} kCal standing bio energy. Harvesting about 1/3 of biomass 22.9 million tonnes would provide 0.93 x

10^{15} kCal energy annually on sustainable basis. The species is suitable for charcoal making as well. Thus about 30 million tones of charcoal can be produced annually by utilizing 1/3rd of standing biomass. In this context, the use of improved smokeless stoves also save a lot of fuel in domestic cooking due to better efficiency, Alternatively, wood can be utilized to generate electricity through gasification. All this requires a careful planning, especially in arid region.

Biogas

Biogas is an alternative source of fuel, which is generated when organic materials, such as cattle dung, are digested anaerobically in biogas plants. It contains about 65% methane, 34% carbon dioxide and traces of other gases, such as hydrogen sulphide and ammonia. It is an efficient fuel having a calorific value of about 4,800 kcals/m^3 (Ramana, 1991). It can be used for generating electricity and running small mechanical systems besides lighting and providing fuel for cooking and producing better quality organic manure. There are frequent crop failures due to droughts and hence survival and economy in arid region is livestock based. Organic wastes, available abundantly in various forms, can be used to produce biogas by individual farmers and also in cow shelters *gaushalas.* Standard models of biogas plants suitable both for individual households as well as for institutions or communities are available. It includes floating gasholder type, popularly known as Khadi and Village Industries Commission (KVIC) Model and fixed dome type, commonly known as Deenbandhu Model. In addition, Flexi model Bag digester type plant made of rubberised nylon fabric are also manufactured. More than 3.9 million biogas plants have been installed in the country. In Rajasthan, only 66990 numbers have been installed in contrast to potential of 915000 (Anon., 2007). It is estimated that in arid region there is a potential of generation of 5.3 million m^3 biogas/day if collection efficiency of dung is 70%. The generated bio-gas is equivalent to annual saving of 4526 million kg firewood. In addition, manure having 1055 million kg nitrogen is ensured every year. Work on development of suitable biogas plant for arid region was carried out at CAZRI (Garg *et al*., 1980b). CTAE at Udaipur has been providing a good training for the construction of bio-gas plants. Ensuring availability of water and regulation of temperature to increase output in winter may make it valuable source of renewable energy.

Bio-fuel

Bio-fuel can emerge as one of the most promising sectors for rural area enabling farmer to grow oil crop(s) and use it to produce bio-fuel, a cleaner and sustainable source of energy. Many developed countries, particularly USA, Germany and Australia, have ventured into the use of vegetable oils as a viable alternative to diesel, but in India edible oil cannot be utilized for bio-diesel production due to its inadequate availability. Therefore, the emphasis is on use of non-edible oil sources for bio-diesel production, which can be obtained from plant species viz. Neem (*Azadirachta indica*), Karanj (*Pnngamia pinnata*), Mahua (*Madhuca spp*.), Undi (*Calophyllum inophyllum*), Jatropha (*Jatropha curcas*), *Salvadora* and *Citrullus colocynths*, etc. Some of these plants are already available in the region and certain pockets of semi arid region are used for this purpose. In places where water is available such as IGNP command area, these plants can be grown. However, lower humidity remains a constraint for seed production. Genetic improvement is one approach while identifying the most suitable plant for the purpose requires attention. Meanwhile, studies on the development of low cost technologies for biodiesel production in rural areas are given due importance.

In India, Jatropha is considered more promising (Patil and Singh, 1991; Vyas, 1993; Raina and Gaikwad, 1995). Presently more than 30 organizations are working on various aspects of Jatropha all over India. Some of them are engaged in germplasm screening and improvement, and standardization of location specific plantation techniques. Others are working on oil extraction and estrification machinery development, analyzing physico- chemical characteristics of extracted oil and assessing the efficiency of bio-diesel in motor vehicles and railway locomotives. NRC Agroforestry, Jhansi evaluated 27 Jatropha accessions collected from U.P., M.P., Maharashtra, A.P. and Chattisgarh and is to release a high yielding variety of the species. The accession NRCJ-7 found to be yielding 510 g plant^{-1} after 3 years and accession NRCJ-168 has yielded 848 g plant^{-1} only after 1 year of plantation. RRS of Gujarat Agriculture University at Sardar Krushinagar has released a high verity named ‘Chatrapati’.

These oil bearing trees can also be planted as part of watershed management programmes due to soil binding ability and capacity to gain a foothold even in shallow soils. The potential of Jatropha in reclamation and restoration of mining scarred landscapes is also quite high. National Programme of Jatropha in India envisages 20% contribution of bio diesel of the total diesel demand with production of some 13 million tonnes bio diesel for mixing in petrol diesel by the year 2013 indicating a need to enhance Jatropha production by 1000 times. It is expected that the cost of bio diesel would be around Rs. 20-21 L^{-1}, if Jatropha seed is available @ Rs. 8 per kg and one litre oil is extracted from 3.2 kg seeds.

Directorate of oilseed research, Hyderabad, identified 6 accessions of the species viz., DORJc 54, 56, 57, 71, 73 and 74 as ideal bio-diesel types based on high octane number. CSIR, collaborating with a German university, has initiated a project of 6 lacs Euro on public-private partnership basis for testing IC Engine using Jatropha oil. GBPUAT, Pant Nagar; JNKV, Jabalpur; and CRIDA, Hyderabad, are working on establishment, silviculture and management aspects of Jatropha. CAZRI, Jodhpur evaluated Jatropha seeds collected from Rajsamand district in Rajasthan and found them drought resistant.

As cultivation of *Jatropha* and *Pongamia* is in progress for assessing economical productivity in this region, efforts are afoot at CAZRI, Jodhpur on the extraction of non-edible oil from the seed of these plants to prepare bio diesel at village level for safe utility in diesel engine with partial blending A small sized and solar energy based bio-diesel production unit for small and marginal farmers is also being developed. Notwithstanding the advantage of reduction in fossil fuel consumption with the production of bio-fuel, a detailed study is still required for arid regions before arriving at conclusions.

Ethanol

There is another dimension of bio- fuel in the form of ethanol, which is quite popular in Brazil. Generally it is produced from sugar/starch and some efforts are made from sweet sorghum in India whereas in US it is mainly produced with corn and its by-product is used for animal feed. In this context residues of crops like mustard, sesame, cotton, etc. as well as energy efficient grasses/crops for base material containing cellulose can be utilised to produce bio-ethanol. Efforts are afoot to evolve biochemical and thermo-chemical processes in which lignocellulosic materials can be enzymatically hydrolyzed at a relatively mild condition (50^{o}C and pH 5), thus enabling effective cellulose breakdown without formation of byproducts that would otherwise inhibit enzyme activity. New technologies for cellulosic ethanol production may find a new dimension in this field of renewable energy for arid region (Lynd, 1996).

Fuel Cells

A fuel cell is a controlled electrochemical device converting fuel energy into electrical energy without the involvement of any intermediate step e.g., burning processes or associated ‘hefty’ chemical processes. The chemical energy of the fuel is released in the form of a stream of electrons when the fuel is oxidized. These are normally distinguished by different types of electrolytes used between the anode and cathode. Various types of fuel cells have been developed according to specific power output requirements. Proton exchange membrane fuel cell (PEMFC), Direct methanol fuel cell (DMFC) and Solid oxide fuel cell (SOFC) are in the forefront. Fuel cells have no moving parts, low maintenance, long operating life and high energy conversion efficiency of more than 40-50% that is higher than an internal combustion engine or a coal based power station. Fuel cells have been developed for transport applications as well as stationary and portable applications (Srinivasan, 2006).

The scope of fuel cell can also be extended for solar power generation. Proton Exchange Membrane fuel cell (PEMFC) fits best to solar energy utilization due to many advantages associated with it. PEMFC is comparatively simple to design and can be based on flat plate collector operating at relatively low temperatures (<100°C) (Chaurasia *et al*., 2007, 2009). This new method utilizes coupling of chemical reactions (2-propanol/acetone/hydrogen) in the PEM fuel cell through solar thermal energy, which is sufficient to support required chemical reactions (dehydrogenation/hydrogenation) involved in the generation of power

Epilogue

The scope of solar energy, wind power and bio-fuel is tremendous to supplement the energy needs in arid and semi arid region and to make the region more self -dependent on energy. Utilization of these renewable sources of energy will curtail the consumption of fast depleting conventional fuels and reduce green house gas emissions. There is a great need of harnessing and integrating different renewable systems for the sustainable development of the area. Dissemination of these environment-friendly technologies requires active participation of different sections of the society with higher impetus on R & D. The availability of ensured energy sources in rural areas would enable farmers to accrue higher monetary benefits through agro-based industries and in turn improve their livelihood.

References

Anonymous 1987. Annual Report of AICRP on RES, CAZRI, Jodhpur, pp. 21-43.

Anonymous 1988. Annual Report of AICRP on RES, CAZRI, Jodhpur, pp. 42-55.

Anonymous 2005. Management of technology in arid areas: a long term programme, Indian Institute of Management, Ahmedabad.

Anonymous 2007. Annual Report 2006-2007, Ministry of Non-conventional Energy Sources, Govt. of India.

Anonymous 2008. Annual Report 2007-2008, Ministry of Non-conventional Energy Sources, Govt. of India. http://mnes.nic.in/annualreport/ 2007_2008_English/ chapter5/ chapter5_1.htm

Chaurasia, P.B.L. 1991. Design study of a solar candle device for melting wax. *International Journal of Energy* 16: 879-881.

Chaurasia, P.B.L. 2000. Solar water heaters based on concrete collectors. *International Journal of Energy* 25: 703-716.

Chaurasia, P.B.L. and Gupta, J.P. 1989. Melting of wax by solar energy based on one shift. *International Journal of Energy Research* 13: 491-497.

Chaurasia, P.B.L. and Twidell, J. 2001. Collector cum storage solar water heater with and without TIM material. *Solar Energy* 70: 403-416.

Chaurasia, P.B.L., Ando, Y. and Tanaka, T. 2007. Investigation on proton exchange membrane fuel cell for solar power generation. *International Journal of Sustainable Energy* 26: 107-119.

Chaurasia, P.B.L., Gupta, J.P. and Ramana Rao, B.V. 1983. Comparative study of performance of two models of solar device for melting wax during winter season. *Energy Conversion and Management* 23(2): 73-75.

Chaurasia, P.B.L., Kendall, K., Bujalski, W., Du, S. and Pollet, B.G. 2009. Influence of temperature on VI characteristics for solar power generation based on chemical method using fuel cell, *International Journal of Chemical Sciences* (in press).

Chaurasia, P.B.L., Singh, Harpal and Prasad, R.N. 2005. Passive cool chamber for preservation of fresh vegetables. *Journal of Solar Energy Society of India* 15: 47-57.

Chowdhry, S.C. and Krishnan, A. 1978. A low cost sail wing wind mill. *Research and Industry* 213: 81-84.

Chowdhry. S.C., Sharma. P. and Ramana Rao, B. 1980. Studies on performance of low cost sailwing windmill. *Agricultural Mechanisation in Asia, Africa and Latin America* 12(1): 66-68

Dhariwal, S.R. and Mirdha, U.S. 1995. Analytical expressions for the response of flat-plate collector to various transient conditions. *Energy Conversion and Management* 40:1809-1836.

Garg, H.P. 1975. Year round performance studies on a built in storage type solar water heater at Jodhpur. *Solar Energy* 17(3): 167-172.

Garg, H.P. and Krishnan, A. 1973. Solar energy utilisation potential. *Indian Journal of Meteorology and Geop.* 25(3&4): 473-478.

Garg, H.P. and Krishnan, A. 1974. Solar drying of agricultural products Part I: Drying of chillies in a solar cabinet dryer. *Annals of Arid Zone* 13(4): 285-292.

Garg, H.P. and Mann, H.S. 1976. Effect of climatic operational and design parameters on the year round performance of single slope and double slope solar still under Indian arid zone conditions. *Solar Energy* 18(2): 159-174.

Garg, H.P., Mann, H.S. and Thanvi, K.P. 1978a. Performance evaluation of five solar cookers. *Proceedings of International Solar Energy Conference,* New Delhi, pp. 1491-1494.

Garg, H.P., Pande, P.C. and Thanvi, K.P. 1980a. Design and development of a fruit and vegetable agricultural dryer. In *International Symposium on Arid Zone Research and Development* (Ed. H.S. Mann), pp. 405-410. Scientific Publishers, Jodhpur.

Garg, H.P., Pande, P.C. and Thanvi, K.P. 1980b. Designing a suitable biogas plant for India. *Appropriate Technology* 7(2): 29-31.

Garg, H.P., Thanvi, K.P. and Pande, P.C. 1978b. Solar water heater cum steam cooker. *The Indian and Eastern Engineer, India* 120(8): 315-317.

Gupta, Ajit K, 2006. Role of renewable in future energy supply in Rajasthan. *Journal of Social Policy Research* 2(1): 91-101

Gupta, J.P. and Chopra, R.K. 1976. Solar space heating under high altitude conditions. *Solar Energy* 18: 51-57.

Gupta, J.P. and Nahar, N.M. 1988. Feasibility of 30 MW solar thermal power station at Jodhpur. *Urja* 23: 468-470.

Gupta, J.P. and Purohit, M.M. 1986. Role of renewable energy sources for mitigation of cooking fuel problem. *Transactions of Indian Society of Desert Technology and University Centre of Desert Studies* 11(1): 7-17.

Gupta, J.P., Nahar, N.M., Chaurasia, P.B.L. and Sharma, P.1988. Design consideration for passive cooling of houses in arid areas. In *Renewable Energy for Rural Development* (Eds. V.V.N. Kishore and N.K. Bansal), pp. 250-253. Tata McGraw-Hili Publishing Co. Ltd., New Delhi.

Gupta, J.P., Nahar, N.M., Purohit, M.M. and Pushpak, S.N. 1994. Deterioration in specular reflectance of mirror materials by exposure to desert environment. In *Proceedings of the National Solar Energy Convention,* pp. 42-44. Gujarat Energy Development Agency, Vadodara.

Gupta, J.P., Sharma, P. and Purohit, M.M. 1990. Improved method for pre-treatment of brackish water for solar distillation to prevent algae growth and scale formation. Renewable Energy and Environment. In *Proceedings of the National Solar Energy Convention* (EdsA.N. Mathur and N.S. Rathore), pp. 33-36. Dec. 1-3, 1989, Himanshu Publication, Udaipur.

Gupta, J.P., Sharma, P., Nahar, N.M., Kackar, N.L. and Purohit, M.M. 1994. Design of suitable green house for arid areas. In *Proceedings of the National Solar Energy Convention,* pp. 123-126. Gujarat Energy Development Agency, Vadodara.

Jacobson, A. 2000. Solar Energy Managements for Ladakh, India. Renewable Energy Technology for the New Millennium. In *Proceedings of the 24th National Renewable Energy Convention 2000,* pp 5-10. Allied Publishers Ltd.

Krishnan, A. and Garg, H.P. 1975. Wind power for pumping water. *Indian & Eastern Engineer* 117(3): 105-109.

Lynd, L.R. 1996. Overview and evaluation of fuel ethanol from cellulosic biomass: technology, economics, the environment, and policy. *Annu Rev Energy Environ* 21:403–465.

Mali, P.C., Pancholi, R., Mathur, B.K. and Pande, P.C. 1999. Effect of drying methods on the chemical composition of hay made from two desert grasses. *Tropical Grasslands* 33(1999): 51-54.

Mani Anna and Rangarajan, S. 1982. *Solar Radiation over India*. Allied publisher Pvt. Ltd., New Delhi, 646 pp.

Mann, H.S., Singh, R.P. and Pande, P.C. 1980. Utilizing solar energy for agriculture and rural development in India - Problems and Prospects. *Agricultural Mechanisation in Asia, Africa and Latin America(Japan)* 11(4): 15-19.

Mathur, M.L. 1985. Solar Passive Systems for Buildings. Paper presented in *Workshop cum Seminar on Unconventional Energy Resources and Social Forestry*, Oct. 23-31, 1985, CAZRI. Jodhpur.

Mehta, N. 1994. Paper presented in Seminar on Commercialization of Renewable Energy Sources. N.P.C., Jaipur, Jan. 24, 1994.

Mirdah U.S. and Dhariwal, S.R. 2008. Design optimization of solar cooker. *Renewable Energy* 23(3): 530-544.

Nahar, N.M. 1988. Performance and testing of a low cost solar water heater-cum-solar cooker. *Solar & Wind Technology* 5: 611-615.

Nahar, N.M. 1992. Energy conservation and payback periods of natural circulation type solar water heaters. *International Journal of Energy Research* 16: 445-452.

Nahar, N.M. and Gupta, J.P. 1985. Performance and testing of an.improved natural circculation type solar water heater. *Energy Conversion and Management* 27(I): 29-32.

Nahar, N.M. and Gupta, J.P. 1989. Studies on gap spacing between absorber and cover glazing in flat-plate solar collectors. *International Journal of Energy Research* 13: 727-732.

Nahar, N.M. and Gupta, J.P. 1988. Studies on collector-cum-storage type solar water heaters under arid zone conditions of India. *International Journal of Energy Research* 12: 147-153.

Nahar, N.M. and Gupta, J.P. 1990. Effect of dust on transmittance of glazing materials for solar collectors under arid zone conditions of India. *Solar & Wind Technology* 7: 237-243.

Nahar, N.M., Gupta, J.P. and Sharma, P. 1993. Performance and testing of an improved community size solar cooker. *Energy Conversion and Management* 34: 327-333.

Nahar, N.M., Gupta, J.P. and Sharma, P. 1994a. Design development and testing of large size solar cooker for animal feed. *Applied Energy* 48: 295-304.

Nahar, N.M., Marshall, R.H. and Brinkworth, B.J. 1994b. Studies on hot box solar cooker with TIM. *Energy Conversion and Management* 35: 787-791.

Nahar, N.M., Sharma, P. and Purohoit, M.M. 2003. Performance of different passive techniques for cooling of buildings in arid region. *Building and Environment* 38(1):109-116.

Nahar, N.M., Mo, G.H. and Ignatiev, A. 1986. A spectraly selective high temperature stable Al_2O_3 -Co solar absorber coating. *Solar Energy Materials* 14: 129-141.

Pande, P.C. 1980. Drying Fruits and Vegetables using solar technology. *Indian and Eastern Engineer* 122(7): 303-305.

Pande, P.C. 1980a. Performance studies on solar air heater with different design parameters. *Proceedings National Solar Energy Convention,* pp. 90-95. Annamalainagar, Allied Publishers.

Pande, P.C. 1980b. Performance studies on an improvised solar cabinet dryer. *Proceedings National Solar Energy Convention,* Annamalainagar, Allied Publishers, pp. 1-5.

Pande, P.C. 1984. A study on various forms of CdS solar cells. *Ph.D. Thes*is. University of Durham. United Kingdom.

Pande P.C. 1988. Conservation of plant resources through use of renewable sources of energy. Wastelands development and their utilisation (Ed. K.A. Shankarnarayan), pp.141-153. Scientific Publishers, Jodhpur.

Pande, P.C. 1990a. Optoelectronic and structural aspects of various forms of CdS solar cells. *Journal of Semiconductor Materials and Devices* II(i): 22-26.

Pande, P.C. 1990b. Development of PV systems for arid region. In *Energy and the Environment into the 1990s.* Proceedings 1st World Renewable Energy Congress (Ed. A.A.M. Sayigh), I: 314-318. Pergamon Press, Oxford,

Pande, P.C. 1992a. Effect of dust on the performance of PV panel. In *Proceedings of the 6th International Conference on Photovoltaic Science & Engineering* (Eds. B.K. Das and S.N. Singh), pp.539-542. Oxford and IBH Publishing Co. Pvt., New Delhi.

Pande, P.C. 1992b. Development of solar PV system for crop protection. In *Proceedings of the 6th International Conference on Photovoltaic Science and Engineering Conference* (Eds. B.K. Das and S.N. Singh), pp. 979-984. Feb. 10-14, 1992, New Delhi. Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi.

Pande, P.C. 1992c. Preparatory aspects of electrophoretically deposited CdS-CdTe device. Proceedings 6th International Photovoltaic Science and Engineering Conference. Feb. 10-14, 1992, New Delhi (Eds. B.K. Dass and S.N. Singh), pp. 905-909. Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi.

Pande. P.C. 1994. A study on electrophoretically deposited CdS-CdTe devices. In *Role of Renewable Energy* in *Energy Policy* (Eds. K.M. Dholakia, M.M. Pandey, N. Gandhi and D. Vaja), pp.140-144. Gujarat Energy Development Agency, Vadodara.

Pande, P.C. 1997a. Design and development of a novel solar cooker cum still. In *Proceedings of the 21st National Solar Energy Convention*, pp. 322-326. Dec. 22-24, 1997, Anna University, Chennai, 39 pp.

Pande, P.C. 1997b. Design and development of PV systems for rural and agricultural applications. In *Proceedings of the Workshop on Low Cost Electronic Materials and Solar Cells*, pp. 45-52. Colombo, March 5-6, 1997.

Pande, P.C. 1998. A novel solar device for dusting insecticide powder. In *Proceedings of the National Solar Energy Convention,* pp 117-122. University of Roorkee, Roorkee.

Pande, P.C. 2001. Design and Development of an Integrated Solar Device. In: Energy Security for India, Role of Renewables. In *Proceedings of the 25th National Renewable Energy Convention Hyderabad* (Eds. T.L. Sitharama Rao, S. Subramanyam, Anil Misra and A.V. Narasimha Rao), pp. 88-93. Allied Publishers Ltd., New Delhi.

Pande, P.C. 2002. Recent advances in photovoltaics. In *Proceesdins of the International Conference on Recent Advances in Solar Energy Conversion Systems* (Eds. R.M. Sarviya, R.K. Neema and J.L. Bhagoria), pp. 48-54. MNIT, Bhopal.

Pande. P.C. 2003a. A solar PV winnower. In *Proceedings of the 26th National Renewable Energy Convention and International Conference in New Millennium*, pp. 22-26. Coimbatore.

Pande, P.C. 2003b. Solar PV systems for arid agriculture. In *Energy Technologies for Sustainable Development* (Eds. Upendra Pandel and M.P.Poonia), pp. 355-359. Prime Publishing House, Delhi.

Pande, P.C. 2003c. Design and development of solar technologies for arid region. In *Impact of Human Activities on Thar Desert Environment* (Eds. Pratap Narain, S. Kathju, Amal Kar, M.P. Singh and Praveen Kumar), pp.554-565. Arid Zone Association of India and Scientific Publishers, Jodhpur.

Pande, P.C. 2006. Design and development of PV winnower-cum-dryer. In *Proceedings of the International Congress on Renewable Energy* (ICORE 2006) (Eds. E.V.R. Sastry and D.N. Reddy), pp. 265-269. Allied Publishers Pvt. Ltd., New Delhi, India.

Pande, P.C. 2007. An Improved integrated solar device for multipurpose applications. In *Advances in Energy Research. Proceeding 1st International Conference on Advances in Energy Research*, pp. 349-353. IIT Bombay. Macmillan India Ltd., India.

Pande, P.C. 2009a. Watermelon Processing in Three in one Intergrated device In *Proceedings of International Solar Food Conference,* Indore, Jan 14-16,2009. pp. pande-26_1-5 (CDROM).

Pande, P.C. 2009b. Performance of PV winnower cum dryer for processing of agricultural products. In *Proceedings of the International Solar Food Conference*, Indore, Jan 14-16, 2009. pp. 27_ pande. pp1-8 (CDROM).

Pande, P.C. 2009c. A PV mobile unit for multipurpose rural applications. In *Proceedings of the International 18th Photovoltaics Solar Engineering and Science Congress, Calcutta* (Eds. Swati Ray and P. Chatterjee), pp. 398-403. McMilllan Press, India.

Pande, P.C. and Dave, B.K. 1999. Effect of boosters on the performance of PV panels. In Renewable Energies and Energy Efficiency for Sustainable Development. In *Proceedings of the 23rd National Renewable Energy Convention* (Eds. R.L. Shawney, D. Buddhi and R.P. Gautam), pp. 120-121. Dec. 20-22, 1999, Devi Ahilya University, Indore.

Pande, P.C. and Dave, B.K. 2007 Economical Production of Electricity from PV Mod ules for Application in Post Harvest Operations. In: Advances in Energy

Research. In *Proceedings of the 1st International Conference on Advances in Energy Research*, pp 296-300. IIT Bombay. Macmillan India Ltd.

Pande, P.C. and Gupta, J.P. 1997. Management of Energy Resources. In *Desertification Control in the Arid Ecosystem of India for Sustainable Development* (Eds. Surendra Singh and Amal Kar), pp. 359-370. Agro Botanical Publisher (India), Bikaner.

Pande, P.C. and Narain, P. 2006. Solar devices for Energy Management in Arid Region. *Journal of Social Policy Research* 2(1):172-179.

Pande, P.C. and Thanvi, K.P. 1982. Solar dryer for maximum energy capture. In *Proceedings of the NSEC* pp. 400.9-400.12. Allied Publishers, New Delhi, India.

Pande, P.C. and Thanvi, K.P. 1987. Design and Development of a solar cooker for maximum energy capture in stationary mode. *Energy Conversion and Management* 27(1): 117-120.

Pande, P.C. and Thanvi, K.P. 1988a. Design and development of solar cooker-cum-dryer. *International Journal of Energy* 12: 539-545.

Pande, P.C. and Thanvi, K.P. 1988b. Practical evaluation of integrated solar energy gadgets. In *Energy option for 90's Proceedings NSEC*. IIT New Delhi (Eds. N.K. Bansal, V.V.N. Kishore and Anil Mishra), pp. 178-183. Tata McGraw Hill Publishing Co. Ltd., New Delhi.

Pande, P.C. and Thanvi, K.P. 1991. Design and development of solar dryer cum water heater. *Energy Conversion and Management* 31(5): 419-424.

Pande, P.C., Bocking, S., Miles, R.W., Carter, M.J., Latimer, J.D. and Hill, R. 1996. Recrystallization of electrophoretically deposited CdTe films. *Journal of Crystal Growth* 159: 930-934.

Pande, P.C., Bocking, S., Miles, R.W., Carter, M.J. and Hill, R. 1997. Laser Induced Recrystallisation of Electrophoretically Deposited CdTe and $CuInSe_2$ Films. *Solid State Phenomena*. 55: 146-148.

Pande, P.C., Chowdhry, S.C. and Thanvi, K.P. 1990. Development of Solar Insecticide Sprayer. Renewable Energy and Environment (Proceedings of NSEC), Dec. 1-3, 1989, Udaipur (Eds. A.N. Mathur and N.S. Rathore), pp. 403-407. Himanshu Publication, Udaipur.

Pande, P.C. and Garg, H.P. 1978. Review of thermal storage materials from the view point of solar energy application. In *Proceedings of the National Solar Energy Convention,* pp.191-202.vBhavnagar, Allied Publishers, New Delhi.

Pande, P.C., Garg, H.P. and Thanvi, K.P. 1978. Effect of boosters on the performance of flat-plate collectors. *Proceedings National Solar Energy Convention,* Bhavnagar, Allied Publishers, India, pp. 61-70.

Pande, P.C., Garg, H.P. and Thanvi, K.P. 1979. Performance studies on solar air heaters for the development of solar fruit and vegetables dryer. In *Proceedings of the National Solar Energy Convention* pp. 23-28. IIT, Bombay

Pande, P.C., Claybourn, M., Russell, G.J., Brinkman, A.W. and Woods, J. 1985. Deep levels in single crystals of $Zn_x Cd_{1-x} S$. *Journal of Crystal Growth* 72: 174-178.

Pande, P.C., Russell, G.J. and Woods, J. 1983. Interface effects in Cu_xS-CdS photovoltaic cells formed by the dry barrier process. *Journal of Physics D: Applied Physics* 16: 2307-2316.

Pande, P.C., Russell G. and Woods, J.1984. The properties of electrophoretically deposited layers of CdS. *Thin Solid Films* 121: 85-94.

Pande, P.C., Russell, G.J. and Woods, J 1988. The effect of temperature and bias light illumination on the spectral sensitivity of CdS/Cu_2S solar cells. *Thin Solid Films* 164: 313-319.

Pande, P.C., Claybourn, M. Russell, G.J., Brinkman, A.W. and Woods, J. 1985. Deep levels in single crystals of Zn_x Cd_{1-x} S. *Journal of Crystal Growth* 185: 174-178.

Pande, P.C., Singh, A.K., Ansari, S. and Dave, B.K. 2008. PV generator for multiple applications in arid farming. In *Diversification of Arid Farming Systems* (Eds. Pratap Narain, M.P. Singh, Amal Kar, S. Kathju and Prvaeen Kumar), pp. 273-278. AZRAI & Scientific Publishers (India) Jodhpur,

Pande, P.C., Singh, A.K., Purohit, M.M. and Dave, B.K. 2008. A mixed mode solar PV dryer. *Proceedings World Renewable Energy Congress,* Glasgow, U.K. pp. 1746-1751.

Pande, P.C., Singh, Harpal and Nahar, N.M. 1998. Energy management by non conventional energy sources. In *Fifty Years of Arid Zone Research* (Eds. A.S. Faroda and Manjeet Singh), pp. 427-446. CAZRI Jodhpur.

Pande, P.C., Thanvi, K.P., Nahar, N.M. and Ramana, Rao, B.V. 1981. A multipurpose solar energy device. *Sun World* 5(5): 141-143.

Patil, Vinak and Singh, Knawarjit 1991. *Oil Gloom to Oil Boom Jatropha curcus: A Promising Agroforestry Crop*, Agroforestery Federation Maharashtra and National Wasteland Development Mission, MoEF, GOI, New Delhi, p. 82.

Pasiecznik, N.M., Felker, P., Harris, P.J.C., Harsh, L.N., Cruz, G., Tiwari, J.C., Cadoret, K. and Maldonaldo, L. 2001. The *Prosopis juliflora – P. palida* complex: A monograph, HRDA, Coventry, U.K. (2001), 162 p.

Raina, Ashok and Gaikwad, B.R. 1995 Chemobotany of Jatropha species in India and further characterization of `curcus oil. In *Proceedings of the Workshop on Energy Crops and Liquid Biomass Fuel: Jatropha curcus*. Swiss Development Corporation, Embassy of Switzerland, New Delhi, 10th August 1995.

Rathore, N.S. and Mathur, A.N. 2002 Design and development of solar tunnel dryer for industrial use. In Proceedings of the All India Seminar on Advances in Solar Technologies (Ed. Rajendra Karwa), pp.189-196. MBM Engineering College, Jodhpur. Jan. 29-30, 2002.

Ramana Rao, B.V. and Pande, P.C. 1982. Prospects of solar energy utilization for pumping water for irrigation in India. *Proceedings Symposium on Rain Water and Dry land Agriculture,* Indian National Science Academy, New Delhi, pp.131-138.

Ramana, P. Venkata 1991. Biogas Programme in India. *TIDE* 1(3): 1-13.

Rao, S.K. 1984. An oasis in the cold Desert- Field Research Laboratory, Leh. *Def. Sc. Journa*l. 34(2): 213-220.

Roy, M.S., Raju, P.P., Kumar, M., Sharma, G.D. 2008. Dye sensitized solar cells based on rose bangal dye and nano crystalline TiO_2. *Solar Energy Materials and Solar Cells*. 92(8):909-913.

Sebastian, S. 2009. A water wonder in the middle of a desert. http://www.thehindu.com./2009/03/06/stories/2009030656090800.htm

Sharan, G. and Jadhav, R. 2002. Greenhouse cooled by earth tube heat exchanger at Kothara (Kutch). *Alumunus* 34(1): 33.

Sharan, G. and Mania, N. 2005. Construction details and operational details of solar café-A solar cooking facility. IIM Ahmedabad.

Srinivasan, S. 2006. Fuel Cells – From Fundamental to Applications, Springer Science, New-York ISBN-10:0-387-25116-2.

Swaroop, Rajeev 2006. Potential, status and growth of non-conventional energy in Rajasthan. *Journal of Social Policy Research* 2(1):102-119.

Thanvi, K.P. 1985. Performance studies on family size solar stills in arid zone of India. Proceedings U.S. India symposium on solar energy research and applications, Univ. of Roorkee, pp. 291-294.

Thanvi, K.P. and Pande, P.C. 1980. Effect of boosters on the performance of solar stills. In *Proceedings of the National Solar Energy Convention,* Allied Publishers, pp. 116-122.

Thanvi, K.P. and Pande, P.C. 1982. Designing a suitable solar still. In *Proceedings of the National Solar Energy Convention,* Bangalore, India, Allied Publishers, New Delhi, pp. 4020-4022.

Thanvi, K.P. and Pande, P.C. 1987. Development of low cost solar agriculture dryer for arid region of India. *Energy in Agriculture* 6: 35-40.

Thanvi, K.P. and Pande, P.C. 1988a. Designing low cost solar dryer with alternative materials. Energy options for 90's. In Proceedings NSEC. IIT, New Delhi (Eds. N.K. Bansal, V.V.N. Kishore and Anil Mishra), pp. 70-74. Tata McGraw Hill Publishing Co. Ltd., New Delhi.

Thanvi, K.P. and Pande, P.C. 1988b. A step basin type solar water heater cum still. *International Journal of Energy Research* 12: 363-368.

Thanvi, K.P. and Pande, P.C. 1988c. Energy balance studies in stepped basin single sloped solar still. In *Energy Option for 90's*. Proceedings NSEC IIT, New Delhi (Eds. N.K. Bansal, V.V.N. Kishore and Anil Mishra), pp. 95-101. Tata McGraw Hill Publishing Co. Ltd., New Delhi.

Thanvi, K.P. and Pande, P.C. 1989a. Performance evaluation of solar dryers developed at CAZRI, Jodhpur. In *Solar Drying* (Eds. A.N. Mathur, Yusuf Ali and R.C. Maheshwari), pp. 159-164. Himanshu Publications, Udaipur.

Thanvi, K.P. and Pande, P.C. 1989b. A low cost tilted type solar dryer. In *Renewable Energy for Rural Development,* pp. 405-409.Tata McGraw Hill Publishing Co. Ltd., New Delhi

Thanvi, K.P. and Pande, P.C. 1989c. Design and development of solar still for electric grid station. *Research and Industry* 34: 56-59.

Thanvi, K.P. and Pande, P.C. 1989d. Development of solar still for rose water production. In *Renewable Energy for Rural Development,* pp.380-384.Tata

McGraw Hill Publishing Co. Ltd., New Delhi.

Thanvi, K.P. and Pande, P.C. 1990. Development of inclined solar dryer with alternate materials. Renewable Energy and Environment (Proceedings of NSEC), Dec. 1-3, 1989, Udaipur (Eds. A.N. Mathur and N.S. Rathore), pp.41-45. Himanshu Publication, Udaipur.

Thanvi, K.P., Pande, P.C. and Kalla, J.C. 1987. Integration of biomass and solar energy for rural development. In *Solar Energy and Rural Development* (Eds. S.H. Pawar, C.D. Lokhande and R.N. Patil), pp.102-108. Shivaji University, Kolhapur.

Vyas, B.N. 1993. Agroforestery practices for Jatropha, Salvadora and Jatropha plantations. In *Proceedings of the Developments in Vegetable Oils Industry.* Oil Technologists Association of India, West Zone, B.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 238-277 pp.

Genetic Resources and Improvement of Crops, Seed Spices, Grasses, Trees and Horticultural Crops for Arid Zone

O.P. Yadav[1], I.S. Khariwal[2], K.N. Rai[3], D. Kumar[1], A. Henry[1], H.R. Mahala[1], B.B. Singh[4], G.P. Dixit[4], S.B.S. Tikka[5], S. Acharya[5], J.B. Patel[5], Z.S. Solanki[6], S.R. Kumhar[6], B.R. Choudhary[6], P. Joshi[6], N.K. Dwivedi[7], S. Gopala Krishnan[7], M.M. Anwer[8], R.K. Kakani[8], M.P. Rajora[1], S.K. Jindal[1], P.R. Meghwal[1], T.A. More[9] and R.S. Singh[9]

[1] *Central Arid Zone Research Institute, Jodhpur*
[2] *All India Coordinated Pearl Millet Improvement Project, Mandor, Jodhpur,*
[3] *International Crops Research Institute for the Semi-Arid Tropics, Patancheru,*
[4] *G.B. Pant University of Agricultural Sciences and Technology, Pantnagar*
[5] *S. D. Agricultural University, Sardarkrushinagar, Gujarat*
[6] *RAU Agricultural Research Station, Mandor, Jodhpur*
[7] *National Bureau of Plant Genetic Resources, Regional Station, Jodhpur*
[8] *National Research Centre on Seed Spices, Tabiji, Ajmer*
[9] *Central Institute for Arid Horticulture, Bikaner*

Arid zone of northwestern India is bestowed with a number of diverse plant species including food crops, shrubs, grasses, trees and horticultural crops. These species possess a unique adaptation to prevailing climatic conditions of the regions as they have been cultivated here over centuries under harsh conditions leading to development of specific germplasm resources/ecotypes adapted to this zone. These resources consist of landraces, cultivars, genetic stocks, elite germplasm and wild and weedy relatives of cultivated plants. They play a very critical role in providing food, fodder and nutritional security in arid regions. The major arable crops are pearl millet, legumes including mung bean, moth bean, clusterbean, pigeonpea, sesame and Indian mustard. Seed spices chiefly include coriander, cumin, fennel and fenugreek and main horticultural crops are *ber*, date palm, pomegranate, *aonla*, *bael* and *gonda*. The main grass species are *Cenchrus ciliaris*, *C. setigerus* and *Lasiurus sindicus*. The trees species being improved are *Prosopis cineraria*, *Tecomella undulata*, *Acacia senegal*, *Salvodora oleoides* and *S. persica.* Many research institute located in arid zone have been enduring to address several issues toward genetic improvement and management of genetic resources of these species. We present here salient findings in germplasm management and genetic improvement of these species. The issues that are pertinent in future research are also addressed.

Genetic Resources from Arid Regions

The arid zone, which forms a part of the 12 bio-geographical zones of India, is unique from the point of view of both floristic as well as climatic factors. The dry arid region in India encompasses the Thar Desert of Rajasthan and Kachchh and adjoining regions of Gujarat. The genetic diversity of this region is of great significance because of its adaptability to harsh environmental conditions. It is the storehouse of genes for stress tolerance and represents germplasm, which can be used as donor in developing hardy varieties. The diversity in this region is now becoming increasingly threatened in view of large scale over exploitation and overgrazing of the resources on the one hand; and change in consumption pattern, increasing irrigated agriculture, urbanization, mining, industrialization, pollution and climatic change on the other hand. Additionally, there is an inadequate knowledge of potential uses of this immense diversity for benefit of human. Therefore, there is an urgent need to conserve genetic resources of wild species and weedy forms which are of potential value for future need. Since 1976, the National Bureau of Plant Genetic Resources (NBPGR) is actively engaged in the conservation of germplasm of plants, their wild relatives and weedy forms from arid region.

Germplasm collection

In all, 17396 germplasm accessions comprising of cultivated crops and related wild species have been collected from arid and semi-arid regions of northwestern India. These include cereals (1191), millets and minor millets (1257), pulses and legumes (5942), oilseeds (2046), vegetables (1950), fruits (1507), spices and condiments (224), fiber crops (543), medicinal and aromatic plants (1095), forage and fodder (301), wild and weedy species (623), and other economically important plants (591).

Germplasm introduction

As on December 2008, 3688 germplasm accessions of different crops/plants have been introduced in the arid and semi-arid region of northwestern India both from abroad and from other agro-climatic regions of India. Some of the notable exotic introductions include jojoba (*Simmondsia* *chinensis*), wild species of clusterbean (*Cyamopsis senegalensis, C. serrata*), salt bush (*Atriplex* spp.), 24 species of *Acacia*, while the introductions from within the country include budded ber, pomegranate, sesame, etc.

Germplasm conservation

A total of 729 germplasm accessions belonging to 107 species of vegetatively propagated and perennial crops are being maintained in the field gene bank at the Regional Station, Jodhpur. As on June 2009, 30560 germplasm accessions belonging cereals and millets (6709), legumes (13668), oilseeds (6005), economic plants (924), medicinal plants (572), horticultural plants (1650), fiber/fodder (120), released varieties (46), wild species (166) and other economically important species (165) are being conserved as active collections at the medium-term storage facility housed at the Regional Station, Jodhpur. This germplasm includes 10195 germplasm accessions from other research institutes of the region.

Germplasm registration

A genetic stock of clusterbean (CH/55-2) with foliaceous bracts in the inflorescence has been registered (INGR No. 08027). This germplasm accession produces foliaceous bracts, wherein the bracts are modified into small leafy structures. Besides, this genetic stocks for specific traits such as short internodes, determinate plant type, branched and all node cluster bearing, high gum content have been identified in clusterbean and an extra bold seeded accession in mung bean.

Germplasm distribution

One of the important steps in utilization of germplasm is the distribution of germplasm with specific traits for need based research to different crop based/region based institutes. As on December 2008, 17117 germplasm accessions of different agricultural crops (14029), horticultural plants (774) and other economic plants (2314) have been supplied for research purposes to different indenters throughout the country.

Documentation

The publication of the germplasm characterization and evaluation are being made available to the breeders of different crops through the publication of catalogues, proceedings of the workshops, research papers and book chapters.

Future perspectives

The challenges for the future in the area of plant genetic resources conservation are technical and scientific, socio-economical, legal and political, including public awareness. Therefore, continuous monitoring of biodiversity is essential for its conservation and sustainable utilization. The plant species in the desert ecosystem are unique, not only in their characteristic features enabling their survival and proliferation, but also in its utility value for human beings directly or indirectly. Thus survey, collection and conservation of useful and rare, threatened and endangered plant species are essential before they become extinct due to over exploitation. Conservation *in-situ* in protected habitats and *ex-situ* through seed gene banks and field gene banks, biodiversity gardens and cryopreservation should be the priority and NBPGR plays an important role in order to achieve this objective through survey, collection, characterization and conservation along with documentation and verification of the indigenous knowledge for its utilization.

Genetic Improvement of Crops

Pearl millet

The arid zone of north-western India is a unique adaptation zone for pearl millet because of its inherent features like severe moisture stress, high temperatures and poor soil fertility. Arid zone represents approximately 25% of the total acreage of this crop in the country. At the national level, both the production and productivity have been increasing although the area has been declining. Average pearl millet productivity has increased from 408 kg ha^{-1} to 908 kg ha^{-1} during the last more than four decades. This allowed the local people to meet their pearl millet grain and stover needs from relatively smaller area releasing additional land for other industrial and cash crops like cotton, sunflower, maize and groundnut.

The productivity gains have been achieved largely due to adoption of high yielding hybrids and cultivars. In contrast, hybrid adoption and productivity gains have been much more limited in the arid zone of the north-western India. Farmers in this zone still largely cultivate stress-adapted traditional landraces on a large scale, mainly to minimize the risk of crop failure due to severe drought. The lack of adoption of currently available pearl millet hybrids is largely due to their inadequate adaptation to the marginal environmental conditions. Hence, increasing the productivity of pearl millet in the arid (A_1) zone has remained a continuing challenge for breeders. Significant progress in pearl millet productivity in this region through crop improvement, however, is feasible. The likely approaches to be followed and the resources needed to address the various issues of genetic improvement of pearl millet for arid zone are presented here.

Delineating the arid environments: Looking at the unique climatic conditions in arid regions of north-western India, the All India Coordinated Pearl Millet Improvement Project (AICPMIP) carved out a specific A_1-zone within A-sub zone of north and north-western India in order to cater to the needs of arid regions. There are still large differences within arid regions in terms of prevalent environmental stresses or farming system needs, meaning large diversity in cultivar requirement within the arid zone. The variation in the amount and distribution of rainfall from east to west across arid region creates a wide range of soil moisture availability. In addition, as the environment becomes drier, the relative importance of millet grain stover becomes increasingly more important. Yadav *et al.* (2003) classified arid zone in three groups viz., extreme stress environments, moderate stress environments and near-optimum environments within arid zone according to production constraints and then described the breeding objectives for each sub-zone.

Role of adapted germplasm: A number of studies have established that the more marginal the conditions, the better was the relative performance of landrace-based materials compared to those bred for high yield potential under favorable conditions. Hence, AICPMIP has recognized the importance of adapted germplasm in breeding both hybrids and open-pollinated varieties. Hybrids HHB 67 and HHB 67-improved, which have been most popular hybrids in arid regions are based on the pollinators derived from landraces from western parts of India. Similarly, composites CZP 9802 and RCB 2, recommended for cultivation in arid regions, have been bred from adapted landraces from drought prone areas. A comprehensive list of pearl millet cultivars for A_1 arid zone has been provided by Khairwal *et al.* (2009)

Need for genetic diversification: Landraces and elite populations have contrasting, but complementary combinations of traits. Landraces, possessing a fair amount of adaptation to abiotic stresses, often fail to capitalize on the additional resources and hence are inherently low in their grain productivity. In contrast, the elite materials with high grain yield potential might not necessarily possess adaptation to stress environments of arid zone. There is enough evidence that crosses between landraces and elite exotic populations have certain advantages over their parental combinations and it is possible to combine adaptation with high yield potential through hybridization between adapted germplasm and elite genetic materials. The performance of populations bred by introgressing non-landrace germplasm into landrace backgrounds also increases the responsiveness of landrace germplasm to better-endowed arid zone environments (Presterl and Weltzien, 2003; Yadav, 2007; Yadav, 2008), but selection in such materials needs to be done in a typical arid zone environment to retain the adaptation of the landraces.

Indian national breeding programme has also given a high priority to diversify the hybrid parental lines in pearl millet specifically for arid regions. Currently, a large number of male-sterile lines (seed parents) and restorers are being utilized in hybrid development from a wide range of germplam sources with the result that several downy mildew resistant hybrids have been developed with high grain and stover yields with a wide range in maturity time.

Exploitation of heterosis in arid zone environments: It is generally argued that heterosis is best exploited under favourable environment. While this could largely be true, several studies conducted in arid zone have demonstrated that heterosis can also be effectively exploited to amalgamate drought tolerance and high productivity in order to improve both grain and stover yields in pearl millet under marginal conditions (Yadav *et al.*, 2000 & 2009) of arid zone. Average improvement in grain yield of landrace-based topcross hybrids over their landrace pollinators has often been in the range of 20% to 40%.

Requirement under arid conditions is that the improvement in grain yield should not be at the cost of stover production; total biomass productivity needs to be increased. Yadav *et al.* (2000) reported an average of 15% heterosis in growth rate in topcross hybrids based on landrace pollinators, which translated to a positive biomass heterosis where crop duration of the hybrid equaled that of the pollinator. The partitioning of this extra biomass to either grain or fodder appeared to be controlled by the harvest index of the seed parent, resulting in differential heterosis for either grain or stover yields, depending upon the seed parent used. Bidinger *et al.* (1994) and Yadav *et al.* (2000) suggested that it may be possible to meet farmers' needs for increased grain and stover production, while retaining critical adaptation to arid zone environments, by exploiting heterosis between locally adapted landraces and male-sterile seed parents that partition the extra dry matter to both grain and stover.

The variation in biomass heterosis is the major determinant of both grain-yield heterosis and stover-yield heterosis (Bidinger and Yadav, 2009). The contribution of harvest-index heterosis to grain and stover yield heterosis has been observed to be of a compromising nature. Harvest index heterosis accounted for substantial variation in grain-yield heterosis, but positive heterosis in harvest index resulted in negative heterosis for stover yield suggesting that strategy for increasing grain yield by improving harvest index will not result in the desired outcome in the marginal arid environments where stover yield is also important. There are exploitable genetic differences among the male-sterile lines and landrace-based restorers for their ability to produce heterotic crosses for biomass (Bidinger *et al.*, 2003a; Bidinger and Yadav, 2009).

Opportunities for hybrids in the arid zone: The lack of adoption of current hybrids does not necessarily mean that farmers are averse to hybrids. Currently available hybrids don't meet requirements of grain and stover in drought years. This is because these hybrids were bred from the parental lines with little adaptation to the arid zone and/or to farmers' requirements in this zone. Early research assessed the performance of topcross hybrids made with conventional seed parents and adapted landrace pollinators in the arid zone. Results indicated that it is possible to achieve high yields in these environments, initially by producing topcross hybrids from elite male-sterile lines and landraces (Bidinger *et al.*, 1994; Yadav *et al.*, 2000), but obviously additional work was required to identify seed parents with acceptable adaptation, and to breed disease resistant restorers, with good general combining ability, from adapted landraces.

Subsequently a large-scale assessment of all publicly available male-sterile lines was undertaken to assess their combining ability for grain and stover yields, stability, responsiveness to improved environmental conditions, drought tolerance, downy mildew resistance and plant type of their hybrids (Bidinger *et al.*, 2002; Bidinger *et al.*, 2003b) to identify sets of male-sterile lines with characteristics necessary for arid environments, ranging from low-input subsistence environments to those with supplemental irrigation facilities (Yadav *et al.*, 2003b). The key trait for seed parents was a positive general combining ability for biomass (Bidinger *et al.*, 2003a) which can be combined with good adaptation from pollinators bred from landraces to increase both grain and stover yields and to maximize yield stability. Specific male-sterile lines possessing good general combining ability (GCA) for biomass have been identified.

A set of landrace-based populations adapted to arid zone, with a range of phenotypes and of diverse origin have been used as source material for breeding adapted inbred restorer lines. The lines derived from two landrace-based populations showed differences in their combining abilities for adaptation and produced hybrids that comprehensively outyielded the best available checks under typical drought environments (Yadav *et al.*, 2009). The advantage with these adapted hybrids is that they have more chances of being delivered to farmers through well-established seed delivery channels of both private and public sectors in India. We have begun developing inbreds from a number of other restorer populations based on improved germplasm developed by AICPMIP programmes in the arid zone and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). .

Role of molecular biology: Molecular marker-assisted breeding has been an important activity in breeding downy mildew resistant hybrids of pearl millet. The first product from this approach has been released for drought-prone environments in A_1 zone as HHB 67-improved, which is a downy mildew resistant replacement for popular extra-early maturing hybrid HHB 67 (matures in 65 days). The male parent of this hybrid was improved by backcrossing quantitative trait loci (QTL) determining downy mildew resistance. HHB 67-improved marked the first marker-assisted product in public domain in India that was released and marketed.

Because of a history of limited success in breeding for drought adaptation by conventional phenotypic breeding, molecular breeding has become a prime focus. Molecular mapping and genomics approaches offer new opportunities and strategies to dissect major genes and QTL underlying drought tolerance. Identification of genomic regions determining drought tolerance of arid zone adapted landraces is underway at CAZRI. Research at ICRISAT has identified QTL which had significant effects on pearl millet yield under drought stress (Yadav *et al.*, 2002; Yadav *et al.*, 2004; Bidinger *et al.*, 2005). Comparison of hybrids with and without these QTL showed that QTL-based hybrids were significantly, but modestly, higher yielding under terminal drought (Bidinger *et al.*, 2005).

Arid legumes

Arid legumes comprising clusterbean [*Cyamopsis tetragonoloba* (L.) Taub.], cowpea [*Vigna unguiculata* (L.)], moth bean [*Vigna aconitolifolia* (Jacq.) Marechal] and horsegram [*Macrotyloma uniformis* (Lam)] are predominantly grown in arid zone of Indian sub-continent. The arid legumes are important crops for food and nutritional security and livelihoods worldwide. These crops are known for versatile uses like food, fodder, forage, vegetable, medicine and soil health enrichment. Arid legumes are an important source of dietary proteins, essential amino acids and minerals for the predominantly vegetarian population in India. Being highly adapted to hostile agro-climatic conditions, the arid legumes exhibit higher degree of tolerance to biotic and abiotic stresses.

Area, production and productivity of arid legumes in Rajasthan: The area of clusterbean in Rajasthan hovers around 25 lakh ha while the productivity is around 250 kg ha^{-1}. The moth bean is cultivated over an area of about 14 lakh ha with productivity of less than 200 kg ha^{-1} while cowpea is being cultivated over an area of 1.2 lakh ha with productivity over 300 kg ha^{-1} (Table 1). Almost 80% acreage of clusterbean, 90% of moth falls in north western districts of Rajasthan viz., Ganganagar, Hanumangarh, Churu, Bikaner, Nagaur, Jodhpur, Barmer and Jaisalmer. The potential productivity of clusterbean is more than 2500 kg ha^{-1}, of moth 700-800 kg ha^{-1} and of cowpea over 1000 kg ha^{-1}. Despite development of high yielding and early maturing genotypes of these crops during last 15 years production and productivity are still very low compared to their yield potential because of several factors:

1. Erratic and low rainfall.
2. Cultivation of these crops on marginal soils having low fertility.
3. Poor economic conditions of farmers.
4. Planting local genotypes having low productivity and long maturity due to inadequate supply/availability of the quality and certified seeds of improved genotypes.
5. High risk due to biotic and abiotic factors, large price fluctuations and no minimum support price also discourage the farmers to grow arid legumes.
6. Further, arid legumes are crop of secondary importance, if there are timely rains farmers prefer to grow pearl millet, sesame and mung on fertile and good soils instead of clusterbean, moth and cowpea.

Breeding for improved seed yield, plant types and earliness: Arid legumes have traditionally been cultivated under aberrant drought prone situations with least inputs and care. These crops have shown increased grain yield under existing situations with little fertilizer application with lesser agronomic inputs. For instance, in clusterbean recently developed varieties like, HG-884, RGC-1038, RGM-112, RGC- 1017, RGC-1002, RGC-1003, HGS-365, HGS-563 and GRC-936 maturing in 90-100 days have yield potential of 1000-1500 kg ha^{-1} in rainfed conditions, while RGC-1031, RGC-986 and RGC-197 (unbranched) are late in maturity (110-125 days) and suitable for high rainfall zones or irrigated and better soils conditions and have yield potential over 2.0 tones per hectares.

In cowpea, varieties developed in late nineties, Vamban-1, KBC-2, V-585, V-130, V-240 and GC-3 are late maturing types (90- 100 days) with the yield potential of 900-1200 kg ha^{-1} while the varieties developed in recent years, viz., RC-101 (2001) and CoVu-702 (2005) are maturing in just 65-70 days with same yield levels. In moth, varieties maturing in 58-60 days (FMM-96), 60-65 days (RMO-40, RMO-225, RMO-257, RMO-225 and CAZRI Moth-3), 65-67 days (CAZRI Moth-2) and 70-75 days (CAZRI Moth-1, Jawala and IPCMO- 880) days having erect, semi-erect and semi-spreading plant types possess yield potential of 600-1000 kg ha^{-1} compared with traditional types (Baleswar-12, Type-3 and Jadia) maturing in 90-100 days and yielding 200-400 kg ha^{-1} only.

Alteration in plant types concomitant with early maturity befitting the region and rainfall distribution is therefore desired. Research efforts in moth bean have resulted in the development of promising genotypes characterized with erect growth habit and early maturity (58-62 days) compared with traditional genotypes having spreading plant habit and late maturity (90-100 days). These genotypes, inspite of shortening the growth period by 30-35 days have great yield potential. For instance, mutant lines CZM32 and CZM18 maturing in 63 days may yield as high as 780 kg ha^{-1}. These lines besides, improved plant types and being early, are a potent source of drought tolerance. CAZRI Moth-1, a variety developed from Jadia also represents semi-erect growth habit and source of yellow mosaic virus (YMV). Other genotypes of moth bean like RMO 40, RMO 257, RMO 225 and FMM 96 released for cultivation represent effective alteration in plant types and high yield. CAZRI Moth 2 and CAZRI Moth 3 released ion 2003 and 2005, respectively, have high drought tolerance and grain yield potential under extreme arid situations of arid western Rajasthan receiving very less rainfalls (200-300 mm).

In cowpea also, compact and erect plant types with earliness is required, as the existing varieties with bushy and trailing growth habit yield less. A growth period of 65-70 days is therefore, required. Some genotypes like C 480, C 653 and C 722 maturing in 70 days, and RC 101 maturing in just 65 days had been induced. Similarly, mutants from Pusa Falguni (V 37, V 38, V 585 and V 240) with compact growth habit have been developed. Some of the mutants developed by Bhabha Atomic Research Centre are also showing synchronous maturity with determinate growth habit, very high yield levels (1300-1500 kg ha^{-1}) and maturing in just 60-65 days. The lines developed at the International Institute of Tropical Agriculture have been introduced in India and are performing well and may fit in wheat-rice cropping system of Indo-Gangetic Plains for summer cultivation as they are maturing in 60-65 days with grain yield of 1200-1500 kg ha^{-1}. In clusterbean, HG 563 and RGC 936 maturing in 85-90 days with very good yield potential have been developed for irrigated and rainfed situations, respectively. Further, development of unbranched genotypes like RGC 1066 and RGC 197 paved the way for clusterbean cultivation in irrigated areas having heavy soils as they are yielding over 3000 kg ha^{-1} and suitable for mechanized harvesting. These genotypes are also suitable for mixed and inter-cropping with irrigated (groundnut) as well as rainfed kharif crops (pearl millet and sesame).

Issues and future strategies*:* The breeding strategies of these main crops of the arid regions need to address several issues which may include:

1. Breeding for need-based alteration in plant types, so as to make them more acceptable under existing unpredictable environmental fluctuations.

2. Curtailing the maturity period of these crops so as to match specifically with the regions, soil types, rainfall pattern and social needs of the inhabitants.

3. Breeding varieties with 20-30% higher biomass per unit water.

4. Development of plant types suited to aberrant situations of mid June to end of August plantings.

5. Development of varieties suitable for specific cropping systems: inter-cropping, mixed cropping, agro-forestry, agri-horti and agri-pasture systems.

6. Attempting more and more inter-specific crosses, particularly between cultivated and wild types to tap genes from wild types for adaptations and resistance to biotic and abiotic stresses.

7. Increasing clusterbean gum content from existing 31 to 35% with carried viscosity profile level through breeding strategy.

Mung bean

Mung bean (*Vigna radiata* L. Wilczek), also known as green gram, is an important short duration grain legume with wide adaptability is an important crop in arid and semi-arid regions. In the last 3 decades, mung bean has registered phenomenal increase both in area and production. The area has increased from 1.99 m ha in 1964-65 to 3.77 m ha in 2007-08 and it became third largest pulse crop in the country. The production has increased from 0.60 million tones to 1.56 million tones during the same period. This expansion in area has resulted due to development of relatively photo- and thermo-insensitive varieties which allowed a greater flexibility in their planting dates. Further the shortening of crop duration paved the way for its inclusion in a wide range of intensive cropping systems.

Production constraints: This crop is grown mostly during rainy season, however development of short duration and disease resistant varieties led its cultivation during spring/summer season in almost all parts of the country and during winter (rice fallows) in peninsular India. The major constraints in this crop are:

1. Insect pests during kharif/spring seasons causing major losses to the crop.
2. Mung bean yellow mosaic in kharif and spring in northern part and powdery mildew during winter season in southern part of the country.
3. Lack of high yielding varieties of efficient plant type for different situations.
4. Pre-harvest sprouting in rainy season which restricts its intercropping with other companion crops such as maize, sorghum, pigeonpea etc., grown at the onset of monsoon.
5. Lack of on-farm storage facilities and its vulnerability to store grain pests like bruchids. Resistance against the insect is not available in germplasm.
6. Low seed replacement rate (10%) of improved varieties.

Varietal development: The initial phase of varietal development had been aimed at improving locally adapted but genetically variable populations mainly by pure line and mass selections with major emphasis on traits other than yield. This resulted in the release of large number of pure lines, some of which are still cultivated in certain parts of the country. Establishment of All India Co-ordinated Pulses Improvement Project (AICPIP) in 1967 provided an access to pulse breeders to improved germplasm and to test improved breeding lines in multi-location evaluations across the country. As a result more than 110 varieties of mung bean were developed. During the last three decades, major emphasis has been to breed short duration, photo- and thermo-insensitive varieties coupled with resistance to biotic stresses viz., yellow mosaic virus and powdery mildew, which contributed significantly to the national production.

The first variety of mung bean T 1 has extensively been utilized in hybridization programme to develop mung bean varieties T 2, K 851 and T 44 and Sunaina. Being a short-duration and acceptable seed quality variety T 44 became very popular in spring/summer season. T 44 was used in hybridization programme to develop Pusa Baisakhi, Pant moong-2 and Pant moong-4. Pusa Baisakhi has been utilized to develop PIMS 4 and Jyoti. Two varieties of mung bean ML 1 and ML 5 were developed from PAU, Ludhiana, during the early 1970s and these were used to develop ML 131, ML 267, ML 337 and ML 23. During the same period a variety Mohini (S 8) was developed through hybridization between T 2 and BR 2. Iranian germplasm PS 16 and S-8 were used in hybridization programme to develop KM-1, which has become a very popular variety of Southern zone of the country. Large seeded varieties of mung bean, Pusa Vishal, Pant mung 5 and SML 668 were developed from the selection of AVRDC material. Mutation has also resulted in development of Pant mung 2, MUM 2, Co 4, LGG 407, LGG 405 and BM 4. Three varieties of mung bean Pant mung 4, HUM 1 and IPM 99-125 were also developed through wide hybridization between mung bean and urdbean. Pedigree analysis of mung bean varieties revealed that very limited genetic variability has been exploited in mung bean breeding programme (Katiyar *et al*., 2007). Variety T44 has been used extensively in mung bean varietal development programme in India and it is one of the parents for more than 16% mung bean varieties.

Impact of improved varieties at farmers' field: To demonstrate the production potential of newly released high yielding varieties, 1133 FLDs were conducted in different states. On an average, improved genotypes recorded grain yield of 781 kg ha^{-1}, which was 22% higher than the local varieties.

Role of wide hybridization: The nature of research reported on wild germplasm related to grain legumes in comparison to cultivars and landraces has contributed to increased opinions of the value of wild germplasm. Studies have suggested that about 150 species of *Vigna* exist in nature and 22 *Vigna* species including cultivated and wild are found in Indian gene centre. Various reports indicate that many desirable traits having great potential for mung bean improvement are available in wild or related species. However, most of these species remain unutilized due to complications such as crossing barriers and linkage drag. A wild accession of *Vigna radiata* var. *sublobata*, PLN 15, is found to be the potential donor for higher number of pods per plant and seeds per pod. Efforts are in progress at AVRDC to utilize *V. radiate* var. *sublobata* for resistance to bruchids (*Callosobruchus chinensis* and *C. maculates*) which is controlled by a single dominant gene.

There are some successful examples where the wide hybridization led to the development of cultivars with added advantage for practical use. Five mung bean cultivars, HUM 1, Pant Mung 4, IPM 99-125, Pant mung 6 and IPM 02-3 have been developed from mung bean x urdbean crosses. Several other derivatives from mung bean x urdbean crosses exhibit many desirable features such as MYMV resistance, lodging resistance, synchrony in podding and non – shattering. A few mung bean x rice bean and mung bean x *V. radiate* var*. sublobata* having high degree of resistance to MYMV were also recovered.

Priorities and thrust area

- Incorporation of photo- and thermo-insensitivity traits.
- Incorporation of resistance to pre-harvest sprouting and bruchids.
- Pyramiding of genes for resistance to major insect pests (Thrips, Jassids and pod borer) and diseases (YMV, PM and CLS) for which resistance is not high in cultivated germplasm.
- Identification of diverse germplasm source for important economic traits and plant types.
- Accessing desirable genes from wild species.
- Development of short duration varieties with distinct vegetative and reproductive phase for fitting the crop in narrow windows in cereal-cereal cropping system.
- Improved seed production and supply systems (seed village, community seed bank, etc.).

Development of new plant type: The presently available plant type in mung bean is largely photo- and thermo-sensitive, overlapping vegetative and reproductive growth habit with low harvest index and low grain yield. To remain a commercially competitive crop mung bean has to fit in high input cereal-cereal cropping systems. For this plant type that are determinate, photo- and thermo-insensitive, early maturing, high yielding (1500-2000 kg ha^{-1}) with balanced vegetative growth, less plasticity in vegetative growth and high harvest index, and resistant to lodging is to be developed. A plant type with thick stem with two–three erect branches, short internodes, having small and thick leaves needs to be developed. Good seedling vigour, a clear-cut distinction between vegetative and reproductive phases and high harvest index will be essential component of the plant type.

Pigeonpea

Pigeonpea [*Cajanus cajan (L.)* Millsp.] owing to its constitutive traits like deep root system and immense flexibility in morphological/ phenological characters is inherently suitable for arid and semi-arid agro-climatic conditions. Pigeonpea with an annual production of around 3 m tones constitutes about 5% of the total world production of pulses. A major part of this is produced in India (90%). Traditionally the crop has been growing in India along the Indo-Gangetic plains but off late the crop has spread to Maharashtra, Karnataka, Andhra Pradesh, Madhya Pradesh, Uttar Pradesh and Gujarat. The area and production of pigeonpea in India have been growing at an annual rate of more than 2% since 1970. However, stagnant yields at around 700 kg ha^{-1} have been the major concern, though development of hybrid pigeonpea has raised new hopes for busting yield plateau.

The production enhancement through genetic amelioration has been a continuous process. Both conventional and modern plant breeding methods have been employed to breed improved types. Unlike other crops, pigeonpea gets bog down with increased input application. Whenever water is applied to pigeonpea vegetative growth is promoted with less flowering leading to less yield. This evinces that the plant type of pigeonpea is structured for evolutionary advantages like excessive growth, spreading habit, height, shattering, low harvest index and indeterminate growth with inapt ratio or balance of vegetative and reproductive phase. Thus, restructuring of plant type is the top priority. Breeding for appropriate spread, growth habit, maturity, height and characters as per requisite crop husbandry may serve the purpose.

Short duration varieties are known for their limited biological yield and further enhancement of harvest index would not guarantee high productivity in these cultivars. Therefore, sufficiently large biomass is equally necessary under arid conditions. Efforts should be directed to increase biological yield with optimum harvest index in short duration cultivars.

Wild species as potent tools for pigeonpea improvement for arid situations: Wild relatives of pigeonpea are expected to have accumulated useful genes to tolerate droughts, floods, extreme temperatures, insect pests and diseases that wreak heavy damage to cultivated species. The natural defense mechanisms in crop plants have been lost during intense selection for high yield, wider adaptability and improved nutritional quality. The arid situations being very harsh, the use of mining these important genes for enhancing yield potentials can not be over emphasized.

Discovery and incorporation of genes from wild species provide means to sustain crop improvement. Exploitation of cytoplasm from compatible wild germplasm has resulted in development of new cytoplasmic male sterility systems in pigeonpea, development of high protein lines, cleistogamous flower and dwarf pigeonpea lines. Utilization of wild species in secondary and tertiary gene pools has been generally restricted due to sterility, constrained recombination or cross incompatibility. Nevertheless, these species are extremely important as they contain high levels of resistance to several important biotic and abiotic stresses.

Breaking yield plateau through heterosis breeding: Pure line pigeonpea varieties released for commercial cultivation have crossed a century mark ever since the first pigeonpea variety was developed by selecting a wilt resistant genotype from landraces. These concerted research and developmental efforts have made substantial dent in pigeonpea production and areas, but the productivity has remained by and large static, despite various breeding methods such as pure line breeding, population breeding and mutation breeding. In fact, a hybrid breeding system using partial natural out-crossing of the crop coupled with genetic male-sterility was tried to break yield stagnations by Reddy *et al.,* 1978 and Saxena *et al.,* 1983. Combining these two components, Saxena *et al.*, 1992 developed the world's first pigeonpea GMS based hybrid ICPH 8 that was released for cultivation in 1991 which recorded an average increase of 30.5% in grain yield over the best available pure line variety UPAS 120 (Saxena *et al.*, 1992). Despite these achievements in genetic male sterility based hybrids in 90s to bust the yield plateau, they could not be exploited commercially due to inherent seed production problem with the system. This necessitated breeding for a more efficient cytoplasmic nuclear male-sterility (CMS) system. The pigeonpea breeders took up this mission and the first report of developing stable, versatile and commercially viable alternative cytoplasmic genetic based male sterility system using wild species *C. scarabaeoides* came from Sardarkrushinagar (Gujarat). The plant to plant selfing and back crossing of the sterile and fertile counterparts culminated in the development of stable cytoplasmic male sterility system in 1997. The system became viable with the identification of fertility restorer genes and first ever CGMS based hybrid viz. GTH 1 was identified in 2004.

Appreciating that genetic diversity is the backbone of any successful hybrid development programme; the nation wide successful efforts were aimed at diversification of A and R lines. The success of the programme can be gauged from the fact that as on day Sardarkrushinagar (Gujarat) alone has identified and characterized 98 stable CGMS lines and 81 stable restorer lines besides host of other materials in pipeline. The research conducted so far in this aspect has used the following five CMS cytoplasms (A_1 through A_5) conditioning male sterility.

Broadening of narrow genetic base: Broadening of narrow genetic base makes an important activity for breeding under arid situation so that the varieties so developed may withstand the vagaries of the harsh weather. This has been successfully attempted through use of both indigenous and exotic germplasm. Lately exotic lines from Kenya (ICP-9140 and ICP-9135), Tanzania (ICP-12116 and ICP-12161), Myanmar (ICP-11488) and Canada (ICP-13555) and diverse indigenous genotypes (GT-100, GT-101, Banas and ICP-11912) were used to develop different types of derivatives. The exotic germplasm though has very long duration but evinced immense complimenting ability of variability to Indian counterparts and, therefore, seemed very useful both for broadening the narrow genetic base and providing good combination for adequate exploitation of yield components and heterosis in pigeonpea. The studies indicated that combinations of Indian pigeonpea as female with exotic germplasm, particularly the African as male gave better specific combinations for yield per se.

Abiotic stress resistance*:* Drought and soil salinity are the indispensable abiotic stresses in arid areas where pigeonpea is produced. Consequent up on lack of appropriate screening technologies and drought being highly complex and stage specific in nature, no systematic breeding program has been undertaken to breed varieties with high levels of resistance to these stresses. Though pigeonpea has deep roots, yet yield losses due to drought are large and widespread, especially when it occurs during critical seedling and reproductive stages. Lopez *et al.*, 1996 reported genotypic differences for drought resistance in pigeonpea. Such variation was associated with the ability of resistant genotypes to maintain efficient production and partitioning of dry matter during periods of drought. Chauhan *et al.*, 1994 identified a promising short duration cultivar ICPL 88039 that showed a moderate level of drought resistance.

Consequent upon strong relationship between the yield potential and the sensitivity of genotypes to end-of-season drought, the first approach to minimize yield losses due to terminal drought has been to breed for earliness for escaping drought. However, drought resistance being growth-stage specific such relationships do not hold true for mid season drought there by necessitating specific genetic enhancement programmes for drought resistance.

Little effort has been made to develop lines with genetic resistance against salinity stress in pigeonpea. A pigeonpea mini-core collection along with some wild species and field collections from predominantly saline areas was evaluated for resistance to irrigation with 75 mM NaCl solution (Srivastava *et al.*, 2006).

Dry matter production and harvest index*:* Pigeonpea produces the high dry matter though only a part of it is converted to economic yield. Exotic cultivars produced more biomass *i.e.*, more branches and leaves and had bushier and more compact canopy structure than the local genotypes. Pod yield was higher in the local genotypes than that in exotic cultivars (Fakir *et al.*, 1992). Dry matter production is also affected by environmental factors. Harvest index in pigeonpea varies between 10 and 52% depending upon genotypes, environments and agronomic managements.

Plant breeder should aim such a plant type where the canopy closure is achieved prior to pod filling to ensure maximum interception of incident, photo-synthetically active radiation during reproductive ontogeny, but after start of flowering, to avoid excessive vegetative growth. The manipulation of photo-thermal sensitivity offers the most powerful tool for improving harvest index.

Genetic transformation*:* Judicious application of biotechnological tools holds great potential for alleviating some of the major constraints to productivity. The genetic engineering of pigeonpea could provide an effective complementary approach to *Helicoverpa* control. Several insect resistance genes have been identified as candidates for transforming pigeonpea including the genes coding for the insecticidal crystal protein of Bt, soybean trypsin inhibitor (SBTI) and pigeonpea trypsin inhibitor (PPTI). *35S:cry1Ab, 35S:sbti,* 35S:*cry1Ac, Ubi:cry1Ac* have been introduced successfully in pigeonpea against *Helicoverpa armigera,* which were being tested in contained field at ICRISAT and at present various events are available. For Bio-fortification for the nutritional components like ß-carotene, Sulphur-rich amino acids (methionine), the genes namely *oleo*:*psy* and *Vicilin:SSA* have been transferred to pigeonpea and the events being tested are available.

Genetic engineering approaches to introduce agronomically desirable genes from other sources into pigeonpea has, so far not been possible due to the want of an efficient and reproducible regeneration system. An effort to develop efficient regeneration procedures a prerequisite to plant improvement several regeneration protocol via direct and indirect organogenesis or embryogenesis using diverse explants on different media have been established. However, the regeneration frequency is very low dependent on the explant nutritional and hormonal regimes and genotype specificity. Regeneration of plants from protoplast, anther and rescued embryo cultures have been achieved with limited success. Very few studies have so far been undertaken for genetic transformation in pigeonpea. Development of primary transformants expressing reporter and selectable marker genes have been achieved at very low frequency using direct shoot organogenesis from cotyledonary nodes and *Agrobacterium tumefecians*. However, a protocol which can routinely be used for genetic transformation in pigeonpea is still far from being reached (Singh *et al.*, 2003)

Large scale development of microsatellite markers has been initiated in pigeonpea. Two enriched libraries were created resulting in low recovery rate of only 10 useful microsatellite markers. Due to the substantial amount of time and cost incurred, there is considerable interest in establishing a more cost effective and labour saving alternative in generating additional markers for drought tolerance.

Marker-assisted selection: In most breeding programmes, the genetic improvement for drought resistance is accomplished through selection for yield and because of low heritability of yield under stress and the spatial as well as temporal variation in the field environment, conventional breeding approaches are slow. Whereas molecular markers such as restriction fragment length polymorphism (RFLP), random amplified polymorphic DNA (RAPD) and isozyme will facilitate to develop drought-resistant genotypes more effectively as their expressions are independent of environmental effects.

Until recently, there have been no microsatellite markers available in pigeonpea. However, a collaborative project between ICRISAT and Birmingham University is now developing SSR markers that have already been used in the first high throughput project at ICRISAT, to assess the molecular diversity of one thousand pigeonpea accessions from across India.

Meanwhile, a number of components of drought tolerance have been characterized in pigeonpea, including early vigor, leaf area maintenance, root and shoot growth rate, and developmental plasticity.

Molecular markers are also important for investigating gene flow between crops and their wild species. Work has been initiated by many institutions for the development of a model for gene flow in pigeonpea, using DNA markers, to understand the risk of genetic erosion as well as to have a tool for risk assessment when transgenic plants of this crop become available for field-testing.

Seed production and maintenance breeding: The maintenance of genetic purity is quite arduous in crops like pigeonpea owing to its often cross pollination nature. The situation cannot be more warranting than crop improvement programme in general and hybrid programme in particular where a single gene migration can set in enormous genetic upheaval for attaining gene and gene frequency equilibrium. A simple but very effective technology for maintenance of genetic purity was designed at Sardarkrushinagar (Gujarat). The technology comprises 8 feet iron poles with detachable top. The net is erected on the arches made of poles and tops. The technology was further improved and presently the mobile insect proof net houses are being used country wide for maintaining genetic purity and maintenance breeding.

Researchable issues in arid regions

- Pigeonpea in arid region has special niches in marginal and sub-marginal land under rainfed areas. Therefore, development of short duration varieties/hybrids with appropriate vegetative growth, suitable spread, balance between vegetative and reproductive phase, least bud dropping, consumers' friendly quality, resistance to biotic and abiotic stress with due emphasis on anti-evolutionary characters like non-shattering, may be targeted to increase and stabilize pigeonpea production under arid regions.
- Development of situation specific and physiologically efficient varieties.
- Utilization of wild relatives for introgression of drought resistance, high protein and pest/disease resistance genes in to cultivated pigeonpea.
- Development of value added dual purpose varieties with good quality attributes.

- Tolerance to biotic and abiotic stresses for escalating and stabilizing production over locations and years under arid conditions with particular emphasis on the development of drought tolerant varieties with due emphasis on photo-thermo-insensitivity.
- Development of molecular based mechanism and techniques to enhance for drought, pest/disease resistance.
- Incorporating resistance to Helicoverpa.
- MAS could be resorted for selection for resistance to drought and salinity.
- Genes for higher harvest index may be exploited in pigeonpea for increasing the harvest index and yield.
- Development of character based specific molecular techniques for DUS and precise identification of varieties/hybrids for GOT at juvenile stage.

Sesame

Sesame is the oldest indigenous oil crop cultivated in India for its excellent nutritional, medicinal, cosmetic and cooking qualities of oil. It is a rich source of protein (24%) and carbohydrates (15%) in addition to excellent source of quality oil (50%). India is the world leader with the largest area (29.3%), maximum production (25.8%) and highest export of sesame seed (40%). Rajasthan, Gujarat, Utter Pradesh, Madhya Pradesh, Maharashtra, Andhra Pradesh, Orissa, Tamil Nadu and Karnataka are sesame growing states of India. Among these, Rajasthan is the major sesame growing state in the country, which contributes 18.2% in area and 14.1% in production. The productivity trend (254 kg ha^{-1} to 356 kg ha^{-1}) of the state during the past decade (1990-2000) as compared to productivity of 146 kg to 300 kg ha^{-1} during 1970-90 reflects the contribution of research in development of drought, disease and pest tolerant and high yielding varieties adopted by farmers. But still productivity level (327 kg ha^{-1}) of the state is low in comparison to the national productivity of 421 kg ha^{-1}.

There are several constraints in sesame production as it is mainly grown in the *kharif* season under vagaries of monsoon, which is further aggravated by several pests and diseases. Recently prospects of export of white seeded sesame have brightened and Rajasthan is contributing greatly in its export. However to meet the growing demand, the yield ceilings of sesame need to be raised by developing high yielding varieties having tolerance to biotic and abiotic stresses. Not only the higher productivity but desired traits like whiteness of seed, technology for raising pesticide residue-free and organically produced crop also needs due attention.

Systematic and scientific efforts to increase the production and productivity of this crop in the Rajasthan state started in early 1970s and since then several varieties have been released.

Rajasthan Til 46: It is a white seeded high yielding variety resistant to oozing complex, tolerant to *Macrophomina*, *Alternaria* leaf spot, *Antigastra* and gall fly. It matures in 76 to 85 days and is suitable for both rainfed as well as irrigated conditions. Its seed yield ranges from 600-800 kg ha^{-1} and has 49.4% oil content. It is recommended for cultivation in J & K, Himachal Pradesh, Punjab, Haryana, Rajasthan and Western U.P.

Rajasthan Til 54: A brown seeded and comparatively dwarf variety which is resistant to leaf blight and Macrophomina. It is comparatively late shattering type and matures in 73-78 days. Seed yield ranges from 6-8 q ha^{-1} under natural conditions and is recommended for cultivation in Gujarat, Maharashtra and Telangana region of A.P.

Rajasthan Til 103: A white seeded variety suited for both rainfed and irrigated conditions, highly tolerant to bacterial leaf blight and insects, is a late shattering type variety with seed yield of 600-800 kg ha^{-1} under rainfed conditions. It is recommended for Gujarat, Maharashtra and Telangana region of A.P.

Rajasthan Til 125: It is characterized by yellowing of leaves, stem and capsules as the crop reaches physiological maturity. It is tolerant to diseases and insects and gives seed yield of 600-800 kg ha^{-1} under rainfed conditions and has 48.7% oil content. It is recommended for cultivation in J & K, H.P, Punjab, Haryana, Rajasthan and Western U.P.

Rajasthan Til 127: A shiny white bold seeded variety for cultivation in whole Rajasthan state. It is drought hardy and well suited for both arid & semi arid conditions. It is tolerant to Macrophomina stem & root rot, phyllody, bacterial leaf spot & powdery mildew and has less infestation of gall fly and mites. It is also tolerant to moisture stress conditions. Its average seed yield is 6-9 q ha^{-1} and oil content 50.6%.

Rajasthan Til 346 (Chetak): It is a white seeded, early maturing (83 days) and high yielding variety. It has 3-4 branches, non hairy capsules arranged alternatively in a compact manner. It is resistant to leaf curl, phyllody and moderately resistant to *Macrophomina* stem and root rot, powdery mildew and *Alternaria* and *Cercospora* leaf spot and has less infestation against *Antigastra*. This variety also showed tolerance against moisture stress. Its average seed yield is 700-900 kg ha^{-1} and oil content 50%. It is suitable for cultivation in hot and arid ecosystem of the National zone-I, comprising of Rajasthan, Haryana, Punjab, Himachal Pradesh, Gujarat and adjoining areas of western Uttar Pradesh, Maharashtra and Karnataka.

Impact of sesame varieties developed: Variety RT 46, RT 125 and RT 127 have already become popular in the Rajasthan state. In front line demonstrations conducted in western Rajasthan varieties RT 46, RT 125 and RT 127 have exhibited 35-40% higher seed yield over local varieties. Seed demand of these varieties is continuously rising in the state due to its high realized productivity on farmers' field. Varieties RT 46, RT 125 and RT 127 are presently grown in more than one lakh hectare area, which is about 35% of the area under sesame in Rajasthan. With more support of state seed producing agency, the 50% area under these varieties can be attained in next 3-4 years.

Rapeseed and mustard

Brassica species is an important component of human diet as major sources of edible oil and vegetables. Seven important annual oilseeds are grown world wide. India has traditionally been a *Brassica* growing country. Three ecotypes of *B. rapa* namely brown *sarson*, yellow *sarson* and *toria* are grown to a limited extent while Indian mustard (*B. juncea*) is the chief oil-yielding crop. Black mustard or *Banarsi rai* (*B. nigra* [L.] Koch) is cultivated for condiments in a few pockets. Two more oilseed *Brassica* species i.e. rapeseed (*B. napus*) and Ethiopian mustard (*B. carinata*) have been created. *B. tournefortii* is also grown sporadically in the drier habitats of Rajasthan on marginal areas.

The production of oilseed *Brassica* increased to 1 m t the 1956-57 to 7.5 m t in 2006-07 due to concerted efforts of breeding and crop management. Rajasthan has the largest acreage under these crops and is ranked first in area (3.21 m ha) as well as in production (3.81 m t) in the country and accounts for about 50% production. Low irrigation requirements of these crops compared to other *rabi* crops like wheat and barley has played an important role in popularizing the crops in Rajasthan where water is scanty.

Genetic diversity*:* The divergence studies are necessary to understand the trend of evolutionary pattern, to assess the relative contribution of different components of yield to total divergence and to determine the nature of forces operating at intra- and inter-cluster levels. Choudhary and Joshi (2001) assessed genetic diversity among 88 entries including eighty F_4 derivatives of interspecific crosses and eight parents. The genetic distances calculated among different *Brassica* species revealed that *B. tournefortii* had maximum diversity with *B. juncea* followed by *B. napus*, *B. rapa* var. *toria*, and *B. rapa* var. yellow *sarson*. The clustering pattern showed that many derivatives of the cross fell into the same cluster but in many cases in spite of common ancestry descendants of the cross spread over different clusters. The characters like plant height, secondary branches per plant, days to flowering and 1000-seed weight contributed maximum towards genetic divergence.

In another study of genetic divergence of 84 entries of *B. juncea* showed that all the 28 entries having tetralocular siliqua were accommodated in a single cluster, whereas remaining 56 genotypes with bilocular siliqua were spread over in five clusters (Choudhary *et al.*, 2007). The mean values of the traits in various clusters exhibited that different clusters were superior in respect of different characters. Contribution of different characters towards total genetic divergence revealed highest contribution of seeds per siliqua followed by main raceme length, siliquae on main raceme and siliqua length.

Genetics of economic important traits: Numerous studies on genetics of quantitative and qualitative characters revealed availability of genetic variability in different *Brassica* species. The inheritance of siliqua locule number and seed coat colour in *B. juncea* was investigated using three lines each of tetralocular brown seeded and bilocular yellow seeded (Choudhary and Solanki, 2007). Brown seed colour and bilocular siliqua characters were found to be dominant over yellow seed and tetralocular siliqua, respectively. Another study on the inheritance of siliqua orientation and seed coat colour in *B. tournefortii* showed that seed colour was to be under monogenic control with brown being dominant over yellow (Choudhary, 2008).

Crop improvement*:* Crop improvement objectives focus largely on attempts to tailor plants for higher seed yield, resistance/tolerance to pests and diseases, frost, shattering, and for oil and meal quality. The breeding approaches have led to the development of over 150 improved cultivars in last few decades resulting in higher productivity of crop. Pusa Jaikisan (Bio 902) of Indian mustard is the first somaclonal variety developed through tissue culture. With regards to quality, Hyola 401 is the first '00' hybrid of *B. napus* while Neelam (HPN 3) is the first '00' variety of the same species. PGSH 51 is the first CMS based hybrid of *B. napus*. Variety CS 52 has been recommended for salt affected soils. Indian mustard variety JM 1 is reported to be tolerant to white rust while variety RGN 13 is tolerant to frost and

Alternaria blight. Some important varieties recommended for arid western plain zone Ia are Varuna, RH 30, RH 819, Pusa Jaikisan (Bio 902), CS 52, GM 2, JM 1, Urvashi and Ashirwad of Indian mustard and ITSA, T 27 and RTM 314 of taramira.

Seed spices

The seed spices are a group of annual crops, the dried fruit or seeds of which are used as spices. The seed spices are aromatic vegetable products of tropical origin and are commonly used in pulverized state, primarily for seasoning or garnishing the foods and beverages. They are also used in preparation of various value-added products viz. spice oils, oleoresins and spice powders. The area under seed spices in India is 9,22,274 ha and the production is 5,94,120 metric tonnes. India is the largest producer, consumer and exporter of seed spices earning Rs. 5440 millions by exporting 52,550 tonnes seed spices to various countries (Anonymous, 2009).

Crop Improvement achievements*:* After inception of AICRP on Spices in 1975, major achievements have been made and over 50 improved varieties in seed spices have been released. These include 19 in coriander, 7 in cumin, 10 in fennel, 16 in fenugreek, 7 in ajowan, 2 in dill and one each in nigella, celery, and anise. Different biotic and abiotic stresses are major yield reducing factors in seed spices. Therefore the breeding objectives for seed spices include resistance against these factors and also enhancement of nutritional, yield and quality characters like high volatile oil content.

Coriander (*Dhania*): *Coriandrum sativum* L belongs to family apiaceae and requires improvement for high yield, higher volatile oil content, resistance to powdery mildew and stem gall disease and small and round seed with luster. So far several varieties viz., RCr-41, RCr- 20, RCr-435, RCr436, RCr-684, RCr-446, Ajmer Dhania-1 (NRCSS ACr 1) for Rajasthan; GCr-1 and GCr-2 for Gujarat; CO 1, CO 2, CO 3 and CS 287 for Tamil Nadu; Rajendra Swathi and Rajendra Sonia for Bihar; Sadhna, Swathi (CS-6) and Sindhu, for Andhra Pradesh and Hisar Sugandh for Haryana have been released.

Cumin (*Zeera*): *Cuminum cyminum* L belongs to family apiaceae and requires improvement for resistance to blight, wilt and powdery mildew diseases, high yield, higher volatile oil content and bold seed with luster. So far varieties developed and released include RZ-19, RZ- 209 and RZ-223 for Rajasthan and GC-1, GC-2, GC-3 and GC-4 for Gujarat.

Fennel (S*aunf*): *Foeniculum vulgare* Mill belongs to family apiaceae and requires improvement for short duration, reduced height, large umbel, high yield, resistance to gummosis and high volatile oil content. Varieties released for Rajasthan include Ajmer Saunf-1 (NRCSS-AF-1), RF-101, RF-125, RF-143; for Gujarat include PF-35, GF-1 (Gujarat Fennel-1) GF-2 and GF-11. Variety Co-1 is released for Tamil Nadu and Hisar Swarup for the state of Haryana.

Fenugreek (*Methi*): *Trigonella foenum-gracium* L belongs to family fabaceae and requires improvement for high yield, resistance to powdery and downy mildew, earliness and improved medicinal properties. The varieties RMt-1, RMt-143, RMt-303, RMt-305, Ajmer Methi 1 (NRCSS-AM-1) and Ajmer Methi 2 (NRCSS-AM-2) are recommended for Rajasthan; GM-1, for Gujarat; CO-1 for Tamil Nadu; Rajandra Kranti for Bihar; Lam Selection–1 for Andhra Pradesh; Hisar Sonali, Hisar Suvarna, Hisar Mukta, Hisar Madhavi (HM-350) for Haryana; Pant Ragini, Pusa Early Bunching, Pusa Kasuri for Uttar Pradesh and Uttaranchal;

Dill (*Sowa*): *Anethum graveolens* L European dill and *Anethum sowa* Kurk. belongs to family apiaceae and requires improvement for high yield, higher volatile oil content, resistance to powdery mildew and root rot disease. Ajmer Sowa 1 (NRCSS-AD-1) and Ajmer Sowa 2 (NRCSS-AD-2) varieties have been recommended for Rajasthan.

Carom Seed (*Ajwain*): *Trachyspermum ammi* L (Sprague) belongs to family apiaceae and requires improvement for high yield, higher volatile oil content, resistance to powdery mildew and root rot disease. The suitable varieties are Ajmer Ajwain 1 (NRCSS-AA-1), Ajmer Ajwain 2 (NRCSS-AA-2), Pratap Ajwain 1 for Rajasthan; GA-1 for Gujarat; Lam Selection-1, Lam Selection–2 for Andhra Pradesh, R.A. 1-80, R.A. 19-80 for Bihar.

Nigella (K*alongi*): *Nigella sativa L.,* belongs to family *Ranunculaceae* and requires improvement for high yield, higher volatile oil content. Ajmer Kalongi 1 (NRCSS AN-1) is suitable for cultivation in semi-arid regions under irrigated conditions.

Anise (*Vilayati Saunf*): *Pimpinella anisum L.,* belongs to family apiaceae and requires improvement for high yield, higher volatile oil content and resistance to powdery mildew. The variety Ajmer Vilayati Saunf 1 (NRCSS AAni-1) is a high yielding variety suitable for cultivation in semi - arid region under irrigated conditions.

Celery (*Ajmud*): *Apium graveolens L.,* belongs to family apiaceae and requires improvement for high yield. The variety Ajmer Ajmud 1 (NRCSS A

Cel-1) is suitable for cultivation in semi-arid regions under irrigated conditions.

Future strategy for crop improvement

1. Serious attention must be paid to the systematic germplasm collection, evaluation and conservation. The prevailing diversity of these crops in remote and tribal pockets and landraces be tapped.
2. Introduction of exotic material from centre of origin and secondary centre of variability.
3. Molecularly characterization of all the germplasm with associated specific characters.
4. Free exchange of germplasm among the breeders involved in the improvement programme needs to be encouraged.
5. Mutation and biotechnological approaches to enhance the variability may be accelerated.
6. Population improvement vis-à-vis selection to be carried out.
7. Detailed studies need to be carried out on floral biology, anthesis, pollination and male sterility – both natural and induced.
8. Heterosis breeding to be initiated.
9. Breeding for disease and pest resistance, quality, stability and responsiveness to agronomical inputs.
10. Breeding varieties tolerant/resistant to abiotic stress of temperature, moisture, salinity, etc.

Range Grasses and Legumes

In the majority of pasture grasses genetic improvement through hybridization is rather difficult due to pre-dominantly apomictic mode of reproduction. Some of these grasses are facultative apomictic with varying degrees of sexuality whereas, a few others are obligate apomictic. Apomixis coupled with polyploidy causes a lot of problems in grass variety improvement programme. Further, the minute floral parts, self-sterility, plurality of species, poor seed production and complex evaluation procedures make the task of the breeder more difficult.

In grassland farming, the compatibility of genotypes with other plant types is more relevant. Not all the species are compatible to each other and this sometimes creates problems. Suitable compatible species need to be grown in the pasture for increased production. *Lasiurus sindicus* and *Cenchrus ciliaris* are more compatible with legume stylo than other legumes. In winter cropping system, suitable ideotype and their use becomes more relevant in formulating compatible mixture of grasses and legumes. The specific growth forms of grasses either artificially tailored or selected from natural source account for better production per unit area and time even with similar input levels. Although their ecological niche governs the occurrence of species, which takes into account various biotic and abiotic factors. The improvement of pasture species in a particular agro-climatic zone is of vital importance. Keeping in view the annual precipitation, its distribution, soil types, topography and temperatures, etc. the choice of suitable species is the kingpin of a pasture improvement programme.

In pasture grasses the breeding system must be determined before undertaking any breeding programme. Simple tests using porous cellophane or nylon fabric bag will indicate whether a species is self or cross-pollinated. Good seed set from bagging a single inflorescence generally indicate self-pollinated species, but in grasses it could be due to apomixis. Progeny testing and embryological studies may be necessary to distinguish between apomictic and sexual grasses.

Many important tropical grasses are apomictic including buffel grass, birdwood grass and *Panicum maximum*. Apomixis is a barrier to improvement of these grasses and can be overcome only if sexual types are found. Sexual types are found in *C. ciliaris* (Bashaw, 1962) and *P. maximum*. Most of the sexual tropical grasses viz., *Setaria* and *Digitaria* are predominantly cross-pollinated and self-sterile. In making crosses between ecotypes it is wise to check first that the representative genotypes are self-incompatible. The critical information in grass improvement includes magnitude of genetic variation, stability and polymorphism.

Genetic variability*:* Variability in morphological and physiological characters in 10 strains of *Cenchrus setigerus* showed that some of the strains could provide useful germplasm to breed desirable forage type for pasture production (Chakravarty and Bhati, 1968). Wide genetic variation was observed in the characters contributing to forage yield, forage quality and underground biomass for *C. ciliaris*, *C. setigerus*, *L. sindicus*, *Dichanthium annulatum* and *Pennisetum pedicellatum* (Singh and Yadav, 1971; Yadav *et al.*, 1980; Yadav and Krishna, 1985; Yadav and Krishna, 1987; Rajora, 1998). The extent of variability, heritability estimates and genetic advance were high for plant height, number of spikes/plant, spike length, seeds/spike, 1000-seed weight, seed germination and seed yield in winter regenerated flush of *C. ciliaris* genotypes (Rajora and Singh, 2005). A wide range of variation was observed for growth habit, plant pubescence, spike colour, stigma colour root rhizome production in *C. setigerus* (Yadav, 1981). In a three year study Rajora *et al.* (2009) observed that in *C. setigerus* var. CAZRI 76 maximum variation in seed yield was due to spike density and seed yield could be harvested from the established plots up to 3 years under rainfed arid environmental conditions. High coefficient of variation, moderate to high heritability and high genetic advance were observed in *C. ciliaris*, *L. sindicus* and *D. annulatum* for tiller number, stem thickness and fodder yield. A wide range of variation was observed in *L. sindicus* for quality traits, viz. dry matter, silica, lignin and crude protein content. These characters showed high heritability and high genetic advance (Gupta and Yadav, 1985). Significant genotypic differences were observed in ten genotypes of *L. purpureus* for seed yield per plant, seeds per pod, 100-seed weight, pod length, pod weight, seed weight per pod, dry matter yield per plant and seed germination (Rajora and Yadav, 1999).

Stability: Sharma (1985) evaluated eight cultivars of *Stylosanthes* species received from Australia. Preliminary studies under irrigated conditions revealed that their germination was low; some of the cultivars did not establish and set seed. *Stylosanthes hamata* C.P.I. 38842 and *S. scabra* were superior in forage yield and seed production. Maximum dry forage yield (2.71 t ha^{-1}) was obtained from *S. scabra*. C.P.I. 40205. Suitable harvest time for maximum forage yield was found to be December. Promising strains of *C. ciliaris*, *C. setigerus*, *Pennisetum pedicellatum*, *L. sindicus*, *Dichanthium annulatum* and *Lablab purpureus* were studied under different locations, years, soil types, fertility, defoliation stress, photoperiods and grazing (Yadav, 1981; Roy *et al.*, 1995). Four genotypes of *C. ciliaris* differed significantly for plant height, spikes/plant, dry matter yield/plant, dry matter yield, seed yield/plant, seed yield and seed germination. CAZRI 358 and extant variety having maximum spikes/plant (100.4), seed yield/plant (20.74 g), seed yield ha^{-1} (266.0 kg) with high germination (44.1%), was more suitable for seed production in arid areas (Rajora *et al.* 2008).

Development of improved varieties and genetic stocks: Variety CAZRI 75 of *Cenchrus ciliaris* developed at CAZRI is tall (90-125 cm), erect, thick stemmed, leafy, drought hardy, with green yield potential of 7 t ha^{-1} $year^{-1}$ yielding 53% higher over the check var. Molopo. It has high crude protein (8.3%), which is 32% higher over the check (Yadav and Sharma, 1998). The variety CAZRI 76 of *Cenchrus setigerus* is a clonal selection from exotic material EC 17655, medium tall (50-60 cm), thin stemmed, leafy (leaf-stem ratio 2.3) foliage remains green up to December. It is drought hardy, high tillering ability (29 tillers plant^{-1}), m fast regeneration (2-3 cut in a year), average green fodder yield (4 t ha^{-1}) and 1.5 t dry ha^{-1} matter which is 38% higher over the check var. Pusa Yellow Anjan. It is also nutritious, having 9.6% crude protein at 50% flowering stage (Yadav and Sharma, 1998).

Accession CAZRI 2221 of *C. ciliaris* was identified as an *elite* genotype. It is semi-erect with has luxuriant growth, profuse tillering and branching, pink and smooth nodes, thin stem, yellowish foliage, longer leaves, high leaf: stem ratio (> 57%) than the best check. Long creamish spikes, plant height 100-105 cm. Green forage yield potential was 24 t ha^{-1}, which was 20% more than the best check. It has high survival ability under arid conditions (>6-year) and IVDMD (61.9%). The accession CAZRI 2178 had overall 15.2% more green fodder yield than the best check CAZRI 75, 59% more CP than CAZRI 75, higher survival (89.3% in 3rd year), erect, and thin stem. CAZRI 2178 can be used as a genetic stock for the improvement programme.

Genetic Improvement of Tress and Shrubs

Trees and shrubs play a great role in arid ecosystem as both human and livestock depend on these especially in drought years. The productivity of the deserts can be increased by using genetically improved stocks of trees and shrubs.

Identification of mating system in arid zone trees and shrubs: Information about the breeding system of trees and shrubs is usually lacking. Studies showed that *P. cineraria, T. undulata, S. oleoidis, S. persica, Acacia senegal* and *Azadiracta indica* have both systems of pollination. Self -pollination is dominant in most of the species, except *T. undulata* and *A. senegal* . Reproductive capacity in these trees was found to be very low (1-2% even less than that). Flowers appearing in February - April in A. indica fall before fertilization while those appearing late in April and May set into fruits. *In S. oleoides* and *S. persica* flowers appearing in December-February fall while those appearing in March-April set into fruits. Similarly, *T. undulata* flowers of November-January fall without forming fruits Seed setting during theses periods was only when the environment was conducive for the natural pollination in terms of air temperature, relative humidity and number of pollinators. Mostly trees and shrubs of this area are cross pollinated, but when the environment is not favorable for the pollinators and the dehiscence of the anthers, the same species produce seed with self pollination, but with very low in number. So, in case of trees where pods and seeds are consumed, the late flowering genotypes should be selected for better fruit set.

Exploration, collection and ex-situ conservation of diversity: Large area of Rajasthan including districts of Jodhpur, Barmer, Jalore, Bikaner, Churu and Jaisalmer and Gujarat were surveyed for distribution of species like *Prosopis cineraria, Tecomella undulata, Acacia senegal, Salvodora oleoides, S. persica, Lawsonia inermis, Cassia angustifolia* and *Commiphera wightii*. From different sites, plus trees/shrubs were identified and their seeds/cuttings were collected plant wise. Progenies of these plants were evaluated in nursery. Poor ones were rejected and the plants of better progenies were transplanted in the field as half- sib plant progenies trials in case of plants using seeds, and clones for clonally propagated species like mehndi and guggal to study the variation, heritability, genetic advance of different growth parameters over different years. More than 4000 plants of different accessions of different multipurpose trees and shrubs are being evaluated at CAZRI. Clonal seed orchard of *P. cineraria* has been established.

Selection methodology for trees of arid zone: In *T. undulata*, estimates of family heritability, single- tree habitability and genetic gains for family and mass selection indicated that the gains were low with both the methods for tree height. Components of variance tend to stabilize after fourth year of growth. So, in this tree species, mass selection will not be effective and the selection of the plants should be done after fourth year.

In *P. cineraria* and *S. oleoides* high values of heritability due to families and single trees coupled with high genetic gain suggested these trees can be improved by simple mass selection which is perhaps the easiest breeding method in forestry. To maximize gains there should be control of pollen parents, which can be achieved by progeny trials, and selecting the best families and best plants within the families. Similarly, combined selection for effective improvement in *A. senegal* has also been advocated.

Seed orchards: The half-sib progeny trials can be converted into seed orchards by removing the poor families and poor trees within the family. In *P. cineraria* eleven half-sib progenies trial establishment in 1984 by CAZRI was converted into seed orchard. Before roguing the number of surviving trees varied from 11 to 31 out of 42 trees planted per progeny. About one third of the trees which had poor growth, crooked stem, infested with galls were removed. Total of 134 trees were retained in the seed orchard. Height, collar diameter and DBH before and after roguing of the trees in the orchard showed that performance of the retained trees was 17.6% better for tree height, 19.6% for collar diameter and 25.3% for DBH than the performance before rouging

Genetic Improvement of Horticultural Plants

The Indian arid zone is characterized by high temperature and low and variable precipitation which limit the scope for high crop productivity. However, these conditions greatly favour the development of high quality in a number of fruits such as date palm, *ber*, aonla, bael, pomegranate, kinnow, lasoda. It is now realized that there is a limited scope for quantum jump in fruit and vegetable production in the traditional production areas. The recent awareness regarding the potential of these ecologically fragile lands for production of quality produce has not only opened up scope for providing sustainability for the people of this region, but also for bringing in new areas to increase horticultural production. The area expansion and yield potential of arid horticultural crops has increased because of availability of new varieties and advancement in production techniques in arid region.

Constraints in arid horticulture: The soils of arid region are very poor in fertility. The soils often have high salinity. The ground water resource is not only limited owing to poor surface and sub-surface drainage, but is also saline in quality. The irrigation water resources in the region are seasonal rivers and rivulets, surface wells and some runoff water storage devices (e.g., *nadi, tanka*, *khadins*) and canal irrigation in arid region. Thus, the water resources in arid region are limited and can irrigate hardly 4% of the area.

The annual average rainfall in the Indian arid regions is very low and varies from 100 mm in north-western sector of Jaisalmer to 450 mm in the eastern boundary or arid zone of Rajasthan. In some parts of arid region, occurrence of frost is also common features during winter season which affects vegetative growth of plants as well as productivity, quality of fruits especially in ber and aonla. There is no heat tolerant variety of arid horticultural crops which should be developed to achieve higher production.

One of the major bottlenecks in development of horticulture scenario in arid parts of the country is lack of sufficient quality seed and planting material. The weak processing infrastructure and marketing of horticultural produce, lack of proper cold storage facility and knowledge and equipment for grading and packaging of fruits and vegetables are major constraints in production.

Genetic resource management: Diversity of major arid horticultural crops is being conserved in field repository at CIAH, Bikaner and CAZRI, Jodhpur. Among 318 *ber* (*Ziziphus mauritiana*) genotypes, the *ber* varieties Gola, Seb, Umran, Kaithali and Banarasi Kadaka are performing well under hot arid climate. Varietal evaluation resulted in delineation of varieties for arid zone under different situations Early maturing varieties of *ber* such as Gola and CAZRI Gola were identified for rainfed areas, where as cultivars such as Umran, Seb, Illaichi, Tikadi, Banarasi, Dandan, etc. were found suitable under partially irrigated situations. Tikadi, a local cultivar of *ber* was found to be resistant to fruit fly (Singh and Vashishtha, 1984), but its fruit size was small. The cultivars Seb was found to be a good mid-season cultivars, but it was susceptible to fruit fly. The F_1 of Seb X Tikadi was found to be resistant to fruit fly but the dominance of Tikadi prevailed as regards to fruit size was concerned. Therefore, it was back-crossed with Seb, which resulted in acceptable fruit quality along with fruit fly resistance. Similarly hybridization was done between Seb and Katha to improve the shelf-life of Seb. The F_1 of Seb x Katha had 3 days more shelf life than Seb. Studies were also conducted on biosystematics of 59 cultivars of *ber* (Vashishtha and Pareek, 1993) which helped to divide these varieties into three groups, viz. erect, semi-erect and spreading type based on morphological characters. The cultivars Umran, Ajmeri and Katha was found to be isogenic, but named differently at various locations.

Out of 154 genotypes of pomegranate (*Punica granatum*), Jalore Seedless, Ganesh, G-137, Mridula, Phule Arakta are the better genotypes for yield and quality. Evaluation of 15 cultivars resulted in identification of the cultivars better adapted in arid regions with limited irrigation facility. Under breeding programmes, 13 cross combination were tried. The F_1 of Ganesh x Jalore Seedless, Bedana-1 x Ganesh, Bedana II x Jalore Seedless, Jalore Seedless x Ganesh and Ganesh x Bedana Bosec were found promising. The varietal evaluation of aonla (*Emblica officinalis*) revealed that the NA-7 (Neelam) is a prolific bearer followed by Chakaiya and NA-6 (Amrit).

Among 16 bael (*Aegle marmelos*) genotypes, NB-5 and NB-9 performed well under irrigated hot arid ecosystem. A five-year-old budded plant of NB-5 produced about 40 fruits tree^{-1} while NB-9 produced 29 fruits tree^{-1}. The fruit size of NB-5 is smaller (1 kg fruit^{-1}) than NB-9 (1.4 kg fruit^{-1}). The fruit quality is excellent in both the varieties. New varieties were introduced during 1983-84. Evaluation of cultivars revealed better performance in Laljeet Sambhipuri, Dhara Road and Faizabadi local. Later three accessions were added in 2003, of which two were wild type having small fruit size, but with strong flavour highly desirable quality for processing.

In National repository of date palm (*Phoenix dactylifera*), sixty indigenous and exotic cultivars/genotypes are maintained and evaluated for different horticultural traits. The cultivars Halawy, Khalas, Khuneizi, Barhee, Zahidi, Medjool, etc. are suitable for cultivation in hot arid region. In addition to this, a number of minor underutilized crops are also being conserved and evaluated for different traits (More and Singh, 2008). Out of 20 cultivars introduced and evaluated (Vashishtha, 1981), Halawy, Barhee and Muscat-2 have been found suitable for raw eating at doka stage while those of Khadrawy and Medjool for preparation of Chuhhara and Halawy, and Jahidi for pind khajoor.

The work on germplasm survey, collection and evaluation in custard apple was started in 1985.The survey of Annona growing areas revealed that in Rajasthan it occurs in wild forms in Chittor Garh, Kubhal Garh, and Aravali hill ranges. Promising seedlings were identified from the germplasm collection of various locations. Chittorgarh Local was most promising followed by Bangalore local.

Ten *gonda* accessions collected from different parts of Rajasthan and adjoining areas were evaluated for fruiting behavior and fruit yield for seven years. There was not much variation for fruit shape, size and growth habit of the plants but a great deal of variability was invariably observed in total fruit yield per plant. Four promising types were identified based on total fruit yield. Accession No. G2012, G2021, G2025 and G2061 were found to be high yielding.

Six accessions and a variety (Pant Manohar) of Karonda have been introduced at CAZRI. They could be grouped into two broad categories based on fruit colour. The selection CZK2000-1 has pink peel on white back ground with 3.4 g mean fruit weight and ovoid in shape. Another selection CZK2001-17 has purplish green color peel with mean fruit weight of 4.8 g and elongated ovoid in shape

Survey of Khejri (*Prosopis cineraria*) germplasm for desirable pod types for culinary purpose resulted in identification of two superior types of plants having longer pods and thornless. Large fruited lime (*Citrus latifolia*) is also a is high yielding fruit species with mean fruit weight of 75 g with 56.5% juice and seedless but its foliage was found to be susceptible to hot winds during summer.

Twenty five accessions of Kair (*Capparis decidua*) were collected from differenced parts of Rajasthan. Recently a yellow flowered type, different from normal scarlet red flowered and a thornless type have been added.

Realizing the importance of vegetable crops, particularly under exploited and less popular, and having commercial production potentials in arid and semi-arid regions, systematic research work on germplasm collection, conservation and utilization was started in 1993 at CIAH, Bikaner. In this context, intensive crop specific surveys in target variability pockets and explorations were undertaken in arid and semi-arid regions and a large number of land races, semi-cultivated and popular types of mateera, kachri, snap melon, beans and some perennial horticultural species of vegetables potential were made over the years for systematic evaluation, characterization and conservation of indigenous germplasm. A number of variety of arid vegetables like mateera, kachri, snap melon, Indian bean and cluster bean has been released for cultivation.

Fruit and vegetable improvement

CIAH has released 16 varieties of arid fruits and vegetable crops which includes, Thar Bhubharaj, Thar Sevika, Goma Kirti of ber, Thar Shobha of khejri, Goma Aishwarya of aonla, Thar Samridhi of bottle guard; AHW-19, AHW-65, Thar Manak of mateera; AHK-119, AHK-200 of Kachri, AHS-10, AHS-82 of snap melon, AHC-2, AHC-13 of kakri and Goma Manjri of clusterbean. A number of varieties of arid horticultural crops are at prerelease stage. These include AHRM-1 of round melon; AHG-13 in clusterbean, Indian bean AHDB-3, AHDB-16 and Sward bean (AHSB-1) besides some promising lines in ber, mulberry, lasora and ker, have been identified for evaluation and release (More *et al.*, 2008).

Varietal variation in endurance to drought has also been observed in horticultural crops. Early ripening cultivars seem to escape stress during receding soil moisture after monsoon. Ber cultivars Gola, Seb and Mundia for extremely dry areas, Banarasi Kadaka, Kaithli, Umran and Maharwali for dry regions, and Sanaur-2, Umran and Mehrun for comparatively humid regions have been recommended. Apart from morphological parameters, plants should also have physiological parameters for endurance to drought for commercial cultivation in this region. Some physiological parameters identified in *ber* are no mid day depression in photosynthetic rate, low rate of transpiration, maintenance of leaf water balance, growth, canopy development, dry matter allocation, high water-use efficiency, etc. It has been demonstrated that plant having capacity for drought endurance are able to maintain turgour, dry matter allocation, leaf and fruit growth even under low soil moisture level.

Biotechnological tools for improvement: Micropropagation has been commerciallized in many ornamental crops and herbacious fruit crop species worldwide. However, its wide spread commercial use is still limited in fruit tree species because of several inherent problems of *in vitro* culture system. Keeping in view these inherent limitaions of micropropagation of fruit tree species, a new concept of micropropagations of fruit tree species has developed using single or double node explants from the mature trees. Direct morphogenesis of shoot and root formation was achieved in lasoda (*Cordia myxa*), mulberry (*Morus alba*) and lime (*Citrus aurantifolia*) using single or double node explant having physiological active axillary buds.

In another study with citrus, direct shoot and root formation was achieved in double node explant within 35 days of culture period. These results conform the production of plantlets within a short period completely eliminating subculturing process. Thus, using this technique of micropropagation, the fruit tree species can be multiplied in vitro with minimizing inherent problems of tissue culture in greater way to obtain a large number of genetically identical, physiologically uniform and developmentally normal plantlets preferably with high photosynthetic or phototrophic potential to survive the harsh ex-vitro condition.

Attempts have been made for mass multiplication of ker through tissue culture technique since it is a hardy plant and suitable for hot arid environment. Work on date palm tissue culture is being done at various places in the country However; some good results have been achieved through organogenesis and embryogenesis in date palm tissue culture at CIAH, Bikaner.

Prospects in arid horticulture

Presently, there is a scope in expansion of horticultural crops in arid region and it has vast potential for changing scenario of horticulture of the country. Vast land resource, surplus family labourers, increasing canal irrigated area, developing infrastructural facilities, plenty of solar and wind energy, etc. are the strengths in arid region for development in arid horticulture. Further, minimum pressure of diseases and insects in the region is good scope for production of seed and planting material. Ber is commercially grown in more than 80,000 ha. with production of 0.9 million tonnes under semi arid and arid regions. It requires more attention for value addition. Pomegranate production (area 0.132 millions ha) and production (1.14 million tonnes) is increasing very fast in dry part of the country. Since, it has tremendous scope of export of this crop from semi arid and arid regions of the country. Presently, the export value from pomegranate is Rs.70 million. The crops like fig, custard apple are also coming very well under dry land conditions. At present, fig is cultivated in more than 1,000 ha area in Maharashtra, Karnataka. Likewise, custard apple is grown in about 50,000 ha area in the state of Maharashtra, A.P., Karnataka, Rajasthan and Tamil Nadu. Aonla is a medicinal fruit plant and cultivated in over 55,000 ha area producing 150 m t fruits/year. Date palm is most suitable fruit tree of hot arid region and it is grown in Rajasthan, Gujarat, Punjab and Haryana in over 12,493 ha producing 85,000 t fresh fruit. However, date is imported from Gulf countries due to its meager production. Bael is also an important fruit crop of semi-arid and arid regions. Now, attention is being given on its commercial production. India is the second largest producer of vegetables (125.88 million tonnes from 5.77 million hectare area in 2007-08). In case of vegetables in the same period the increase in area and production was observed to be 92.12 and 147.60%, respectively. In the reported period under major spices, the increase in area and production was recorded to be 6.98 and 83.73%. The per capita consumption of vegetable in the country has increased from 47 kg in 1984 to 76 kg in 2000, with annual growth rate to 2.9%. By the improvement in production technology in arid region, many seed spices likes Coriander, Cumin, Fenugreek, Ajowain, Fennel, Dill and Nigella, are being cultivated on large scale and also exported to earn foreign exchange. There is a vast potential of floriculture in some parts of Rajasthan because of low infection of disease and insects. The prospect of floriculture under hot arid condition is also important from seed and plant production point of view.

References

Bashaw, E.C. 1962. Apomixis and sexuality in buffel grass. *Crop Science* 2: 412-415.

Bidinger, F.R. and Yadav, O.P. 2009. Biomass heterosis as the basis for grain and stover yield heterosis in arid zone pearl millet (*Pennisetum glaucum* (L) R Br) hybrids. *Crop Science* 49: 107-112.

Bidinger, F.R., Serraj, R., Rizvi, S.M.H., Howarth, C., Yadav, R.S. and Hash, C.T. 2005. Field evaluation of drought tolerance QTL effects on phenotype and adaptation in pearl millet [*Pennisetum glaucum* (L) R Br.] topcross hybrids. *Field Crops Research* 94: 14–32.

Bidinger, F.R., Thakur, R.P., Yadav, O.P., Sharma, M.M. 2003b. Male-sterile seed parents for breeding landrace-based topcross hybrids of pearl millet (*Pennisetum glaucum*) for arid conditions. II. Downy mildew resistance, plant type, fertility restoration and terminal drought tolerance. *Indian Journal of Genetics & Plant Breeding* 63: 99-105.

Bidinger, F.R., Weltzien, R.E., Mahalakshmi, V., Singh, S.D. and Rao, K.P. 1994.

Evaluation of landrace topcross hybrids of pearl millet for arid zone environments. *Euphytica* 76: 215-226.

Bidinger, F.R., Yadav, O.P. and Sharma, M.M. 2002. Male-sterile seed parents for breeding landrace-based topcross hybrids of pearl millet (*Pennisetum glaucum*) for the arid zone. I. Productivity, responsiveness and stability. *Indian Journal of Genetics and Plant Breeding* 62: 121-127.

Bidinger, F.R., Yadav, O.P., Sharma, M.M., van Oosterom, E.J. and Yadav, Y.P. 2003a. Exploitation of heterosis for simultaneous improvement in both grain and stover yields of arid zone pearl millet (*Pennisetum glaucum* (L) R Br). *Field Crops Research* 83: 13-26.

Chakravarty, A.K. and Bhati, G.N. 1968. Selection of grasses and legumes for pastures of the arid and semi-arid zones. I. Variations of morphological and physiological characters in the different strains of *Cenchrus setigerus* and selection of a promising strain for forage production. *Indian Forester* 94: 667-674.

Chauhan, Y.S., Johansen, C. and Saxena, K.B. 1994. Physiological basis of yield variation in short-duration pigeonpea grown in different environments of the semi-arid tropics. *Journal of Agronomy Crop Science* 174: 163-174.

Choudhary, B.R. 2008. Inheritance of siliqua orientation and seed coat colour in *Brassica tournefortii*. *Plant Breeding* 127: 211-213.

Choudhary, B.R. and Joshi, P. 2001. Genetic diversity in advanced derivatives of *Brassica* interspecific hybrids. *Euphytica* 121: 1-7.

Choudhary, B.R. and Solanki, Z.S. 2007. Inheritance of siliqua locule number and seed coat colour in *Brassica juncea*. *Plant Breeding* 126: 104-106.

Choudhary, B.R., Solanki, Z.S. and Kumhar, S.R. 2007. *Genetic analysis in Indian mustard* (*Brassica juncea* Czern & Coss.). In Proc. 12th Int. Rapeseed Cong, Wuhan, part I, 386-388.

Fakir, M.S.A., Prodhan, A.K.M.A. and Rahman, M.L. 1992. Study of some morphological features and biomass production of pigeonpea (*Cajanus cajan*). *Legume Research* 15: 29-38.

Gupta, A.K. and Yadav, M.S. 1985. Genetic variability and association of forage quality characters in strains of *Lasiurus sindicus* Henr. *Annals of Arid Zone* 24: 57-62.

Katiyar, P.K. and Dixit, G.P. 2007. Ancestral relationship of greengram advance breeding lines developed in India. *Indian Journal of Agricultural Sciences* 77: 579-82.

Khairwal, I.S., Rai, K.N., Yadav, O.P., Rajpurohit, B.S. and Negi, S. 2009 Pearl millet cultivars: Seeds of choice. All India Coordinated Pearl Millet Improvement Project, Mandor, Jodhpur. 36 pp.

Lopez, F.B., Johansen, C. and Chauhan, Y.S. 1996. Effects of timing of drought stress on phenology, yield and yield components of short-duration pigeonpea. *Journal of Agronomy and Crop Science* 177: 311–320.

More, T.A. and Singh, R.S. 2008 Conserving biodiversity in different areas, The Hindu Survey of Indian Agriculture, Chennai, pp 50- 54..

More, T.A., Samadia, D.K., Awasthi, O.P. and Hiwale, S.S. 2008. Varieties and Hybrids of CIAH. Tech. Bull. No. 30, Bikaner, 11p.

Presterl T. and Weltzien, E. 2003. Exploiting heterosis in pearl millet population breeding in arid environments. *Crop Science* 43:767–776.

Rajora, M.P. 1998. Variability and character association in buffel grass. *Annals of Arid Zone* 37: 99-101.

Rajora, M.P. and Singh, Manjit 2005. seed yield and its components in winter regenerated flush of buffel grass (*Cenchrus ciliaris*, Linn.) under rainfed conditions of Rajasthan. *Seed Research* 33: 65-69.

Rajora, M.P. and Yadav, M.S. 1999. Analysis of seed yield components in *Lablab purpureus* L. *Annals of Arid Zone* 38: 157-160.

Rajora, M.P., Jindal, S.K. and Singh, Manjit. 2008. Seed yield components and stability analysis in buffel grass (*Cenchrus ciliaris*). *Indian Journal of Agricultural Sciences* 78(3): 225-229.

Rajora, M.P., Singh, Manjit, Jindal, S.K and Patidar, M. 2009. Seed production and germination in birdwood grass (*Cenchrus setigerus*) under hot arid conditions. *Indian Journal of Agricultural Sciences* 79: 148-151.

Reddy, B.V.S., Green, J.M. and Bisen, S.S. 1978. Genetic male-sterility in pigeonpea. *Crop Science* 18: 362–364.

Roy, P.K., Yadav, M.S. and Sudhakar, N. 1995. Analysis of genotype x environment interaction in buffel grass. *Annals of Arid Zone* 34: 111-114.

Saxena, K.B. 2005. Pigeonpea (*Cajanus cajan* (L.) Millsp.). In *Genetic Resources, Chromosome Engineering and Crop Improvement* (Eds. R.J. Singh and P.P. Jauhar), pp 86-115. Taylor and Francis, New York,

Saxena, K.B., Chauhan, Y.S, Johansen, C. and Singh, L. 1992. *Recent developments in hybrid pigeonpea research*. In *New Frontiers in Pulses Research and Development*. November 10-12, 1989. Indian Institute of Pulses Research, Kanpur, India, pp. 58–69.

Saxena, K.B., Wallis E.S. and Byth, D.E. 1983. A new gene for male sterility in pigeonpeas. *Heredity* 51: 419-421.

Sharma, S.K. 1985. Preliminary trial on *Stylosanthes* cultivars in arid regions of western Rajasthan. *Indian Journal of Range Management* 6: 13-18.

Singh, A.P. and Yadav, M.S. 1971. Internode pattern in *Pennisetum pedicellatum* Trin. *Journal of Indian Botanical Society* 50: 285-288.

Singh, M.P. and Vashishtha, B.B. 1984 Field screening of some *ber* cultivars for resistance to *ber* fruit fly. *Indian Journal of Plant Protection* 11: 55-56.

Singh, N.D., Kumar, P.A. and Jaiwal, P.K. 2003. *In vitro regeneration and genetic transformation of pigeonpea*. In Applied genetics of leguminosae biotechnology (Eds. P.K. Jaiwal and R.P. Singh). pp. 47-68.

Srivastava, N., Vadez, V., Upadhyaya, H.D. and Saxena, K.B. 2006. Screening for intra and inter specific variability for salinity tolerance in pigeonpea (*Cajanus cajan* L. Millsp.) and its related wild species. *E-Journal of SAT Agriculture Research* 2:1.

Taliaferro, C.M. and Bashaw, E.C. 1966. Inheritance and control of obligate apomixis in breeding buffelgrass. *Crop Science* 6: 473-476.

Vashishtha, B.B and Pareek,O.P.1993. Biosystematics relationship in some ber cultivars, Golden Jubilee Symposium on Horticultural Research, IIHR, Bangalore.

Yadav, M.S. 1981. Gene x environment response for fodder yield and quality characters in *Cenchrus* complex. *Ph.D. Thesis*, Jiwaji University, Gawalior.

Yadav, M.S. and Krishna G.V.S.R. 1985. Studies on variability, correlations and path analysis in *Lasiurus sindicus*. *Annals of Arid Zone* 25(2): 157-163.

Yadav, M.S. and Krishna G.V.S.R. 1987. Factor analysis of fodder yield components in *Lasiurus sindicus*. *Annals of Arid Zone* 26: 1-4.

Yadav, M.S. and Sharma, S.K. 1998. *Grasses and grassland management*. In: Fifty years of arid zone research in India (eds: A.S. Faroda and Manjit Singh). Central Arid Zone Research Institute (Indian Council of Agricultural Research), Jodhpur-342 003 India.

Yadav, M.S., Patil, B.D. and Bhagmal 1980. Biometrical approaches to selection for fodder yield attributes in arid zone grass, Buffel (*Cenchrus ciliaris* Linn.). *Annals of Arid Zone* 19: 477-479.

Yadav, O.P. 2007. Genetic diversification of landrace-based populations of pearl millet (*Pennisetum glaucum* L.R. Br.) to enhance productivity and adaptation to arid zone environments. *Indian Journal of Genetics and Plant Breeding* 67: 358-364.

Yadav, O.P. 2008. Performance of landraces, exotic elite populations and their crosses in pearl millet (*Pennisetum glaucum*) in drought and non-drought conditions. *Plant Breeding* 127: 208-210.

Yadav, O.P., Bidinger, F.R. and Sharma, M.M. 2003. Male-sterile seed parents for breeding landrace-based topcross hybrids of pearl millet (*Pennisetum glaucum*) for arid conditions III Matching A-lines and specific target environments. *Indian Journal of Genetics & Plant Breeding* 63: 106-114.

Yadav, O.P., Bidinger, F.R. and Singh, D.V. 2009. Utility of pearl millet landraces in breeding dual-purpose hybrids for arid zone environments of India. *Euphytica* 166: 239-247.

Yadav, O.P., Weltzien, R.E., Bidinger, F.R. and Mahalakshmi, V. 2000. Heterosis in landrace-based topcross hybrids of pearl millet across arid environments. *Euphytica* 112:285–295.

Yadav, R.S., Hash, C.T., Bidinger, F.R., Cavan, G.P. and Howarth, C.J. 2002. Quantitative trait loci associated with traits determining grain and stover yield in pearl millet under terminal drought stress conditions. *Theoretical & Applied Genetics* 104: 67–83.

Yadav, R.S., Hash, C.T., Bidinger, F.R., Devos, K.M. and Howarth, C.J. 2004. Genomic regions associated with grain yield and aspects of post-flowering drought tolerance in pearl millet across stress environments and testers background. *Euphytica* 136: 265– 277.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 278-353 pp.

Agronomic Management for Sustainable Crop Production in Arid Environment

N.L. Joshi[1], Devi Dayal[1], Anurag Saxena[1], R.N. Kumawat[1], Ishwar Singh[2], D.S. Bhati[3], N.D. Yadava[1], U. Burman[1], S.S. Rao[1], P.L. Regar[1], S.P.S. Tanwar[1], Harpal Singh[1] and A.K. Singh[1]

[1]*Central Arid Zone Research Institute, Jodhpur*
[2]*Agricultural Research Station, RAU, Mandor*
[3]*PC Unit, All India Coordinated Pearl Millet Imporvement Project, Agricultural Research Station, Mandor*

In the arid regions of India, over-exploited fragile natural resources are predominantly under mixed farming; (pastoral as well as arable). Total cultivated area is 59.2% and the farming is almost entirely rainfed in this zone with low and unstable yields. The climate is a major determinant of crop yields in this zone. Erratic behaviour of the meager rainfall (100-450 mm; ~90% during July-September), extreme temperatures (often >45°C in the peak of summer and sub-zero in winter) and high summer winds (>30 km h^{-1} during sandstorms in summer) are the perpetual climatic problems to reckon with, especially for agriculture. Drought is and will remain a major determinant of agriculture in the region. In western Rajasthan, which carries the onus of 62% of the arid zone, has a distinct rainfall gradient from east to west that is best reflected in the arid western plain where the mean annual rainfall varies from 100 mm in the western most part of Jaisalmer district to 370 mm in the east of Jodhpur, most of it is received during July-September.

The terrain is dominantly sandy, with sand dunes of 10-30 m average height, interspersed with interdune plains of different sizes covering more than 60% area. The soils are dominantly sandy, with 60-90% fine sand and 2-10% of silt-clay in the topsoil. These are generally low in organic carbon, low to medium in available phosphorus and medium to high in available potassium. Most of the micronutrients are adequate, but deficiency of Zn, Mn and Fe are reported from some of the intensively cropped irrigated fields, especially in the eastern half of the region.

Due to prevailing socio-economic situations, cropping in the Indian arid zone has been considered to be, by and large, a subsistence rather than commercial activity. The typical characteristics of subsistent farming is that most of the farmers resort to growing a number of rainfed crops on their farm holdings primarily to fulfill their household needs, and follow the practice of rotating a particular crop combination over a period of 3-4 years. It results in a multiplicity of cropping systems, which remain dynamic in time and space, making it difficult to precisely determine the spread of different cropping systems using conventional methods, over a larger territory. The productivity in recent past has improved due to adoption of new cultivars and technologies. Results of research efforts on various aspects of crop production in arid zone are reviewed in this chapter.

Tillage and Residue Management

Soil tilth is the physical conditions of a soil described by its bulk density, porosity, structure, roughness and aggregate characteristics as related to water, nutrient, heat and air transport, stimulation of microbial and micro fauna population and processes and impediment to seedling emergence and root penetration. Tillage is necessary to control weeds and to bring out optimum tilth and soil physical environment conducive to proper germination and crop stand establishment.

Soil type is the main factor to determine the kind and the level of tillage operations for field preparation. The light soils require less tillage than heavier soils (Venkatesswarlu, 1981). Excessive tillage on light sandy soil may be detrimental for sustainable agriculture in the arid regions due to wind erosion hazards (Gupta and Gupta, 1981). Therefore, optimum tillage practice for light soil may be different from what may be the best for heavy soil. Conservation tillage is more appropriate strategy for rainfed production system. Conservation tillage is generic term encompassing many different soil management practices. It is generally defined as tillage system that reduces loss of soil or water relative to conventional tillage, mostly a form of non-inversion tillage, allow protective amount of residue mulch on the surface. However, experiments on reduced or zero tillage in arid regions did not give encouraging results so far. Farmers generally adopt a system of plough planting which can be considered as minimum tillage.

A combination of tillage and mulches can benefit soil organic matter content, bulk density and erodibility properties besides improved soil and moisture conservation (Bhatnagar and Sur, 1984). Thus the results obtained in different locations clearly indicated that crops gave better response when tillage especially minimum/zero tillage was combined with surface residue or mulches.

When adequate crop residues are available, conservation tillage is highly effective for conserving soil and water; achieving favourable crop yields, maintaining soil organic carbon contents and soil and water quality. However, when crop residues are limited or removed for some other purposes, other tillage methods, namely, contouring, tide ridges, graded furrows terracing etc., along with appropriate conservation practices may be needed (Paul *et al.*, 1997).

Experience from several experiments in the country showed that minimum or reduced tillage does not offer any advantage over conventional tillage in terms of grain yield without incorporation of surface residues. Leaving surface residue is key to control runoff, soil erosion and hard setting in rainfed areas, which are the key problems. In view of the shortage of residue in rainfed areas, in arid regions, several alternative strategies have emerged for generation of residue either through *in situ* cultivation and incorporation as a cover crop or harvesting from perennial; plants grown on bunds and adding the green leaves as manure cum mulching. Agroforestry and alley cropping systems are other options where biomass generation can be integrated along with crop production (Venkateswarlu *et al.*, 2009).

The choice and type of tillage largely depend on the soil type and rainfall. Leaving crop residues on the surface is another important component but in rainfed areas due to its competing uses as fodder, little or no residues are available for surface application (Venketeswarlu *et al.*, 2009).

Response of field crops to tillage

In arid region, zero tillage was found to be significantly inferior to conventional tillage with pearl millet. Pearl millet yields were higher under conventional tillage over no tillage in four years continuously. In the fourth year, the crop failed completely in no till plot. The root growth was poor and considerable reduction in biomass production was noticed due to reduction in initial plant population (Aggarwal *et al.*, 1998). Studies on preparatory tillage showed that one subsurface cultivation with a sweep at the onset of the monsoon and again prior to sowing were conducive to good crop stand and higher yield of pearl millet (Mann and Singh, 1978). Yadav and Singh (1978) recorded the highest yield of pearl millet (3.6 t ha^{-1}) with one deep ploughing followed by one cross harrowing of the field. Tillage requirement has been a rapidly changing concept. Reduced tillage implies economy in time, labour and energy besides reduced soil moisture losses, maintenance of soil structure and increased cropping intensity. Singh *et al.* (1973) and Singh and Singh (1988) advocated that one tillage was enough for sandy soils that had improved the yield by 43%. However, in another study at Jodhpur, deep tillage resulted in increased yield of pearl millet over conventional and minimum tillage due to improved soil moisture storage providing relatively better moisture conditions throughout the crop growth period (Saxena *et al.*, 1997). Gupta (1987) also reported reduction in crop yield due to no tillage. To evaluate the possibilities of minimum tillage for pearl millet, the plough plant seeding and bed preparation by varying degrees of tillage were compared (Singh *et al.*, 1973). Though plough plant seeding gave grain yield statistically similar to the plots with more tillage, yet a trend of higher yield was shown by plots receiving two preparatory ploughings. Detailed studies that seeding after field preparation through harrowing was better than plough plant seeding (CAZRI 1978a). In plough plant method higher weed population (344%) and more weed dry matter (243%) as compared to one shallow preparatory tillage caused intense competition for water and nutrients to the pearl millet and consequently resulted in low yield. Almost complete control of *Cyperus rotundus* was achieved using plough board plough for seedbed preparation. If weeds could be controlled through chemical means, the practice of plough plant seeding could be advocated or else, one preparatory tillage would be a minimum requirement for satisfactory harvest from pearl millet in light arid soils (Kathju *et al.*, 1998). Praveen Kumar *et al.* (2009) reported that even after four years of cultivation, pearl millet yield under reduced tillage remained lower than in tilled plot. However its yield after legumes or after compost application under reduced tillage gradually increased and by the end of two cycles became higher than that obtained in tilled plot under continuous pearl millet cultivation.

In another experiment involving sorghum – mung bean rotation, conventional and reduced tillage were compared in an 8-year study (1998-2005). The pooled analysis indicated that reduced tillage across all integrated nutrient management treatments remained consistently lower in terms of sorghum grain yield but at the end of 8 years, the yield came close to the conventional tillage indicating that it takes long period under semiarid-arid conditions before reduced tillage comes on par with the conventional tillage (Sharma *et al.*, 2005).

In case of cow pea, deep tillage along with soil mulching increased the soil moisture content significantly over the shallow and no tillage treatment thereby affecting the grain yield favourably (Gupta and Gupta, 1986). Gupta

(1987) reported that one discing with harrow significantly increased grain yield of cowpea compared with no tillage.

Patidar *et al.* (1996) conducted field experiment on clusterbean at Jodhpur and reported that the increased tillage allowed better availability of moisture in deeper layer. WUE was maximum under disc harrowing (30.2 kg ha^{-1} cm^{-1}) followed by modified farmers practice (27 kg ha^{-1} cm^{-1}). At Bikaner, deep ploughing brought significant improvement in grain yield of crops *viz*, clusterbean, mung bean and pearl millet (CAZRI, 2006a).

At Pali deep tillage during monsoon increased the yield of taramira and mustard by 26.9 and 54%, respectively, compared to deep tillage before monsoon (CAZRI, 1999). Sundara Rajan *et al.*, (1991) observed no reduction in pod yield of groundnut as a result of no tillage under rainfed conditions. Pitting with deep ploughing was the best soil working practice for successful plantation of *A. indica*, *P. cineraria* and *T. undulata* (Gupta and Meena, 1993).

Residue Management

Pearl millet residue and stubble mulch decrease wind erosion, increase organic matter and yield of pearl millet when pearl millet stubbles of 45 cm height were left in the field at harvest (Misra, 1962). The practice however has some limitation to its large scale adoption. The farmers of the arid region are reluctant to leave stubbles in the field as these are used as animal feeds.

In a study conducted by Painuli and Ahuja (2009), regarding uses of pearl millet residue in arid ecosystem, it was found that farmers were aware of the benefits of utilizing residue in field however, farmers used residue as fuel and fodder but might spare it for field use provided supply of fuel and fodder was ensured. They further observed that about 71-90.5% of the farmers used residue as fuel, whereas residue use as fodder ranged from 76-90.5% in study area. Praveen Kumar *et al.* (2009) also observed that one of the reasons for lower productivity under reduced tillage is low availability of crop residue. Residue production under arid region is very low on one hand, and on the other residue of pearl millet, a major crop of the region are used as animal feed. . Further even when applied in the field on experimental scale, pearl millet residues are easily destroyed by termites. Thus scope of their application under reduced tillage is largely limited.

Crop Stand and Crust Management

Crust formation on soil surface is common in arid soils. Crusts are formed as a result of beating effect of raindrops and subsequent drying of oriented particles in compacted layer. The impact of rain on exposed soil causes structural break down. The dispersed finer fractions of soil deposit on soil surface as well as move downwards with percolating water and impregnate the soil pores. The consequent rapid drying of soil, owing to high radiation intensities available in arid areas, results in surface crust formation. These crusts cause mechanical impedance to the emerging seedlings and often result in very poor crop stands or total crop failures. Crust is thus a serious problem in the arid zone. The poor plant stand is often a serious problem encountered in crust prone soils. This is one of the major productivity constraints observed in arid and semi-arid regions of the country. Gupta and Yadav (1978) recorded low emergence of mustard (59-75% and 38-54%, under low and high crust strength, respectively) and sunflower (39-57% and 21-40%) while maximum emergence of mustard and sunflower was 68-80 and 60-65%, respectively under no crust formation. Some methods for minimizing crust impedance to seedlings emergence have been evolved at CAZRI. Farmyard manure (FYM) application on the seeded row after sowing reduced crust strength from 0.74 kg cm^{-2} to 0.33 kg cm^{-2} (CAZRI, 1976). Application of FYM over seed furrows reduced the crust strength to 49 KPa on 3rd day and 69 to 74 KPa on 7th day after sowing as compared to 108-128 KPa on 3rd day and 162-172 KPa on 7th day under drill sowing (Joshi 1987). The lower crust strength with FYM allowed higher rate and ultimate emergence with low mean period of emergence. The FYM over seed furrows firstly reduced the beating effect of raindrops and thus caused lesser breaking of aggregates. Secondly, FYM being amorphous in nature, absorbed more rain water besides its mulching effect and kept 2.26% higher moisture content in the surface layer. Other methods such as use of pearl millet husk as mulch (CAZRI, 1976) and mixing of legume (mung bean) seeds with pearl millet seeds (Joshi, 1987) have also been found satisfactory for securing better plant populations and final yields in crusted soils.

Adverse effects of crust could also be minimized by sowing the crop in furrow in ridge-furrow system. Ridge-furrow system laid out in N-S direction or with 25^{o} diversion either in west or east (NW-SE or NE-SW) was effective in combating the crust problem as it reduced wind action and lowered the soil temperature which resulted in reduced soil surface drying rate by 25-35% (Singh, 1984). The success of ridge-furrow system of land preparation was largely dependent on compactness of ridges (Joshi, 1987). The dislodging of loosely packed ridges on light arid soils due to high rain intensity after sowing resulted in poor emergence and low yields in two out of four years of study. Soil packing after sowing helps to overcome the crust problem. Beneficial effect of packing wheels attached to seed drills on the emergence of pearl millet seeding when sowing was followed by rains was observed (Yadav and Singh, 1978).

Suitable Crops and Varieties

The suitability of the crop in the region depends on many factors like soil type, rainfall pattern and socio-economic conditions. The arid zone has been endowed with variety of soils (Dhir, 1977), the choice of crops should be based on nutrient and moisture requirement *vis-à-vis* soil type. The soil fertility is quite low for crop production considering the nutrient status of the soil and nutrient requirement of the crops. Cropping systems practiced in the region are pearl millet- fallow on light to medium soils, pearl millet+moth bean-fallow on dune sand, pearl millet-sorghum/sesame on medium soils, fallow-wheat/barley on heavy soils and clusterbean-wheat on hard pan salt affected light soils (Kolarkar and Dhir, 1981).

The crop-growing period in western Rajasthan varies from less than 6 weeks to 12 weeks (Table 1). Legumes fit very well in this situation (Rao and Singh, 2004) as they have very low consumptive use (CU). The CU of moth bean, mung bean, cowpea and clusterbean was only 218, 226, 280 and 332 mm, respectively. *Kharif* pulses were found to be more drought-prone than pearl millet (Sastri *et al.,* 1984). For obtaining stable productivity in the arid region, longer duration crops like pearl millet and sorghum in 45% area, pulses in 23% area and grasses in 32% area should be considered. Venkateshwarlu (1992) gave allocation of cropping patterns depending on the rainfall distribution.

Table 1. Crop growing period in arid zone

Rainfall range (mm)	Growing season (weeks)	Cropping pattern
<150	<6	Only trees and shrubs
150-250	6-8	Grasses
250-300	8-10	Short duration pulses
300-400	10-12	Pearl millet and short duration pulses

Source: (Rao *et al.,* 1994)

Choice of a suitable variety plays paramount role for obtaining efficient and successful crop production in arid zone. Peak rainfall is received during July and August and generally recedes by first fortnight of September. Thus, the rainy season in the region remains only for 50-60 days (Rao and Singh, 1998) showing the limitation of cropping period. Hence, it is pre-requisite that variety should mature within this limited period of moisture availability. As the rainfall is very low and erratic, the high inter-annual variability of rainfall is a major single factor influencing crop yield in arid region (Rao and Singh, 1998). Some short-duration varieties that suit to this condition are: HHB 67, CZP 9803 (pearl millet), RMO 40, CAZRI moth 3 (moth bean), RMG 62 (mung bean) and RGC 936 (clusterbean), RT-13, RT-46 (sesame), CH 1, CH 4 (castor).

Sowing Time

Crop production under rainfed situation in arid regions largely depend upon the amount and distribution of rainfall. The normal annual rainfall of western Rajasthan varies from 100 mm in the north-western sector of the Jaisalmer district to 600 mm in the south-eastern sector of the Pali district (Rao and Singh, 1998). More than 85% of the total rainfall is received during the south-west monsoon between July to mid-September. The crop growing period in arid Rajasthan varies from 7 to 14 weeks depending upon the location and type of soil (Rao *et al.*, 1994). Hence, pearl millet, clusterbean, moth bean, mung bean, sesame and castor are in cultivation since ages in these regions of Western Rajasthan owing to short growing period and well matching with the rainfall pattern of the region. Though the normal period of occurrence of sowing rains in the arid Rajasthan is 1 to 15 July, rainfall records of the Indian Arid Zone shows that the sowing rains can be delayed as late as 1st week of August in western parts and 3rd week of July in the eastern parts of the western Rajasthan (Rao and Singh, 1998). With the early onset of monsoon, pearl millet and sesame get preference while with delayed onset of monsoon clusterbean, mung bean and moth bean get preference (Shankarnarayan and Singh, 1985). However, performance of clusterbean under late sown condition was invariably the best over other legumes in the arid regions (Henry, 2003).

Sowing date has considerable effect on the production and productivity of dry land crops. In *kharif* under rainfed situations, the onset of monsoons is the single most factor deciding sowing time. The onset of rainfall may be delayed by a few days to even more than four weeks compared to the normal dates of sowing. Under such situations, sowing of the crops gets delayed and the dry seeding practice of legumes and transplanting of pearl millet has been tried to compensate the delay in sowing time. If rains are delayed for a substantial period, the crops suitable for timely onset of rains may not perform well under delayed conditions. Delaying the sowing operations not only prevented rapid differentiation, but also allowed phenological stages to coincide with required atmospheric factors like photoperiodic and thermal regimes.

Pearl millet is generally sown with the onset of monsoon and seeding is the common practice. However, better results with seed sowing could only be obtained if the rains set in time from last week of June to mid-July. Drastic yield reduction has been reported in delayed sowing (CAZRI, 1978b). The thermal time requirement for different development stages was influenced by the date of sowing (Singh *et al.*, 1998). Delayed sowing in pearl millet led to shortening of vegetative phase due to lesser utilization of heat units which causes reduction of dry matter accumulation in vegetative parts of the plant and thereby lowering straw yield. (Singh *et al.*, 2001). Drastic yield reduction in millet crops has been reported in delayed sowing (Joshi, 1988). In late sowing where all the crops encountered prolonged drought, pearl millet yielded much better than other millet crops, indicating drought tolerance due to well-developed root system (Joshi, 1988). However, under delayed conditions of monsoon yield loss could be minimized by transplanting seedlings with the onset of rains. Under conditions when monsoon sets in between mid-July to mid-August, transplanting of 21-25 days old seedlings resulted in 22-36% higher grain yield than direct seeded pearl millet (Singh, 1978). Seedlings prepared on well-fertilized raised seedbed measuring 1/12th ha is sufficient to plant one hectare area. Transplanting, although labour intensive, has given reasonably good yield in the years of low rainfall and in good rainfall years also (Mann and Singh, 1978). Misra *et al.* (1966) in a laboratory study, reported differential germination response of pearl millet varieties under varying temperature. The cultivar JJN germinated better at higher temperature and, therefore was suitable for pre-monsoon dry sowing. The dry sowing (pre-monsoon) was reported to be practicable for soils that are not prone to crust formation (CAZRI, 1982). For normal sowing conditions, BJ 104 was found suitable while CM 46 was better for late sowing (CAZRI, 1980).

Traditionally, castor is grown as rainfed in different parts of the country during *kharif* season. The most ideal time to plant *kharif* castor in dry land is immediately after the receipt of rains from south west monsoon. The suggested optimum seeding time for rainfed castor in different parts of the country is second fortnight of June in Andhra Pradesh and first fortnight of July in Gujarat and Rajasthan (Ikisan, 2000). Though total yield is the summation of primary, secondary and tertiary spikes formed during the life cycle of plant, primaries contributed 59% in the total yield. Early planting results in higher yield of primaries and lower yield of tertiaries compared to delayed planting and *vice versa*. From the results of the study conducted by Kumar *et al.* (1997) it was observed that yield of primaries reduced considerably due to delayed planting of castor because production of primary spikes in castor depends largely on photoperiod (61%) and to a lesser extent on moisture adequacy index (39%). Sowing after 20th July gives poor yields in *kharif* season. Late sowings are not desirable as the incidence of serious pest, castor semi-looper will be high, which cause extensive damage to the crop. With the introduction of new, early and high yielding varieties and hybrids, its cultivation is also extended to *rabi* and summer seasons. Optimum planting time of *rabi* and summer castor for different regions varies from September to January. The optimum sowing date of *rabi* sown castor was found to be January 5 to December 20 in southern states of India (Sree and Reddy, 2004).

Being a rainfed crop, sesame is also sown with the onset of monsoon in the end of June or beginning of July in different states of the country. In Madhya Pradesh early sowing (30 June) of sesame proved most advantageous in respect of productivity and monetary returns (Thakur *et al.*, 2000) while June 20 was found optimum sowing time in Uttar Pradesh (Mishra *et al.*, 2005). In Rajasthan and Gujarat first fortnight of July is considered optimum sowing time of crop. Yield decreases progressively with the delay in planting from optimum time of sowing.

Systemic research on clusterbean agronomy was initiated in 1971 (Singh and Henry, 1981). The optimum sowing time for clusterbean is from the onset of monsoon to third week of July (Henry, 2003). Taneja *et al.* (1995) reported that 10 July is the optimum time for sowing of clusterbean, further delay in sowing to 30 July caused more than 70% reduction in the seed yield. Similarly, Bhati (1989) found that optimum sowing time of moth bean was second week of July. Sowing of moth bean beyond second rain after onset of monsoon significantly reduced the seed yield (Shekhawat, 1992). Sowing of rainfed cowpea is also done with the onset of monsoon. Cowpea, cultivar Charodi gave better performance under normal sowing while K-11 gave promising performance under late sown conditions (Henry and Daulay, 1988). Delayed sowing reduced the seed yield of mung bean (Singh and Faroda, 1982), moth bean (Bhati, 1989), cowpea and clusterbean (Sharma *et al.,* 1984). Optimum sowing time of horse gram was found 2nd fortnight of July (Sinde *et al.*, 1993).

Seed Rate and Spacing

Proper plant stand is pre requisite for successful crop production. Therefore, depth and seed rate play a vital role in maintaining the adequate plant population. Placement of seed at a proper depth would ensure conducive environment for uniform germination. Seed placement at 7.5 cm followed by 5.0 cm depth was optimum for seedling emergence and grain yield (Misra and Kumar, 1963). Seed rate depends on several factors, *viz*. method of sowing, soil moisture, seed size and purpose for which crop is grown. Use of seed in adequate amount would be helpful in maintaining the optimum plant stand and yield. The optimum seed rate of pearl millet found was 3.36 kg ha^{-1} (CAZRI, 1961).

In arid areas competition for moisture is more severe. Row spacing of 45 cm in pearl millet (Garg *et al.*, 1993), 30 cm in late sown and 45 cm spacing in early-sown clusterbean (Yadav *et al.,* 1989; Rana *et al.*, 1991), 30-40 cm in cowpea (Mali and Mali, 1991; Anitha *et al.,* 2004) and 45 cm in moth bean (Shekhawat, 1992; Yadav and Beniwal, 2006) gave the highest seed yields. The row spacing of 30 cm for unbranched and 45 cm for branched genotypes of clusterbean (Taneja *et al.,* 1982) under normal season and 40 cm row spacing in drought year gave the highest seed yield (Garg *et al.,* 2003), whereas Patel *et al.* (2004) found 45 cm row spacing as optimum.

Crop Geometry

Crop geometry is distribution and arrangement of crop plants in field. It determines the area available to each plant and the competition for inputs mainly moisture, nutrients, light and space. In arid region, particularly under rainfed condition, larger canopy may be disadvantageous as it may exhaust the available soil moisture from root zone during the drought condition (Singh, 1977). Therefore in the drought prone areas, enough considerations should be given for maintaining optimal plant stand and row spacing. While studying effect of intra row spacing and time of thinning in pearl millet hybrids, it was observed that thining at three week stage keeping 15-20 cm intra row spacing (at recommended row spacing of 45 cm) is a beneficial practice (ARS, 1990a). Garg *et al.* (1993) reported similar results. Experiment planned to judge the stage and method of thinning in pearl millet revealed that the highest mean seed yield of 746 kg ha^{-1} was observed when it was sown at 45x20 cm row x plant spacing (1.11 lac ha^{-1} plant population) which was 50, 28 and 27% higher than alternate row thinning, alternate plant thinning and 90 x 10 cm row x plant spacing, respectively (ARS, 1990 b).

Trial conducted to see effect of plant stand and row spacing in pearl millet revealed that plant population of 1.00 lac ha^{-1} recorded 1202 kg ha^{-1} higher yield over lower stand of 0.75 lac ha^{-1} (887 kg ha^{-1}). Row spacing of 45 to 60 cm was found optimum whereas 30, 75 and 90 cm row spacing reduced the yield significantly (ARS, 1991a). Five years results revealed that sowing of pearl millet at 50x15 cm (1.33 lac plants ha^{-1}) row x plant spacing recorded highest yield of 1228 kg ha^{-1} while reducing the plant stands to 0.66 lac plants ha^{-1} (50x30, 75x20, 100x15 cm rows x plant spacing) suppressed the seed yield significantly (ARS, 1991b). While exploring possibilities of other planting system Singh *et al.* (1978) reported 9% higher yield of pearl millet in paired row than in uniform row system. Rao and Joshi (1986) observed that skipping every 4th row in uniform planting system (border row system with adjusted population on hectare basis) gave 14% higher yields over uniform row system despite 25% lesser population.

In clusterbean, at Mandore, the highest grain yield of 329 kg ha^{-1} was recorded at 30x15 cm (2.22 lac plants ha^{-1}) sown crop which was at par with 45x10 cm (2.22 lac plants ha^{-1}, 308 kg ha^{-1}) but was significantly superior over 45x15 cm, 1.48 lac plants ha^{-1} and 30x10 cm, 3.33 lac plants ha^{-1} (ARS, 1994). At Hissar, Yadav *et al.* (1992) and Rana *et al.* (1991) reported that 30 cm row spacing under late sown condition and 45 cm spacing under early sown condition for clusterbean gave better results.

Reducing plant population from 1.33 lac ha^{-1} to 0.66 lac ha^{-1} in various crop geometries did not significantly affect the seed yield of mothbean (ARS, 1985a). Yadav and Gupta (1990) observed that mung bean, moth bean and clusterbean produced higher branches $plant^{-1}$ and dry matter at wider row spacing whereas under paired row arrangement system it was at par under low and erratic rainfall condition. Moth bean variety 'RMO 40' which is erect in growth, recorded highest mean seed yield of 755 kg ha^{-1} when sown at 30 cm row spacing indicating need of higher seed rate (15 kg ha^{-1}) whereas 'Jwala' and 'IPCMO-880' which are creeping/spreading in nature gave better performance at seed rate of 10 kg ha^{-1} (ARS, 1991c). Moth bean has deep root system which can extract moisture from much lower portion of soil. The habits of fast canopy coverage at early vegetative stage conserved moisture which is utilized by the moth bean plant at reproductive stage hence the crop perform better under drought/moisture stress at later stage of growth.

Dauley and Singh (1982) observed that sesame yields was highest with lowest plant density (2.50 lac plants ha^{-1}) in subnormal years whereas in the good rainfall year plant densities did not influence the seed yield significantly. Single stem sesame variety 'C-50' preferred 30x8 cm crop geometry whereas branched variety 'TC 25' gave better result at 30x15 and 30x10 cm geometries (ARS, 1985b). Trial conducted to study effect of intra row spacing in sesame at 30 cm row-to-row spacing revealed that 15 cm intra row spacing produced maximum seed yield of 563 kg ha^{-1} which was at par with 10 cm intra row spacing (554 kg ha^{-1}). However, 15 and 10 cm intra row spacing remained significantly superior over 8 cm intra row spacing indicating plant stand of 2-3 lac ha^{-1} in sesame is sufficient to achieve good yield under arid environmental conditions (ARS,1990c). A study conducted to see performance of newly released sesame varieties (RT 127, RT 46 and RT 274) at varying crop geometry revealed that these varieties recorded significantly higher seed yield at 30x15 cm (632 kg ha^{-1}) crop geometry than 30x10 cm (596 kg ha^{-1}) and 30x08 cm (531 kg ha^{-1}) crop geometries (ARS, 1996).

Castor plants which are prolific in growth produced maximum seed yield of 3732 kg ha^{-1} at 90x60 cm row x plant spacing closely followed by 60x60 cm (3616 kg ha^{-1}) geometry. At 60x30 cm spacing castor produced lowest seed yield of 3320 kg ha^{-1} (ARS, 1992a). At Mandore, it was concluded that planting senna at 45 cm row spacing gave the highest mean leaf yield of 1253 kg ha^{-1} followed by 30 cm (1180 kg ha^{-1}). However, the highest net return (Rs. 6392 ha^{-1}) and B:C ratio (1.73) was observed in 60 cm row spacing. Plant to plant spacing of 10 cm gave maximum seed yield of 1257 kg ha^{-1} (ARS, 1997a). Bhan and Misra (1970) reported that under arid conditions increased spacing between peanut plants favored the development of roots and nodules formation.

Intercropping

Inter/mixed cropping system is the best way to minimize the risk and sustain the production in arid zones. The intercropping increases the yield and stabilizes production (Waghmare and Singh, 1982) by not only with increasing water (Singh and Joshi, 1994, 1997) and nutrient/fertilizer use efficiency (De, 1980) but also due to minimising the competition for space and improved light energy conversion (Joshi, 1999). Intercropping suppresses weeds better than sole cropping and thus provides an opportunity to utilize the crops themselves as a tool of a weed management. Intercropping of pearl millet also found the reduce the intensity of diseases and pest like yellow mosaic disease in moth bean (ARS, 1997c) Hence, among the feasible approaches to overcome the constraints of low production the intercropping has been recognized as a potential system to increase production in arid and semi-arid zones (Willey, 1979a). The sustainable yield advantage may be especially important because they are achieved not by means of costly inputs but by simple exponent of growing crops together (Willey, 1979b) and better resource utilization (Joshi, 1999). Thus, the intercrops make better use of resources over time than the two sole crops (Natarajan and Willy, 1986). Intercropping improves soil fertility and has yield advantage in comparison of cereal crops, besides providing insurance against complete crop failure and high sustainable yield compared to the sole cropping (Joshi, 1999a, ARS, 1992c). To get best results, a suitable mixed or intercropping system i.e., row arrangement in intercrop and seed proportion in mixed cropping is desired as per the availability of soil moisture, climatic and soil condition of the field. The selection of main and intercrop and their cultivars mainly depends upon rainfall pattern and its amount, rate of evapo-transpiration soil types and it's water retention capacity and soil moisture available at the time of sowing. Moth bean varieties, IPCMO 880, RMO 256, Jwala and Jadia were found suitable for next cropping with pearl millet crop (ARS, 1991d and ARS, 1997c). Mixed or intercropping are practices in rainfed areas of Rajasthan in particular for reduction of risk but now recently intercropping has been recognized as potentially beneficial system in crop production. The productivity in terms of base (main)-crop equivalent in dry land agriculture increases by 700-2500 kg ha^{-1}, thereby achieve additional monetary return of 15-100% as compared to sole crop (Rathore, 1992). Advantage of inter cropping over sole cropping had also been reported by many other workers (De and Singh, 1981; Bhati, 1992, 1997).

On the basis of plant population pressure of the main and inter/mixed crops, there are two types of systems, one is of additive type in which the plant population of main crop is kept as per recommendation and in addition to this excess plant population of inter crop is grown simply by row adjustment like paired planting of main crop and adjusting one or two additional rows of intercrop, and in case of mixed cropping, recommended seed rate (RSR) of main crop and in addition to this 10-40% additional RSR of mixed crop is mixed. Other is replacement inter/mixed cropping system in which plant population of main crop is reduced by about 30 to 40% and replaced with plant population of inter/mixed crop. To ensure soil moisture up to crop maturity period in arid Zone, where rain fall is less than 350 mm, and less soil moisture is available at the time of sowing replacement system of inter/mixed crop may be beneficial. Additive inter/mixed cropping system is suitable in areas where rain fall is sufficient and water holding capacity of the soil is good so that soil moisture may remain available till the crop is mature. Under limited and varying moisture supply conditions, the number of plant per unit area should be a guiding factor for yield responses. Osiru and Willey (1972) and Joshi (1999a) indicated that where intercropping gives advantages, the total optimum population may be higher than either of sole crops under semi-arid conditions (additive intercropping system). But higher plant population may lead to intense competition for limited available moisture in early growth stages and leave no moisture for reproductive stages (Joshi, 1999a). On the other hand, sub-optimal crop stands can also reduce the yields as the area of polygon space occupied by the plant in a non-linear fashion (Willey and Heath, 1969) performance of intercropping relative to sole cropping was found to be enhanced under limited moisture availability (Natrajan and Willey, 1986).

Mixed cropping of pearl millet with one or two grain legumes from clusterbean, moth bean and/or mung bean, sesame and few seeds of *mathira*, *tumba*, *kakari*, and/or *kachari* mixed together is locally known as *Tera*. Sowing of *Tera* is common practice in extremely arid zone of the western Rajasthan. On the basis of this, experiment was planed to find out a suitable mixture of different crops for arid zone under rainfed condition at Mandor which revealed that 75% of recommended seed of pearl millet + 50% RSR of clusterbean, moth bean and sesame (1:1:1 ratio) gave higher monetary returns than any other different mixtures and their sole crop tried (ARS, 1983). In another experiment on mixed cropping of pearl millet + grain legumes, 100% RSR of pearl millet + 75% of RSR of moth bean and 75% RSR of pearl millet + 25% RSR of clusterbean was found appropriate seed ratio for realizing higher pearl millet equivalent yield and net return compare to sole crop of pearl millet (ARS, 1992b). Similarly, experiment conducted at Mandor on mixed of pearl millet grain legume revealed that mixed cropped of pearl millet + mung bean at the seed rate of 2:1 RSR was found effective and gave higher pearl millet grain yield (2017 kg ha^{-1}) over other system of mixed intercropping and sole pearl millet, mung bean clusterbean and moth bean (ARS, 1990d). A mixture of 75% of recommended seed rate of pearl millet + 25% of recommended seed rate of each moth bean, cluster bean and mung bean in arid zone (ARS, 1992b).

In pearl millet grain legume intercropping of at paired planting system of 30/60 cm row spacing and taking one row of intercrop (clusterbean/moth bean) in the space left between the paid rows were found more remunerative under rainfed condition compare to sole crops (ARS, 1997b). In one of the experiment conducted at Mandor for 4 years revealed that sowing of pearl millet + sesame 1:1 row gave higher return (Rs. 3398 ha^{-1}) than any other intercrop system and sole crops (ARS, 1988).

Due to occurrence of severe or moderate drought the possibility of totally or partially failure of annual grain crop become more common. Under such condition, sowing of *Tumba* at 10 m row spacing and intra row spacing sowing of pearl millet/clusterbean 2 m away from *Tumba* rows were found to get some yield from *Tumba* and or intercrop under such harsh condition (ARS, 1993).

Singh and Joshi (1980) found better land utilization due to legume intercropping than sole crop of pearl millet in arid zone of Rajasthan. Joshi (1999) recorded that without any significant reduction in the yield and energy output of pearl millet, additional yield of 265, 291 and 268 kg ha^{-1} of moth bean, mean gram and clusterbean, respectively in paired rows of pearl millet with one row of grain legume in the inter pair space under rainfed condition of arid zone.

Rathore *et al.* (2006) obtained higher pearl millet equivalent yield, land equivalent ratio (LER) and gross return with intercropping of pearl millet and clusterbean as compared to pearl millet, moth bean intercropping. They further observed that intercropping system of 2:4 (pearl millet : legume) was more beneficial as compared to 1:1, 1:2, 2:1, 2:2 and 4:2 as well as sole crop of pearl millet, clusterbean and moth bean. Similarly, in northern dry zone (zone III) of Karnataka on shallow black soils, intercropping of pearl millet + groundnut in 2:4 and pearl millet + pigeon pea in 4:2 row proportion gave higher production (Kalaghatiagi, 1995). Whereas, Reddy and Willey (1981) reported in semi-arid condition of Hyderabad higher yield from pearl millet + groundnut intercropping as compared to sole crop. Mixed/ intercropping of cereals like pearl millet, sorghum and maize with grain legume like cluster bean, moth bean, cowpea also increased the yield and quality of green fodder (Jatasra *et al.*, 1990, Tripathi *et al.*,1990).

Intercropping of grasses like *dhaman* (*Cenchurs ciliaris*) and s*ewan (Lasiurus sindicus*) with grain legumes like moth bean, clusterbean or mung bean increased the fodder yield of grasses by 20-30% as compared to grasses alone on deep loamy soil (Daulay *et al.*, 1968). During drought year clusterbean was found to be best legumes for intercrop. Faroda (1998) reported that the overall productivity of grassland under dryland condition in arid zone can be increased by incorporating (mixing) perennial legumes like *Lablab purpureum, Clitoria ternatea* and *Stylosynthes* spp.

Mixed/intercropping of cereals like pearl millet, sorghum and maize with legumes like clusterbean moth bean and cowpea increase the yield and quality of green fodder (Jatasra *et al.*, 1990 and Tripathi *et al.*, 1990). Similarly, Alagundagi *et al.* (2002) observed that intercropping of sweet sorghum + cow pea/field bean in rainfed condition of Dharwad (Karnataka) in 2:1 proportion for producing higher green forage yield with better probability.

Growing of castor as a main crop and legumes like clusterbean, mung bean, black gram as intercrop under dryland condition on medium texture soil Rajasthan and Gujarat increased net return and LER as compared to intercropping with cereals and sole crops (Gupta and Rathore, 1993; Singh and Singh, 1988). On light textured soils of Bikaner (Rajasthan) intercropping of castor and pearl millet with mung bean and clusterbean were found beneficial under rainfed condition, but pearl millet based cropping system was better over castor based intercropping (Yadava and Beniwal, 1999).

Cropping Systems

To sustain the arid agriculture, efficient cropping systems contribute to a great extent. An effective crop rotation not only helps to increase the crop productivity and soil fertility, but also improve the water and nutrients use efficiency by reducing weeds, providing conducive micro-climatic for plant growth and development, reduction in soil thermal regime and improving physical properties of the soil. Long term experiment conducted in the rainfed condition on light textures soils of Jodhpur revealed that grain legume – pearl millet rotation should be followed in place of mono-cropping of pearl millet after pearl millet to maintain the soil health and sustained the crop production. This system also saves the phosphatic fertilizer by applying in alternate year to legume crop (ARS, 1995). Moth bean - pearl millet rotation was found most remunerative in this experiment. Pearl millet - mustard system gave the highest pearl millet equivalent yield as well as net returns (Saxena *et al.*, 2003). Weed infestation was least in pearl millet – mustard rotation as mustard residue on decomposition release S containing volatile compounds, which were effective in controlling weeds (Saxena and Lodha, 2003). Pearl millet - clusterbean rotation gave 11% higher pearl millet yield compared to continuous pearl millet cultivation (Singh *et al.*, 1985). Saxena *et al.* (1997) reported 23.6% higher grain yield of pearl millet when it was grown after clusterbean compared to continuous pearl millet. During years of good rainfall, for double cropping under rainfed condition, growing of legumes crops like mung bean, urd bean or cowpea for grain and clusterbean, sorghum or pearl millet as fodder crop in *kharif* and mustard in *rabi* as rainfed crop is most common. In monocropping system, moisture conservation is done during *kharif* season with ploughing and planking the field after every effective rains at field condition than mustard or barley is grown during rabi on conserved soil moisture as their inter crop or sole crop.

Nutrient Management

The fertilizer use in the arid zone is very low and irrational. The average production level is 320 kg ha^{-1} and fertilizer use is about 2.0 kg and 27 kg ha^{-1} in *kharif* and *rabi*, respectively. The nutrient balance with respect to N, P_2O_5 and K_2O shows a deficit of about 90.4, 14.3 and 95.4 thousands tones and the gap is expected to widen in near future. In these areas application of nutrients or follow-up of integrated nutrient management is very important for increasing the production as well as maintaining the soil fertility status in future (Venkateswarlu and Aggarwal, 1991). There is direct relationship between nutrient applied and yield obtained. It has been estimated that for every ton of grain yield of cereals approximately 50-60 kg ha^{-1} nutrient must be applied and also the applied fertilizers like: N, P and K must be in a desired proportion.

Nitrogen

Rainfed arid lands are deficient in nitrogen but marked responses had been received to applied nitrogen in majority of crops. Different experiments all over India under AICRP project has proved that one kg of fertilizer N produced additional yield of 4.3 to 38 kg in different crops under different rainfall situations. Response of fertilizer-N depends on the time and method of application, received rainfall, crop type and cropping season. The application of nitrogen is affected by climate and moisture status in soil. A very high correlation between the climatic parameter and nitrogen losses and its utilization by crop has been described by different workers. In arid situation due to high temperature the losses of nitrogenous fertilizers becomes more. Shrotriya *et al.* (1966) in a study of correlation between the climatic parameter with nitrogen economy in relation to grain and straw yield reported that increasing yield responses were obtained up to 112 kg N ha^{-1} which was statistically significant over 0, 22.4 and 44.8 kg N ha^{-1} in pearl millet. Application of 55 kg N ha^{-1} at sowing, half as ammonium sulphate and half as compost gave highest test weight, maximum content of protein and yield of pearl millet (Tomer , 1970).

Nitrogen application always increases the growth of crop plants which proved a boon for forage production when they are cut at green stage. Singh *et al.* (1971a) reported that in fodder sorghum, application of nitrogen increased the forage yield and 24 kg N ha^{-1} was optimum for the total yield of dry matter obtained from different crop mixtures (cowpea, clusterbean and mung bean) including sorghum alone. Singh *et al.* (1971b) reported that the yield of green forage increased with the increasing level of N but 53.7 kg N

ha^{-1} was found to be optimum. The response of N increased at the normal rainfall, but decreased with high rainfall. The yield of pearl millet was doubled with the application of 40 kg N ha^{-1} (Singh *et al.*, 1979). Agarwal *et al.* (1997) reported that the efficiency of inorganic N fertilizer is very poor. In an economic analysis of response of the pearl millet genotypes under rainfed condition for pearl millet a dose of 40 kg N ha^{-1} could be recommended (Porwal and Mathur, 1973).

Increased nitrogen use efficiency in crops has been reported by many workers in different crops. Singh *et al.* (1973) working on the tillage and N interaction effect on pearl millet reported that application of FYM to supply11.2 and 22.4 kg N ha^{-1} increased the grain yield over control by 60 and 100 kg ha^{-1}. Ammonium sulphate on equal N basis gave higher yield and profit. Faroda (1974) reported that significant increase in plant height, green and dry matter production of anjan grass was obtained with increasing dose of nitrogen. Application of 20 kg N ha^{-1} was economical dose for anjan grass (*Cenchrus ciliaris*).

The fertilizer application in different intercropping systems has been reported recording the benefits to the intercrops during fertilization in main crop. Singh and Singh (1977) working on intercropping of annual legumes with sunflower reported that application of 60 kg N ha^{-1} to sunflower grown as a pure crop led to significant increase in yield over 30 kg N ha^{-1} and control. However, in case of intercropping system involving mung bean and cowpea application of 30 kg N ha^{-1} in second year gave as good yield as obtained with 60 kg N ha^{-1}.

The placement or broadcasted application of nitrogen at the rate of 40 kg N ha^{-1} increased the grain yield of pearl millet from 44-96% over the control. The response at different doses of N application at 40, 80 and 120 kg ha^{-1} was 10, 5.3 and 3.4 kg grain kg^{-1} N. The half dose of N (20 kg N ha^{-1}) as a deep placement (10 cm deep) at the time of sowing and remaining half (20 kg N ha^{-1}) as a top dressing at 35-40 days after sowing was found to be more economical (Singh *et al.*, 1978). Singh *et al.* (1981) reported that in pearl millet - pearl millet system application of 40 kg N ha^{-1} every year was superior over application of sheep manure at the rate of 40 tones ha^{-1} once in 2 years. The application of sheep manure also increased the WUE and soil organic carbon.

In rainfed condition the water use efficiency of pearl millet in terms of kg grain produced per mm of evapo-transpiration was highest with 60 kg N ha^{-1} which was 3.54, 5.38 and 4.83 kg per mm under N_0, N_{60} and N_{120} kg N ha^{-1}, respectively (Krishnan *et al.*, 1981). Singh *et al.* (1981) reported that continuous application of sheep manure gave substantially higher yields over application of urea alone. Daulay and Singh (1982) reported that the seed yield increased with the increase in N dose in sesame. The response per kg N was 9.3 kg seed at 30 kg N ha^{-1} and 8.0 kg seed at 60 kg N ha^{-1}. Bhati and Singh, (1982) working on fertilizer management in perennial grasses reported that dry matter and crude protein yields along with the growth parameters and N, P uptake increased with the application of 60 kg N ha^{-1} in *Cenchrus setigerus*.

Application of 40 kg N ha^{-1} significantly increased the grain and stover production of pearl millet (Joshi and Singh 1985). Joshi and Singh (1985) reported that nitrogen alone as an independent input increased the grain yield of pearl millet linearly up to 40 kg N ha^{-1}. Joshi and Kalla (1986) found that the nitrogen alone could not generate the coefficient (R^2) more than 18%. The highest nitrogen use efficiency for maximized and optimized production was 17.86 and 20.56 kg grain per kg nitrogen in pearl millet with var. BJ 104. Application of small quantity of ammonium sulphate before the use of urea increases the efficiency of nitrogen (Kumar and Agarwal, 1988). Aggarwal and Venkateswarlu, (1989) suggested that for better response of crops, apply the nitrogen fertilizers with bulky manure.

Nitrogen application not only improves the yield of cereal crop but also has marked influence on the performance of legumes in arid region (Yadav *et al*., 1990) and performance of oilseed crops, viz., sesame (Daulay and Singh, 1982) and sunflower (Daulay and Singh, 1980).

Application of 80 kg N ha-1 was as good as 120 kg N ha-1 but proved superior to 40 kg N ha-1 and resulted in 72% increased in grain yield of pearl millet (Parihar *et al*., 1998; Aggarwal and Kumar, 1996). Application of crop along with 20 kg fertilizer N ha-1 provided pearl millet grain yield equivalent to that of 40 kg fertilizer N with no residue (Aggarwal *et al*., 1997). Yadava and Beniwal (2000) working on the nutrient management on perennial grasses under rainfed condition at Bikaner reported highest dry matter yield of 4.70 and 4.53 t ha^{-1} of Cenchrus ciliaris and Lasiurus sindicus, respectively, at 40 kg N ha^{-1}, which was significantly higher over control.

At Bikaner under rainfed condition the highest plant height, total dry matter production of pearl millet was recorded at 5 tone FYM ha^{-1} + 40 kg N ha^{-1} during 1995 which was at par with 2.5 tone FYM ha^{-1} +20 kg N ha^{-1} but significantly higher over the yield obtained during 1994 at same level of fertilization (Yadava and Beniwal, 2001). At Hissar the application of 20 kg N ha^{-1} recorded highest clusterbean yield of 790 kg ha^{-1}, which declined to 640 kg ha^{-1} at 40 kg N ha^{-1}. The green and dry matter yield was not affected due to increase in N doses while crude protein was affected significantly. Singh and Khan (2003) reported that application of 20 kg N+ 40 kg P_2O_5 ha^{-1} significantly increased the grain yield of clusterbean by 25.1% while water use efficiency was 21.7% higher over control. Yadava *et al.* (2008) reported that among different verities of clusterbean var. RGC-986 gave highest grain and straw yield at 10N +20 P_2O_5 kg ha^{-1} under rainfed condition.

Phosphorous

Phosphorus is a major nutrient playing very important role in plant metabolism. Deficiency of phosphorus in soil leads to severe disorders in the plant and hence affects the productivity potential. The phosphorus deficiency affects the nitrogen fixation and other metabolic activity of legumes. Experiment conducted at Mandore (Jodhpur) on the method of application of different fertilizers on pearl millet revealed that the method of application *i.e.,* broadcast or placement of phosphorus has no effect on yield. Basal application of 30 kg N ha^{-1} with 15 kg P_2O_5 ha^{-1} gave the highest yield of pearl millet (Mehta *et al.*, 1970).

Response of arid legumes to phosphorus fertilization has been observed in rainfed as well as in irrigated conditions in sandy loam soils of western Rajasthan. Tomer *et al*. (1973) reported that application of 40 kgP_2O_5 ha^{-1} significantly increased the forage yield of clusterbean over control but no substantial yield beyond 40kg P_2O_5 ha^{-1}. Study on response of moth bean to different nitrogen doses in arid zone revealed that application of phosphorus did not affect the seed yield of moth bean (Singh and Singh, 1980) where as application of 30 kg P_2O_5 ha^{-1} and inoculation of seed of moth bean with 'Nitragin' resulted the significant increase in yield in 1978 (Singh and Singh 1981). Singh (1982) reported that application of 30 to 60 kg ha^{-1} phosphorus increased the grain and straw yield of mung bean in arid zone over control. The placement of fertilizer was better over broadcast and the response varied from 1.3-2.7 kg per kg P_2O_5 in normal sown and 0.9-2.0 kg per kg P_2O_5 in case of late sown crop.

A 16-year study on pearl millet revealed that pearl millet grown with clusterbean gave 11% higher yield over pearl millet - pearl millet rotation. Application of 26 kg P_2O_5 ha^{-1} applied once in 2 years to legume instead of to pearl millet in rotation gave 36% higher yield. Application of 60 kg N ha^{-1} +

26 kg P_2O_5 ha^{-1} to legume in alternate years resulted in high yields and maintained the soil productivity (Singh *et al*., 1985).

In loamy sand soil of Haryana with moderate phosphorus status, 13.2 kg P ha^{-1} was found as the economic dose (Dahiya *et al*., 1986). Joshi and Mali (2004) reported that gum content increased with the application of 10 kg P ha^{-1} over control. Kathju *et al*. (1987) reported that application of phosphorus did not reveal any marked effect in different arid legumes on consumptive moisture use under rainfed condition. The effect on seed yield was very marginal and not significant. The weight of nodules increased with the increase in P level from 40-60 kg ha^{-1}, which was more in clusterbean followed by mung bean and moth bean.

The quantum of phosphorus that need to be applied in rainfed crops largely depend the soil type and type of crop. It was found that the response of rainfed crops to phosphorus will not be increased without the increase in soil moisture contents through efficient rainwater management (Katyal *et al*., 1987).

In cowpea the dry weight of nodules, nitrogen accumulation in nodules uptake and other yield attributing characters improved with phosphorus application .The graded dose of phosphorus significantly affected the grain yield whereas the phosphorus at 17.2 kg ha^{-1} registered the highest yield (Mali and Mali, 1991).

Application of 40 kg P_2O_5 ha^{-1} significantly increased the height, branches $plant^{-1}$, pods $plant^{-1}$, pod length, seed pod^{-1} and test weight compared with that of 20 kg P_2O_5 ha^{-1} Bhati (1993). Phosphorous application was found to improve the pearl millet seed yield (Singh and Singh, 2002), and nodulation and seed yield in arid legumes (Mali and Mali, 1991). Application of 18 kg P ha^{-1} was found superior to 9 kg with regard to increase in yield and yield attributes of clusterbean in loamy sand soil (Shivran *et al*., 1996). Bhadoria *et al.* (1997) reported that clusterbean yield increased with the successive increase of 20 kg P_2O_5 ha^{-1} up to a level of 60 kg P_2O_5 ha^{-1} that was 44.7% over control at Gwalior. Application of 30 kg P_2O_5 ha^{-1} increased the seed yield of clusterbean significantly by 16% over control, however there was no additional benefits of 60 kg P_2O_5 over 30 kg P_2O_5 ha^{-1}. At Bikaner application of 40 kg P_2O_5 ha^{-1} significantly increased the growth and yield of clusterbean, which was 38.4 and 22.7% over control and 20 kg P_2O_5 ha^{-1}, respectively (Solanki *et al.,* 1998).

Nagar (2001) also reported the beneficial effects of P on growth of clusterbean. Growth improvement under increased P application may increase the metabolic processes in the plant, resulting in greater meristematic activity and apical growth, thereby improving the growth parameters and ultimately resulting in improved photosynthetic surface of the plant. Singh *et al.* (2001) reported that application of phosphorus at the rate of 60 kg P_2O_5 ha^{-1} gave significantly higher grain yield of pearl millet as compared to control. The increase in yield was recorded from 858 kg ha^{-1} (control) to 1107 kg ha^{-1} (60 kg P_2O_5 ha^{-1}).

The application of 60 kgP_2O_5 ha^{-1} increased the seed yield of clusterbean by 27.3 and 11.9% over control and 30kg P_2O_5 ha^{-1}, respectively (Kumawat and Khangrote, 2001). The increased availability of P increased growth and yield attributing characters which reflected in higher yield of pearl millet (Jat and Shaktawat, 2003). Application of 25 kg P ha^{-1} resulted in 9.13% higher crude protein and gum contents besides significantly increasing seed yield over control and 13.2 kg P ha^{-1} (Joshi and Mali, 2004).

A recent study showed that application of phosphorus beyond 20 kg ha^{-1} has no response towards increase in yield of clusterbean (Kumar *et al.*, 2005). Kandpal *et al.* (2006) working at Jaisalmer under rainfed condition reported that highest growth and yield of moth bean was recorded at 20N+40 P_2O_5 kg ha^{-1}, which was higher by 21.1% in plant height, 15.3% in biomass $plant^{-1}$, 9.6% in seed yield and 24.4% in straw yield over 10 N+20 P_2O_5 kg ha^{-1}. Highest P use efficiency has also been recorded at 20 kg P_2O_5 $ha^{-1}$and further increase in P_2O_5 decreased the P use efficiency (Bhunia *et al.* (2006).

Micronutrients

In rainfed arid areas especially in western Rajasthan there is generally no deficiency of micronutrients except in tube well irrigated pockets where intensive cultivation of groundnut-wheat rotation is followed from year to year. Sulphur deficiency has been observed in most of the soils put under intensive cultivation. In Haryana on an average 51.6% soils are found deficient in Zn, 24.9%, in Fe, 2.3% in Cu, 6.8% in Mn, 26.8% in S. The Zn is considered as most limiting nutrient in Haryana. At Jobner it was found that sulphur increase the growth, yield attributes, seed yield and harvest index up to a dose of 60 kg S ha^{-1} in rainfed condition. The increase in seed yield was 19.5 and 33% over 30 kg S ha^{-1} and 10 kg S ha^{-1}, respectively (Shivran *et al*., 1996).

Application of cobalt to the soil has been found beneficial for improving nodulation and nitrogen fixation in clusterbean and the effect was more in the presence of seed inoculation with Rhizobium (Venkateswarlu *et al*., 1982). With the increase in cropping intensity and changes in nutrient management strategy with the application of huge quantity of N, P and K only have resulted in the deficiency of Zn and S in arid soils. It was reported that groundnut has significant response to sulphur (Bahl *et al*. 1986; Singh and Chaudhary, 1998).

Arid legumes although do not show the deficiency symptoms of micronutrient in most of the parts of rainfed areas but under intensive cultivation tracts, there are some pockets where the micronutrient deficiency has been observed. Nandwal *et al.* (1990) reported that application of zinc to clusterbean increased the nitrogenase activity, carbohydrates and protein contents, which was higher at 60 days over 80 days crop. Seed yield and dry matter production was higher with the application of zinc as $ZnSO_4$. At Gwaliar application of 40 kg S ha^{-1} increased the growth yield of clusterbean up to 10.7 and 28.3% over 20 kg S ha^{-1} and control. It also enhanced the sulphur, phosphorus, protein and gum content in seed. Under rainfed condition, application of S at the rate of 20 kg ha^{-1} increased the yield of clusterbean at SK Nagar. The application of sulphur did not affect the status of N and P in soil. In case of supplement through different sources the studies at Bikaner showed that application of sulphur through Gypsum was better than Pyrite and increased in seed yield with 30 kg S ha^{-1}.

The pearl millet crop has also shown responses to micronutrients in some pockets of western Rajasthan, but in Jodhpur conditions effect of sulphur application to pearl millet was found non-significant (Singh *et al.,* 2001). Studies showed that foliar spray of one kg $ZnSO_4$ ha^{-1} (0.2%) on clusterbean at 45 days of sowing was better than soil application of 5-10 kg Zn ha^{-1}. At Bawal, application of 0.5% $ZnSO_4$ either at 25 or 45 days after sowing or at both the stages significantly increased the yield of clusterbean over control and 25 kg $ZnSO_4$ ha^{-1} as a basal application at the time of sowing. FeSO4 did not affect significantly the seed yield (Yadav *et al.*, 2003).

The combined application of 40 kg S ha^{-1} and 5 kg Zn ha^{-1} significantly increased the pod yield of groundnut (2251 kg ha^{-1}) where as maximum cost: benefit ratio was recorded at 40 kg S ha^{-1} +2.5 kg Zn ha^{-1} (Singh and Mann, 2007). Kumawat *et al.* (2009) reported that application of 40 kg S ha^{-1} significantly increased the grain and biological yield by 65.9 and 37.7%, respectively over control. Soil applied $FeSO_4$ (25 kg ha^{-1}) significantly improve the accumulation of dry matter, grain and biological yield of mung bean by 66.6 and 41.9%, respectively over control.

Microbial inoculants

Different types of microbial inoculants like Rhizobium, Azotobactor, PSB are available and helps in saving the fertilizer and increase the crop yield with a very little investment. Many blue green algae growing in arid zone help in controlling the soil erosion along with the promotion of soil fertility. The nitrogen-fixing bacteria are present in the Indian arid soils but they vary with increase and decrease in organic matter content in the soil.

Rhizobium inoculation alone in mung bean obviates the needs of N and P under natural conditions in arid agriculture (Singh, 1977). Microbial properties of arid soils have large variation with their land use pattern, soil moisture status and soil organic matter content (Rao and Vankateswarlu, 1983). Joshi and Rao, (1989) reported that inoculation by *Azospirillum brasilense* to pearl millet led to increase of 37.9% in tillers, 44.3% in heads and 32.1% in test weight of pearl millet. The inoculation effect was reduced with increase in N application. Soils of dry lands are considered not only thirsty but also hungry. Crops grown in dry land my not respond to the fertilizer application in some cases or other where moisture availability is poor. Integrated nutrient management also has its own restrictions in rainfed condition. Bio-fertilizer has a scope of fertilizing the crop through augmenting the nutrient supply or their enhancement in availability to crop. Most of the nitrogen-fixing bacteria relevant to the rainfed cropping are legume-*Rhizobium* symbiosis, which is related to number of pulse crops, groundnut and soybean. Most of the cultivated soils in India are reported to have relatively large population (>100 g^{-1} dry soil) of *Rhizobia* capable of nodulating the legumes.

The strains of *Azospirillum* isolated from arid zone plants were found to be tolerant to chlorides and sulphate but sensitive to carbonate. Increase in seed yield in moth bean and clusterbean has been observed by 8-15% whereas by inoculation of Azospirillum a considerable increase in yield of cereals could be obtained under normal situation in arid ecosystem (Trafdar and Rao, 1990). Very encouraging response of Phosphate solubilizing bacteria (PSB) towards the effective utilization of native P in arid soils for pearl millet has also been recorded (Tarafdar *et al*., 1991).

In mobilizing soil phosphorus some phosphatase producing fungi were identified and in their application it was found to significantly enhance the dry matter production and grain yields of clusterbean and mung bean (Tarafdar *et al*., 1995). Tarafdar and Rao (1997) reported that phosphatase activity was enhanced significantly due to VAM inoculation. An improvement in dry matter production (20-38%) and grain yield (15-22%) due to inoculation was obtained in legumes.

Application of nitrogen and phosphorus showed significant increase in growth and yield of clusterbean. Application of 10 kg N+20 kg P_2O_5 ha^{-1} + Bio fertilizer inoculation (*Rhizobium*+PSB) gave highest in seed yield (28% higher yield over control) and net returns which was at par with 20kgN+40kg P_2O_5 ha^{-1} (Singh *et al.,* 2004). Singh and Singh (2008) reported that highest yield attributes and seed yield of clusterbean was recorded with the application of 2.5 t FYM ha^{-1} + (10 kgN+20 P_2O_5 ha^{-1}) + bio-fertilizer (*Rhizobium* + PSB). The seed yield increased by 30, 14.3 and 8.3% over control, 5 t FYM ha^{-1} and 20 kg N+40 kg P_2O_5 ha^{-1}, respectively.

Integrated nutrient management

In rainfed arid situations where soils are very poor in nutrient status and losses of applied nutrient are more due to adverse climatic situations, the INM plays a very important role in crop production of this region. Leaving crop residue in soil had shown the positive effect on grain yield of crops (Hadmani *et al.*, 1982).

The application of nitrogen and phosphorus led to significantly higher uptake of N and P in both seed and straw yields of clusterbean (Yadav *et al.,* 1991). Green manuring with *Leucaena* improved the efficiency of fertilizer-N and overcome with N immobilization (Katyal and Das, 1993). Substitution of 50% of fertilizer through organic manure (FYM) resulted in higher yield levels nearly to the similar to those obtained with full fertilization (Rao and Singh, 1993). Rao and Singh (1993) reported crop residues to be as efficient sources of nutrient *as* farm yard manure and compost. It also increased the organic matter content of soil.

In arid soils application of FYM gave not only the beneficial effects but also a synergistic effect of simultaneous application of fertilizers on crop yield (Agarwal and Praveen Kumar, 1994). The yield increased with the optimum use of NPK and high yield stability was observed when recommended NPK was used with the 10 t FYM ha^{-1} (Hegde and Gajanan, 1996). The pearl millet-cluster bean rotation and monoculture of pearl millet with application of 5 t ha^{-1} FYM gave 17.2 and 6.1% higher yield than pearl millet monoculture alone, respectively (Saxena *et al.*, 1997).

Application of all needed nutrients through chemical fertilizers had deleterious effect on soil fertility leading to unsustainable yields; while integration of chemical fertilizers with organic manure and biofertilizers would be able to maintain soil fertility and sustain crop productivity (Jeyabal *et al.,* 2000). The increase in water-use efficiency under treatments having combined application of FYM and inorganic fertilizer is due to relatively rapid root and shoot growth (Ghosh *et al.,* 2003). Combined application 10 kg N + 9 kg P_2O_5 +(Rhizobium + PSB) gave at par seed yield of clusterbean but higher net returns to that recorded with 20 kg N+ 18 kg P ha^{-1} (Singh *et al.,* 2004). Kumar *et al.* (2005) reported that application of 5t FYM + 50% of recommended dose of fertilizer (40 kg N ha^{-1} + 8.75 kg P ha^{-1}) gave significantly higher dry matter in forage sorghum over control.

In clusterbean inoculation with *Rhizobium* and PSB individually increased the yield by 17.06 and 19.69% where as their combined application increased the yield by 22.35 (Anonymous, 2006a). At Jodhpur, the maximum yield of moth bean was recorded due to the integration of 2.5 t FYM + Nitrogen + Bio-fertilizer (PSB). At S.K. Nagar the inoculation of seed with PSB alone or in combination with Rhizobium resulted in significant increase in seed yield over control (Anonymous, 2007-08). In barley–moth bean rotation at Bikaner revealed that application of 10 t compost ha^{-1} +50% recommended dose of fertilizer in barley recorded highest grain and straw yield over control its residual effect on moth bean crop gave 235 and 345 kg higher grain and straw yield over control (Anonymous, 2007). Rao *et al.,* (2007) working at Pali district of Rajasthan reported that the application of 5 t FYM + 50% of recommended dose of 30 kg N ha^{-1} and 8.75 kg P ha^{-1} significantly increased green and dry fodder yield of sorghum by 35.1 and 35.7%, respectively over control. The water use efficiency in FYM treated plots was higher over control.

Crop Response to Water Stress

Growth and Yield

In general, susceptibility to drought increases with the age of the plant although magnitudes of responses may alter in different phases with respect to different characters under consideration (Lahiri and Kharabanda, 1965). A marked reduction in the growth of pearl millet with respect to height was observed when drought was imposed at the advanced stages. Similarly, for leaf number drought susceptibility increased from the 4th week stage. For the characters of time taken for ear and anther emergence, grain initiation, to attainment of milky stage and for maturation of grains, drought caused minimum adverse effect at the 3 week and the climax of sensitivity was attained at the 6th week while intermediary effects were produced at 4 and 5 week stages. The length of ear was also significantly reduced by droughting at the 5 and 6 week stages. Reduction of thousand grain weight due to drought was only found at the 6 week stage but difference over the control was of a low order of significance. Drought at the 3 week stage caused marked increase in the grain yield per ear but significant reduction was noted at 5 and 6 week stages of droughting. Thus, the reversion of drought effect in the young plants and weakening of this reversion mechanism with age suggests a close relationship of drought sensitivity and senescence in pearl millet (Lahiri and Kumar, 1966). Study also revealed that the capacity of any variety or strain to develop a root system rapidly in the early stages of growth is an important feature of drought resistance in plants (Misra, 1956). In the severe drought season, the pearl millet landraces produced significantly greater biomass, grain and stover yields than elite populations. There was a strong relation between panicle size and ability to produce panicles and delay in flowering under severe stress. it is possible to combine drought adaptation with high yield potential through hybridization between adapted landraces and elite genetic materials (Yadav, 2008). Hybrids exhibited higher grain yield, plant height and ear length along with reduced earliness over parental lines under all the environments, indicated that hybrids had better growth and vigor as compared to their inbred parental lines (Kumar *et al*., 2007).

Growth and yield of prominent oil seed crops grown in Indian arid zone were also adversely affected by soil moisture stress. Seedling stage was identified as critical stage for moisture stress in sunflower crop that is capable of surviving at very low moisture content in the soil profile (Daulay and Singh, 1983). In groundnut, however, soil moisture stress during the vegetative, flowering, pegging and early pod development caused no significant losses in yields. On the other hand plants with adequate water supply in the above phases that were exposed to stress in their late pod development and pod maturation periods showed significant reduction of yields (Ramesh Babu *et al*., 1984). Water stress significantly reduced dry matter yield, number of flowers, total and effective pegs, pod: peg ratio, pod: haulm yield ratio, pod yield and shelling percentage. These parameters decreased with increase in the cycle/period of water stress. The magnitude of reduction in pod yield due to single, double and triple cycle of water stress over that of unstressed plants was 48.2, 58.1 and 69.7%, respectively. Pod development stage alone or in combination with any other stage(s) with water stress was found most sensitive for pod yield, reproductive efficiency and shelling percentage whereas pegging stage alone or in combination with any other stage(s) was sensitive to haulm yield (Garara and Yadav, 1992). In contrast, maximum stress induced adverse effects was recorded at 30 and 40 days from sowing when the grand period of growth and flowering just commenced in sesame. Favourable moisture condition at subsequent stages did not alleviate these effects (Vyas *et al*., 1983). Further, the effects of water stress on the growth, development and yield, uptake and concentration of N and P in the shoot and also the oil, protein and carbohydrate contents of seeds at harvest generally increased with the increase in stress intensity (Vyas *et al*., 1985).

Metabolism

Results of various studies on clusterbean, mung bean, moth bean and pearl millet indicated stress mediated changes in various leaf metabolites and enzyme activities that modulated the growth and yield of the legumes (Kathju *et al*., 2001; Garg and Burman, 2002a, b). Osmotic adjustment is the active accumulation of solutes within the plant tissues in response to lowering of soil water potential. A wide variety of organic solutes in plant tissues during water stress contribute to osmotic adjustment. Stress induced accumulation of free proline, free amino acids and reducing sugars has been observed in clusterbean and moth bean (Garg *et al*., 1998, 2001a, 2005a; Vyas *et al*., 1996) and other crops. However, clusterbean and pearl millet accumulate high levels of free proline as compared to moth been and sesame plants under water deficits.

Carbon and nitrogen metabolism were also altered under water stress. Alterations in the nitrogen metabolism were largely influenced by the tissue hydration. Ammonia nitrogen, which could only be detected in the wilted plants, showed a sharp decrease on re-watering with an associated increase in the level of amide nitrogen suggesting quick incorporation of ammonia with organic acids as a measure against ammonia toxicity (Lahiri and Singh, 1968). A drop in plant water potential of -0.4 MPa significantly reduced the nitrogenase activity in clusterbean, mung bean and moth bean. The loss of activity due to water deficits varied from 13% to 100% at different growth stages and was related to the plant water potential (Venkateswarlu and Rao, 1987). The threshold limits for nitrogenase activity were found to be -2.4, -2.2 and -1.8 MPa in clusterbean, mung bean and moth bean, respectively. For a comparative stress level the activity in clusterbean was found to be the least sensitive followed by mung bean and moth bean (Rao and Venkateswarlu, 1987). The pathway of ammonia assimilation has also been shown to shift from the normal GS-GOGAT to GDH pathway under severe water stress in moth bean, which prevents accumulation of ammonia to toxic levels (Vyas *et al.* 1996). Upon re-watering, rapid recovery in the activity was noticed which seems to be related to the adaptation of this legume to arid region (Venkateswarlu *et al.,* 1983; Garg *et al.*, 2005a).

Observations on ψ_{plant}, relative leaf water content, stomatal resistance and also contents of free amino acids, free proline and soluble protein, indicated that the adverse effects of water stress were more severe in plants which were given shorter (3 and or 6 days) compared to longer (9 and 12 days) periods of adequate soil moisture between two droughts. Changes in the activities of amylase, nitrate reductase, malate dehydrogenase and glucose-6-phosphate dehydrogenase generally revealed a similar trend. Among other factors, the period of favourable moisture between droughts has a significant influence on metabolism and crop performance (Lahiri *et al.*, 1992). High leaf turgidity, net photosynthetic rate and stomatal conductance along with least alternations in metabolites in moth bean was reflected in its yield stability under drought as compared to clusterbean, mung bean and cowpea (Garg *et al.*, 2005a).

Drought Management

Utilizing genotypic variations and agronomic practices

Better crop management including appropriate planting dates, row spacing and plant populations, optimum fertilizer use and adoption of drought ameliorative measures may greatly help in alleviation of drought effects. Genotypic differences to water stress have been demonstrated in pearl millet (Garg *et al.*, 1981; Kathju *et al.*, 2001), clusterbean (Garg *et al.,*1998, 2003) and moth bean (Garg *et al.*, 2004a). Genotypic variation in the ability of pearl millet to withstand water stress is well known since early sixties. Pearl millet variety JTR (Jetsar) showed better ability to withstand drought when subjected to 5, 7 and 9 day periods of drought compared to JJNU (Jhunjhunu), SRDR (Sardarshahar) and RSK (Misra, and Daulay, 1963). Variation in adaptation of pearl millet cultivars to arid conditions was also indicated by relatively higher yields of land races than composites comparable with those of hybrids (Kathju *et al.*, 2001).

In recent years several attempts have been made to minimize the detrimental effects of drought in arid zone crops which are briefly outlined here. Both seed size and genotypes significantly influenced early vigour, number of tillers per plant, plant height, days to wilting initiation, days to permanent wilting and dry matter production. Pearl millet plants from larger seeds took longer to initiate wilting and then permanent wilting compared with plants from smaller seeds (Manga, and Yadav, 1995). Further, a moderate population of 88 888 plants ha^{-1} (equal proportion of pearl millet and clusterbean) was optimum for row intercropping (1:1) and strip cropping (4:4) in the moisture sufficient season, and low (40 000 plants ha^{-1}) to moderate populations produced satisfactory yields in the moisture stressed season. Intercropping systems used 8 to 14 mm more water than sole pearl millet, but the improvement in water use efficiency was conspicuous, more so in the moisture stressed season (Singh and Joshi, 1997). However, improved performance of individual pearl millet plants under wider spacing could not compensate for the losses accrued due to a decrease in plant population per unit area beyond a point (Garg, *et al.*, 1993).

Among arid legumes, moth bean displayed the highest drought tolerance, while the least tolerance was observed in mung bean at the vegetative and in cowpea at the flowering stage. Different legumes showed variable recovery on re-watering in their water status and most of the biochemical parameters studied, the yield and dry matter did not recover fully when the plants were subjected to water stress at the flowering stage (Garg, *et al.*, 2005a). In clusterbean and moth bean seed yields were significantly more in early flowering/maturing genotypes under low rainfall situation. In moth bean the maintenance of higher photosynthetic rates and better metabolic efficiency in early genotypes under water stress at either growth stages led to significantly less reduction in their seed yield and dry matter production as compared to late flowering genotypes (Garg, *et al.*, 2004a). Early genotypes also displayed higher nitrogen harvest index as well as higher nitrogen use efficiency than late genotypes under low rainfall while these were comparable under high rainfall condition indicating a better partitioning and utilization of nitrogen by early genotypes under arid conditions as in clusterbean (Garg *et al.*, 2003).

For stability of yield, planting of early and late genotypes of these legumes in 1:1 ratio was found most appropriate under low as well as higher rainfall condition. The improved performance of mixed crop, particularly under low rainfall situation could be attributed to more efficient use of water, low initial canopy development and higher photosynthetic rates (Kathju *et al.*, 2003; Vyas *et al.,* 2003).

Weeds in crop field markedly reduced light interception, increased ratio of red to infrared radiation, decreased transpiration rate and enhanced soil temperature and revealed poor microenvironment in arid zone (Bhati *et al.*, 2005). Thus weeding is an important cultural practice that mellows adverse effects of drought.

Supplemental irrigation (60 mm) during drought in pearl millet, , if resources permit, coupled with N fertilization increased the grain yield from 560 to 1663 kg ha^{-1} under rainfed condition (Kathju *et al.*, 1993). Similar results have been obtained with sesame where supplemental irrigation to recharge 50 cm soil depth to field capacity and 60 kg ha^{-1} N application increased seed yield by approximately 33% over rainfed fertilized control plants (Vyas *et al.,* 1999). Irrigation with saline water, at the critical stage in the beginning of a dry spell, may be more rewarding than irrigation with saline waters at a belated stage when the clusterbean plants have already suffered water stress (Garg *et al.*, 1986). Irrigation at belated stage may cause severe detrimental effect on crop performance due to cumulative adverse effects of drought and salinity on plant growth and leaf metabolism (Garg *et al.*, 2005b).

Fertility

Crops in the arid and semi-arid regions suffer not only from moisture stress but also from nutrient stress as poor fertility of arid soils is a major limitation to increasing yields. Thus, addressing the soil fertility constraints can also alleviate drought stress effects on crop productivity in arid environments. Studies suggested that tissue hydrature was not an infallible index of metabolic efficiency as nutritional status of plants was more critical under water deficits for enhanced leaf metabolism, photosynthesis, growth and yield in pearl millet (Garg *et al.,* 1993; Kathju *et al.*, 1993; 2001), wheat (Garg *et al.*, 1984; Kathju *et al.*, 1990), Indian mustard (Vyas *et al.*, 1995; Garg *et al.*, 2001b; Burman *et al.*, 2003b) and sesame crops (Vyas *et al.*, 1987; 1999) where nitrogen-moisture interactions were explored under field conditions.

The adverse effect of drought, no matter at which stage of growth the water shortage was experienced, may be substantially evaded where optimum plant vigour was induced by adequate level of soil fertility (Lahiri *et al.*,1973).

In wheat, significant alleviation of growth and yield, despite the higher stress experienced by plants under improved soil fertility, seems to be related to larger root growth and greater post-drought nutrient uptake and not to favourable tissue water modulations (Garg *et al.*, 1984). Adequate nutrition conducive for greater plant vigour brings about an efficient enzyme activity and higher chlorophyll content, despite desiccation, as compared to plants raised under low soil fertility (Kathju and Lahiri, 1976).

In pearl millet, improved soil fertility imparted significant beneficial effects, per plant or per unit area, in both good and bad rainfall years. However, the magnitude of this effect was less in the drought year (Garg *et al.*, 1993).

High soil fertility under low moisture conditions seems to favourably influence the yields of arid legumes also. Alleviation of drought effects in arid legumes has also been achieved through P application which favourably modulates various physiological and biochemical processes (Garg *et al.*, 2007; Burman *et al.*, 2004, 2007) particularly in the late genotypes (Garg *et al.*, 2004b).). Furthermore, in late moth bean genotypes where impact of drought was more severe P application (40 kg ha^{-1}) significantly ameliorated the detrimental effects of water stress on plant water potential, relative water content, rate of net photosynthesis, levels of total chlorophyll, starch, soluble protein and nitrate reductase activity (Garg *et al.*, 2004b). In clusterbean also increasing stress intensity progressively at the critical pre-flowering stage decreased plant water potential (ψ_{plant}), relative water content, levels of different leaf metabolites, photosynthetic rate and nitrate reductase activity. However, P-fertilized plants displayed higher photosynthetic efficiency, leaf metabolism and enzyme activity than unfertilized plants, though decrease in plant water status was more in P-fertilized plants. Recovery upon re-watering was also more in P-fertilized than unfertilized plants. The results indicate the possibility of alleviation of water stress effects by P nutrition in clusterbean, at least up to moderate stress level (Burman *et al.*, 2009).

Interaction studies revealed that dry matter production and seed yield of sesame plants under one or two cycles of drought were also significantly more under IF ($N_{60}P_{40}K_{20}$) than under LF ($N_0P_0K_0$)conditions notwithstanding the fact that ψ plant RT% and diffusive resistance indicated relatively more water stress in the former than in the latter condition. This advantage was, however, lost after three cycles of drought (Vyas *et al.*, 1987). Further, beneficial effects of longer wet periods between two drought events on performance parameters enlarged with improvement in soil fertility status (Vyas *et al.*, 1991).

K fertilization too, induced growth and yield restoration, irrespective of the stage at which drought was imposed (Lahiri and Kackar, 1985). Improved water status with K in terms of RWC and shoot water potential significantly increased the seed yield in HG-75, a drought-sensitive clusterbean cultivar subjected to water stress at flowering stage (Sharma and Kuhad, 1999)

Growth regulators

Growth regulators have been shown to influence plant growth and performance. Few attempts of utilizing regulators for improving productivity have also been done on arid zone crops under soil moisture stress. Sodium sulphate, sodium chloride and potassium nitrate proved better than ammonium sulphate as pre-seed treatment to induce drought resistance in cereals (Misra, 1962). However, overall performance of pearl millet plants was not improved by morphactin treatment under low moisture regime. Morphactin application reduced the plant height, increased the tillering and leaf number of the main shoot and adversely affected the growth characters associated with the grain production (Kackar *et al*., 1978). Kinetin (5 ppm) applied as either pre-sowing seed treatment or foliar spray (at 25 and 40 DAS) or both also significantly improved the growth, dry matter production and seed yield of field grown clusterbean under moisture deficit condition. Kinetin mediated response was due to higher content of different leaf metabolites (starch, soluble protein, etc.) thereby, prolonging the active growth phase (Burman *et al*., 2003a). Similarly seed treatment with thiourea (500 ppm) followed by foliar sprays (1000 ppm) at vegetative and flowering stages significantly mitigated the detrimental effects of field drought in clusterbean through enhancement of photosynthetic efficiency and nitrogen metabolism (Garg *et al*., 2006). Adverse effects of drought could also be significantly mellowed by adequate phosphorus nutrition in combination with thiourea application due to their favourable effects on leaf area development, photosynthetic efficiency and nitrogen metabolism (Burman *et al*., 2004).

Moisture Conservation

Rainfall in the arid region is low and scanty. The annual average rainfall varies from 150 to 400 mm and its annual coefficient of variation being 37 to >50% (Rao and Singh, 1998). The annual estimated potential evapo-transpiration values range from 1600 mm in eastern part to >1800 mm in western part. The soils of the region are generally coarse textured with sand content varying from 90% in dunes to 60% in comparatively heavy soils and are deficient in organic matter as well (Joshi, 1993). The availability of surface water is very limited. Underground water is very deep, limited and mostly brackish in nature. Under such situations, the only option available is to harness the precipitation to its fullest.

Increasing water storage in soil

A significant cause of low production and crop failure in rainfed agriculture is lack of water in the soil. Soil moisture management is, therefore, a key factor when trying to enhance agricultural production. Increasing the amount of water stored in the soil is reviewed under following sub headings.

Bunding and vegetative barriers

Bunding has been the age old practice to reduce runoff and improve moisture storage in the soil. At Pali, bunding prevented runoff, increased infiltration and improved the availability of moisture to rabi crops i.e., mustard, taramira and chickpea by 11.4 mm in a soil core of 100 cm (CAZRI, 1998; Regar *et al.*, 2007). Contour bunding is extensively recommended for controlling soil erosion and moisture conservation in arable areas on slopes ranging from 1 to 6%. In an early study, Kanitkar (1944) proposed bunds of 0.30-0.60 m height to be sufficient for sandy soils. The bunds must be placed in series from ridge to bottom of a valley to form terraced slopes. It was observed that 25 mm of rain water can penetrate upto 13-15 cm depth for future use of growing crops. Wasi Ulah *et al.* (1972) conducted an exhaustive study on the performance of contour furrows and contour bunds on water conservation in grasslands in western Rajasthan. They observed that contour furrows alone stored more soil moisture (39%) than the contour bunds alone (27%) and the combination of contour bunds and furrows (26-32%). Singh (1984) recommended contour bunding of 75 cm height and 80 cm vertical spacing combined with contour furrowing of 10-15 cm depth and 100-125 cm vertical spacing. This system had recorded higher forage yield than control/bunding. Moisture pattern of the system was studied and highest soil moisture was recorded at the centre of furrow and middle of ridges throughout the season (Verma *et al.*, 1977; Sharma *et al.,* 1980; Sharma, 1983). Hence, the middle of ridge recorded highest population, dry matter production and precipitation use efficiency (Sharma *et al.*, 1983)

In partial modification to conventional water conservation measures like contour bunds, Sharma *et al.* (1997) designed contour vegetative barriers (CVB). Under this technique locally available fast growing perennial grasses with extensive root system such as *Cymbopogon jwarancusa, Cenchrus ciliaris* and *Cenchrus setigerus* are transplanted 0.3 m apart on contours at 0.6-1.0 m vertical interval forming a dense hedge. In a four year study of this system, it was found that the runoff volume was reduced by 28 to 97%. The CVB plots stored about 2.5 times more soil moisture than control and improved clusterbean and pearl millet yield by 37-51% and 19-40% over control, respectively. In another study vegetative barriers of different grasses were established at a horizontal interval of 30 m and pearl millet was sown in between. For the cumulative rainfall of 105 mm only, about 36.5, 72.1 and

54.2% higher moisture storage as compared to control (36.9 mm every 60 cm) was recorded under the alleys of *Cenchrus anguistifolia, Lasirus sindicus* and *Saccharum munja*, respectively. The average yield of pearl millet improved by 39.1% over control (CAZRI, 1998). Combination of bunding and vegetative barriers of *Cenchrus ciliaris* improved profile moisture in a field having 1-2% slope and resulted in 40% increase in yield of mung bean and moth bean (CAZRI 2000). These barriers being easy to raise, less expensive and provide fodder during lean period are readily adopted by the farmers.

In situ moisture conservation

Systematic studies on *in situ* moisture conservation were initiated during the year 1969. Since then inter-plot, micro-catchment and inter- row techniques are evolved and perfected for different soil, topographic and rainfall situations. Two *in situ* water harvesting systems were devised at CAZRI, Jodhpur during seventies and eighties (Singh, 1988b). In inter-plot water harvesting, micro-catchment is prepared in one or both sides of cropped area and 2/3rd of area is cropped, leaving 1/3rd as catchment (1.5 m or 0.75 m area is used as catchment on both sides, respectively) with a slope of 5% towards the cultivated area increase soil moisture and yield of many crops (Singh *et al.*, 1973, Singh 1988a, Singh 1985). It has also resulted in saving of 1/3rd of inputs. In semi- arid part (Pali) catchments with 4 - 8% slope provided 50-80% runoff to the cultivated area and enhanced the yield of crops like castor, sunflower and mung bean (Jain and Singh, 1982).

Ridge and furrow system (inter row system) was designed in modification of inter- plot water harvesting (Singh 1988b). In this no land is wasted for catchment purposes. The furrows of about 30-40 cm width and 15-20 cm depth are made. Distance of 60-90 cm is kept between two ridges. This system is particularly suitable for medium to heavy textured and deep to moderately deep soils (Faroda *et al*., 2007). In light soils, the crops are sown in furrows whereas in heavy soils, planting may be done on ridges to eliminate water logging hazards. Under this system, pearl millet yield improved by 210% over regular flat planting, whereas comparative value for micro catchment was 120% (Singh and Saxena, 1998). Laying out of ridge-furrow configuration against the prevailing wind direction of south-west to north-west was found effective for increasing moisture availability in the arid region (Singh and Bhati, 1998).

Another approach developed to conserve rain water is to adjust row spacing and make conservation furrows at the time of intercultivation. Planting of pearl millet at 60 cm and making ridge - furrow after interculture

(30 DAS) in wider row spacing (60 cm) with 50% N through FYM recorded significantly higher grain (49.7 and 53.41%) and fodder yield (40.36 and 43.14%), respectively in Jodhpur and Barmer districts over farmers' practice (30 cm sowing). Plants maintained higher relative water content (RWC) and stomatal conductance at grain formation stage (Makkhan Lal *et al.,* 2007). In sorghum, Inter pair row conservation furrow improved grain yield by 63.0% over Control (Regar *et al.,* 2006). In henna, inter row and inter paired row water harvesting (conservation furrow) provided 8.6 and 7.0% higher leaf yield over inter triplet row water harvesting and control (Regar *et al.,* 2005).

Sub surface moisture barriers

A vast area of arid region is occupied with sandy soils. These soils being coarse textured have high infiltrability. High percolation rates not only affect moisture retention but also cause nutrient leaching. Such soils can be made productive by the use of sub surface barriers. A systematic study on sub - surface moisture barrier was initiated in 1971 at Central Arid Zone Research Institute, Jodhpur. As it is a costly input and cannot be applied over larger areas, the trials were initiated on vegetable crop i.e., round gourd (*Citrullus vulgaris*). Pits of 50 cm diameter were dug by tractor augur and bentonite was placed at a depth of 75 cm and pit walls were also thoroughly dusted with bentonite. The results showed that this technique yielded 49% higher yield than for conventional system (Singh *et al.*, 1975; Singh, 1980). Other materials like pond sediments, asphalt and vermiculite were also tried. Bentonite clay and pond sediments at 60 cm depth in 5 mm thickness were 60-70% and 50-60% effective in retaining total rainfall in the root zone, respectively (Singh *et al.*, 1979). Use of Asphalt as a sub surface barrier (2 mm thick at 60 cm depth) restricted deep percolation loss to 24 mm compared to 120 mm from unbarriered soil profile and increased pearl millet yield by 40 -50% (Gupta and Aggarwal, 1978, 1980). Large scale use of these barriers is limited due to cost of barriers and non availability of machinery to incorporate them.

Soil amendments

In arid regions where the organic matter level of soil is very low and soil structure is very weak, soil amendments like pond sediments, vermiculite, FYM etc. were found very promising in improving moisture retention capacity of soil. Pond sediments available from widely scattered ponds are commonly utilized for improving soil productivity. The mixing of pond silt upto 30-40 cm soil depth @ 76 t ha^{-1} increased available water storage capacity from 6.5-6.9%, reduced infiltration rate from 15 to 13.2 cm h^{-1} and hence increased the yield of pearl millet by 40-50% and mung bean by 35-40% over control. Use of vermiculite @ 20 t ha^{-1} increased 0.1 bar moisture retention from 10.3-12.4%, reduced saturated hydraulic conductivity from 8.6- 6.5 cm h^{-1} and bulk density from 1.62-1.57 g cm^{-3} (Gupta *et al.*, 1979). Since a long time farmyard manure, has been known to maintain physico-chemical properties of soil and widely used by the farmers. Surface application of FYM and calotropis increased the yield of pearl millet by 30% (Agarwal and Sharma, 1980, CAZRI, 2007a).

Reducing water losses from soil

Loss of water from plant and soil surface occurs through evapo-transpiration (ET). Because it is difficult to measure E and T separately, most data simply combine the two. The water loss through transpiration is used for essential evaporative cooling, while stomata play a major role in controlling water loss. As more than 90% of the water taken up by the plant is lost by transpiration from the leaves, researchers have long proposed the use of antitranspirants to reduce loss of water under moisture stress condition. Evaporative losses from a partly or entirely bare soil are an important source of water loss until a full plant cover is established. Many dryland crops do not provide a complete soil cover over a large part of the growing season. As long as the soil surface is exposed to radiation, E from the surface can be considerable.

Use of antitranspirants

The mechanism for reducing the transpiration component of ET is generally associated with reduced CO_2 uptake, so that there is a trade-off between decreased transpiration and yield. There are three basic types of antitranspirants compounds that cause stomatal closure, film-type compounds, and reflectants (Das and Raghavendra, 1979). Yadav and Singh, (1981) reported significant reduction in daily ET after the application of stomata closing type chemicals (phenyl mercuric acetate [PMA] or atrazine) used in conjunction with reflecting type antitranspirant (Kaolin). The moisture conservation effects of these chemicals lasted about two weeks under clear weather conditions. Such rainless periods occurred during anthesis and grain development of barley in the 1977-1978 crop seasons, explaining the significant increase in WUE following the use of PMA or atrazine with kaolin which only occurred in this crop season.

Use of mulches

Deficiency of water and high thermal regimes of the soil are the two most important factors which adversely affect crop production. The use of mulches has been reported to favorably modify the hydrothermal regimes of soil and suppress weeds (Parihar *et al.,* 1977; Gupta, 1978, 1980; Gupta and Gupta, 1985). In normal years, the effect of mulches may not be visible because top surface of sandy soil act as self mulch after drying for few centimeters. However, during drought years, mulches delays drying of soils.In such situations covering of soil surface with mulch like grass waste, pearl millet husk and organic matter waste, immediately after sowing, may delay the surface drying, promote better establishment of crop and result in higher yields. Singh (1977) has reported that mulches effectively conserve soil moisture till the 50% ground area was covered with crop canopy. Daulay *et al.* (1979) reported beneficial effect of mulch in pearl millet crop during drought years.

Different mulches were used for reducing the evaporative loss of moisture and lowering the thermal regime of soil. Application of grass mulch at the rate of 6 t ha^{-1} decreased the maximum temperature of soil by 1 to 9^{o}C, reduced the evaporation loss and increased the seedling emergence of pearl millet during hot months of June. During *kharif* season (July-September), however, the magnitude of temperature reduction narrowed down to 1-6^{0}C. Polyethylene mulch, on the contrary, raised it by 1 to 3^{0}C. These mulches also suppressed weed growth and improved soil moisture status. Mulching increased the yield of mung bean, moth bean and clusterbean by 178, 90 and 71% over control, respectively. Chickpea seed yield increased by 12.6 and 18.1% due to grass and polythene mulch, respectively (Gupta and Gupta, 1983). Bhaskar (1985) recorded significantly higher grain and straw yields of sorghum with straw mulch + anti transpirant (kaoline). Mulching (straw and polythene) improved the yield of pearl millet at farmers' field. Plastic mulch increased the crop yield by 23.7% which was on par with straw mulch. The use of polythene and straw mulch conserved 28 and 24% more soil moisture than control (CAZRI, 2000). The waste plant materials like grass, straw etc. available at the farm can be profitably used as mulch for general field crops and the polyethylene mulch can be used for high cash crops like vegetables.

Water Management

Water is the most important key input not only for ensuing food security and sustainable socio-economic development but also for impacting the basic existence of life *per se*, and will continue to play crucial role in enhancing agricultural production in future as well. Arid zone is showing permanent negative water balance, ground water is deep and often brackish too. Evaporation losses accounts for 20-25% water loss in arid area. The arid belt of Rajasthan comprising 19.7 million hectares land is a known site for finiteness of water. About 1169 mcm water from reservoirs and tanks, $1.723x10^6m^3$-$2.961\ x10^6m^3$ flow from canal and $2435.4x10^6m^3$ from ground water is extremely scarce in this part. The ground water is largely deep, expensive and saline at many places. Together these sources irrigate 1.82 m ha land at present and it is expected that about 2.69 m ha land would come under irrigation by 2015 upon the full development of canal command area. But indiscriminate use of water on undulating highly permeable sandy soils through conventional irrigation practices resulted in 3-7 m fall in groundwater table and water logging in canal command area of Indira Gandhi Nahar Pariyojna (IGNP).

Water use efficiency (WUE) and water productivity (WP)

Hydrologists, physiologists, economists and agronomists define the WUE in different ways depending on the goals to be achieved (Joshi and Singh, 1994). Since farmers' interest lies in maximum harvestable yield, WUE can more simply be expressed as the maximum harvestable yield per unit of water used and expressed as kg $hamm^{-1}$. Water productivity (WP) is defined as the ratio between the actual yield achieved and the total water use including rainfall and expressed in physical terms (kg m^{-3}) (Kijine *et al.*, 2002). Thus, the relationship between WUE and WP can be written as WP (kg m^{-3}) = 0.1 x WUE (kg ha mm^{-1}).

Efficient rainwater management acts as insurance for the crop during the rainfall deficit periods. Management techniques that increase infiltration and soil water storage, and decrease water losses by runoff, evaporation and evapo-transpiration by weeds would lead to increase the amount of water retained in the soil for subsequent use by crops. Joshi (1987) reported occurrence of rainfall intensity of 56-65 mm h^{-1} for 18-20 minutes in arid zone. Such high intensities produce significant runoff. Low moisture retention capacity of sandy soils further deteriorates the situation. Therefore, rainwater harvesting will not only conserve the soil, its fertility and vegetation; but also could be utilized as supplementary irrigation that will be advantageous in enhancing total water supply available to crop plants during low rainfall period (Singh, 1985).

Water Harvesting

Inter-row water harvesting

Under inter-row system (ridge furrow configuration), furrows of about 30-40 cm width (15 cm deep) are made with the distance of 60-90 cm between two ridges. The ridges are prepared at right angle to the field slope. This reduces runoff and at the same time, water is concentrated in furrows causing better water availability. This system is particularly suitable for medium to heavy-textured and deep to moderately-deep soils. In light soils, the crops are sown in furrows, whereas in heavy soils planting may be done on ridges to eliminate the water logging hazards. Laying out of ridge-furrow configuration against the prevailing wind direction of south-west to north-west was found effective for increasing moisture availability and adoptability to farm situations in the arid region (Singh and Bhati, 1988).

Inter-plot water harvesting

In inter-plot water harvesting, micro-catchment is prepared in one or both sides of cropped area. In this system 2/3rd area of the field is to be used for cropping and leaving 1/3rd as catchment. Cultivated strips are alternated by benches with a slope of 5% towards the cultivated area, which increase soil moisture and yield of crops (Singh, 1988). In this system 1.5 m or 0.75 m area is used as catchment on one or both sides, respectively.

Water harvesting at surface

The runoff water is harvested in several surface bodies like khadin, ponds, tanks, etc. The harvested water can be used for supplementary irrigation at critical stages of the crop growth during moisture stress periods.

Khadin: In larger catchments, runoff is carried to distant places in small streams and collects wherever it meets a depression or a natural topographic barrier, which limits its further movement. Runoff water is harvested from shallow, gravely and rocky upland catchments in the low lying valley plains that are converted into the bunded farm land structure (khadin) where either kharif or rabi crops are raised, depending upon the amount of rainfall and consequent runoff received during the monsoon. Any excess water in khadin is passed out through a spillway provided in the bund. The crop is grown in the khadin during kharif and rabi seasons, depending upon the availability of water. Soils in the khadins are extremely fertile because of the frequent deposition of fine sediment, while the water that seeps away removes salts (Kolarkar *et al*., 1983). Crops like wheat, mustard, taramira (Eruca sativa) and chickpea are successfully grown during post-rainy season on receding moisture. Average pearl millet yield ranges from 300 to 500 kg ha^{-1} during poor rainfall (60-70 mm) year. Similarly, during better and high intensity rainfall season, wheat yield ranges from 1200 to 2000 kg ha^{-1} and chickpea from 1000 to 1500 kg ha^{-1} (Kolarkar and Singh, 1984). Khan and Singh (2005) recorded the 1803 kg ha^{-1} seed yield of chickpea (cv. RSG-44) grown under khadin system, besides improving the physico-chemical properties of the soil.

Farm ponds: Runoff water is collected from a treated or untreated catchment and stored in reservoir or farm pond. The stored water is utilized for supplemental irrigation during long dry spells at critical stages of plant growth. Farm ponds are the bodies of water made either by constructing an embankment across a water course or by excavating a pit. Farm ponds hold a great promise as a life-saving device for rainfed crops in low and erratic rainfall areas. Experience has shown that a supplemental irrigation of 5 to 7 cm given to rainfed pearl millet or legumes at reproductive stage can make all the differences between success and failure of the crop.

Breeding for Improved Drought Resistance and WUE

Empirical breeding for improved yields in water-limited environments has been slow due to year-to-year variation in rainfall and within-season variation in rainfall distribution. This has led to attempts to breed for specific phonological, morphological, and physiological or biochemical characteristics that putatively improve yield in water-limited environment. Crop species and varieties varies in the level of depletion that crop can tolerate without affecting its growth and/or actual Evapo-transpiration (ETa) and even with varieties of same crop. Pearl millet, clusterbean and castor bean exhibit relatively more tolerance to drought even though; their mechanism and growth tolerance stages may considerably vary. Pearl millet showed better drought tolerance than other millet crops, due to its well-developed root system (Joshi, 1988). The mung bean and moth bean being drought tolerant, the former showing escape mechanism due to short growth and the letter showing resistance right from germination to maturity. Moth bean is credited with twin tolerance to heat and moisture deficit. The clusterbean, a long duration arid legume, shows quick recovery towards precipitation at any growth stage, thus, depicting drought avoidance phenomenon. In general, the breeding objectives for improvement of arid zone crops are evolution of physiologically efficient plant types with high harvest index, wide adaptation, moderate level of input responsiveness and tolerance to important abiotic and biotic constraints.

Minimizing Evaporation Relative to Yield

Evaporation from soil surface causes considerable reduction in water availability to crops. In *kharif* crops particularly pearl millet, cowpea, mung bean, sorghum and cluster bean, the evaporation were 20, 23, 34, 38 and 40%, respectively, of total ET. Faster drying of loamy sand soils helps reducing conductivity for movement of water from lower depths. The evaporation losses can be minimized by reducing the availability of energy to the soil and limiting heat or vapour exchange between the soil and the atmosphere. Some of the factors to reduce evaporation are elimination of weeds, use of mulches, planting geometry including direction of sowing and population, use of organic manure/fertilizers, bio-fertilizers and wind breaks and intercropping. Weeds compete for water, nutrients, and light particularly at early stage cause considerable reduction in yield.

The seasonal evapo-transpiration of unstressed pearl millet, clusterbean, moth bean and mustard were 618, 654, 295, and 530 mm, respectively (Rao and Singh, 1998). Moisture stress takes place whenever evapo-transpiration exceeds the moisture availability. The moisture stress severely affects the physiological activities, growth and development of plant and yield. The application of grass mulch (6 t ha^{-1}) decreased the maximum soil temperature by 1 to 9^0C, reduced evaporation loss and increased emergence of pearl millet during June (Gupta and Gupta, 1983). Mulching increased the yield of mung bean, moth bean and clusterbean by 178, 90 and 71% over control, respectively. Chickpea seed yield increased by 12.6 and 18.1% due to grass and polyethylene mulch, respectively. Bhaskar (1985) recorded significantly higher grain and straw yields of sorghum (SPV-233) with straw mulch + anti-transpirant (kaolin).

Weed control is days old mechanism to increase water available to crops. In pearl millet weeding resulted in substantial increase in yield in sub optimal and optimal rainfall condition at Jodhpur. It improved the WUE for 3.1 to 3.4 under normal rainfall year (450-550 mm) and 4.2 to 6.0 cm in suboptimal rainfall (252 mm) years. Use of improved weeding tools like peg tooth weeder, two/three tyne shoved animal drawn, slotted hand hoes covers more area and also facilitate soil mulching (Rao *et al.*, 2007). Chemical weed control followed by mechanical weeding at appropriate stages is able to eliminate weeds and make water available to crops.

Generally top soils dry very fast owing inadequate canopy cover at vegetative stage, which result in evaporation losses. Mulching immediately after sowing delay the soil drying which helps in better plant establishment. Application of grass mulch (Regar *et al.*, 2007) which acts as bad conductor of heat helps in reducing soil thermal energy used in evaporation, suppress weeds and reduce runoff etc.

Integrating Agro Techniques for High Water Productivity

Relying on water alone for higher production will not be logical unless it is combined with other factors of production. Evapo-transpiration is dependent on climate, while improved management practices either do not increase or increase only negligibly the crop ET. Application of 40 kg N ha^{-1} in inter plot or inter row water harvesting enhanced the pearl millet production by 72-75% and improved water use efficiency over control (Singh and Singh, 1996). The characteristics value of crop water productivity at crop/field levels worked out in Indian arid zone is given in the Table 2.

Table 2. Characteristics value of crop water productivity at crop/field level in Indian Arid Zone

Crop	Location	Treatment	WP/WUE	Reference
Pearl millet	Arid, Jodhpur	N- Application	3.2-8.2 kg hamm^{-1}	Krishnan *et al.*, 1981; CAZRI 2007
		Intercropping with cluster bean		
Sorghum	Semi-arid, Pali	Moisture conservation	2.76-4.10 kg hamm^{-1}	CAZRI, 2005
Sorghum (Fodder)	Semi-arid, Pali	Fertility levels	16.5-27.1 kg hamm^{-1}	Rao *et al.*, 2007
		Weed control		
Cowpea	Arid, Hisar		1-2 kg m^{-3}	Phogat *et al.*, 1984
Mung bean	Arid, Hisar		1-2 kg m^{-3}	
Cotton	Semi-arid, Pali	N-application	0.339-0.458 kg m^{-3}	CAZRI, 2007b
Wheat	Arid, Jodhpur	Optimum irrigation	7.7 kg ha^{-1} mm^{-1}	Singh and Singh, 1993
	Arid, Hisar		0.7-1.4 kg m^{-3}	Choudhary and Kumar, 1980
	Semi-arid, Pali	FYM + Deep tillage	1.25-1.26 kg m^{-3}	CAZRI, RRS, Pali 2008,
Mustard	Arid, Jodhpur	N-application	1.22-4.43 kg hamm^{-1}	Garg *et al.*, 2001
	Semi-arid, Pali	Sprinkler irrigation	6.40 kg hamm^{-1}	CAZRI, 2006b
Cumin	Arid, Jodhpur	N-application	4.1 kg hamm^{-1}	Singh and Rao, 1994
	Semi-arid, Pali	FYM + N-application	0.319-0.328 kg m^{-3}	CAZRI, 2007b
Tomato	Arid, Jodhpur	Drip irrigation	101-125 kg hamm^{-1}	Singh *et al.*, 1989
Chillies	Arid, Jodhpur	Drip irrigation	2.05-5.17 kg hamm^{-1}	Singh *et al.*, 1999

Irrigation Water Management

Irrigated area in arid region is very less (about 10.8%). Indira Gandhi Nahar Pariyojna (IGNP) has created a boom to agricultural production and has remarkably improved the socio-economic conditions of local population. However, injudicious use of water from source to fields has resulted in the ill effects of waterlogging and soil salinisation; and therefore, need urgent attention. Emphasis should be on extensive irrigation rather than on intensive irrigation. Drip and sprinkler irrigation systems would be of help in preventing or delaying the process of rise in groundwater table in vulnerable areas.

It is estimated that as much as 70% of water is lost in conveyance, application and distribution (Sharma, 1992). Thus, efforts should be made to reduce the water losses and consequently increasing the irrigation efficiency. Adopting sprinkler and drip systems of irrigation, which also increase crop yield, can save sufficient amount of water. Kushal and Pathak (1977) obtained 38, 18 and 33 cm saving of water in wheat, groundnut and cotton, respectively and the highest water use efficiency as well. Irrigation through sprinklers increased wheat and potato yields by 8.7 and 29%, respectively, over surface irrigation (Aggarwal, 1985). At Jodhpur, yield of cucumber under drip system was 1 to 1.5 times higher over furrow irrigation (Singh and Singh, 1978). The grain yield of wheat was 33 and 37% higher with sprinkler irrigation over check basin and border strip irrigation, respectively in arid region (CAZRI, 1979). However, this method has limitations under high wind velocity and saline water.

Saline water can however, be used with drip irrigation system. Besides higher production, 30-50% water in most of the high-value vegetable crops can be saved with drip irrigation system (Singh *et al*., 1978). Results of a study conducted at Jodhpur revealed that potato and tomato crops were successfully raised with 3 to 10 dS m^{-1} saline waters using drip irrigation method. Detrimental effects of salinity were minimized because it maintained higher moisture content due to daily drip irrigation, thereby salts were drained beyond active root zone (Gupta and Singh, 1983). Water use efficiency increased further by adequately fertilizing the crops through drip irrigation. Drip system provided gainful use of nutrient management with water and provided maximum yield of tomatoes and chillies in arid condition (Singh *et al*., 1989). Thus, adoption of efficient irrigation methods like sprinkler and drip can be effective for increasing water use efficiency in arid zone. Yield of pearl millet increased when a supplementary irrigation of

14.5 cm was applied and it provided the highest water use efficiency (Singh, 1977).

Improved Farm Implements

The soil in arid zone is mostly sandy, loamy sand and sandy loam. About 28% land is tilled; 11% of the cultivated area is irrigated. Cereals, legumes and oil seeds requiring less water are grown in arid zone. There is more emphasis on fodder/grass production. Several fruits such as pomegranate, ber, aonla, etc. have been established and popularised. Due to modern method of irrigation (drip, sprinkler, etc.) more and more area is being commanded under horticultural crops. As a result the intensity of cultivation has improved over the period (Pathak, 2006).

Farm mechanization

Farm mechanization in this part of the State requires timeliness of operation and good quality work as farming is rainfed and resources are unfavourable the risk in crop production is very high. Also, the fields are very scattered which requires frequent movements of tractors. Farm mechanization in Rajasthan started in the 1940s when some progressive farmers tested some agricultural machinery and results were very encouraging. Efforts are being put in mechanization so as to reduce human drudgery. Firstly, the farm power availability in this region stands 0.73 hp ha^{-1}, whereas minimum 1.5 hp hr^{-1} will be required to achieve quick tillage and planting in vast rainfed areas. The additional power supply of 0.77 hp is equivalent to 1.6 lacs tractors. Secondly, implements/tool carrier type tractors should be acquired and evaluated for the production of high value crops such as, vegetables. Mechanized vegetable production irrigated by micro irrigation system can raise the land productivity and returns to the farmers (Singh *et al.*, 1998; 2002).

Availability of tractors and uses

The general usage of the tractor besides agricultural operations like sowing, threshing and chaff cutting are for transportation of agricultural produce, materials for construction, water supply and sometimes carry persons during local weddings. The inter state transfer during off season is predominant. Tractors have been reported to go far off to neighbouring states to keep the machine busy during off seasons and to fetch profits by performing different operations. The total number of useful days of utilisation during the *Kharif* season is 10 days for pearl millet sowing and 3.5 days for mung bean, moth bean and clusterbean. The extended time is in the view of the fact that normally there is rainfall in a small pocket and thus it gives chance for tractor mobilization to another place when the other pocket gets rain. It is also assumed that work is carried out from tractor for 20 h day^{-1} during sowing period to complete the agricultural operations considering the limited moisture availability (Singh *et al.*, 1995).

Sowing devices

In the region the crops are generally sown either by broad casting method or by creating small furrows with the help of tractor drawn cultivator based sowing device provided with tine type furrow opener. The seed is continuously poured manually on to a pointed wooden cylinder, which may get time delay because of picking up of seed from bag and also no seed pressing device is provided. This leads to poor germination and uneven distribution of seed. To overcome the problem, an improved traditional seed drill has been developed by incorporating appropriate seed distribution system and press wheel assembly on the cultivator. It maintains seed rates depending upon size and shape of the seed (Mishra *et al.*, 2009).

The *Kharif* crops *viz.,* pearl millet, mung bean, clusterbean, moth bean, sesame are sown in the region following the first rainfall of the season using a tractor drawn conventional sowing device with tine type cultivator coupled with manual seed metering and attached with a planker to cover the seed, simultaneously. The speciality of the device is that on completion of the sowing operation the seed metering system is removed and the cultivator is used for ploughing of field. The complete attachment costs only about Rs. 1000-1500 and probably the cheapest system available for sowing of crops. However, there is very little scope to collect or conserve rain water in small furrows created under this method; a need of the region for successful crop production. A tractor drawn three furrows (six rows) multi-crop seed *cum* fertiliser drill with the provision for a seed pressing device, which enables the seed to be sown on the slant surfaces of the furrow was designed and developed for highly scarce rainfall region of the Thar Desert (Singh *et al.*, 2007). The specifically created furrow facilitates the collection of run off water to create and maintain a high moisture concentration in the plant root zone providing sustainability to crop during dry spell leading to more yield compared to conventional method of sowing.

In another experiment under drought situation pearl millet planted at wider row spacing 60 cm and inter cultured at 30 DAS gave yield of 1260 kg ha^{-1} compared to 630 kg ha^{-1} obtained from crop grown on 30 cm spacing. Such doubling of crop yield appears to have resulted on account of in-situ water harvesting with ridge and furrow as well as better root tapping and conserved rain water (Anonymous, 2005; Kushwaha, 2001; Prinz and Malik, 2002; Singh *et al.*, 2004; William and Fenster, 1992; Zhao *et al.*, 2004).

Crust breaking

Poor germination and seedling establishment due to crust formation is a major limiting factor for obtaining maximum yield of pearl millet in rain fed area. A research at ARS (Mandore), Jodhpur confirmed that seedling established through soil pressing on planted furrows provided good results. Rubber wheel fabricated locally was attached behind each type of seeding device having 4-6 kg of weight for the purpose of pressing planted furrows. As a result the seed emergence increased considerably by 15-18.5% (Anonymous, 2006b).

Intercultural and plant protection devices

Soils of arid region being light textured only manually operated pull type weeders are convenient for use. Traditional *Kassi*, which is largely used in arid region, has two problems: transport of worked soil accumulated on the blind face of the *Kassi* and high pull requirement (8.5 kg_f). Highest field capacity was found for double slot weeder,193.4 m^2 ha^{-1} with weeding index, 94.5% compared to field capacity 165.3 m^2 ha^{-1} with weeding index, 98.5% for single slot weeder and field capacity 160.5 m^2 h^{-1} with weeding index, 91.8% for traditional *Kassi*. To overcome the problem appropriate slot(s) was/were made in the blind face of the *Kassi* so that the worked soil along with uprooted/cut weeds do not get accumulated on the face and are just released through the slot resulting in reduction in pull requirement (40% of the traditional *Kassi*) through its suitability for farm women and other younger members of famer's family, where as weeder with face width 130 mm, which ensures both low pull requirement (65% of the traditional *Kassi*) and higher field capacity (20% higher than that of the traditional *Kassi*, 165.5 m^2 h^{-1}) was found most suited to men. Further, the small size single slot *Kassi* was preferred due to the reason that it facilitated weeding operation conveniently and effectively even in crop sown by broadcasting method (Singh *et al.*, 2008).

Future Thrust

Considerable research efforts have been made to develop better agronomic practices and technologies during last five decades for obtaining sustainable crop production in the arid region. The impact of technologies can be seen through the enhancement in average yield of most crops. However, considering the ever-increasing food and fodder demand, these efforts are not enough. There is a need to strengthen research on some aspects, which can be useful to further increase yields. Many workers (Yadav *et al.*, 2008; Hegde and Sudhakara, 2009; Yadav *et al.*, 2009; Varughese and Mathew, 2009; Gill *et al.*, 2009; Prasad and Gill, 2009; Baishya *et al.*, 2009; Reddy and Suresh, 2009; Venkateswarlu and Shanker, 2009; Joshi and Kar, 2009; Hedge *et al.*, 2007; Faroda *et al.*, 2007) have identified many such issues. Some of those are given below:

Tillage and residue management

- Extensive studies are needed to work out improved land management technologies that would lead to efficient use of degraded lands and arresting the further degradation.
- Optimum tillage for arid soils needs precise assessment so as to maintain a balance between tillage needs and soil erosion.
- Technology of taking staggered intercrop-green manure has to be developed both in space and time for sustenance of higher level of organic C in the soil, which holds the key for greater activity of other micro-organisms. Research has to be directed to increase the level and quality of organic matter in the soil through *in- situ* incorporation of organic residues in the soil and their faster decomposition.

Crop stand and crust management

- There is scope for improving crop establishment. Possibilities that need in-depth research include pre-soaking seeds, optimum seed rate, improving seed vigour by seed production under high-nutrition conditions, soil compaction, and improving stand by seed placement at proper planting depth and crust management.

Suitable crops and varieties

- The most crucial research intervention for crop-yield improvement would be to develop *kharif* varieties that can perform well under aberrant or increased temperature and under shorter or shifted rainy season.
- Breeding endeavour is needed to increase the plant competence to accept the N_2-fixing bacteria in its fold possibly through encouragement of symbiotic association.
- Evaluation of cultivars of various crops to suit to the requirement of non-traditional areas and seasons.

- Breeding for improved crop varieties with specific reference to growth and flowering phenology, photosensitivity/insensitivity, stability in response to inputs viz., lodging resistant, optimum tillering, harvest index etc.

Crop geometry

- Change in plant geometry and planting or sowing techniques need to be relooked into in the light of their influence on the type and extent of rhizosphere. These non-monetary inputs have a great potential to increase the nutrient-use efficiency.
- In-depth studies are needed on different planting systems viz., paired planting, triplet planting, skip row or border cropping systems etc.

Inter cropping

- Optimum component populations and component crops in intercropping systems are still needed to be worked out for different rainfall situations.
- Intensive studies are needed on how to fertilize the component species in inter cropping, particularly when the species respond differently to a particular nutrient.
- We need to quantify, if intercropping is also advantageous under high input technologies.
- Precise quantification is needed for the extent to which different legumes modify the nutrient responses of the associated cereal.

Cropping systems

- In the highly risky crop production environments of arid regions, it would be useful to examine the potential for alternate land use or area specific cereal/oilseed-legume system that place greater emphasis on enhancing and stabilizing farm income, and hence the sustainability of farm enterprises.
- Extensive studies are needed on crop diversification that would ultimately help achieving sustainable crop production in arid zone. Research for making it demand-driven, need-based, situation-specific and national goal seeking, continuous and dynamic, involving spatial, temporal, value addition and resource complementary approaches, is needed.
- Research has to be geared to the identification of efficient cropping systems not only to boost economic returns but also to improve the soil health and fertility.

- Decreasing grazing land causes poor animal health for which fodder crop may be considered as part of the cropping system or plantation of perennial fodder in the homestead.
- We need to identify new intercropping and novel cropping system combinations including livestock and fisheries that can withstand predicted climate change situations and can be economically viable.

Soil moisture conservation and management

- We need to understand more about the effectiveness of current utilization of rainfall and the potential for improving rainfall-use efficiency by manipulation of cultural and soil conservation practices. We should also lay greater emphasis on maximising the usefulness of limited ground and surface water resources, which consequently would realize high water use efficiency.
- Water harvesting and recycling has the potential for savings and productive use of water through precision technologies and management systems, and thus needs in- depth research.
- Research on rain water harvesting on community basis and distribution through water users association needs strengthening.
- More efforts needed for in-situ water and soil management practices to achieve greater efficiency.
- Promoting conservation agriculture practices especially in water harvesting needs priority.
- In-situ water conservation on vast arable lands, recharging of the soil profile, runoff, harvesting and its efficient and economic utilization through drip, sprinkler or conservation irrigation need in-depth studies.

Crop responses to water stress and drought management

- Need to prepare a contingent planning to counteract the weather vagaries/climate threats under different farming situations.

Nutrient management/INM/microbial inoculants

- The role that legumes play in fertility management in the arid region need to understood clearly in terms of the effects of various legumes on soil fertility. This information is a pre-requisite to improving existing nutrient strategies.

- Research is needed to increase the preponderance as well as the affinity of beneficial micro-organisms in the rhizosphere not only to increase the nutrient availability and their sustained release but also to check the development of soil pathogens.
- Site-specific nutrient management that essentially considers what is available and suggests what is required for maintaining balance and achieving higher input-use efficiency is needed.
- Holistic rather than sympotomatic assessment and correction of problems (e.g., calcium-induced iron chlorosis in groundnut; P and Zn antagonisms in soil and plants etc.) is needed. Development of Integrated Nutrient Management approach to supply secondary and micronutrients particularly S, Fe, Cu and Zn to correct their hidden hunger before visible symptoms appear in the crop should be given priority.
- In depth investigations should be carried out on enhancing the fertilizer use efficiency in different cropping systems through appropriate application frequency of organic manures, crop residues, green manures and bio-manures.
- Search for new fertilizer management strategies in the context of modified planting techniques (ring/pit, deep trench, paired rows), irrigation methods (skip furrows, drip, fertigation), specific soils (water-logged, saline-sodic, extremely sandy), crop environments (drought, frost, flood prone) and cropping systems (mono-cropping, intercropping) with a view to improving nutrient use efficiency.
- Development of ideal fertilizer schedules (application dose, time and method) for specific group of new promising varieties viz., early and mid/late maturing to realize their potentially under different agro-ecological niches.
- Researchers should study and quantify the role of organic agriculture in mitigating the climate change and ill-effects of modern agriculture, and also improve the resource sustainability.
- Bio-intensive agronomy needs to be brought into practice to solve the so called second generation problems of green revolution. The research on rhizospheric engineering and carbon sequestration has to be strengthened to improve soil health and nutrient-use efficiency (NUE).
- We need to develop high-tech organic technology with strict quality control for meeting the quality standards of organic produce. High-value crops and local crops viz., spices, medicinal and aromatic plants, millets etc. having export potential should be given priority.

- There is a need for better understanding and perfection of precision farming technology in the Indian arid zone context, considering the size of the farm and other local constraints.
- Influence of weather/climate change should be considered in fertilization programmes as that has a marked influence on nutrient dynamics in soil and plant uptake
- Nitrogen-nutrient augmentation through improvements and exploitation of alternative sources such as BNF and potential of BNI to control nitrification in cropping systems should be intensified.
- Results of long-term fertilization practices have to be critically examined for their trends of responses for guiding the management strategies.

Improved farm implements

- There is urgent need to develop a planter or a seed drill which can ensure perfect plant to plant population of small seeded crops like pearl millet and sesame besides not allowing collapse of furrows in the event of rains just after sowing in sandy soils.
- As the size of holdings in the arid zone is large and farm operations are needed to be completed in very short span, mechanisation of techniques of in-situ water conservation, water harvesting is a must. Therefore, there is a need to develop appropriate machinery.

References

Agarwal, R.K. and Sharma, V.K. 1980. Availability of nitrogen and phosphorus during the decomposition of *Calotropis procera* (Aak) in desert sandy soil. *Journal of Indian Society of Soil Science* 28: 407-409.

Aggarwal, M.C. 1985. Sprinkler irrigation - A case study in Haryana. In *Proceedings on Sprinkler and Drip Irrigation*, Water Technology Centre, New Delhi.

Aggarwal, R.K. and Kumar, P.1996. Integrated use of farm yard manure and fertilizers N for sustained yield of pearl millet (*Pennisetum glaucum*) in arid region. *Annals of Arid Zone* 35: 29-35.

Aggarwal, R.K. and Praveen Kumar 1994. Availability and management of nitrogen in soils of arid environment. *Annals of Arid Zone* 33(1):1-178.

Aggarwal, R.K. and Venkateswarlu, J. 1989. Long term effect of manures and fertilizers on important cropping systems of arid regions. *Fertilizer News* 34: 67-70.

Aggarwal, R.K., Kumar, P. and Power, J.F. 1997. Use of crop residue and manure to conserve water and enhance nutrient availability and pearl millet yields in an arid tropical region. *Soil and Tillage Research* 41: 43-51.

Aggarwal, R.K., Praveen Kumar, Singh, Y.V. and Lodha, S. 1998. *Enhancing Fertilizer Use Efficiency in Conjunction with Residue Management in Dry Land Crops and Cropping Systems in Low Rainfall Conditions*. Indo-US Project, Consolidated work Report, 1990-98.

Alagundagi, S.C., Hippeswamy and Mansur, C.P. 2002. Productivity potential of forage sweet sorghum (*Sorghum bicolour*) – legume intercropping systems. In *Second International Agronomy Congress on Balancing Food and Environmental Security - A Continuing Challenge*, Extended Summaries Vol. 2, pp. 830-831.

Anitha, S., Srinivasan, E. and Singh, Raj 2004. Cowpea Agronomy. In *Cowpea in India* (Eds. D. Kumar and N.B. Singh), pp. 136-167. Scientific Publishers, Jodhpur.

Anonymous 2005. *Rajasthan ke Sushk Khestra ki faslon mein favvara sinchai prabandhan*. Anusandhan Nideshalaya (Krishi), Rajasthan Krishi Vishwavidyala, Bikaner.

Anonymous 2006b. *Research Highlights.* Rajasthan Krishi Vishwavidyala, Bikaner.

Anonymous 2006a.*Terminal Report* CCSHAU, Regional Research Station, Bawal, Coordinator's unit CAZRI, Jodhpur.

Anonymous 2007. *Research Highlight*, Rajasthan Agricultural University 2007, pp. 34.

Anonymous 2007-08. *Annual Progress Report of AICRP*, Coordinator's Unit CAZRI, Jodhpur.

ARS 1983. *Kharif Report*. Agricultural Research Station Mandore, Jodhpur. pp. 67, 73.

ARS 1988. *Kharif Report*. Agricultural Research Station Mandore, Jodhpur. pp. 82-84.

ARS 1990d. *Kharif Report.* Agricultural Research Station Mandore, Jodhpur. pp.41-44.

ARS 1990e. *Kharif Report*. Agricultural Research Station Mandore, Jodhpur. pp. 129-131.

ARS 1991d. *Kharif Report*. Agricultural Research Station Mandore, Jodhpur. pp. 91-92.

ARS 1992b. *Kharif Report*. Agricultural Research Station Mandore, Jodhpur. pp. 28-31.

ARS 1992c. *Kharif Report*. Agricultural Research Station Mandore, Jodhpur. pp. 99-102.

ARS 1993. *Kharif Report*. Agricultural Research Station Mandore, Jodhpur. pp. 105-106.

ARS 1995. *Kharif Report*. Agricultural Research Station Mandore, Jodhpur. pp. 2, 5-6.

ARS 1997b. *Kharif Report*. Agricultural Research Station Mandore, Jodhpur. pp. 59-63.

ARS 1997c. *Kharif Report*. Agricultural Research Station Mandore, Jodhpur. pp. 65-69.

ARS 1985a. *Kharif Report*. Agricultural Research Station, Mandore, Jodhpur. pp. 61-65.

ARS 1985b. *Kharif Report*. Agricultural Research Station, Mandore, Jodhpur. pp. 77-87.

ARS 1990a. *Kharif Report*. Agricultural Research Station, Mandore, Jodhpur. pp. 24-44.

ARS 1990b. *Kharif Report*. Agricultural Research Station, Mandore, Jodhpur. pp. 28-44.

ARS 1990c. *Kharif Report*. Agricultural Research Station, Mandore, Jodhpur. pp. 277-288.

ARS 1991a. *Kharif Report*. Agricultural Research Station, Mandore, Jodhpur. pp. 27-28.

ARS 1991b. *Kharif Report*. Agricultural Research Station, Mandore, Jodhpur. pp. 18-19.

ARS 1991c. *Kharif Report*. Agricultural Research Station, Mandore, Jodhpur. pp. 96-97.

ARS 1992a. *Rabi Report*. Agricultural Research Station, Mandore, Jodhpur. pp. 105-111.

ARS 1994. *Kharif Report*.Agricultural Research Station, Mandore, Jodhpur. pp. 174-176.

ARS 1996. *Kharif Report*. Agricultural Research Station, Mandore, Jodhpur. pp. 86-98.

ARS 1997a. *Kharif Report*. Agricultural Research Station, Mandore, Jodhpur. pp. 77-80.

Bahl, G.S., Baddesha, H.S., Pasricha, N.S. and Aulakh, M.S. 1986.Sulphur and zinc nutritionon groundnut grown on tolewall loamy sand soil. *Indian Journal of Agriculture sciences* 56: 429-433.

Baishya, A., Hazarika, J.P., Medhi, B.K., Gogoi, J.K., Kalita, M.C. and Ahmed, S. 2009. Constraints and opportunities of crops diversification in Assam. *Indian Journal of Agronomy* 54: 200-205.

Bhadoria, R.B.S., Tomer, R.A.S., Khan, S. and Sharma, M.K. 1997. Effect of phosphorus and sulphur on yield and quality of clusterbean. *Indian Journal of Agronomy* 42:131-134.

Bhan, Suraj and Misra, D.K. 1970. Effects of variety, spacing and soil fertility on root development in groundnut under arid conditions. *Indian Journal of Agricultural Sciences* 40:1050-1055.

Bhaskar, K.S. 1985. Effect of straw mulch and anti-transpirant on growth and yield of sorghum 'SPV -233' –A note. *Annals of Arid Zone* 24: 171-174.

Bhati, D.S. 1989. Effect of sowing date on moth bean. *Farming System* 5(2): 52-54.

Bhati, D.S. 1992. Intercropping in fennel (*Foeniculum vulgate*). *Indian Journal of Agricultural Sciences* 62(3): 518-219.

Bhati, D.S. 1993. Effect of of irrigation and phosphorous on seed yield and yield attributes of fenugreek (*Trigonella foenumgraecum*). *Indian Journal of Agronomy* 38(3): 449-452.

Bhati, D.S. 1997. Mixed/intercropping system in pearl millet for sustainable production under rainfed farming. In Symposium Abstracts *Recent Advance in Management of Arid Eco-system*, p. 40-41. CAZRI, Jodhpur.

Bhati, T.K. and Singh, M. 1982. Effect of nitrogen and phosphorus on forage yield and nutritive of *Cenchrus setigerus. Forage Research* 8: 43-48.

Bhati, T.K., Singh, R.S., Shaktawat, M.S., Joshi, N.L. and Gaur, N.K. 2005. Influence of micro-environmental changes on greengram productivity under arid conditions of Jodhpur in NW India. *Journal of Arid Legumes* 2: 149-156

Bhatnagar, V.K. and Sur, H.S. 1984. Role of tillage and crop residue in controlling water erosion and research needs. *Journal of Indian Society of Soil Science* 12: 43-53.

Bhunia, S.R., Chauhan, R.P.S., Yadav, B.S. and Bhati, A.S. 2006. Effect of phosphorus irrigation and rhizobium on productivity water use and nutrient uptake in fenugreek. *Indian Journal of Agronomy* 51(3): 239-241.

Burman, U., Garg, B.K. and Kathju, S. 2003a. Influence of kinetin on photosynthesis, nitrogen metabolism and yield of clusterbean under moisture deficit condition. *Indian Journal of Plant Physiology* 8(3): 287-291.

Burman, U., Garg, B.K. and Kathju, S. 2003b. Interactive effects of nitrogen and sulphur on Indian mustard under an irrigation gradient. *Indian Journal of Plant Physiology* (Special Issue): 527-533.

Burman, U., Garg, B.K. and Kathju, S. 2004. Interactive effects of thiourea and phosphorus on clusterbean under water stress. *Biologia Plantarum* 48: 61-65.

Burman, U., Garg, B.K. and Kathju, S. 2007. Interactive effects of phosphorus, nitrogen and thiouirea on clusterbean (*Cyamopsis tetragonoloba* L. Taub.) under rainfed conditions of the Indian arid zone. *Journal of Plant Nutrition and Soil Science* 170: 803-810.

Burman, U., Garg, B.K. and Kathju, S. 2009. Effect of phosphorus application on clusterbean under different intensities of water stress. *Journal of Plant Nutrition* 32: 668-680.

CAZRI 1961. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 68.

CAZRI 1976. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 27.

CAZRI 1978a. *Annual Report*. Central Arid Zone Research Institute Jodhpur (Miemo). pp. 75.

CAZRI 1978b. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 143, 191.

CAZRI 1980. *Annual Report*. Central Arid Zone Research Institute, Jodhpur (Mimeo). pp. 68 p.

CAZRI 1982. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 171.

CAZRI 1998. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 39, 71.

CAZRI 1999. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 84.

CAZRI 1999. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 84.

CAZRI 2000. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 48, 72.

CAZRI 2005. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 63.

CAZRI 2006a. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 46, 52.

CAZRI 2006b. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 43.

CAZRI 2007a. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 50.

CAZRI 2007b. *Annual Report*. Central Arid Zone Research Institute, Jodhpur. pp. 57.

CAZRI 2008. *Annual Report*. Central Arid Zone Research Institute, RRS, Pali

CAZRI 1979. *Twenty Five Years of Arid Zone Research 1952-1977*. Central Arid Zone Research Institute, Jodhpur. pp. 48.

Chaudhary, G.R. 1999. Response of fenugreek (*Trigonella foenumgraecum*) to N, P and Rhizobium inoculation. *Indian Journal of Agronomy* 44(2): 424-426.

Choudhury, P.N. and Kumar, V. 1980. The sensitivity of growth and yield of dwarf wheat to water stress at three growth stages. *Irrigation Science* 1:223-231.

Dahiya, S.K., Rana, V., Faroda, A.S. and Yadav, B.S. 1986. Response of clusterbean cultivars to nitrogen and phosphate fertilization under dry land conditions. *Haryana Agriculture University Journal of Research* 16: 156-159.

Das, V.S.R. and Raghvendra, A.S. 1979. Antitranspirants for improvement of water use efficiency of crops. *Outlook Agriculture* 10: 92-98.

Daulay, H.S. and Singh, K.C. 1980. Fertilizers use in rainfed sunflower. *Indian Journal of Agricultural Science* 50:825-828.

Daulay, H.S. and Singh, K.C. 1982. Effect on N and P rates and plants densities on the yield of rainfed sesame. *Indian Journal of Agricultural Sciences* 52: 166-169.

Daulay, H.S. and Singh, K.C. 1983. A note on the effect of soil moisture stress of different growth stages of sunflower. *Annals of Arid Zone* 22: 169-171.

Daulay, H.S. and Singh, R.P. 1982. Effect of N and P rates and plant densities on the yield of rainfed sesame. *Indian Journal of Agricultural Sciences* 52: 166-69.

Daulay, H.S., Chakravarty, A.K. and Bhati, G.N. 1968. Intercropping of grasses and legumes. *Annals of Arid Zone* 7: 265-269.

Daulay, H.S., Singh, H.P., Singh, R.P. and Singh, K.C. 1979. Effect of different mulches on yield and moisture use of pearl millet *(Pennisetum typhoids). Annals of Arid Zone* 18: 108-115.

Dauley, H.S. and Singh, K.C.1982. Effects of N and P rates and plant densities on the yield of rainfed sesame. *Indian Journal of Agricultural Sciences* 52: 166-169.

De, R. 1980. Increasing fertilizer use efficiency through incorporation of legumes in cropping and foliar fertilizer. Paper presented at *India/FAO/Norway Seminar on Maximissing Fertilizer-use Efficiency,* held on 15-18, September, 1980 at New Delhi. pp. 1-19.

De, R. and Singh, S.P. 1981. Management practices for intercropping system. In *Proceedings of the International Workshop on Intercropping*, pp. 17-21. 10-13 January 1979 at International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradesh.

Dhir, R.P. 1977. Soil degradation due to over exploitative human efforts. *Annals of Arid Zone* 16: 321-330.

Faroda, A.S. 1974. Effect of different levels of nitrogen, phosphorus and potash on growth and yield of Anjan grass(*Cenchrus ciliaris*). *Annals of Arid Zone* 13: 114-118.

Faroda, A.S. 1998. Arid zone research – An overview. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and Manjit Singh), pp. 1-16. CAZRI, Jodhpur.

Faroda, A.S., Joshi, N.L., Singh Raj and Saxena, Anurag 2007. Resource management for sustainable crop production in arid zone – A review. *Indian Journal of Agronomy* 52: 181-193.

Garag, B.K., Kathju, S., Vyas, S.P. and Lahiri, A.N. 1993. Effect of plant density and soil fertility on pearlmillet under drought and good rainfall situations. *Annals of Arid Zone* 32: 13-20.

Garara, B.B. and Yadav, B.S. 1992. Yield, reproductive efficiency and quality of groundnut as influenced by water stress at different growth stages. *Annals of Arid Zone* 31: 273-276.

Garg B.K., Kathju S., Vyas, S.P. and Lahiri A.N. 2003. Relative performance, evapotranspiration, water and nitrogen use efficiency and nitrogen metabolism of diverse genotypes of clusterbean under arid environment. In *Advances in Arid Legumes Research* (Eds. A. Henry, D. Kumar and N.B. Singh), pp. 212-220. Scientific Publishers, Jodhpur.

Garg, B.K. and Burman, U. 2002a. Physiology. In *Guar in India* (Eds. D. Kumar and N.B. Singh), pp. 63-83. Scientific Publishers, Jodhpur.

Garg, B.K. and Burman, U. 2002b. Moth bean physiology. In *Moth bean in India* pp. 87-102. Scientific Publishers, Jodhpur.

Garg, B.K., Burman, U. and Kathju, S. 2004a. Effect of water stress on moth bean [*Vigna aconitifolia* (Jacq.) Marechal] genotypes *Indian Journal of Plant-Physiology* 9: 29-35

Garg, B.K., Burman, U. and Kathju, S. 2004b. The influence of phosphorus nutrition on the physiological response of moth bean genotypes to drought. *Journal of Plant Nutrition and Soil Science* 167: 503-508.

Garg, B.K., Burman, U. and Kathju, S. 2005a. Comparative water relations, photosynthesis and nitrogen metabolism of arid legumes under water stress *Journal of Plant Biology* 32: 83-93.

Garg, B.K., Burman, U. and Kathju, S. 2006. Influence of thiourea on photosynthesis, nitrogen metabolism and yield of clusterbean (*Cyamopsis tetragonoloba* (L.) Taub.) under rainfed conditions of Indian arid zone. *Plant Growth Regulation* 48: 237-245.

Garg, B.K., Burman, U. and Kathju, S. 2007. Physiological basis of yield improvement in clusterbean in response to row spacings and phosphorus nutrition. *Journal of Plant Biology* 3 4: 147-154.

Garg, B.K., Kathju, S. and Burman, U. 2001a. Influence of water stress on water relations, photosynthetic rate and nitrogen metabolism of moth bean genotypes. *Biologia Plantarum* 44: 289-292.

Garg, B.K., Kathju, S., Lahiri, A.N. and Vyas, S.P. 1981. Drought resistance in pearl millet. *Biologia Plantarum* 23: 182-185.

Garg, B.K., Kathju, S., Lahiri, A.N. and Vyas, S.P. 2005b. Influence of saline water irrigation on clusterbean grown under different intensities of drought. *Journal of Arid Legumes* 2: 157-161.

Garg, B.K., Kathju, S., Vyas, S.P. and Lahiri, A.N. 1993. Effect of plant density and soil fertility on pearl millet under drought and good rainfall situations. *Annals of Arid Zone* 32: 13-20.

Garg, B.K., Kathju, S., Vyas, S.P. and Lahiri, A.N. 1993. Effect of plant density and soil fertility under drought and good rainfall situations. *Annals of Arid Zone* 32: 15-20.

Garg, B.K., Kathju, S., Vyas, S.P. and Lahiri, A.N. 1998. Influence of water deficit stress at various growth stages on some enzymes of nitrogen metabolism and yield in clusterbean genotypes. *Indian Journal of Plant Physiology* 3: 214-218.

Garg, B.K., Kathju, S., Vyas, S.P. and Lahiri, A.N. 2001. Influence of irrigation and nitrogen levels on Indian Mustard. *Indian Journal of plant Physiology* 6(3): 289-294.

Garg, B.K., Kathju, S., Vyas, S.P. and Lahiri, A.N. 2001b. Influence of irrigation and nitrogen levels on Indian mustard. *Indian Journal of Plant Physiology* 6 (NS) 289-294.

Garg, B.K., Kathju, S., Vyas, S.P. and Lahiri, A.N. 2003. Influence of spacing on performance, water use and nutrient uptake of clusterbean. In *Human Impact on Desert Environment* (Eds. Pratap Narain, S. Kathju, Amal Kar, M.P. Singh and Praveen-Kumar), pp. 294-304. Arid Zone Research Association of India and Scientific Publishers (India), Jodhpur.

Garg, B.K., Vyas, S.P., Kathju, S. and Lahiri, A.N. 1984. Influence of repeated water stress on wheat. *Proceedings of the Indian Academy of Sciences Plant Science* 93: 477-484.

Garg, B.K., Vyas, S.P., Kathju, S. and Lahiri, A.N. 1986. Effect of saline waters on drought affected cluster bean. *Proceedings of the Indian Academy of Sciences, Plant Sciences* 96: 531-538.

Garg, B.K., Vyas, S.P., Kathju, S. and Lahiri, A.N. 1998. Influence of water deficit stress at various growth stages on some enzymes of nitrogen metabolism and yield in clusterbean genotypes. *Indian Journal of Plant Physiology* 3 (New series): 214-218.

Ghosh, P.K., Bandyopadhyay, K.K., Tripathi, A.K., Hati, K.M., Mondal, K.G. and Mishra, A.K. 2003. Effect of integrated management of farmyard manure, phosphocompost, poultry manure and inorganic fertilizers for rainfed sorghum (Sorghum bicolour) in vertisols of central India. *Indian Journal of Agronomy* 48(1): 48-52.

Gill, M.S., Singh, J.P. and Gangwar, K.S. 2009. Integrated farming system and agriculture sustainiability. *Indian Journal of Agronomy* 54: 128-139.

Gupta, G.N. and Meena, J.N. 1993. Tillage practices for tree establishment in arid region *Annals of Arid Zone* 32(2): 115-117.

Gupta, I.N. and Rathore, S.S. 1993. Intercropping in castor (*Ricinus communis*) under dryland condition in Rajasthan. *Indian Journal Agronomy* 38(2): 182-186.

Gupta, J.P. 1978. Evaporation from a sandy soil under mulches. *Annals of Arid Zone* 17(3): 287-290.

Gupta, J.P. 1980. Effect of mulches on moisture and thermal regimes of soil and yield of pearl millet. *Annals of Arid Zone* 19(1&2): 132-138.

Gupta, J.P. 1987. Effect of tillage and mulch on soil and growth and yield of cow pea grown in arid tropics. *Arid Soil Research and Rehabilitation* 1: 161-172.

Gupta, J.P. and Aggarwal, R.K. 1978. Effect of asphalt subsurface barrier on water characteristics and productivity of sandy soils. In Abstracts, *International Symposium on Arid Zone Research and Development*, CAZRI, Jodhpur. pp. 70.

Gupta, J.P. and Aggarwal, R.K. 1980. Use of Asphalt subsurface barrier for improving the productivity of desert sandy soils. *Journal of Arid Environments* 3: 215-222.

Gupta, J.P. and Gupta, G.K. 1986. Effect of tillage and mulching on soil environment and cowpea seedling growth under arid conditions. *Soil and Tillage Research* 7: 233-240.

Gupta, J.P. and Gupta, G.N. 1981. A note on wind erosion from cultivated field in western Rajasthan. *Journal of Indian Society of Soil Science* 29: 278-279.

Gupta, J.P. and Gupta, G.N. 1981. Effect of post emergence cultivation on weed growth, nutrient uptake and yield of pearl millet. *Annals of Arid Zone* 21(4): 241-247.

Gupta, J.P. and Gupta, G.N. 1983. Effect of grass mulching on growth and yield of legumes. *Agriculture Water Management* 6: 375-383.

Gupta, J.P. and Gupta, G.N. 1985. Effect of mulches on hydrothermal environment of soil and crop production in arid western Rajasthan. *Annals of Arid Zone* 24: 131-142.

Gupta, J.P. and Singh, S.D. 1983. Hydro thermal environment of soil and vegetable production with drip and furrow irrigation. *Indian Journal of Agricultural Sciences* 53: 138-142.

Gupta, J.P. and Yadav, R.C. 1978. Soil crust formation and seedling emergence in relation to rainfall intensity and mode of sowing. *Journal of the Indian Society of Soil Science* 26: 20-24.

Gupta, J.P., Aggarwal, R.K and Kaul, P. 1979. Effect of applications of pond sediments on soil properties and yield of pearl millet and greengram in arid areas of Western Rajasthan. *Indian Journal of Agricultural Sciences* 49: 975-979.

Hadmani, A.S., Hegde, B.R. and Satyanarayana, T. 1982. Management of red soils. Review of research in India *Pt. II, 12 International Congress on Soil Science*, pp. 689-702. February 8-16, 1982, New Delhi, India.

Hedge, D.M., Sudhakara Babu, S.N., Queshi A. Aziz and Murthy, I.Y.L.N. 2007. Enhancing nutrient-use efficiency in crop production – A review. *Indian Journal of Agronomy* 52: 261-274.

Hegde, B.R. and Gajanan, G.N. 1996. Nitrogen management in dry land agriculture. In *Nitrogen research and crop production* (Ed. H.L.S. Tondon), New Delhi, India FDCO.

Hegde, D.M. and Sudhakara Babu, S.N. 2009. Declining factor productivity and improving nutrient use efficiency in oilseeds. *Indian Journal of Agronomy* 54: 1-8.

Henry, A. 2003. Cluster bean: An industrial crop for arid zone. In *Human Impact on Desert Environment* (Eds. P. Narain, A. Kar, M.P. Singh and P. Kumar), pp.

287-293. Arid Zone Research Association of India and Scientific Publishers (India), Jodhpur.

Henry, A. and Daulay, H.S. 1988. Grow cowpea variety Charodi in arid regions. *Indian Farming* 38: 9-10.

Ikisan. 2000. Castor Crop. http://www.ikisa.com/links/ap_castorCrop%20Establishment.shtml. Reviewed on 21-07-2009.

Jain, B.L. and Singh, R.P. 1982. Crop yields as influenced by runoff and soil moisture storage. *Annals of Arid Zone* 21:19-23.

Jalota, S.K., Buttar, G.S., Sood, Anil, Chahal, G.B.S., Ray, S.S. and Panigrahy, S. 2008. Effect of sowing date, tillage and residue management on productivity of cotton-wheat system in north west India. *Soil and Tillage Research* 99(1): 76-83.

Jat, B.L. and Shaktawat, M.S. 2003. Effect of residual phosphorous, sulphur and biofertilizers on productivity, economics and nutrient content of pearl millet (*Pennisetum glaucum*) in fenugreek (*Trigonella foenum-graecum*)-pearl millet cropping sequence. *Indian Journal of Agricultural Sciences* 73(3): 134-137.

Jatasra, D.S., Thakral, N.K. and Joshi, U.N. 1990. Quality and production potential of forages under rainfed conditions. In *Proceedings of International Symposium on Natural Resources Management for a Sustainable Agriculture*, Vol II., pp. 46, held on 6-10 February 1990 at New Delhi.

Jeyabal, A., Palaniappan, S.P. and Chelliah, S. 2000. Effect of integrated nutrient management techniques on yield attributes and yield of sunflower (*Helianthum annuus*). *Indian Journal of Agronomy* 45(2): 384-388.

Joshi, D.C. 1993. Soil resources of Rajasthan. In: *Natural and Human Resources of Rajasthan* (Ed. T.S.Chauhan), pp. 77-92. Scientific Publishers, Jodhpur.

Joshi, N.L. 1987. Seedling emergence and yield of pearl millet on naturally crusted arid soils in relation to sowing and cultural methods. *Soil and Tillage Research* 10: 103-112.

Joshi, N.L. 1987. Seedling emergence and yield of pearl millet under naturally crusted arid soils in relation to sowing and cultural methods. *Soil and Tillage Research* 10: 103-112.

Joshi, N.L. 1988. Millet yield under normal drought condition in arid loamy sand soils: Cultivars differences, effect of planting dates and relative energy yield equivalencies. *Arid Soil Research and Rehabilitation* 2: 203-216.

Joshi, N.L. 1999. Effect of component densities on the performance of pearl millet-mung bean intercropping system under different rainfall situations in arid environment. *Annals of Arid Zone* 38(1): 15-25.

Joshi, N.L. 1999a. Pearl millet based cropping systems to achieve sustainability in the arid region. In *Management of Arid Ecosystem* (Eds. A.S. Faroda, N.L. Joshi, S. Kathju, and Amal Kar), pp. 147-154. AZRAI and Scientific Publishers, Jodhpur.

Joshi, N.L. and Kalla, J.C. 1986. Economizing nitrogen use for Pearl millet for the Indian arid Zone. *Annals of Arid Zone* 25: 321-325.

Joshi, N.L. and Kar, Amal 2009. Contingency crop planning for dryland areas in relation to climate change. *Indian Journal of Agronomy* 54: 237-242.

Joshi, N.L. and Mali, P.C. 2004. Effect of application of phosphorous and time of harvest on seed, crude protein and gum yield of cluster bean (*Cyamopsis tetragonoloba*). *Journal of Arid Legumes* 1: 27-31.

Joshi, N.L. and Rao, A.V. 1989. Response of pearl millet to Azospirillum as influenced by nitrogen fertilizer under field condition. *Annals of Arid Zone* 28: 291-297.

Joshi, N.L. and Singh, D.V. 1994. Water use efficiency in relation to crop production in arid and semi-arid regions. *Annals of Arid Zone* 33: 169-189

Joshi, N.L. and Singh, P. 1985. Additive and complementary effects of various agronomic inputs of the yield on pearlmillet. *Annals of Arid Zone* 24: 218-222.

Kackar, N.L., Kathju, S. and Lahiri, A.N. 1978. Influence of morphactin on pearl millet plants under water stress. *Biologia Plantarum (Praha)* 20: 425-430.

Kalaghatagi, S.B., Itnal, C.J., Jiral D.I. and Magad, M.S. 1995. Pearl millet (*Pennisetum glaucum*)- based intercropping system for northern dry zone of Karnataka. *Indian Journal of Agronomy* 40(3): 495-497.

Kandpal, B.K., Kumawat, R. N. and Mertia, R.S. 2006. Agronomic evaluation of promising genotypes of moth bean under hyper arid conditions of Jaisalmer. *Journal of Arid Legume* 3(1): 1-10.

Kanitkar, N.V. 1944. Dry Farming in India. *Scientific Monograph No. 15*. ICAR, New Delhi, pp. 42.

Kathju, S. and Lahiri, A.N. 1976. Effect of soil fertility on the activities of certain enzymes of desiccated wheat leaves. *Plant and Soil* 44: 709-713.

Kathju, S., Aggarwal, R.K. and Lahiri, A.N. 1987. Evaluation of diverse effect of phosphate application on legumes in arid areas. *Tropical Agriculture* 64: 91-96.

Kathju, S., Burman, U. and Garg, B.K. 2001. Influence of nitrogen fertilization on water relations, photosynthesis, carbohydrate and nitrogen metabolism of diverse pearl millet genotypes under arid conditions. *Journal of Agricultural Science, Cambridge* 137: 307-318.

Kathju, S., Garg, B.K., Vyas, S.P. and Lahiri, A.N. 1993. Effects of supplemental irrigation and soil fertilization on pearl millet under drought. *Arid Soil Research and Rehabilitation* 7: 317-326.

Kathju, S., Garg, B.K., Vyas, S.P. and Lahiri, A.N. 2003. Sustainable production of moth bean through genotype management under arid environments. *Journal of Arid Environments* 53: 137-143.

Kathju, S., Joshi, N.L., Rao, A.V. and Praveen Kumar 1998. Arable crop production. In Fifty Years of Arid Zone research in India (Eds. A.S. Faroda and Manjeet Singh), pp. 214-252. Central Arid Zone Research Institute, Jodhpur.

Kathju, S., Vyas, S.P., Garg, B.K. and Lahiri, A.N. 1990. Fertility induced improvements in performance and metabolism of wheat under different intensities of water stress. *Proceedings International Congress of Plant Physiology* 2: 854-858.

Katyal, J.C. and Das, S.K. 1993 Fertilizer management in grain sorghum. In *Fertilizer Management in Food Crops* (Ed. H.L.S. Tondon), pp. 61-78. FDCO, New Delhi, India.

Katyal, J.C., Hong C.W. and Vlek, P.L.G. 1987. Fertilizer management in vertisols In managing of vertisols in semi arid conditions. In *Proceedings No. 6*, pp. 247-266. Bangkok, Thailand IBSRAM.

Khan, M.A. 1989. Influence of tillage methods and mulches on soil moisture and yield of gram and wheat under rainfed conditions. *Annals of Arid Zone* 28(3&4): 277-283.

Khan, M.A. and Singh, Raj 2005. Effect of cultivars, nutrient management and mulching on the production potentiality of chickpea under water harvesting condition of arid zone. *Journal of Arid Legumes* 2: 10-14.

Kijine, J.W., Tuong, T.P., Bennett, J., Bouman, B. and Oweis, T. 2002. Ensuring food security via improvement in crop water productivity, FAO *Challenge Programme on Water and Food*, Back ground Paper 1.

Kolarkar, A.S. and Dhir, R.P. 1981. Observations on cropping pattern and crop performance in various soil taxonomic units in Jodhpur district (Western Rajasthan). *Annals of Arid Zone* 20: 1-5.

Kolarkar, A.S. and Singh, N. 1984. An ancient system of water harvesting. *Indian Farming* 34: 21-22, 25.

Kolarkar, A.S., Murthy, K.N.K. and Singh, N. 1983. *Khadin* - method of harvesting water for agriculture in the Thar desert. *Journal of Arid Environments* 6: 59-66.

Krishnan, A., Singh, S.D. and Sastri, A.S.R.A.S. 1981. Effect of plant population and nitrogen on water use efficiency of Pearl millet in the arid zone of western Rajasthan. *Indian Journal of Agriculture Sciences* 51: 865-870.

Kumar, S., Rawat, C.R., Shiva Dhar and Rai, S. 2005. Drymatter accumulation, nutrient uptake and changes in soil fertility status as influenced by different organic and inorganic sources of nutrients to forage sorghum. *Indian Journal of Agricultural Sciences* 75(6): 340-342.

Kumar, P. and Aggarwal, R.K. 1988.Reducing ammonia volatilization from urea by rapid nitrification. *Arid soil Research & Rehabilitation* 2: 131-138.

Kumar, P., Godawat, S.L., Pandiya, N.K. and Vyas, M. 2007. Effect of drought and seasons on performance and stability of maize genotypes. *Annals of Arid Zone* 46: 157-162.

Kumar, P.V., Ramakrishna, Y.S., Ramana Rao, B.V., Victor, U.S., Srivastava, N.N. and Subba Rao, A.V.M. 1997. Influence of moisture, thermal and photoperiodic regimes on the productivity of castor beans (*Ricinus communis* L.). *Agricultural and Forest Meteorology* 88(1-4): 279-289.

Kumawat, P.D. and Khangarote, S.S. 2001. Response of sulphur, phosphorus and Rhizobium inoculation on growth and seed yield of clusterbean. *Annals of Biology* 17: 189-191.

Kumawat, Ram Narayan, Rathore, P.S. and Mahajan, S.S. 2009. Dry matter partitioning and yield of moongbean (*Vigna radiata*) with sulphur and iron nutrition. *Journal of Arid Legume* 6(1): 52-56.

Kushal, M.P. and Pathak, B.S. 1977. Economics and water use efficiency of sprinkler versus border irrigation on dunes. *Indian Journal of Agricultural Sciences* 47: 240-244.

Kushwaha, S.S. 2001. Improved technique of wheat cultivation on ridges saves 40% irrigation water. Office of the Joint Director, Agriculture, Shreeganganagar (Raj.). Personal Communication.

Lahiri, A.N. and Kackar, N.L. 1985. Influence of potassium on plants under soil water deficit. In *Potassium in Plant Physiology*, pp. 57-65, Potash Research Institute, New Delhi.

Lahiri, A.N. and Kharabanda, B.C. 1965. Studies on plant-water relationships: Effects of moisture deficit at various developmental stages of bulrush millet. *Proceedings of the National Institute of Science of India* 31 B: 14

Lahiri, A.N. and Kumar, V. 1966. Studies on plant-water relationships. *Proceedings of the National Institute of Science of India.* 32 B: 116-129

Lahiri, A.N. and Singh, S. 1968. Studies on plant-water relationships. *Proceedings of National Institute of Science of India* 34 B: 313-322

Lahiri, A.N., Garg, B.K., Kathju, S., Vyas, S.P., Mali, P.C. and Burman, U. 1992. Influence of the duration of favourable moisture between droughts on wheat. *Annals of Arid Zone* 31: 191-194.

Lahiri, A.N., Singh, S. and Kackar, N.L. 1973. Studies on plant-water relationships. *Proceedings of the Indian National Science Academy* 39 B: 77-90

Makkhan Lal, Bora, K.K., Ramesh Verma and Yadav, P.C. 2007. Effect of *in situ* moisture conservation on productivity of pearl millet in arid regions of Rajasthan under farmer's conditions. *Annals of Arid Zone* 46(1): 91-93.

Mali, O.P. and Mali, A.L. 1991. Resonse of promising cowpea (*Vigna unguiculata*) genotypes to row spacing and phosphorous level. *Indian Journal of Agricultural Sciences* 61: 672-677.

Manga, V.K. and Yadav, O.P. 1995. Effect of seed size on developmental traits and ability to tolerate drought in pearl millet. *Journal of Arid Environments* 29: 169-172

Mann, H.S. and Singh, R.P. 1978. Central Arid Zone Research Institute – Achievements and current line of work . *Fertiliser News* 23(9): 22-79.

Mehta, U.R., Shekhawat, G.S. and Mathur, B.N. 1970. Method and rate of fertilizer application in *Bajra* varieties under *barani* conditions. *Annals of Arid Zone* 9:17-21.

Mishra, D., Singh, H. and Kushwaha, H.L. 2009 Improved traditional sowing device for arid region Paper accepted for presentation at International Conference on Nurturing Arid Zone for people and the environment: Issues and Agenda for the 21st century, held during Nov 24-28, 2009 at CAZRI, Jodhpur.

Mishra, D.N., Kumar, Kamlesh, Singh, L.R. 2005. Effect of sowing dates and nitrogen levels on the incidence of bihar hairy caterpillar, *Spilosoma obliqua* (Walker) in sesame. *Annals of Plant Protection Sciences* 13(1): 11-14.

Misra, D.K. 1956. Relation of root development to drought resistance of plants. *Indian Journal of Agronomy* 1: 41-46.

Misra, D.K. 1962. Crop stubble can stop wing erosion in arid zone. *Indian Farming* 12(9): 9-10.

Misra, D.K. 1962. Inducing drought resistance in cereals by pre-sowing seed treatments. *Annals of Arid Zone* 1: 46-53.

Misra, D.K. and Daulay, H.S. 1963. The resistance of *bajra* seedlings to soil drought. *Indian Journal of Agronomy* 7: 240-245

Misra, D.K. and Kumar, Vijay 1963. Influence of depth on seedling emergence, crop growth, crop stand and yield of *P. typhoides* in arid zones. *Annals of Arid Zone* 2: 114 - 122.

Misra, D.K., Bhattacharya, B.B. and Vijay Kumar 1966. Agronomic studies in arid zone II. Germination studies as influenced by seed size, temperature and time interval of varieties of *Pennisetum typhoides*. *Indian Journal of Agronomy* 2: 264-266.

Nagar, Khem Chand 2001. Effect of phosphorous, sulphur and PSB on growth, yield and quality of clusterbean (*Cyamopsis tetragonoloba* L. Taub.) in semi arid climate. *Ph.D. Thesis*, RAU, Bikaner.

Nandwal, A.S., Dabas, S., Bharti, S. and Yadav, B.D. 1990. Zinc effect on nitrogen fixation and cluster bean yield. *Annals of Arid Zone* 29: 99-103.

Natrajan, M. and Willey, R.W. 1986. The effects of water stress on yield advantages of intercropping systems. *Field Crops Research* 13: 117-131.

Natrajan, M. and Willey, R.W. 1980. Sorghum-pigeonpea intercropping and the effect of plant population density II. Resource use. *Journal of Agricultural Sciences*, *Cambridge* 95: 59-65.

Osiru, D.S.O. and Willey, R.W. 1972. Studies on mixtures of dwarf sorghum and beans (*Phaseolus vulgaris*) with particular reference to plant population. *Journal of Agriculture Science, Cambridge* 79: 531-540.

Painuli, D.K. and Ahuja, Usha Rani 2009. Farmers perception on tillage and residue management in arid zone of Rahjasthan - A diagnostic survey. In Abstracts, *4th World Congress on Conservation Agriculture*, pp. 39. Feb. 4-7, 2009, New Delhi, India.

Parihar, G.N., Sahu, M.P. and Joshi, N.L. 1998. Nitrogen, sulphur and thio-urea nutrition of pearl millet (*Pennisetum glaucum* L.R Br.) II. Effect on yield and yield components. *Annals of Arid Zone* 37: 59-67.

Parihar, S.S., Singh, N.T. and Sandhu, B.S.1977. Response of crops to soil temperature changes induced by mulching and irrigation. In *Soil Physical Properties and Crop Production in Tropics* (Eds. R. Lal and D.J. Greenland), pp. 305-315. John Wiley Sons, New York.

Patel, I..C., Patel, M.M., Patel, A.G. and Tikka, S.B.S. 2004. Response of clusterbean [*Cyamopsis tetragonoloba* (L.)] varieties to time of sowing and row spacing on yield under North Gujarat agro-climatic condition. *Journal of Arid Legumes* 1: 24-26.

Pathak, B.S. 2006. Long Term. Strategies and programmes for mechanization of agriculture in Agro Climatic Zone-XIV: Western dry region. In *Final Report of the Study Relating to Formulating Long-term Mechanization: Strategy for* *each Agro-Climatic Zone/State in India*, pp. 249-254. Prepared by the Indian Agricultural Statistics Research Institute, New Delhi for the Department of Agriculture and Cooperation, Ministry of Agriculture, Govt. of India,

Patidar, M., Joshi, N.L. and Singh, H.P. 1996. Effect of tillage on yield and moisture use efficiency of clusterbean in arid zone. *Annals of Arid Zone* 35(2): 147-149.

Paul, W. Unger, Harry, H. Schomberg, Thanh H. Dao and Ordie, R. Jones 1997. Tillage and crop residue management practices for sustainable dry land farming systems. *Annals of Arid Zone* 36(3): 209-232.

Phogat, B.S., Singh, D.P. and Singh, Phool 1984. Responses of cowpea (Vigna unguiculata (L.) Walp.) and mungbean (*Vigna radiata* (L) Wilczek) to irrigation. *Irrigation Science* 5: 47-60.

Porwal, B.L. and Mathur, M.K. 1973.Response of bajra varieties to nitrogen application. *Annals of Arid Zone* 12: 77-81.

Prabhu, T., Narwadkar, P.R., Sajindranath, A.K. and Rathod, N.G. 2002. Effect of integrated nutrient management on growth and yield of coriander *(Corriandrum sativum* L.*). South Indian Horticulture* 50(4-60): 680-684.

Prasad, Kanta and Gill, M.S. 2009. Developments and strategies perspective for organic farming in India. *Indian Journal of Agronomy* 54: 186-192.

Praveen Kumar, Tarafdar, J.C. and Kathju, S. 2009. Increasing efficiency of reduced tillage through legumes and compost application in arid region. In Abstracts, *4th World Congress on Conservation Agriculture*, pp. 81-82. Feb. 4-7, 2009, New Delhi, India.

Prinz, D. and Malik. A.H. 2002. *Runoff Farming*. Article prepared for WCA infoNET, Institute of Water Resources Management, Hydraulic and Rural Engineering, Deptartment of Rural Engineering, University of Karlsruhe, D-76128 Karlsruhe, Germany, pp. 2-39.

Ramesh Babu, V., Murthy, P.S.S. and Reddy, D. Narasimha 1984. Moisture stress effects at different phenophases in four groundnut (*Arachis hypogaea* L.) cultivars. *Annals of Arid Zone* 23: 13-20.

Rana, D.S., Yadav, B.D., Dhokia, R.S. and Midha, L.K. 1991. Effect of row spacing and inter row spacing on seed yield of clusterbean under late sown condition. *Guar Research Annals* 7: 54-56.

Rao, A.S. and Singh, R.S. 1998. Climatic features and crop production. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and M. Singh), pp. 17-38. CAZRI, Jodhpur.

Rao, A.S. and Singh, R.S. 2004. Evapo-transpiration rates, growing degree days and water use efficiency of some arid legumes. *Journal of Arid Legumes* 1: 166-170.

Rao, A.S., Ramakrishna, Y.S. and Venkateswarlu, J. 1994. Determination of crop growing period in arid and semi arid regions of Rajasthan. *Annals of Arid Zone* 35: 229-231.

Rao, A.V. and Venkaseswarlu, B. 1983.Microbial ecology of the soils of Indian desert agriculture. *Ecosystems Environment* 10: 361-364.

Rao, A.V. and Venkateswarlu, B. 1987. Nitrogen fixation as influenced by water stress in selected crop legumes of the Indian arid zone. *Arid Soil Research and Rehabilitation* 1: 89-96.

Rao, G.G.S.N. and Joshi, N.L. 1986. Microclimate in different planting systems of pearl millet under rainfed conditions. *Mausam* 37: 491-494.

Rao, S.S., Regar, P.L., Jangid, B.L. and Singh, Y.V. 2007. Effect of nutrient and weed management on forage sorghum (*Sorghum bicolor*) under rainfed condition. *Indian Journal of Agronomy* 52(2): 139-142.

Rao, V.M.B. and Singh, S.P. 1993.Crop responses to organic sources of nutrients in dry land conditions. In *Recent Advances in Dry Land Agriculture* (Ed. L.L. Somani), pp. 287-304. Scientific Publisher, Jodhpur.

Rathore, M.S., Bhati, D.S., Chandawat, M.S., Singh, I. and Chawra R.S. 2006. Performance of arid legumes and their intercropping system with pearl millet to sustain productivity in arid region of Rajasthan. *Research on Crops* 7(2): 375-377.

Rathore, S.S. 1992. Increased productivity in dryland agriculture by intercropping. In *National Symposium on Resource Management for Sustained Crop Production*, held during 25-28 February 1992 at Bikaner, 137 pp.

Reddy, B.N. and Suresh, G. 2009. Crop diversification with oilseed crops for maximizing productivity, profitability and resource conservation. *Indian Journal of Agronomy* 54: 206-214.

Reddy, M.S. and Willey, R.W. 1981. Growth and resource use studies in an intercrop of pearl millet/groundnut. *Field Crops Research* 4: 13-24.

Regar, P.L., Rao, S.S. and Joshi, N.L. 2007. Effect of *in-situ* moisture conservation practices on productivity of Rainfed Indian mustard (*Brassica juncea*). *Indian Journal of Agronomy* 52(2): 148-150.

Regar, P.L., Rao, S.S. and Singh, Y.V. 2005. Integration of rain water harvesting and planting geometry to improve henna production on gravelly wastelands. In *Abstracts, National Symposium on Efficient Water Management for Ecofriendly Sustainable and Profitable Agriculture*, pp. 154. December 1-3, 2005 held at IARI, New Delhi.

Regar, P.L., Rao, S.S. and Singh, Y.V. 2006. Effect of *in situ* moisture conservation techniques and row configuration on sorghum (*Sorghum bicolor*) productivity. In *Extended Summaries of National Symposium on Conservation Agriculture and Environment,* pp. 84. October 26-28, 2006 held at BHU, Varanasi.

Sastri, A.S.R.A.S., Ramakrishna, Y.S., Rao, G.G.S.N. and Ramana Rao, B.V. 1984. Agricultural droughts and crop planning - A case study for western Rajasthan. *Mausam* 35: 261-264.

Saxena, A., Singh, D.V. and Joshi, N.L. 1997. Effect of tillage and cropping system on soil moisture balance and Pearl millet yield. *Journal of Agronomy and Crop Science* 178: 251-257.

Saxena, A., Singh, D.V. and Joshi, N.L. 1997. Effects of tillage and cropping systems on soil moisture balance and pearl millet yield. *Journal of Agronomy and Crop Science* 178: 251-257.

Saxena, Anurag and Lodha, S. 2003. Integration of *Brassica* amendments and summer irrigation for weed suppression in clusterbean (*Cyamposis* *tetragonoloba*) in hot arid regions. *Indian Journal of Agricultural Sciences* 73: 145-147.

Saxena, Anurag, Singh, D.V. and Joshi, N.L. 1997. Effect of tillage and cropping systems on soil moisture balance and pearl millet yield. *Journal of Agronomy and Crop Science* 178: 251-257.

Saxena, Anurag, Singh, D.V. and Joshi, N.L. 2003. Economic assessment of cropping systems for western arid zone. In *Human Impact on Desert Environment* (Eds. Pratap Narain, S. Kathju, Amal Kar, M.P. Singh, M.P. and Praveen Kumar), pp. 353-357. AZRAI and Scientific Publishers, Jodhpur.

Sharma, B.D., Taneja, K.D., Kairon, M.S. and Jain, Veena 1984. Effect of dates of sowing and row spacing on yield and quality of clusterbean (*Cyamopsis tetragonoloba* L. Taub). *Indian Journal of Agronomy* 29: 557-558.

Sharma, B.L. and Sharma, P.K. 1995. Pearlmillet (*Pennisetum glaucum*) - based crop mixtures under rainfed conditions. *Indian Journal of Agronomy* 40(3): 362-365.

Sharma, K.D. 1983. Soil moisture depletion from contour furrows. *Journal of Indian Society of Soil Science* 31(4): 596-597.

Sharma, K.D. and Kuhad, M.S. 1999. Influence of potassium on plant water relations and yield of clusterbean under soil moisture stress. In *Recent Advances in Management of Arid Ecosystem* (Eds. A.S. Faroda, N.L. Joshi, S. Kathju, Amal-Kar), pp 267-270. CAZRI, Jodhpur.

Sharma, K.D., Vangani, N.S., Singh, H.P., Bohra, D.N., Kalla, A.K. and Joshi, P.K. 1997. Evaluation of contour vegetative barriers as soil and water conservation measures in arid lands. *Annals of Arid Zone* 36(2): 123-127.

Sharma, K.D., Verma, C.M. and Kalla, A.K. 1980. Studies on soil moisture storage under contour furrows during the growing season of *Cenchrus ciliaris*. *Annals of Arid Zone* 19(1&2): 37-42.

Sharma, K.D., Verma, C.M. and Shankarnararayan, K.A. 1983. Soil moisture storage under contour furrows. *Journal of Indian Society of Soil Science* 31(2): 110-114.

Sharma, K.L., Mandal, U.K., Srinivas, K., Vittal, K.P.R., Biswapati Mandal, Kusuma, Grace and Ramesh, V. 2005. Long-term soil management effects on crop yields and soil quality in dryland alfisol. *Soil and Tillage Research* 83: 246-259.

Shekhawat, B.S. 1992. Effect of sowing dates and row spacing on moth bean varieties. *Indian Journal of Pulses Research* 5: 160-163.

Shivran, A.C., Khangarot, S.S., Shivran, P.L. and Gora, D.K. 1996. Response of cluster bean (*Cyamopsis tetragonoloba*) varieties to sulphur and phosphorous. *Indian Journal of Agronomy* 41: 340-342.

Shrotriya, G.C., Pareek, B.L. and Mathur, C.M. 1966. A note on nitrogenous fertilization on wheat in Pali western Rajasthan. *Annals of Arid Zone* 5: 257-258.

Singh, A.K., Mishra, D., Sharma, P., Kavia, Z.D. and Pande, P.C. 1995. Tractor vs Power: Projections for Indian Arid Zone. *AMA* 26(1): 16-21.

Singh, A.L. and Chaudhary, A.L. 1998. Interaction of sulphur and micronutrient in groundnut for sustainable agriculture. In *Plant Physiology* (Ed. G.C. Shrivastava), pp.151-157. Pointed Publisher Jaipur.

Singh, D.V., Saxena, A. and Joshi, N.L. 2001. Response of pearl millet to phosphorus and sulphur in a cropping system. In *Abstract of Impact of Human Activities on Thar Desert Environment*, pp. 41. February 15-17, 2001

Singh, H., Kavia, Z.D. and Narain, P. 2004. Traditional knowledge of Indian Thar Desert and its utilization. Central Arid Zone Research Institute, Jodhpur, India, 1-80.

Singh, H., Kushwaha, H.L. and Mishra, D. 2007. Development of seed drill for sowing on furrow slants to increase the productivity and sustainability of arid crops. Bio Systems Engineering, UK, Elsevier Science, *Pergamon* 98(2): 176-184.

Singh, H., Mishra, D. and Khan, M.A. 1998. Status of farm mechanization in rajasthan. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and Manjit Singh), pp. 443-453.CAZRI, Jodhpur.

Singh, H., Mishra, D. and Nahar, N.M. 2002. *Final Report on ICAR Ad-hoc Research Project on Energy Census and Resource Assessment of Arid Zone (Western Rajasthan),* CAZRI, Jodhpur. pp.1-184.

Singh, H., Singh, A.K. and Kushwaha, H.L. 2008. Design and development of novel weeding tools for arid region. In Souvenir, *Conference on Leveraging Innovations and Inventions: Enhancing Competitiveness*, pp. 157-162. NRDC, New Delhi.

Singh, H.P. 1980. Improving the moisture storage in sandy desert soils by sub-surface moisture barrier. In: *Arid Zone Research and Development* (Ed. H.S. Mann), pp. 245-261. Scientific Publishers, Jodhpur.

Singh, H.P. 1984. Improving soil physical environment for dryland crop production by field surface modification. *Proceedings of Seminar on Soil Resources and Productivity Management,* pp. 141- 142. Indian Society of Soil Science, New Delhi.

Singh, H.P. and Bhati, T.K. 1988. Ridge-furrow system for planting dryland crops for soil and rain water management in the Indian arid zone. In *Challenges in Dryland Agriculture - A Global Perspective,* pp. 575-577. Amarillo, Texas.

Singh, H.P., Singh, R.P. and Singh, K. 1979. Effect of bentonite subsurface barrier and runoff concentration on soil moisture storage and yield of round gourd in sandy soils. *Indian Journal of Agricultural Sciences* 49: 880-885.

Singh, J.P. and Singh, B.P. 1988. Intercropping of mungbean and guar in castor under dryland condition. *Indian Journal of Agronomy* 33(2): 177-180.

Singh, K.C. 1982. Response of greengram to phosphorus application in arid zone. *Annals of Arid Zone* 21:275-278.

Singh, K.C. and Singh, R.P. 1977. Intercropping of annual grain legumes with sunflower. *Indian Journal of Agricultural Sciences* 47: 563-567.

Singh, K.C. and Singh, R.P. 1980. Relative performance of rainfed moth bean varieties under different fertility levels. *Forage Research* 6: 161-164.

Singh, K.C. and Singh, R.P. 1981. Relative performance of moth bean genotypes grown during summer season with different fertility levels. *Forage Research* 7: 43-48.

Singh, M and Joshi, N.L. 1994. Performance of pearl millet based intercropping systems under drought conditions. *Arid Soil Research and Rehabilitation* 8: 313-319.

Singh, M. and Joshi, N.L. 1994. Effect of mixed and inter cropping on dry matter and grain yields of component crops in arid environments. *Annals of Arid Zone* 33: 125-128.

Singh, M. and Joshi, N.L. 1997. Pearl millet based cropping systems in relation to plant population and moisture availability. *Annals of Arid Zone* 36(1): 37-42.

Singh, P and Joshi, N.L. 1980. Intercropping of pearl millet in arid areas. *Indian Journal of Agriculture sciences* 50: 338-341.

Singh, R.C. and Faroda A.S. 1982. Performance of moong bean varieties under different sowing dates in planting conditions. *Journal of Research* (HAU) 12: 639-643.

Singh, R.P. 1978. Dry farming research - Its relevance and prospects for arid zone agriculture. In *Arid Zone Research and Development* (Ed. H.S. Mann), pp. 475-482. Arid Zone Research Association of India, Jodhpur.

Singh, R.P., Dauley, H.S., Singh, K.C. and Gupta, B.S. 1978. Effects of rates and method of nitrogen application on the yield and yield attributes of rainfed bajra HB-3 grown in the arid zone. *Annals of Arid Zone* 17:136-144.

Singh, R.P., Singh, K.C. and Ramakrishna, Y.S. 1978. Effect of systems of planting pearl millet on the yield, total productivity, moisture use and monitory returns. *Indian Journal of Agricultural Sciences* 48: 138-142.

Singh, R.P., Singh, H.P. and Singh, K.C. 1975. A note on the use of Bentonite clay as a sub-soil moisture barrier for vegetable production on drylands of Rajasthan. *Annals of Arid Zone* 14(1): 63-66.

Singh, R.P., Singh, H.P., Daulay, H.S. and Singh, K.C. 1979. *Annual Report All India Coordinated Research Project on Dryland Agriculture.* Jodhpur Centre. pp. 22-27.

Singh, R.P., Singh, H.P., Daulay, H.S. and Singh, K.C. 1981. Effect of periodical application of nitrogen of organic and inorganic form on yield of rainfed pearl millet. *Indian Journal of Agriculture Science*s 51: 409-416.

Singh, Raj 2006. Effect of cropping sequence, seed rate and weed management on weed growth and yield of Indian mustard in western Rajasthan. *Indian Journal of Weed Science* 38: 69-72.

Singh, Raj and Khan, M.A. 2003. Response of clusterbean varieties to fertility levels and cropping systems under arid conditions. In *Advances in arid legume Research* (Eds. A. Henry, D. Kumar and N.B. Singh), pp. 225-228. Scientific publisher, Jodhpur.

Singh, Raj and Singh, B. 2008. Integrated nutrient management in clusterbean – Indian mustard cropping system in arid region. In Abstract, *Enhancing Productivity, Nutritional Security and Export potential through Arid Legumes,* pp. 56. CAZRI, Jodhpur.

Singh, Raj and Singh, Bhagwan 2002. Effect of variety and nutrient management on the pearl millet production in arid zone (in Hindi). In *National Seminar on Soil Degradation and its Control in Rainfed Farming*, pp. 51. CRIDA, Hyderabad.

Singh, Raj, Singh, B. and Saxena, A. 2004. Response of clusterbean genotypes to nutrient management under arid condition of Rajasthan. *Journal of Arid Legume* 1(1):32-34.

Singh, S.D. 1977. Effect of rhizobia inoculation on nodulation and yield of moong bean (*Vigna radiata* L. wilczek.). *Annals of Arid Zone* 6: 79-84.

Singh, S.D. 1977. Optimum utilization of limited water supply. In *Desertification and its Control,* pp. 237-255. ICAR, New Delhi.

Singh, S.D. 1985. Potentials of water harvesting in dry regions. *Annals of Arid Zone* 24: 9-20.

Singh, S.D. 1988. Using pod sediment treated catchments. In *Water Harvesting in Arid Tropics* (Ed. S.D. Singh), p. 1- 11. CAZRI, Jodhpur.

Singh, S.D. 1988a. Using pond sediment treated catchments. In *Water Harvesting in Arid Tropics* (Ed. S.D. Singh), pp. 11-21. CAZRI, Jodhpur.

Singh, S.D. 1988b. Run off utilization for increasing crop yield. In *Water Harvesting in Arid Tropics* (Ed. S.D. Singh), pp. 21-32. CAZRI, Jodhpur.

Singh, S.D. and Singh, M. 1988. Integration of management practices. In *Water Harvesting in Arid Tropics* (Ed. S.D. Singh), pp. 45 -53. CAZRI, Jodhpur.

Singh, S.D. and Singh, M. 1996. Management practices for crops selected for water harvesting and comparative study of catchement type v/s. ridge furrow system. In *Water Harvesting in Deserts* (Ed. S D Singh), pp. 79-91. CAZRI, Jodhpur.

Singh, S.D. and Singh, P. 1978. Value of drip irrigation compared with conventional irrigation for vegetable production in a hot arid climate. *Agronomy Journal* 70: 945-947.

Singh, S.D. and Singh, Y.V. 1993. Yield to water use relationship and use of the concept in managing a limited water supply. In *Arid Land Irrigation and Ecological Management* (Ed. S.D. Singh), pp. 103-158. Scientific Publishers, Jodhpur

Singh, S.D., Bhandari, R.C. and Aggarwal, R.K. 1985. Long term effects of phasing phosphate fertilizer on soil fertility and yield of pearl millet in rotation with grain legumes. *Indian Journal of Agricultural Sciences* 55: 274-278.

Singh, S.D., Daulay, H.S. and Muthana, K.D. 1973. Runoff farming making the best use of available water. *Indian Farming* 23: 7-8.

Singh, S.D., Gupta, J.P. and Singh, P. 1978. Water economy and saline water use by drip irrigation. *Agronomy Journal* 70: 948-951.

Singh, S.D., Misra, D.K., Vyas, D.L. and Daulay, H.S. 1971a. Fodder production of sorghum in association with different legumes under different levels of nitrogen. *Indian Journal of Agricultural Sciences* 47:172-176.

Singh, S.D., Misra, D.K., Vyas, D.L. and Daulay, H.S. 1971b. Forage production of sorghum varieties in relation to different levels of nitrogen. *Indian Journal of Agricultural Sciences* 41: 216-220.

Singh, S.D., Singh, R.C., Vyas, D.L. Misra, D.K and Bhati, N.S. 1973. Studies of tillage, fertility on pearl millet in sandy arid plains of Rajasthan. *Annals of Arid Zone* 12: 145-154.

Singh, S.D., Singh, Y.V. and Bhandari, R.C. 1989. Tomato yield as related to drip lateral spacing and fertilizer application on total and wetted area basis. *Canadian Journal of Plant Science* 69: 991-999.

Singh, Sultan, Yadav, S.S., Tikoo, A. and Yadav, J.S. 2004. *Nutrient and water management for sustainable agriculture in south west Haryana*. CCSHAU, Regional Research Station, Bawal, pp.1-55.

Singh, Y.P. and Mann, J.S. 2007. Interaction effect of sulphur and zinc in groundnut and their availability in Tonk district of Rajasthan. *Indian Journal of Agronomy* 52(1): 70-73.

Singh, Y.V. 1984. Optimum use of scarce water in arid agriculture. In *Agroforestry in Arid and Semi-arid Zones* (Ed. K.A. Shankarnarayan), pp. 227-231. CAZRI, Jodhpur.

Singh, Y.V. 1999. Maximizing water use efficiency for sustainable crop production in arid eco-system. In *Management of Arid Eco-system* (Eds. A.S. Faroda, N.L. Joshi, S. Kathju and Amal Kar), pp. 427-434. Arid Zone Research Association of India, Jodhpur.

Singh, Y.V. and Bhandari, R.C. 1984. Effects of irrigation frequency and mount of water on the yield of cauliflower in an arid region. *Indian Journal of Agricultural Sciences* 54: 581-586.

Singh, Y.V. and Saxena, A. 1998. Management of limited water resources for crop production. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and M. Singh), pp. 189 -213. Central Arid Zone Research Institute, Jodhpur.

Singh, Y.V., Joshi, N.L., Singh, D.V. and Saxena, A. 1999. Response of chilli to water and nitrogen under drip and check basin methods of irrigation. *Annals of Arid Zone* 38: 9 -13.

Singh, S.D. and Rao, J.S. 1994. Yield water nitrogen response analysis in cumin. *Annals of Arid Zone* 33: 29-34.

Solanki, N.S., Shekhawat, R.P.S. and Shekhawat, B.S. 1998. Efficiency of phosphate culture with phosphorus level on growth and yield of cluster bean. *Annals of Arid Zone* 37: 417-418.

Soundara Rajan, M.S., Selvan, V.S. and Ruben, N. 1991. Tillage need of rainfed groundnut in sandy clay loam soils. *Indian Journal of Agriculture Science* 61(11): 803-806.

Taneja, K.D., Gill, P.S. and Sharma, B.D. 1982. Effect of row spacing and intra row spacing on the seed yield of guar cultivars. *Forage Research* 8: 111-115.

Tarafdar, J.C. and Rao, A.V. 1990.Effect of manures and fertilizers on phosphatases in rhizosphere of arid crops. *Potosh Journal of Soil Science* 23: 81-85.

Tarafdar, J.C. and Rao, A.V. 1997.Response of arid legume to VAM fungal inoculation. *Symbiosis* 22: 265-274.

Tarafdar, J.C. Chatarath, R. and Kiran Bala 1991. Role of phosphate solubilizing bacteria in pearl millet rhizosphere as affected by genotypes in arid soils. *Transaction of the Indian Society of Desert Technology* 16: 129-137.

Tarafdar, J.C., Rao, A.V. and Praveen-Kumar 1995. Role of phosphatase producing fungion growth and nutrition of cluster bean (*Cyamopsis tetragonolob*a). *Journal of Arid Environment* 20: 331-337.

Tomar, P.S. 1970. Test weight and protein content of bajra in relation to method of sowing, manorial treatment and seed rate. *Annals of Arid Zone* 9:159-162.

Tomer, P.S., Dalal, S.K., Gill, P.S. and Bishnoi, K.C. 1973. Comparative efficiency of cluster bean(Cyamopsis tetragonoloba) varieties with varying phosphorus levels and seed rates. *Annals of Arid Zone* 12:163-167.

Tripathi, S.N. 1990. Mixed cropping og forage species in relation to herbage yield and quality In *Proceedings of International Symposium on Natural Resources Management for a Sustainable Agriculture,* Vol II, pp. 47.

Varughese, Kuruvilla and Mathew, Thomas. 2009. Integrated farming systems for sustainability in coastal eco-system. *Indian Journal of Agronomy* 54:120-127.

Venkateswarlu, B. and Rao, A.V. 1987. Quantitative effects of field water deficits on N_2 (C_2H_2) fixation in selected legumes grown in the Indian desert. *Biology and Fertility of Soils* 5: 18-22.

Venkateswarlu, B. and Shanker, Arun K. 2009. Climate change and agriculture: Adaptation and mitigation strategies. *Indian Journal of Agronomy* 54: 226-230.

Venkateswarlu, B., Rao, A.V. and Lahiri, A.N. 1983. Effect of water stress on nodulation and nitrogenase activity of guar (*Cyamopsis tetragonoloba* (L.) Taub.). *Proceedings of the Indian Academy of Sciences (Plant Science)* 92: 297-301.

Venkateswarlu, B., Sharma, K.L. and Prasad, J.V.N.S. 2009. Conservation agriculture-constraints, issues and opportunities in rainfed areas. *Lead Papers*, *4th World Congress on Conservation Agriculture*. pp. 80.

Venkateswarlu, J. 1981. Maximization of crop production in dry lands. *Indian Journal of Soil Conservation* 9: 124-140.

Venkateswarlu, J. 1992. Efficient resource management of resources in Rajasthan for sustained crop production. In *Proceedings of 12th National Symposium on Resource Management for Sustained Crop Production,* pp. 157-165. Indian Society of Agronomy, RAU, Bikaner.

Venkateswarlu, J. and Aggarwal, R.K. 1991. Nutrient balance and sustainable agriculture in western dry region. *Fertilizer News* 36: 75-79.

Venkatswarlu, B., Raikhey, N.P. and Aggarwal, R.K. 1982. Effect of inoculation and cobalt application on nodulation and nitrogen uptake in guar (*Cyamopsis tetragonoloba*). *Journal of Indian Society of Soil Science* 30:550-551.

Verma, C.M., Paroda, R.S. and Sharma, K.D. 1977. Effect of sowing time, seed treatment and methods of sowing on establishment of *Cenchrus ciliaris*. *Forage Research* 3: 149-152.

Vyas, S.P., Garg, B.K., Kathju, S. and Lahiri, A.N. 1983. Sensitivity of *Sesamum indicum* L. to soil moisture stress at different developmental stages. *Annals of Arid Zone* 22: 191-197.

Vyas, S.P., Garg, B.K., Kathju, S. and Lahiri, A.N. 1987. Influence of soil fertility on sesame (*Sesamum indicum* L.) under repeated water stress. *Annals of Arid Zone* 26: 259-266.

Vyas, S.P., Garg, B.K., Kathju, S. and Lahiri, A.N. 1995. Influence of nitrogen on Indian mustard grown under different levels of stored soil moisture. *Journal of Arid Environments* 29: 173-184.

Vyas, S.P., Garg, B.K., Kathju, S. and Lahiri, A.N. 2003. Genotypic management of clusterbean for sustainable production under arid environment. *Indian Journal of Pulse Research* 16: 104-107.

Vyas, S.P., Kathju, S., Garg, B.K. and Lahiri, A.N. 1985. Performance and metabolic alterations in *Sesamum indicum* L. under different intensities of water stress. *Annals of Botany* 56: 323-331.

Vyas, S.P., Kathju, S., Garg, B.K. and Lahiri, A.N. 1996. Activities of nitrate reductase and ammonia assimilating enzymes of moth bean under water stress. *Science and Culture* 62: 213-214.

Vyas, S.P., Kathju, S., Garg, B.K. and Lahiri, A.N. 1999. Influence of supplemental irrigation and urea application on productivity and nitrogen metabolism of sesame. *Indian Journal of Plant Physiology* 4 (New series): 197-201.

Vyas, S.P., Kathju, S., Garg, B.K., Lahiri, A.N. and Sharma, P.C. 1991. Effects of duration of 'wet period' between two drought events and soil fertility status on performance and metabolism of *Sesamum indicum* L. *Plant Physiology and Biochemistry* 18: 96-100.

Waghmare, A.B. and Singh, S.P. 1982. Total productivity and net returns of different sorghum-legume intercropping system under varying N levels. *Indian Journal of Agronomy* 27: 423-428.

Wasi, Ullah, Chakravarti, A.K., Mathur, C.P. and Vangani, N.S. 1972. Effect of contour furrows and contour bunds on water conservation in grasslands of western Rajasthan. *Annals of Arid Zone* 11(3&4): 170-182.

Willey, R.W. 1979a. Intercropping-its importance and research needs. I. Competition and yield advantage. *Field Crops Abstracts* 32(1): 1-10.

Willey, R.W. 1979b. Intercropping-its importance and research need. II. Agronomy and research approaches. *Field crops Abstracts* 32(2): 73-85.

Willey, R.W. and Heath, S.B. 1969. The quantitative relationship between plant population and crop yield. *Advances in Agronomy* 21: 281-321.

William, A.H. and Fenster, C.R. 1992. *Understanding Wind Erosion and its Control*. Report No. G 79-474-A, USA, Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska, Lincoln.

Yadav, B.D. Aggarwal, S.K. and Faroda, A.S. 1990. Dry matter accumulation and nutrients uptake in clusterbean as affected by row spacing and fertilizer application. *Forage Research* 17: 39-44.

Yadav, B.D., Agarwal, S.K. and Arora, S.K. 1989. Response of clusterbean to row spacing and fertilizer application. *Guar Research Annals* 5: 8-13.

Yadav, B.D., Aggarwal, S.K. and Faroda, A.S. 1991. Dry matter accumulation and nutrient update in cluster bean as affected by row spacing and fertilizer application. *Forage Research* 17: 39-44.

Yadav, B.D., Joon, R.K. and Sheoran, R.S. 1992. Response of clusterbean to dates of sowing and row spacing under rainfed conditions. *Forage Research* 18: 157-159.

Yadav, J.S., Kumar, V. Yadav, B.D. and Kumar, A. 2003. Effect of sowing time and seed rate on seed yield and quality of cluster bean. In *National symposium on Arid legume for Food, Nutrition, Security and Promotion of Trade*, pp.108-109. CCS HAU, Hisar.

Yadav, N.D. and Beniwal, R.K. 2006. Performance of moth bean varieties to spacing and fertilizer P application in arid western Rajasthan under rainfed condition. *Journal of Arid Legumes* 3: 64-65.

Yadav, N.D. and Gupta, I.C. 1990. Row spacing and special arrangements effect on pulses momno-cropping in rainfed condition in arid zone of western Rajasthan. *Current Agriculture* 14: 9-12.

Yadav, O.P. 2008. Performance of landraces, exotic elite populations and their crosses in pearl millet (*Pennisetum glaucum*) in drought and non-drought conditions. *Plant-Breeding* 127(2): 208-210

Yadav, R.C. and Singh R.P. 1978. Tillage and seeding practices for arid lands of Rajasthan-A perspective. *Agricultural Mechanization in Asia* 9: 71-76.

Yadav, R.L., Yadav, D.V. and Duttamajumder, S.K. 2008. Rhizospheric environment and crop productivity. *Indian Journal of Agronomy* 53: 1-17.

Yadav, R.L., Yadav, D.V. and Shukla, S.K. 2009. Bio intensive agronomy: A paradigm shift in agronomic research. *Indian Journal of Agronomy* 54: 105-112.

Yadav, S.K. and Singh, D.P. 1981. Effect of irrigation and antitranspirants on evapotranspiration, water use efficiency and moisture extraction patterns of barley *Irrigation Science* 2: 177-184

Yadava, N.D. and Beniwal, R.K. 1999. Sustainable cropping systems for rainfed arid eco-system. In *Abstracts of Poster Sessions, 4th Agricultural Science Congress on Sustainable Agricultural Export*. NAAS, RAU and Government of Rajasthan, Jaipur. 17 p.

Yadava, N.D. and Beniwal, R.K. 2000. Effect of nitrogen on productivity of grasses in sole and intercropping system in arid zone under rainfed condition. *Indian Journal of Agronomy* 45(1): 82-85.

Yadava, N.D. and Beniwal, R.K. 2001. Response of pearl millet to N and FYM under rainfed condition of western Rajasthan. In *Abstract - Impact of Human activities on Thar Desert Environment.* pp 37.

Yadava, N.D., Beniwal, R.K. and Soni, M.L. 2008. Effect of fertilizer and spacing on cluster bean varieties under rainfed condition. In *Abstract - Enhancing Productivity, Nutritional Security and Export Potential Through Arid Legumes*, pp.57. June 28-30, CAZRI, Jodhpur

Zhao, C., Shan, L., Deng, X., Zhao, L., Zhang, Y. and Wang, Z. 2004. Current situation and counter-measures of the development of dryland farming in China. *Transactions of the CSAE* 20(4): 280-285.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 354-382 pp.

Alternative Farming Systems for Hot Arid Regions

T.K. Bhati, V.S. Rathore, J.P. Singh, R.K. Beniwal,
N.S. Nathawat, Birbal, Devi Dayal , M. Shamsudheen,
Bhagirath Ram, P.P. Rohilla, S.S.Rao, P.R. Meghwal,
Pardeep Kumar, A.K. Sharma and D.K. Painuli

Central Arid Zone Research Institute, Jodhpur

Farming system came into existence when man placed first seed in ground and domesticated first animal for his use. Since both these components were complementary to each other, they formed a system together in farming and thus qualified to be called as “farming system”. Conceptualization of farming systems, however, is linked with the inception of family institution. Farming is a process of harnessing solar energy in term of economic products (plant and animal) and system is a set of interrelated practices/processes organized into a functional entity. Thus farming system can be defined as a “system, which comprises a set of agricultural activities involving interdependent functional units (farming enterprises) to profitably harvest solar energy, or simply a set of agricultural profession professed on a farm unit”. Zandstra (1981) conceptualized farming system as production and consumption activities by farmers to derive benefit from land and other resources/inputs through growing crop or animal rearing or forestry or combination of them with the use of technologies available to him under specific conditions. Thus, it represents an appropriate combination of farm enterprise (crop, livestock, fishery, forestry, etc.) and the means available to the farmers to raise them profitably. A sustainable and efficient farming system aims for enhances productivity, profitability, sustainability, balanced food, clean environment, recycling of resources, adoption of improved technologies, employment opportunities, high input-output ratio, solving feed, fodder, fuel crisis, promoting agricultural oriented industry and ultimately standard of living of farming community.

Arable cropping in arid regions is risky due to their complex and multifarious problems i.e. environmental, biotic, technological and socio-economic. The crop yields are meager and unstable and consequently the income from the existing cropping alone is hardly sufficient to sustain the farmer's family. Therefore to mitigate the risk and uncertainty of income from conventional cropping, it is essential to integrate various agricultural enterprises in production programme that yield regular and evenly distributed income , cater diverse needs of farmers family along with imparting sustainability through conservation and improvement of natural resources in fragile arid ecosystem. These regions are endowed with appreciable agro-ecolgical diversity and hence various components viz. crop, animals, tree, grass, fruit tree, can be integrated in production system. Choice of these components is dictated by interaction of edapho-climatic, technological, infrastructural, institutional, household, policy and socioeconomic factors.

Integrated farming system (IFS) approach has been widely recognized and advocated as one of tool to harmonize use of inputs and their compounded responses to make the production system sustainable. Several studies conducted in different parts of country have revealed that an integrated farming system (IFS) approach besides increasing system productivity also envisages harnessing complementarities and synergies among different agricultural sub-systems/enterprises and augments the total productivity, profitability, sustainability and gainful employment for a household.Gill *et al.* (2009) examined the average yield gap between 27 predominant and 37 diversified farming systems across different agro climatic zones. They revealed that diversification of existing farming systems by integration of enterprises resulted into higher productivity and 30-50% higher profit.

Various studies undertaken in different parts of country suggests that income of farmers can be increased manifold by way of diversification of farming system for sustainability and economic viability of marginal and small category of farmers (Ganeshan *et al.*, 1990; Shanmugasundaram *et al.*, 1995; Tiwari *et al.*, 1999; Jayanthi *et al.*, 2001; Manjunath and Itnal, 2003; Shelke *et al.*, 2001; Singh, 2004; Gill, 2004; Singh *et al.,* 2007). The agronomic, socio-economic and environmental advantages of IFS are vivid and appealing and these are potentially suitable to all categories of farmers. In view of all these results, there is an urgent need to promote IFS concepts under all agro climatic conditions of country with special thrust on small and marginal farmers of dry lands of arid and semi-arid regions.

Environmental and Socio-Economic Setup

An arid climate is defined as one in which for the greater part of the year precipitation is less than PET and meet less than one third of annual water need (PE).Using an aridity index, the boundaries of the principal hot and cold arid zone of India (Krishnan, 1968) have been delineated, accordingly, 317090 Km^2 area comes under hot arid and 70, 300 km^2 comes under cold arid.

Climate

The climate of hot arid region is characterized by extreme temperature, low and erratic rainfall, high solar radiation, high evapo-transpiration, strong wind regime and low relative humidity. The arid region experienced extreme variation in the diurnal and annual temperature. During the winter season, the north western hot arid region of India experiences very cold temperature ranging from 3-10°C. The temperature begins to rise from March onwards and recorded the highest temperature in May-June, when mean temperature is above 40°C. However on individual day temperature up to 47 to 50°C are also recorded (Ramakrishna and Rao, 1992). The mean annual rainfall of the region varies from <150 mm in north western part to >600 mm in south eastern part. More than 85% of total rainfall is received during the south western monsoon season (July-September). Coefficient of variation (C.V.) of annual rainfall often >50% in most of the parts and is higher than 70% in extreme region of western Rajasthan (Ramakrishna *et al.*, 1992). Crop growing period varies from 7-14 weeks depending upon the location and types of soil (Rao *et al.*, 1994). Occurrence of sowing rains (>25 mm) is another common climatic aberration of the region, which can be delayed as late as first week of August in western part and third week of July in eastern part, instead of normal 1-15 July (Rao and Singh, 1998). In the region sky remains generally clear favoring high insolation by day and rapid back radiation by night (Agnihotri and Singh, 1987). The bright sunshine hours varies from 6.6 hours in July-August to 8.8 hours in winter season and >10 hours in May. Average incoming solar radiation varies from 22.05 MJ m^2 (8.40-27.30 MJ m^2) during month of April-May to 14.7 MJ m^2 (7.98-16.17 MJ m^2) in January (Rao and Singh, 1998).The region experienced very strong wind regime. The average wind speed during hot summer month, monsoon and post monsoon seasons are 14.6-18.5, 9-13, <7 km h^{-1}, respectively. The relative humidity is low in most part of the year. In summer months, especially in the afternoon, the relative humidity (RH) in the region goes down as low as 2-3% .The humidity starts building up from June with the incursion of monsoon air mass over the region during the rainy season and goes up to 60-70% (Ramkrishna, 1997).The annual PET ranges from 160 cm in eastern part to 180 cm in western part of Arid Rajasthan. The evaporation starts increasing from mid of March and reaches 15-16 mm day^{-1} by May. It decreases (6-8 mm day^{-1}) during monsoon period.

Drought is a recurring feature in arid region with variation only in its magnitude from year to year. During last century, 47-62% of the years in arid region of Rajasthan experienced drought of varying intensity and duration (Rao and Singh, 1998).

Soil

Arid region of Rajasthan has been endowed with variety of soils. Soils of arid zone were classified as per US comprehensive System of classification, and accordingly soils of this region grouped into two orders viz. Aridisols and Entisols. The Aridisols and Entisols occupy 41 and 52% area, respectively (Joshi *et al.*, 1998).

Arid zone soils are low in organic matter and N (Jenny and Rayachaudhari, 1960). The region having annual rainfall <300 mm the mean organic carbon varied from 0.05-0.2, 0.2-0.3 and 0.3-0.4%, in light, medium and heavy textured soils, respectively. Average content of P is <20 kg ha^{-1}, out of which 80-85% is in inorganic fraction mainly composed of Ca-bound (Mehta *et al*., 1971; Joshi *et al*., 1973; Choudhari *et al*., 1979). The soils are well supplied with K and total K varied from 0.54-1.57% and is slightly higher in dune and interdunal plains than in sandy soils (Joshi *et al*., 1982). The DTPA soluble Fe , Mn Zn and Cu varied from 2.2-16.7, 1.1-25, 0.27-2.36 and 0.28-1.25 ppm, respectively (Joshi *et al*.,1982; Dhir *et al*., 1983; Sharma *et al*., 1983; Dangarwal *et al*., 1983; Sharma *et al*., 1985) .

About 77.57% of total geographical area of western Rajasthan is affected by wind erosion/deposition hazard (Narain *et al*., 2000). About 22950 km^2 or 10.99% area of the region has been affected by water erosion and 0.11% area is affected by water logging. Thus low fertility, less water retention capacity, high erodibility is major edaphic constraints for crop production in the region.

Vegetation

The vegetation of hot arid region is very sparse and consisted of scattered thorny trees/shrubs and grasses. It is described as Tropical Thorn Forest (Champion and Seth, 1968). Indian Desert has 682 species belonging to 352 genera. According to landforms the vegetation of arid region was divided into five formation types: (i) Mixed xeromorphic thorn forest (ii) Mixed xeromorphic woodland (iii) Dwarf semi-shrub desert (iv) psammophytic scrub and (v) Succulents and halophytic plant community (Satayanaran 1963).

Water resources

Low and erratic rainfall, deep dry sandy soil terrain with dune bodies, absence of and/or disorganized natural drainage in major part, very deep and saline ground water, very high evaporation resulted into scarcity of water in the region. Khan (1996) gave detailed account of surface, canal and ground water resources of the region. Thirteen districts of Rajasthan (Hot arid region) receive an average annual rainfall of 62623 million cubic meters (MCM), which constitutes 89% of the total inflow of water. The total surface water potential is 1361 MCM. The total ground water resources is 4545 MCM in arid Rajasthan, the utilizable ground water resource for irrigation is 3355 MCM and 2957 MCM being gross recharge (Ground Water Department Statistics, 1984). The IGNP is the major canal network that passes through the region. The flow value of the main canal varies from 1.727×10^6 to 2.961×10^6 m^3 in different seasons.

Population

The hot arid region of India is most thickly populated arid region of world. Between 1961 to 2001 the human population in western Rajasthan has increased by 194% and the density increased from 37 km^{-2} to 108 km^{-2}.There is a likelihood that human population will increase from the present 22.5 million to 33.6 million and its density from 108 to 161 by 2025 (Anonymous, 2007).

Land utilization pattern

Low and erratic rainfall, extremes of seasonal temperature, high evaporation loss, meager ground water potential, absence of perennial streams, salinity and duny and rocky/gravelly terrains are the major factors affecting the land use in hot arid region of India (Ram and Lal, 1998). The net sown area has increased from 39.42% in 1960 to 51.56% in 2000 and projected to increase to 55% by 2025. In the same period the fallow land (19.49% to 13.15%) and area not available for cultivation (14.28% to 8.72%,) has decreased substantially (Anonymous, 2007). The intensity of cultivation decreased from east to west. Double cropped area constitutes 7.34% area. Rest of the agricultural land is primarily rain fed. The varying degree of intensity of cultivation viz. 80-100, 60-80, 30-60 and <30% constitutes 18.30, 13.84, 12.20 and 11.17%, respectively of rain fed area of arid Rajasthan. Nearly 28.13% area is occupied by wasteland. The average size of land holding per household decreased from 17.77 ha in 1951 to 6.0 ha at present with over all decrease of 57% during last four decades, and projected to fall <4 ha by 2020.

Source of income

The hot arid region is basically an agrarian economy. An analysis of production and income of year 2004-05 shows that in all four agro climatic zones, returns from agriculture contributes 26-43% of total income and other sectors (including wage/income from service sector, business and allied activities) contributes 56-73% of income. The crop land contribution to total income is 15.03, 21.39, 16.64 and 30.18% in Zone I, II, III and IV, respectively. The income from different sectors of agriculture is also revealing. In all four zones income from cropping provides 59-71% of total agriculture income while livestock rearing provides 28-42% (Anonymous, 2007).

Farming Systems in Vogue

Farming system in arid region of India evolved through centuries of practicing and refining of farming, in consonance with prevailing climatic conditions, available natural resources. The knowledge and experience of people engaged in farming were passed on to successive generation in developing these systems. The arid farming system all through ages were predominantly livestock based. In arid Rajasthan <250 mm rainfall zone grasses and shrubs dominant the scenario and range/pasture development with livestock rearing is the main agricultural preposition. In area receiving rainfall between 250-350 mm besides grasses and shrubs, multi-purpose tree species dominates and mixed farming encompassing agro forestry system, mixed cropping, livestock and pasture management are main livelihood options. In area receiving rainfall >300 mm crops and cropping system diversification, agro forestry and livestock rearing are major system of sustenance of arid zone farmers (Bhati and Joshi, 2007).

There have been several changes in arid landscape in past few decades. There has also been unprecedented increase in human population, resource exploitation and development activities, all exerting immense pressure on resource base of region. This resulted in fragmentation of holding, shift in land use pattern with grassland and tree reserves converted to cultivated field, drastic reduction in fallowing practices, over-exploitation of groundwater resources and erosion of soil fertility and biodiversity.

Over the years, economic considerations have overtaken the sustainability issues. Low and erratic rainfall, frequent drought, the increasing cost of cultivation, lower compensation of labor and inputs has made farming in arid region a challenging enterprise. Employment opportunities in sector other than agriculture have enticed many to cross the floor. The largest segment of farming community however is constrained to make a living from farm related activities. With the opening of market for international trade in farm commodities, the competition have toughened for the resource constrained farmers of arid region of the country. On the other hand, useful technologies have been generated by researchers on many alternative systems, which could be adopted. In this scenario the farmers could benefit greatly by inducing diversification in farming system and by strengthening the traditional systems (Anonymous, 2007).

Opportunities

The mixed crop-livestock, mixed livestock-crop and livestock farming systems form the spectrum of economic activities of farming community in hot arid region of India. The farming systems in arid western Rajasthan represent man-agriculture-tree/shrub- livestock continuum and each component is interdependent. In the region,due to thin population till first quarter of 20th century even through the land productivity was low, these farming system were well balanced and able to meet the requirement of inhabitants because demand then were limited and plenty of rangeland were available for livestock production. However, tremendous population growth of human being as well as that of livestock resulted in destabilization of equilibrium of these systems. Presently, croplands permit no more than subsistence living for the farmers that too, in normal rainfall year.

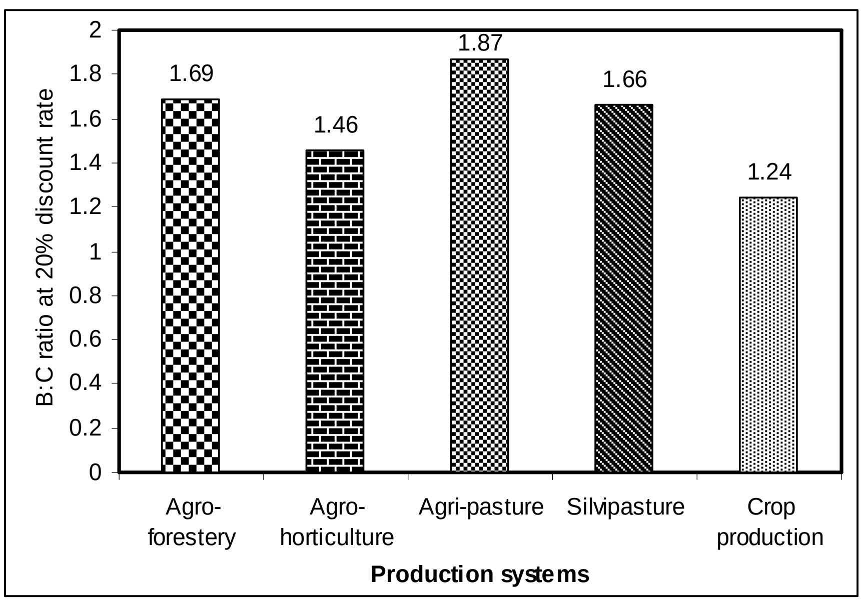


Fig. 2. Benefit:Cost ratio of different land use systems in arid region.

The majority of farming community engaged in dry land farming in arid zone has a subsistence orientation. Dry land farming is main occupation of people as >70% population engaged in it on >90% of cultivable land. About 60-70% farmers in this region reside in village and cultivated their lands only in rainy season. The rest 30-40% farmers made their dwellings on their farms and thus have better control and management of their land and vegetation resources. Absentee landlords are another lot having large holding and leasing out lands for cultivation. Appropriate farming systems could be different for these situations, cropping systems and diversification of crops for first category, integrated farming system with emphasis on perennial component for second category and capital intensive system like agri-tourism may suit last category (Bhati and Joshi, 2007). An economic evaluation of alternate land use system (Fig. 1) over 18 years period clearly demonstrated that integration of perennial vegetation fetched higher benefit cost ratio (1.46-1.87) over arable farming (1.24) (Bhati, 1997).

Diversification is a means of making the arid farming system more remunerative, whereas harsh climatic condition, degraded soils and erratic rains limits choice of vegetation; many alternatives exists, as evidenced by research findings. The indigenous plants with proven potential but neglected or not exploited for their utility need to be introduced in arid farming system. A wealth of medicinal plant suited to arid milieu exists in region, which may be brought under cultivation. Plants and animals from other iso-climatic regions may also be considered. The endemic woody species may also made to yield products such as gum, resins, value additions processes could be undertaken for many other products currently disposed at low costs or not utilized at all.

Sustainability in the existing system may be imparted through judicious and scientific use of available resources. Traditional water conservation structure and practices have become a tale of past. On the other hand, abundantly available solar radiation has not been harnessed exhibiting a poor scenario of resource utilization. The reversal of trend may bring a sea change in productivity of farming system in arid region. The research carried out over the years has generated valuable information. The modules and methods for improvement of productivity of arid farming system need to be adopted by end users to bring prosperity in the region.

An efficient farming system is an integration of appropriate viable technologies within the enterprise and/or integration of one or more additional enterprise at farm according to availability of resources and to sustain and satisfy as many necessities of farm owner as possible along with conservation of natural resources.

Alternative Farming Systems

Alternative crop and cropping systems

The productivity of crops is low under arid region. Diversification of crops and cropping systems with the aim of increasing resource use efficiency and profit seems to be a viable option to impart sustainability in agricultural production system. The intercropping of compatible crops is time tested strategy for improving productivity, resource conservation and reducing risk in arid region. The intercropping of *Ricinus communis* + *Sesamum indicum* (1:3) and *Ricinus communis* + *Arachis hypogea* (1:3) was found more remunerative than sole cultivation of respective crops in Kachchh region of Gujarat (Devi Dayal *et al.*, 2009). Meena *et al.* (2008) reported that intercropping of *Sesamum indicum* + *Cyamopsis tetragnoloba* (1:2) is more sustainable than sole cultivation of these crops in arid region of Gujarat. The intercropping of *Lawsonia inermis* and *Cyamopsis tetragnoloba* (1:1) is also found promising for arid region of Gujarat. The results of an experiment conducted at Bikaner (Rajasthan) revealed that *Vigna aconitifolia* - *Cyamopsis tetragnoloba* cropping systems is better in term of productivity, return and water use efficiency than *Cyamopsis tetragnoloba* - *Pennnisetum typhoides*, *Vigna aconitifolia*- *Pennnisetum typhoides, Pennnisetum typhoides*- *Pennnisetum typhoides, Pennnisetum typhoides* + *Cyamopsis tetragnoloba* cropping systems (Rathore *et al*, 2006).

Diversification of traditional *Gossypium-Triticum* cropping system with low water requirement crops e.g. *Vigna radiate, Cyamopsis tetragnoloba, Cajanus cajan, Riccinus communis* + *Vigna aconitifolia* in kharif season and *Hordeum vulgare, Brassica juncea* and *Cicer aeritinium* in Rabi season was found more remunerative (Table 1) (Goswami, 2006).

Diversification of arable cropping through inclusion of more efficient, competitive and high value- low volume commodities like medicinal, dye yielding crops is also an important strategy to overcome many constraints faced by the farmers in arid region. Possibilities of Amaranths cultivation in Kachchh was explored and results indicated that cultivar GA-2 is promising. Grain yield 1206 kg ha^{-1} with net return of Rs. 20000 ha^{-1} are possible with its cultivation (Vyas, 2007; Anonymous, 2009). The cultivation of nutritious minor millet (Proso millet, barnyard millet, foxtail millet and finger millet) is also a viable crop diversification option for the kachchh region and results revealed that grain yield of minor millets varied from 513 to 785 kg ha^{-1}.

Highest yield was registered by foxtail millet followed by proso millet and finger millet (Bhagirath Ram and Vyas, 2005).

Table 1. Economics of Crop Diversification in Canal Command of Irrigated North Western Rajasthan.

Crop	Area (ha)	Total irrigation water (ha- cm)	Irrigation water saving (ha -cm)	Production (q/ha)	Total income (Rs)
Kharif					
G. americanum	10	500 (5)	--	12	216000
G. americanum (50%)	5	250 (5)	250	12	108000
Vigna radiata (80%)	8	96 (2)	--	10	144000
C. tetragnoloba (40%)	4	72 (2)	--	12	48000
C.cajan (10%)	1	30 (3)	--	12	21600
R. communis + V. aconitifolia (20%)	2	52 (4)	--	12 +2	38400+ 12000
Rabi					
T. aestivum	10	500 (4)		30	210000
T. aestivum (50%)	5	250 (4)	250	30	105000
B. juncea (35%)	3.5	105 (2)	--	16	89600
H. vulgare (20%)	2	70 (3)	--	26	31200
C. aertinium (30%)	3	75 (1)	--	10	45000

*In *Kharif* crops on an average 300 mm effective rainfall have been considered for cotton and pigeon pea and 270 mm for other *Kharif* crops. Values in parentheses indicate the number of post sowing irrigations.

During last decades, rising population, inadequate supply of the drugs in certain parts of the world, high cost of synthetic medicine and their side effects have increased the interest in herbal drugs. This lead to the spurt in the use of herbal medicine and consequently the international trade in medicinal plants has recorded a sharp rise. Some of plants with proven medicinal properties have potential for cultivation in hot arid region. *Cassia angustifolia, Aloe vera, Plantago ovata* are promising medicinal plants for commercial scale cultivation in region. Under average rainfall condition in arid region of Gujarat, *C. angustifolia* provides 522.6 kg ha^{-1} total dry matter productivity with net return of Rs. 3020 ha^{-1}. Application of 100 kg N and 40 kg P ha^{-1} with planting at 40 x 40 cm spacing was found optimum for getting higher productivity in the hot arid region of Gujarat.

The effectiveness of cultivation of Aloe in strip plantation to arrest soil erosion was explored at Bikaner. The result showed that strip plantation of Aloe resulted in net soil deposition of 179.2 t ha^{-1} against soil loss of 248.3 t ha^{-1} from bare soil, at Bikaner. Thus preliminary results showed that introduction of Aloe along with arable crops in strips provide opportunity for conservation of soil resources (Rathore *et al.*, 2008).

Lawsonia inermis is a promising dye yielding shrub and widely used as herbal hair dye and staining body's skin. Its cultivation has been proved to be profitable enterprises for farmers in drought prone area of Western Rajasthan. Its cultivation provides an average net return of ~ Rs. 12500 ha^{-1} under rainfed situation (Chand *et al.*, 2005). Suitable agro-techniques for optimizing the productivity and quality of *Lawsonia* have developed. The crop can be grown along with the multipurpose trees and in the orchard of fruit plants like *Mangefera indica, Emblica* etc. (Vyas and Swamy, 2003). The maximum dry leaf yield and return was obtained at the plant population of 50,000 plants ha^{-1}. Even during bad rainfall years (52.9 mm) it could provide a net return of Rs.6331 ha^{-1} at Bhuj (Vyas, 2005).

Growing environmental hazard, non-sustainability of food production and less safe food quality in modern chemical input intensive crop production are some of the important concerns that are being projected in favor of organic agriculture. In hot arid region due to high risk associated with crop production, the use of agro chemicals is very less. Thus farmers are practicing organic agriculture since age by default. The system despite its low productivity compared to conventional system has established itself highly efficient in terms of resource recycling and providing better food and economic sustainability in the arid region Some promising crops for production under organic system are cumin (spice), psyllium (medicine), sesame (oilseed), cluster bean (gum), moth bean (traditional confectionery items e.g. *papad*, *bhujia*), etc. Enhanced quality of these corps's products in the existing production system with better utilization of local resources could make a considerable contribution in strengthening the economic sustainability of this region. The improvement in this production system is possible by intervention in nutrient management and plant protection aspects. For nutrient management practice of ley farming, inclusion of legume in crop rotations and efficient recycling of biomass are important for the region. Even under prolonged dry spell it provided some produce to meet the farmer needs. For effective non-chemical plant protection some measures e.g. crop rotation (Lodha, 2008), use of compost as soil application along with foliar spray of compost extract (Lodha and Burman, 2000), application of oil cakes or residues of mustard with one summer irrigation (Lodha, 2008) and application of neem based pesticides (Satyavir and Yadav, 2005) have found promising. Thus organic cultivation of selective crops having higher export potential provides an opportunity to strengthen the economy of the region.

Agri-silviculture

Growing of trees with agricultural crops is an age old practice in arid and semi-arid region of India. Trees by virtue of their perennial nature impart stability in production along with improvement in microclimate and soil fertility. *Prosopis cineraria*, *Holoptelia integrifolia* and *Hardwickia binata* are some of the tree species suitable for agrisilviculture system in dry land area of this region (Muthana and Arora, 1977; Shankarnarayan *et al.*, 1987). Harsh (1995) outlined suitable tree and shrub for different rainfall region of arid zone (Table 2).

Table 2. Tree species for different rainfall regions

Rainfall (mm)	Species
>250	*Zizyphus nummularia, Acacia tortilis, A. senegal, Prosopis cineraria, Calligonum polygonoides, P. juliflora, Tecomella undulata*
250-400	*P. cineraria, Hardwickia binata, Colophospermum mopane, Dichrostachyus nutans, Ailanthus excelsa, Acacia catacheu, Grewia tenax, Acacia nilotica, Zizyphus mauritiana*
400-600	*Albizzia amara, A. lebbek, Cassia siamea, Emblica officinialis, Hardwickia binata, Alianthus excelsa, Moringa olefera*

Harsh and Tewari (1993) found that growing of trees with crops increase the total productivity per unit of land as compared to sole arable cropping in arid region.Agri-silvi system consisting *Tecomella undulat* as woody component with various dryland crops was found promising due to improved soil fertility, microclimate and moisture availability. A tree density of 100-200 plants ha^{-1} was found optimum for minimum interference with yield of dry land crop like *Cyamopsis tetragonoloba* under *P. cineraria* canopy shade. *Vigna sinensis* and *Pennisetum typhoides* showed better performance with tree species than *Vigna radiata* and *Vigna aconitifolia*. Besides good yield of dry land crops, bonus yield of dry leaves and twigs (650-1050 kg ha^{-1}) and fuel wood (1.8-2.6 t ha^{-1}) could be obtained from *Prosopis* tree (Table 3) through annual lopping (Bhati *et al.*, 2008).

A study conducted in arid region of Haryana on *Prosopis cineraria* based agro forestry system revealed that the tree influenced grain and fodder yield of associated crops. Fodder yield and net return was more in association with tree as compared to sole cropping. Maximum net returns (Rs. 15197 ha^{-1}) was obtained with pearlmillet - *Brassica tournefoila* cropping system in association of Prosopis (Kaushik and Kumar, 2003)

Table 3. Yield of various dry land crops and *Prosopis cineraria* as influenced by tree-crop combination

Crop	Radial distance from tree bole (m)				Produce from *P. cineraria* (kg ha^{-1})	
	2	3	4	5	Dry leaves and twigs	Fuel wood
V. radiata	75	112	125	125	800	2000
V. aconitifolia	16	42	84	113	1050	2500
V. sinensis	106	175	156	173	850	2200
P. typhoides	780	1037	1354	1388	650	1800

In arid region of Gujarat, *Azadirachta indica and Ailanthus excelsa* based agri-silvi culture system involving cowpea, green gram, clusterbean and sesame, on an average fetched 59.3% and 25.7% more income, respectively than sole cropping. Besides higher economic return the system also improve soil organic carbon along with catering diverse need of farmer viz.fodder, fuel wood and timber. These agri-silvi systems are promising for north and north western Gujarat (Patel *et al.,* 2008).

Preliminary results of an experiment conducted Bikaner to assess performance of *Calligonum polygonoides* and *Acacia jacquemontii* in agri-silvi-pasture system indicated that integration of perennial vegetation imparts stability in production.As out of four years of experimentation (2003-2007) the arable crops failed to attained harvest maturity due to paucity of rainfall. Under these situation, the perennial woody components viz. *Calligonum polygonoides* and *Acacia jacquemontii* provided fodder and fuel wood. Further the growth of *Calligonum* is influenced by associated component and it attained maximum growth in association with legume (*C. tetragnoloba* and *V. aconitifolia*) and least with association of grasses (*L. sindicus and C. ciliaris*). Studies conducted at Pali revealed that strip cropping of *Lawsonia inermis* consisting 4 rows of henna alternated with 4 rows of *C. tetragnoloba* at 60 cm spacing provided higher return than their sole planting (Singh *et al.*, 2005).

Proper management of tree and crops is vital for optimizing productivity of agri-silviculture production system. Harsh (1995), reported that in an agri-silvi system comprising *Holoptelia integrifolia* (12 years old plantations) and arid legume. The yield of *V. radiata* was 25% higher under lopped tree as compared to un-lopped trees.

Besides improving productivity, the agri-silviculture system improves the soil properties. Tarfdar (2008) made an attempt to study the effect of different farming system on improvement in beneficial biological activities under arid ecosystem and reported substantial improvement in soil biological activities under agri silvi system as compared to sole crop (Table 4).

Table 4: Improvement in microbial population and biomass under different agri-silvi system as compared to sole crop.

Silvi component	% increase over sole crop			
	Fungi	Bacteria	Actinomycetes	Microbial biomass
P. cineraria	13-24	21-37	9-18	18-23
T. undulata	18-27	27-39	10-16	19-25
Z. mauritiana	19-39	23-53	23-53	20-77

Agri-pasture

Studies conducted at Jodhpur and Bikaner on agri-pastoral systems i.e. cropping between grass strips laid out against prevalent wind direction revealed that average yield of *C. tetragonoloba* at Jodhpur was 418 kg ha^{-1} under unprotected plot, which increased up to 503 kg ha^{-1} in protected plot. Thus with strip cropping at least some biomass is produced in low rainfall years besides reducing soil erosion. In good rainfall year, production of arable crops increased along with increased forage yield of grasses. At Bikaner, average yield of cluster bean during normal and low rainfall were 589 and 181 kg ha^{-1}, respectively. Dry forage yield of *Lasirus sindicus* with strip cropping system obtained during normal and low rainfall year were 6400 and 2650 kg ha^{-1}, respectively. This practice of strip cropping of legumes and grasses holds promises for Bikaner region (Singh, 1989 and 1995). Ley farming also increased grain yield of crop significantly over control (Singh and Gupta, 1997). Dauley (1994) reported that intercropping of arid legumes with *Cenchrus ciliris* gave higher yield, return and moisture use efficiency than sole pasture.

Agri-horticulture

Due to harsh edapho-climatic conditions arable crop production is risky in hot arid region and threatening the agriculture, Under such situation, horticulture based production system is considered effective strategy for improving productivity, employment opportunities, economic condition and nutritional security (Chundawat, 1993; Pareek, 1999; Chadha, 2002). Several drought hardy fruit crops like *Cappirs decidua*, *Salvadora oleoides*, *Cordia dichotoma*, *Cordia gharaf*, *Zizyphus nummularia* var. *rotundifolia*, *Z. mauritiana* are suitable for the area receiving rainfall <300 mm. Besides providing fruit these plant produce moisture laded nutritious leaves for animal. Several other fruit such as *Emblica officinialis*, *Punica granatum*, *Aegle marmelos*, *Phoenix dactylifera*, and *Tamarindus indica* can be grown in the area having irrigation facilities. Among the vegetable crops *Solanum melongena*, *Lagnaeria siceraria*, *Luffa acutangula*, *Luffa cylindrica*, *Citrullus lanatus*, *C. lanatus* var. *fistulosus*, *Cucumis melo* var. *utillismus*, *C.* melo var *momardica*, *C. callosus*, *Moringa oleifera*, *Cymopsis tetragnoloba* and *Vigna ungiculata* are suitable for horticultural based framing systems (Pareek and Awasthi, 2008).

The management practices of horticultural crops have been standardized for optimizing the productivity. Suitable rootstocks for improved cultivar of ber have identified. Bio-fertilizer inoculation of ber seedlings recorded improved growth and nutrient uptake (Meghwal *et al.*, 2006). Seed treatment of *Cordia myxa*'s seed with GA (250 and 500 ppm) improved the germination (Meghwal, 2007). Seed treatment of karonda with treatment of GA_3 (Anonymous, 2001) and of *Emblica* with 1% KNO3 improved the germination. In some of indigenous fruit plants the vegetative propagation techniques have standardized. In Kair (*Capparis decidua*), hardwood cutting rooted better (30-40%) in July-August (Meghwal and Vashishtha,1998). In *Cordia myxa*, I-budding during July-September gave highest success (Meghwal, 2007). Pruning management of fruit is very important to attain sustainable yield. As regards to pruning severity in ber is concerned, pruning at 17-23 nodes on the main axis produce vigorous shoot with maximum fruit production. The main axis of the branches should be pruned keeping 15-25 nodes depending on climatic conditions i.e., 20-25 nodes in arid areas and 15 nodes in semi-arid area along with complete removal of secondaries (Pareek and Vishalnath, 1996; Pareek, 2001). In case of Phalsa, pruning in last week of December at 120 cm from ground level was found optimum (Meghwal, 2006).

Water harvesting techniques has developed to augment water availability to fruit plants. Higher run-off yield was obtained from catchments having 5% slopes (Sharma *et al.*, 1982). Circular catchments around each tree (1.5 m radius) with 5% slope towards tree trunk and covering the catchment with black polyethylene sheet has found effective to conserve moisture. The application of irrigation water at 1.0 IW: CPE ratio at 10 cm depth with 11 to 12 irrigation from June to February was found to be the best for pomegranate for higher fruit yield (Anonymous, 1990-91). Drip irrigation resulted in early commercial fruit production in *Ziziphus, Punica granatum* and *Emblica* and application of water equal to 60% of pan evaporation (PE) registered significantly higher fruit yield compared to 40% PE.(Anon., 2007).Beniwal *et al.*(2006) attempted to schedule irrigation in Kagzi lime under drip irrigation. They found irrigation at 0.7 Etc was better over 1.0 and 0.40 Etc in terms of plant growth and saving of water.

Results of different agri-horticultural system evaluated at Pali showed that highest yield of mungbean (2.70 q ha^{-1}) was in lemon plants and of clusterbean (3.8 q ha^{-1}) in Karonda plants. Maximum increment in height was found in pomegranate and collar diameter was found in *ber*. Intercropping of bottle guard and during *kharif* season and pea (arkel) and kasuri methi with ber plantation did not cause adverse effect on three year old ber and produced 40900 kg ha^{-1}, 5200 kg ha^{-1} and 8100 kg ha^{-1} green leaves and 880 kg seeds ha^{-1} of bottle guard, peas and methi respectively. (Singh and Kumar, 1993)

In arid region, agri-horti system involving *Z. rotundifolia + V. radiata/V. aconitifolia/C. tetragonoloba* and *Z. mauritiana + V. radiata/C. tetragonoloba* have been found environmental friendly and economically viable even during drought years. In agri-horti system involving *Ziziphus* and *V. radiata* during subnormal year when rainfall was 51% less than long term average of 360 mm, the yield of mungbean was reduced by 44% whereas under sole crop mungbean yield was reduced by 51%. The inventory of system showed that this agri-horti system can provide round the year supply of fodder for 5 goat/sheep ha^{-1} and fuel wood for family off 4 members, besides efficient nutrient cycling and increase in economic stability (Faroda, 1998). Gupta *et al.* (2000) reported that 3-years old plantation of *Z. maruitiana* @ 400 plants ha^{-1} in association with green gram performed well with seasonal rainfall of 210 mm and fruit yield from intercropped increased net profit to Rs. 288.6 ha^{-1}, this shows that agri-horti system minimize risk in arid regions and thus helps in imparting economic stability. This system is recommended for the region having rainfall <250-300 mm. Saroj *et al.* (2003) recommended *C. tetragonoloba – B. juncea* and Indian aloe as ground storey component in ber to optimize productivity and profitability under arid ecosystem. Experiment conducted at Pali (Rajasthan) revealed that integration of *C. tetragonoloba*, *V. radiata* and *Sesamum* with *Z. mauritiana* (Cv. Seb), the yield of fruit increased three fold (14.8 kg $tree^{-1}$) as compared to pure orchard (5.2 kg $tree^{-1}$) (Singh, 1997). Intercropping in newly planted ber orchard had no adverse effect on plant growth up to 5 years. The intercrop also exhibited higher yield when planted with ber compared to monoculture under rain fed conditions. Agri-horti system comprising *Zizyphus* + mungbean provided fruit, fuel wood and round year employment even in below average rainfall year (Sharma and Gupta, 2001). Intercropping of mungbean in ber orchard was recommended by Gupta (1992). According to Singh *et al.* (2003) intercropping of legumes with ber orchard produced higher grain yield of intercrops by 5-20% over their sole cropping and intercropping is promising particularly during juvenile period of fruit plantation.

An experiment conducted at Pugal (Bikaner) revealed that intercropping of annual crops with fruit trees provides the extra income to farmers when fruit trees are in their juvenile phase . Highest total income and net profit was realized with bael + groundnut intercropping followed by ber +groundnut and kinnow + groundnut (Yadava *et al*., 2006). The highest B:C ratio was recorded with bael + clusterbean followed by bael + Mothbean (Table 5).

Table 5. Economics of different agri-horti system at Pugal in District Bikaner

Agri-horti system	Net profit (Rs ha^{-1})	B:C Ratio
Ber + Mothbean	10854.0	2.06
Ber + Clusterbean	12970	2.33
Ber + Groundnut	20379	2.45
bael + Mothbean	14310	2.86
Bael + Clusterbean	16054	3.02
Bael + Groundnut	21799	2.75
Kinnow + Mothbean	11015	2.20
Kinnow + Clusterbean	11122	2.10
Kinnow + Groundnut	19830	2.50

A study on kinnow based agri-hortisystem under irrigated arid condition at Sriganganagar showed that intercrop did not show any significant negative effect on fruit yield .The yield was highest under mung bean and lowest under cotton intercropping, the fruit yield was at par with intercropping of mungbean, cotton-barley and cotton- chickpea (Bhatnagar *et al*., 2007). Lal (2005) reported that integration of arable crops (clusterbean, horse gram, mungbean and henna) with pomegranate improve the profitability over sole pomegranate on medium soil of Pali (Table 6). Pomegranate has been found compatible with pearl millet, mung bean, Isabgol, sorghum and cumin in jalore district of Rajasthan (Gupta, 2000).

Table 6. Fruit yield and return from pomegranate based agri-horti system

System	400 plants ha^{-1}		500 plants ha^{-1}		667 plants ha^{-1}	
	Yield (kg ha^{-1})	Gross return (Rs. ha^{-1})	Yield (kg ha^{-1})	Gross return (Rs. ha^{-1})	Yield (kg ha^{-1})	Gross return (Rs. ha^{-1})
Fallow	816.0	12507	1475	22345	1734	26197
Clusterbean	908.0	15351	1625	26410	2247	35009
Horsegram	640.0	13383	1230	24260	2487	42885
Mungbean	544.0	10967	1055	21008	1647	34076
Henna	452.0	16292	1835	49931	1087	25785

Aonla based multi storey production system initiated at Central Institute of Arid Horticulture (CIAH), Bikaner, comprising aonla-ber-brinjal-mothbean-fenugreek and aonla-bael-karonda-moth bean-gram showed that ground storey crops did not affect growth of over storey crop and vice versa and these systems have been promising under arid conditions of Rajasthan (Awasthi *et al.*, 2005; 2008).The net return obtained from above cropping through ground storey crop during first year was to the tune of Rs. 23614 and 25662 ha^{-1}, respectively, which increased up 20 and 15%, respectively, in 2nd and 3rd years. This indicates that during juvenile phase of fruit tree, there are ample opportunities for raising annual, biennial and perennial crops which can meet diversified need of farmers. Samadia *et al.* (2004) proposed suitable horticultural crops for agricultural production system of arid region (Table 7)

Table 7. Vegetable crop components for cropping system in the hot arid region

Rainfall	High storey crop	Medium storey crop	Ground storey			Microwind break, biofence
			Vegetable	Agronomic crop	grasses	
Rain fed (rainfall < 150-300 mm)	Khejari, Ber	Ber, kair	Materra, kachari, snape melon, tumba	Guar, moth, bajra, til	Cenchrus, Lasirus	Ker, Phog, Khimp, Jharber
Rain fed (rainfall < 300-500 mm)	Br, lasora, khejari	Sehjana, Lasora	Materra, kachari, snape melon, tinda, brinjal, Indian bean, Clusterbean, cowpea	Guar, moth, bajra, til	Cenchrus, Dicanthium, Pannicum	Ker, Khimp, Jharber
Irrigated	Datepalm, ber ,aonla	Lime, guvava, pomegranate	Cucurbits, chilli, tomato, brijal, cole crops, peas, beans, onion, okra and leafy vegetables	Cumin, Isabgol, groundnut, mustard		Lasora, Shenjna, Karonda

Silvipastoral system

Silvipasture refers to combination of pasture grasses/legumes with trees for optimizing land productivity, conserving plants, soil and nutrient to produce forage, fuel wood, timber etc on sustainable basis. About 75% area of hot arid region of country is degraded (Dhurvanarayan, 1993). Therefore it is essential to renovate the degraded land through perennial vegetation to check further degradation and to meet requirement of livestock and human. Silvipasture system has been found as an ideal alternative for development of such degraded land in our country (Rai, 2008). Keeping 10-15% of total land holding as fallow for 2-3 years is normal practice among farmers of arid areas. Such areas may be developed as silvi-pasture and then as agroforestry and agri-horti system. For silvi-pasture development, *A. lebbeck, T. undulata, C. mopane, A. Senegal, Z. numularia* and *Z. rotundifolia* are some woody species that are compatible with grass component. Among pasture legumes *C. ternata* and *L. purpureus* showed good compatibility with *L. sindicus* and *C. ciliaris* (Bhati *et al.*, 1986).Shankar (1980) opined that compared with other land use in marginal and submarginal land, the silvi-pasture provide forage/grazing availability and quality for a longer period of year and 5-7 times more forage yield compared to natural grazing land can be obtained. The silvii-pasture systems are more remunerative as compared to rainfed farming in arid and semi-arid region. He emphasized that for getting optimum production from this system, knowledge of species for different zones, planting techniques, fertilizer application and harvesting schedule are of prime importance (Shankar, 1995). Gupta and Mohan (1982) attempted an analysis of arid and semiarid areas and concluded that silvipasture system provided more net annual return than arable crop, and recommended that multiple use of silvipasture system to be economically attractive in addition to many ecological benefits. Shankarnarayan *et al.* (1987) worked out the productivity and economics of *Acacia tortilis* based silvi-pastoral system in arid Rajasthan and inferred that this system fetched more return than sole tree or grass planting, they reported higher revenue generation (Rs. 3895 ha^{-1}) from silvipasture system compared to sole *Acacia tortilis* (Rs. 3000 ha^{-1}) and sole grass (Rs. 1150 ha^{-1}) (Table 8). Gajja *et al.* (1999) reported that silvipasture was more profitable than arable farming. Economics of different silvipasture system at CSWRI, Avikanagar revealed that three tier system was more remunerative (Rs. 2056.3 ha^{-1}) followed by two tier system (Rs. 1913.47 ha^{-1}), single tier system (Rs. 1616.29 ha^{-1}) and natural pasture (Rs.922.42 ha^{-1}). (Anonymous, 1998). Gajja and Harsh (2002) rated silvipasture with cattle grazing as an economically viable preposition in arid region.

Integration of *Z. nummularia* with *Cenchrus ciliaris* strips in 1:2 ratio gave higher live weight (33 kg ha^{-1} yr^{-1}) and wood production (5.65 kg ha^{-1} yr^{-1}) over sole pasture there by high return Rs. 1326 ha^{-1} $year^{-1}$ from grazing of mixed flock of sheep and goat (Bhati *et al.*, 1987). Further silvipasture of *Z. rotundifolia* and *Cenchrus ciliiris* could sustain 554 tharparkar cattle days ha^{-1} with 60% pasture utilization (Partap Naraian and Bhati, 2004).

Table 8. Productivity and economics of *A. tortilis* based silvipastoral system

System	Fuel wood (t ha^{-1})	Grass yield (t ha^{-1})	Total revenue (Rs ha^{-1})
Acacia tortilis (5 x 10m) + Natural grass	6.0	-	3000
Acacia tortilis (10 x 10m) + Natural grass	3.2	-	1600
Acacia tortilis (5 x 10m) + *Cenchrus ciliris*	5.0	5.6	3895
Acacia tortilis (10 x 10m) + *Cenchrus ciliris*	2.8	5.3	2795
Grass alone	-	4.6	1150

Silvipastoral studies conducted at Bhuj with combination of trees like neem, Acacia and subabul and grasses namely *C. ciliaris* and *C. setegerus* showed that Neem + grasses combination is the most productive silvi-pastoral system for the Kachchh region in term of both grass yield and tree growth. Among the grasses, Cenchrus ciliaris was found to be superior to *C. setigerus* in terms of fodder production. Total number of tiller per grass plant and dry fodder yield of grass did not differ significantly due to association of trees with grasses in a silvipasture system (Devi Dayal *et al*., 2008). Silvipastoral systems improve the soil organic carbon and K content of degraded (Shamsudheen *et al*., 2009).

Horti-pastoral system

This involves growing of fruit crops and grasses together as per suitability of species. . To meet the growing demand of fruits and fodder, horti-pasture system was therefore identified as on of the potential alternate land use option in shallow to medium deep soils (Singh and Osman, 1995). In view of the assured income from fruit trees and greater demand of fodder, several attempts were made to integrate fruit trees and pasture so as to make the system more productive and lucrative to the farming community.

Horti-pastoral studies on sandy rangelands of Rajasthan revealed that *C. ciliris-Z. mauritiana* system produced 1.2 t ha^{-1} forage yields and did not affect fruit yield (Sharma and Diwakar, 1989). Study conducted at Avikanagar by Singh and Jain (1990) showed that higher yield of grass can be obtained with ber. Long term study conducted at Samadari (in District Pali of Rajasthan) on sandy rangeland with plantation of *Z. rotundifolia* @ 280, 140 and 170 ha^{-1} with *C. ciliris* produced 624 to 824 kg ha^{-1} forage yield and density of 280 plants ha^{-1} can be safely kept(Sharma and Vashishta, 1985). Under semi arid condition of Jhansi, introduction of pasture did not show adverse effect on growth parameters of orchard during establishment phase up to 5 years and produce 3-7 t dry matter ha^{-1} forage in initial 3 years (Sunil Kumar *et al.,* 2002). Gajja *et al.* (1999,2004) viewed that hortipasture system are more profitable than arable cropping under arid condition and they revealed that horti-pasture comprising ber and C. ciliaris are highly economic viable on the basis of B:C ratio, net present worth and annuity value at 10% rate of interest under arid ecosystem.

Consrtraints

There are several constraints which impede the implementation of the alternative farming system in arid region (Bhati, 1995). Beside climatic constraints, the uncontrolled and free grazing after harvest of Kharif crop is major handicap for the adoption and development of these production systems. Further long gestation period i.e. considerable time lag between investment and return also a reason of apathy among farmers towards adoption of these systems. Lack of co-ordination of different agricultural and rural development agencies coupled with lack of orientation of research and development professionals about farming system perspective is another important bottleneck for fostering these programmes. There are also lack of suitable policy to implement these systems at larger scale and harmonizing with other agricultural and rural development policies and programmes.

Conclusion

In the light of research evidences outlined in this paper, it is clear that alternative farming system comprising perennial component and livestock imparts stability and sustainability in production under arid ecosystem. The increasing human and livestock pressure, degrading and squeezing resources, daunting energy crisis, climate change and competition imposed by trade liberalization pose serious threats to farming profession in the fragile arid ecosystem and the alternative farming system seems to viable option to overcome these threats and secure livelihood of resource poor peasants. However, there is an urgent need to foster these production systems in holistic manner with sound policy and in effective people-public - private perspective.

Future Thrust

1. Identification and characterization of micro-farming situations covering bio-physical and socio-economic parameters.
2. Developing sustainable farming system models in farmer participatory mode in accordance with resource endowment and need of farmers.
3. Developing multidisciplinary team comprising biological, physical and social scientist to undertake research on farming system perspective with proper incentives.
4. Preparation of a contingent planning to counteract the weather vagaries/climate threats under different farming situations.
5. Policy framework for logistic support to the farmers for quick and large scale adoption of farming systems models developed by the research and development institutions.

References

Agnihotri, C.L. and Singh, M.S. 1987. Absorption of short wave radiation in atmosphere over India. *Mausam* 38(1):79-84.

Anonymous 2007. *Vision 2025: Perspective Plan.* CAZRI, Jodhpur. p 94.

Anonymous 2009. Amaranthus- a new commercially viable option for arid Kachchh. *Indian Farming* (Feb) special issue on conservation agriculture. pp 52.

Anonymous 1998. *35 Years of Research*. Central Sheep and Wool Research Institute, Avikanagar, p.128.

Awasthi, O.P., Saroj, P.L., Singh, I.S. and More, T.A. 2008. *Fruit based Diversified Cropping System for Arid Region*. CIAH Technical Publication No. 25 p.18.

Awasthi, O.P., Singh, I.S. and Dhandhar, D.G. 2005. Aonla based mulitier cropping system for sustainable production in Western Rajasthan. In *Proceedings of National Seminar on Globalization of Aonla*, organized by Aonla Grwer Association of India, Madurai (TN) October 7-9, 2005.

Beniwal, R.K., Soni, M.L.,Yadav, N.D., Chander, P. and Talwar, H.S. 2006. Effect of irrigation scheduling on moistutre and salt distribution and growth of Kagzi lime under drip irrigation in arid Rajasthan. *Annals of Arid Zone* 45(2): 169-174.

Bhagirath Ram and Vyas, S.P. 2005, Relative performance of minor millets in arid Gujarat. *GAU Research Journal* 30(1-2): 51-53.

Bhatanagar, P., Kaul, M.K. and Singh, J. 2007. Effect of intercropping in kinnow based production system. *Indian Journal of Arid Horticulture.* 2(1):15-17.

Bhati, T.K. 1995. Integrated Land use system for drylands. In *Land Resources and their Management for Sustainability in Arid Region* (Eds. A.S. Kolkar, D.C. Joshi and A. Kar), pp: 175-185. Scientific Publishers, Jodhpur (India).

Bhati, T.K. 1997 . Integrated farming system for sustainable agriculture in drylands. In *Sustainable Dryland Agriculture*, pp 102-105. CAZRI, Jodhpur.

Bhati, T.K. and Joshi, N.L. 2007. Farming systems for the sustainable agriculture in Indian Arid zone. In *Dryland Ecosystem: Indian Perspective* (Eds. K.P.R. Vittal, R.L. Srivastava, N.L. Joshi, A. Kar, V.P. Tewari and S. Kathju,), pp. 35-52. Central Arid Zone Research Institute and Arid Forest Research Institute, Jodhpur,

Bhati, T.K., Bhati, G.N. and Shankarnarayan, K.A. 1986. Legume-shrub grasslands in western Rajasthan. Annual Progress Report, CAZRI, Jodhpur.

Bhati, T.K., Tewari, J.C. and Rathore S.S. 2008. Productivity nad dynamics of integrated farming systems in western Rajasthan. In *Diversification of Arid Farming System* (Eds. Pratap Narain, M.P. Singh, A. Kar, S. Kathju and Praveen-Kumar), pp. 23-30. Arid Zone Research Association of India and Scientific Publisher (India) Jodhpur,India,

Chadha, K.L. 2002. Diversification to horticulture for food, nutrition and economic security. *Indian Journal of Horticulture* 52: 137-140.

Champion, H.G. and Seth, S.K. 1968. A Revised Survey of the Forest Type of India. Managers of Publication, Government of India, Delhi. P 404.

Choudhari, J.S., Jain, S.V. and Mathur, C.M. 1979. Phosphorus fraction in some soils orders of Rajasthan and their sequence at weathering stage *Annals of Arid Zone* 18: 260-268.

Chundawat, B.S. 1993. Intercropping in orchards. *Advances in Horticulture* 2: 763-775.

Dangarwal, R.T., Trivedi, B.S., Patel, M.S. and Mehta, P.M. 1983. *Micronutrient Research in Gujarat*, GAU, Ananad, 137 pp.

Dauley, H.S. 1994. Intercropping systems for the Indian Arid zone. In *Sustainable Development of the Indian Arid Zone* (Eds. R.P. Singh and S. Singh,), pp. 251-259. Scientific Publisher, Jodhpur.

Devi Dayal, Swami, M.L., Bhagirath Ram, Meena, S.L. and Shamsudheen, M. 2008, Production potential of grasses under silvipastoral system in Kachchh region of arid Gujarat. *Abstracts.* National symposium on Agroforestry knowledge for sustainability, climate moderation and challenges ahead" (15-17, December, 2008) NRC-Agroforestry, Jhansi (UP). pp. 195.

Devi Dayal, Vyas, S.P., Meena, S.L., Shamsudheen, M. and Bhagirath Ram 2009. Sustainable production of rainfed oilseeds through intercropping in Kachchh region of Gujarat. *Journal of Oilseeds Research* 26: 273-274.

Dhir, R.P., Sharma, B.K. and Joshi, D.C. 1983. Avilability of iron, manganese, zinc and copper in some soils of western Rajasthan. *Annals of Arid Zone* 22: 343-349.

Dhurvanarayan,V.V. 1993. Land capability classification. In *Soil and water Conservation Research in India*, pp. 57-61. Indian Council of Agricultural Research, New Delhi.

Faroda, A.S. 1998. Arid Zone Research: An overview. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and M. Singh), pp. 1-16. CAZRI, Jodhpur.

Gajja, B.L. and Harsh, L.N. 2002. Economic performance of pasture management under alternative farming system in arid zone of Rajasthan. *Current Agriculture* 26: 35-40.

Gajja, B.L., Bhati, T.K., harsh,L.N. and Khan, M.S. 1999. Comparative economics of silvipasturue, horticulture and annual crops on marginal lands of arid zone of Rajasthan. *Annals of Arid Zone* 38: 173-180.

Gajja, B.L., Meghwal, P.R. and Harsh, L.N. 2004. Economic performance of dryland horticultural crops in arid zone of Rajasthan-ex-ante analysis. *Current Agriculture* 28: 59-62.

Ganesan, G., Chinnasamy, K.N., Bala Subarmanian, A. and Manickasundaram, P. 1990. Studies on rice based farming system with duck cum fish culture in deltic region of Thanjuvar district, Tamilnadu. *Farming System News Letter* 1(2): 14.

Gill, M.S. 2004. Methodologies for farming system approach: A case study. In *Proceedings of National Symposium on Alternative Farming System* held at PDCSR, Modipuram, 16-18 September 2004, pp 95-108.

Gill, M.S., Singh, J.P. and Gangwar, K.S. 2009. Integrated farming system and agricultural sustainability. *Indian Journal of Agronomy* 54(2): 128-139.

Goswami, R.N. 2006. Role of Crop Diversification in Sustainable Agriculture. In:. Compendium of Winter School on Sustainable Farming Systems for Arid and Semi-arid Ecosystems". Organised by CAZRI, RRS, Bikaner. pp. 120-123.

Gupta, J.P. 1992. Role of agroforestry for sustainable production in arid areas. 2nd Annual Group Metting cum Symposium on Agroforestery, College of Agriculture, Nagpur.

Gupta, J.P. 2000. Agroforestery for sustained production. In *Technonolgy Approach for Greening Arid Lands*, CAZRI, Jodhpur.

Gupta, J.P., Joshi, D.C. and Singh, G.B. 2000. Management of arid ecosystem. In: *Natural Resource Management for Agriculture Production in India* (Eds. J.S.P. Yadava, and G.B. Singh), pp. 551-668. Indian Society of Soil Science, New Delhi.

Gupta, T. and Mohan, D. 1982. Economics of afforest ration in hot arid zone of India. Proceedings of Second Forestry Conference, FRI, Dehradun.

Harsh, L.N. 1995. Alternate land use system for sustainable development: Silviculture. In *Land Resources and their Management for Sustainability in Arid Region* (Eds. A.S. Kolarkar, D.C. Joshi and A. Kar), pp 187-196. Scientific Publisher, Jodhpur.

Harsh, L.N. and Tewari, J.C. 1993. *Desertification and its Control in the Thar, Sahara and sahel Regions* (Eds. A.K. Sen and A. Kar), pp 269-280. Scientific Publisher, Jodhpur.

Jayanthi, C., Rangasamy, A., Mythili, S. ,Balasumay, M, Chinnusamy, C, and Sankaran, N. 2001. Sustainable productivity and profitability to integrated farming system in low land farms. In *Extended Summaries of National Symposium on Farming System Research on New Millenium* (Eds. A.K. Singh, B. Gangwar, Pankaj and P.S. Pandey), pp. 79-81. PDCSR, Modipuram.

Jenny, H. and Rayachaudhari, S.P. 1960. Effect of climate and cultivation on nitrogen and organic matter reserves in Indian soils. ICAR, New Delhi.

Joshi, D.C., Choudhari, J.S. and Jain, S.V. 1973. Distribution of sulphur fraction in relation to forms of phosphorus in soils of Rajasthan. *Journal of Indian Society of Soil Science*. 21: 289-294.

Joshi, D.C., Gupta, B.S. and Dutta, B.K. 1982. Factors affecting forms of potassium and potassium fixation in some soils of India. *Annals of Arid Zone* 21: 199-205.

Joshi, D.C., Singh, N., Sharma, B.K. and Raina, P. 1998. Soils: distribution, characteristics and nutrient dynamics. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and M. Singh), pp. 55-79. CAZRI, Jodhpur.

Kaushik,N. and Kumar, Virendra 2003. Khejari (*Prosopis cineraria*)- based agroforestery system for arid Haryana, India. *Journal of Arid Environments* 55: 433-440.

Khan, M.A. 1996. Status of water resources in arid zone of Rajasthan, India. In *Towards Solving Global Desertification Problem for Research on the Evaluation of Interaction between Desertification and Human Activities* (Eds. Takakuru Myazaki and Atsushi, Tsuenkans), pp. 79-89. National Institute of Environmental Studies.

Krishnan, A. 1968. Distribution of arid areas in India. In *Proceeding of Symposium on Arid Zone* (Eds. S.P. Chattarjee, B.B. Roy and S.P. Das Gupta), pp. 1-15. Sree Sraswatay Oress Ltd., Calcutta,

Lal, G. 2008. Pomegranate based cropping system for sustainable production in arid ecosystem. In *Diversification of Arid Farming System* (Eds. Pratap Narain, M.P. Singh, A. Kar, S. Kathju and Praveen-Kumar), pp. 55.60. Arid Zone Research Association of India and Scientific Publisher (India) Jodhpur, India,

Lodha, S. 2008. Organic amendments and biocontrol agents for plant disease management. In *Organic Agriculture* (Eds. J.C. Tarafdar, K.P. Tripathi and M. Kumar), pp.200-218. Scientific Publisher, Jodhpur.

Lodha, S. and Burman, U. 2000. Efficacy of composts on nitrogen fixation, dry root rot and yield of legumes. *Indian Journal of Agricultural Sciences* 70: 846-849.

Manjunath, B.L. and Itnal, C.J. 2003. Farming sytem options for small and marginal holdings in different topographies of Goa. *Indian Journal of Agronomy* 48(1): 4-8.

Meena, S.L., Shamsudheen, M. and Devi Dayal 2008. Impact of row ratio and nutrient management on performance of (*Cyamopsis tetragonoloba*) + sesame (*Sesamum indicum*) intercropping system. *Indian Journal of Agronomy* 53(4): 285-289.

Meghwal, P.R. 2006. Effect of time and intensity of pruning on vegetative growth, fruit yield and quality of phalsa. *Annals of Arid Zone* 45(1): 59-62.

Meghwal, P.R., Aseri, G.K. and Rao, A.V. 2006. Raising bioinoculant aided rootstocks for higher yield in ber. *Indian Horticulture* 51(4): 16-17.

Meghwal, P.R. 2007. Propagation studies in lehsua(*Cordia myxa). Indian Journal of Agricultural Science* 77(11): 765-767.

Meghwal, P.R. and Vashishtha, B.B. 1998. Effect of time of planting and auxin on rooting of cuttings of ker (*Capparis decidua* L. Forsk). *Annals of Arid Zone* 37(4): 401-404.

Mehta, P.C., Puntakumar, S.S. and Seth, S.P. 1971. Vertical distribution of phosphorus in soils of western Rajasthan*. Journal of Indian Society of Soil Science* 21: 389-294.

Muthana, K.D. and Arora, G.D. 1977. Studies on the establishment and growth of the economic tree species viz. *Holoptellia intrifolia* in integrated land use pattern in arid environment. *Annual Progress Report*, CAZRI, Jodhpur.

Narain, P., Kar, A., Ram, B., Joshi, D.C. and Singh, R.S. 2000. Wind erosion in western Rajasthan, AZRAI, Jodhpur, 36 p.

Pareek, O.P. 2001 Ber. *International Center for Underutilized Crops. Southampton* U.K.

Pareek, O.P. 1999. Dryland horticulture. In *Fifty years of Agricultural Research in India*, pp. 475-484. CRIDA, Hyderabad.

Pareek, O.P. and Awasthi, O.P. 2008. Horticulture-based farming systems for arid region. In *Diversification of Arid farming System* (Eds. Pratap Narain, M.P. Singh, A. Kar, S. Kathju and Praveen-Kumar), pp. 12-22. Arid Zone Research Association of India and Scientific Publisher (India) Jodhpur, India.

Partap Narain and Bhati, T.K. 2004. Alternative Farming System: Issues and opportunities in arid ecosystem. In *Alternative farming Systems* (Eds. A.K. Singh, B. Gangwar and S.K. Sharma), pp 57-64. Farming System Research And Development Association, Modipuram.

Patel, J.M., Jamini, S.N. and Patel, S.B. 2008. Evaluation of neem and ardu based agri-silvi system. In *Diversification of Arid Farming Systems* (Eds. Pratap Narain, M.P. Singh, A. Kar, S. Kathju and Praveen-Kumar), pp 114-118. Arid Zone Research Association of India and Scientific Publisher (India) Jodhpur, India.

Rai, P. 2008. Management of arid rangelands. In *Diversification of Arid farming systems* (Eds. Pratap Narain, M.P. Singh, A. Kar, S. Kathju, and Praveen-Kumar), pp. 79-102. Arid Zone Research Association of India and Scientific Publisher (India) Jodhpur, India.

Ram, Balak and Lal, G. 1998. Land use. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and M. Singh), pp. 127-129. CAZRI, Jodhpur.

Ramakrishna, Y.S. 1997. Climatic feature of the Indian arid zone. In *Desertification Control in the Arid Ecosystem of India for Sustainable Development* (Eds. S. Singh and A. Kar), pp 27-35. Agrobotanical Publishers, Bikaner (India).

Ramakrishna, Y.S. and Rao, A.S. 1992. Climatic features of Indira Gandhi canal region. In *Prospects of Indira Gandhi canal Project* (Eds. I.P. Abrol and J. Venkatswarlu), pp 1-10. ICAR, New Delhi.

Ramakrishna, Y.S., Agnihotri, C.L. and Rao, A.S. 1992. Climatic resopurces of thar desert and adjoining areas of India. In *Perspective of Thar and Karkum* (Eds Amal Kar, R.K. Abhichandani, K. Ananthram and D.C. Joshi), pp. 10-20. DST, GOI, New Delhi.

Rao, A.S. and Singh, R.S. 1998. Climatic feature and crop production. In *Fifty Years of Arid Zone Research in India* (Eds. A.S. Faroda and M. Singh), pp 17-38.CAZRI, Jodhpur,

Rathore, V.S., Singh, J.P., Soni, M.L. and Beniwal, R.K. 2006. Effect of integrated nutrient management on productivity of cropping systems of hyper arid zone of Rajasthan. In *Proceedings of the International Symposium on Balanced Fertilization for Sustaining Crop Productivity* (Eds. S.S. Mukopadhyay, MS. Brar and P. Sharma), pp. 176-178. International Potash Institute, Horgen, Switzerland.

Rathore, V.S., Singh, J.P., Soni, M.L. and Beniwal, R.K. 2008. Response of rainfed aloe to FYM application. In *National Seminar on Opportunities and Challenges of Arid Horticulture for Nutrition and Livelihood*. Organized by Indian Society for Arid Horticulture, Central Institute for Arid horticulture, Bikaner. pp. 54.

Samadia, D.K., Vashishta, B.B. and Raturi, G.B. 2004. Prospects of vegetables production in the Arid zone of India. In *Impact of Vegetable Research in India* (Eds. Sant Kumar, R.K. Joshi and S. Pal), pp.101-114. Natonal Centre for Agricultural Economics and Policy Research, ICAR, New Delhi.

Saroj, P.L., Dhandhar, G., Sharma, B.D., Bhargava, R. and Purohit, C.K. 2003. Ber (*Ziziphus Mauritiana* L.) based agri-horti system: a Sustainable land use for arid ecosystem. *Indian Journal of Agro Forestry* 5: 30-35.

Satyanarayan, Y. 1963. Ecology of Central Luni basin, Rajasthan. *Annals of Arid Zone* 2: 82-97.

Satyavir and Yadav, S.S. 2005. Managing insect pest complex in arid legumes: an eco-friendly approach. *Journal of Arid Legumes* 2: 357-360.

Shamsudheen, M., Devi Dayal, Meena, S.L. and Bhagirath Ram 2009. Improvement of soil properties under silvipastoral systems in the Kachchh region of arid Gujarat. 4th World Congress on Conservation Agriculture: Innovations for Improving Efficiency, Equity and Environment, (February 4-7, 2009), National Academy of Agricultural Sciences, New Delhi, India. pp.253-254.

Shankar, V. 1980. Silvipasture research: a review. *Forage Research* 6: 107-122.

Shankar, V. 1995. Ecological consideration of rangeland development. In *Land Resources and Their Management for Sustainability in Arid Region* (Eds.

A.S. Kolkar, D.C. Joshi and A. Kar), pp 87-104. Scientific Publisher, Jodhpur (India).

Shankarnarayan, K.A., Harsh, L.N. and Khatju, S. 1987. Agroforestry in arid zone of India. *Agroforestry System* 5: 60-88.

Shanmugasundaram, V.S., Balaswamy, M., Rangaswamy, A. 1995. Integrated farming system research in Tamil Nadu. *Journal of Farming System Research and Development* 1 (1 and 2):1-9.

Sharma, A.K., Tewari, J.C., Rathore, S.S. and Khan, M.A., 2006. Improvement in default organic system of arid zone. In *Proceedings of the National Seminar on Organic Farming for Alleviation of Rural Poverty,* pp.10-11. APOF, Banglore, Aug. 8-9, 2006.

Sharma, A.K. and Gupta, J.P. 2001. Agroforestery for sustainable production under increasing biotic and abiotic stresses in arid Zone. Abstract In *Impact of Human Activities on Thar Environment*, pp 95-96, AZRAI, Jodhpur.

Sharma, B.K., Dhir, R.P. and Joshi, D.C. 1985. Avialble micronutrient status of some soils of arid zone. *Journal of Indian Society of Soil Science* 30: 547-549.

Sharma, B.K., Joshi, D.C., Gupta, B.S. and Raina, P. 1983. Influence of phsoigraphy soil association on the vertical distribution of different forms of copper and zinc in some soils of Rajasthan. *Current Agriculture* 7: 174-180.

Sharma, S.K. and Diwakar, G.D. 1989. Economic evaluation of hortipastoral system on arid region of western Rajasthan. *Indian Journal of Range Management* 10: 119-122.

Sharma, S.K. and Vashishta, B.B. 1985. Evaluation of jujube-buffel grass hortipastoral system under arid environment. *Annals of Arid Zone* 24: 203-209.

Shelke, V.B., Kulkarni, S.N., Waghmore, D.B. and Chavan, A. 2001. Study on integrated farming system in Marathwada. In *Extended Summaries: 1st National Symposium on Farming system research in New Millennium,* pp 99-100. PDCSR, Modipuram, 15-17 October, 2001,

Singh, K.C. 1989. Importance of grasses in management of sandy soils-strip cropping of grasses. In *International Symposium on Managing Sandy Soils*. CAZRI, Jodhpur, pp 561-564.

Singh, Y.V., Regar, P.L., Rao, S.S., Jangid, B.L. and Chand, K. 2005. Henna-legume intercropping for sustainability in arid and semi-arid regions. In *Henna: Cultivation, Improvement and Trade* (Eds. M. Singh, Y.V. Singh, S.K. Jindal, and P. Narain), pp 31-34. Central Arid Zone Research Institute, Jodhpur.

Singh, G. 2004. Farming System options in sustainable management of natural resources. In *Proceedings of National Symposium on Alternative Farming System* held at PDCSR, Modipuram, 16-18 September 2004, pp 80-94.

Singh, J.P., Gill, M.S. and Tripathi, D. 2007. Development of integrated farming system model for marginal and small farmers. In *Extended summaries of 3rd National Symposium on Integrated farming System and Its Role towards Livelihood Improvement*, pp 51-57. ARS, Durgapura, Jaipur, 26-28 Novemeber, 2007.

Singh, K.C. 1995. Management of pasturelands in arid regions. In *Sustainable Development of Dryland Agriculture in India* (Eds. R.P. Singh), pp. 415-423. Scientific Publishers, Jodhpur.

Singh, K.C. and Gupta, J.P. 1997. Ley farming for sustainable production in arid region of Rajasthan. In *Proceedings of the Symposium on Recent Advances in Management of Arid Ecosystem*, held at CAZRI, March 3-5, 1997, pp. 95.

Singh, R.P. and Osman, M. 1995. Alternative land use system for drylands. In *Sustainable Development of Dry Land Agriculture in India* (Ed. R.P. Singh), pp. 375-398. Scientific Publisher, Jodhpur (India).

Singh, R.S. 1997. Note on effect of intercropping on growth and yield of ber (*Ziziphus maurtiana* Lamk) in semi arid region. *Current Agriculture* 21: 117-118.

Singh, R.S. and Kumar, A. 1993. Agri-horticulture systems under semi-arid conditions. *Agroforestry News* 5(1): 3-5.

Singh, R.S., Gupta, J.P., Rao, A.S. and Sharma, A.K. 2003. Micro-climatic quantification and drought impacts on productivity of green gram under different cropping systems of arid zones. In *Human Impact on Desert Environment* (Eds. P. Naraian, S. Kathju, A. Kar, M.P. Singh and Praveen-Kumar), pp.74-80.Scientific Publishers, Jodhpur.

Sunil Kumar, Sudhir Kumar, Baig, M.J., Chaubey, B.K. and Sharma, R.R. 2002. Effect of nitrogen on productivity of aonla based horti-pastoral system. *Indian Journal of Agroforestry* 4: 94-97.

Tarfdar, J.C. 2008. Biological manipulation through farming syatems for the arid regions of India. In *Diversification of Arid Farming System* (Eds. Pratap Narain, M.P. Singh, A. Kar, S. Kathju and Praveen-Kumar), pp. 200-209. Arid Zone Research Association of India and Scientific Publisher (India) Jodhpur, India.

Tiwari, S.P., Ravi, R. and Nandeha, K.L., Vardia, H.K., Sharma, R.B. and Rajgopal, S. 1999. Augmentation of economic status of bastar tribal through integrated (crop, livestock, poultry, duck, fish) farming system. *Indian Journal of Animal Sciences* 69(6): 448-452.

Vyas, S.P. 2005. Performance of *Lawsonia inermis* L. in arid parts of Gujarat. *Indian journal of soil conservation* 33(1): 73-75.

Vyas, S.P. and Swamy, M.L. 2003. Henna: A cash crop for arid Gujarat (Package of practices). Central Arid Zone Research Institute, Regional Research Station, Kukma, Bhuj-Gujarat 370105.

Vyas, S.P. 2007, Amaranthus- a new crop for arid Kachchh. *ICAR News* 13(3): 12.

Yadava, N.D., Beniwal, R.K. and Soni, M.L. 2006. Crop diversification under fruit based cropping systems in arid zone of western Rajasthan, *Indian Journal of Arid Horticulture* 1(1): 20-22.

Zandstra, H.G. 1981. Cropping systems for the Asian rice farmers. *Agricultural Systems* 4: 135-153.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 383-410 pp.

Value Addition in Farm Produce

M.S. Khan[1], N.V. Patil[1], A.K. Patel[1], L.N. Harsh[1], H.A. Khan[1], J.C. Tiwari[1], P.R. Meghwal[1], N. Kondaiah[2], M.M. Azam[1], S. Raghvender[4], D.B. Shakyawar[3], N.P. Gupta[3], S.A. Karim[3], R.S. Mertia[1], R.N. Kumawat[1], S.S. Mahajan[1], S.K. Singh[1], R. Pathak, R.R. Bhansali[1], S. Vir[1], J.P. Singh[1], V.S. Rathore[1], M.L. Soni[1], Pratibha Tewari[1] and P.K. Malaviya[1]

[1]*Central Arid Zone Research Institute, Jodhpur*
[2]*National Research Centre on Meat, Hyderabad*
[3]*Central Sheep and Wool Research Institute, Avikanagar*
[4]*College of Biotechnology, SPV University of Agriculture and Technology, Meerut*

The livelihood security of the thickly populated hot arid region is a difficult proposition due to extreme ambient temperature (up to 48^{0}C), very low, erratic rainfall and low biomass. The productivity of the land, crops, forest and horticulture trees and shrubs, creepers and animals is usually low. Problem is further compounded due to low shelf life of most of the vegetable and horticultural farm produce, 20-40% transit losses, lack of storage infrastructure, inappropriate market linkages, absence of processing/value addition and glut in the market during harvest time. All these issues lead to heavy losses to the farmers. Such losses can be averted, if the farm produce emanating from forest and horticulture trees, shrubs, creepers, weeds, mushrooms and farm waste, milk, meat and wool and hair is judiciously used in making value added products employing latest technologies/processes developed for income generation. Surprisingly, only 10-15% of farm produce, particularly of horticulture, *Aloe vera*, mushrooms, goat and camel milk, meat and hair and wool is value added and marketed as against 80-90% in the developed countries. There is an urgent need, therefore, to adopt the value addition techniques developed by various agencies to realise the dream of “Farm to Plate” so that the farmers could get the full benefit of his labour and inputs and the livelihood security in the region is improved. A few of the processes and technologies developed by CAZRI, CSWRI, NRC on Camel and NRC on Meat for making value added products is discussed here.

Products from Trees

Traditionally farmers use the fruits and seeds of Kumat *(Acacia senegal),* Beri (*Ziziphus nummularia*), Ber (*Ziziphus rotundifolia*)*,* Gunda (*Cordia myxa*) Peelu (*Salvadora oleoides*) and pods of *Prosopis cineraria* and *Prosopis juliflora* for animal feed and/or human needs, but not as a means for income generation. Work carried out at CAZRI on value addition in some of the seeds and fruits of these species have given an array of hope for additional income generation for the farmers.

Meetha Jal, Peelu: *Salvadora oleoides* occurs abundantly in arid to hyper arid regions with fruit productivity of 30-80 kg tree^{-1} year^{-1}. Peelu is pulpy, sweet and edible, yellow to pink or reddish brown in colour (Troup, 1921; Chundawat, 1990). Edible portion of peelu has about 78% moisture, 6% crude protein, 2% fat, 2% crude fibre, 14% ash and 6% total carbohydrates. The fruits contain calcium (630 mg), phosphorous (167 mg), zinc (2 mg), iron (8 mg) and manganese (2 mg) per 100 g dry weight (Duhan *et al.,* 1992). Peelu also has 40-50% non-edible fat, which can be used in soap and candle industries. CAZRI has made Peelu squash, Peelu jam, and dehydrated Peelu fruits (Khan *et al.,* 2004).

Peelu squash: Fresh fruits are crushed by hand in small quantity of water and filtered through a muslin cloth. The extracted Peelu juice has 18% TSS with 0.2% acidity. To prepare peelu squash having fruit juice 33%, TSS 45% and acidity 1%, different ingredients needed are: Fruit juice 1000 ml, sugar 1145 g, citric acid 24 g, water 830 ml and processed as under step by step: Extraction of juice → Straining → Preparation of sugar syrup → Addition of citric arid to syrup → Straining of sugar syrup → Cooling of syrup → Mixing of syrup and juice → Addition of potastium metabisulphite → Bottling.

The cost of processing one kg Peelu fruits for squash comes to around Rs. 32, which provides 1.5 litre squash and sold at Rs. 40 a litre. The seeds left after processing the fruits for squash contain 40-50% fat, which may be used for soap and candle making etc. and left over oil-cake for animal feed. Thus, the net return will be Rs. 8574 ha^{-l} yr^{-l}, if only 10 trees are maintained (Harsh *et al.*, 2005).

Peelu jam: Peelu jam is prepared from the pulp of the fruit. Ingredients needed are: Fruit pulp 1 kg, sugar 1 kg, citric aid 5 g and pectin 5 g and made as under: Separation of pulp from fruits → Heating of pulp by addition of sugar in two steps → Addition of citric acid → Further heating to end point (When TSS of the concentrate rises to above 68%) → Addition and mixing of pectin → Filling hot preparation into sterilized jam bottles → Cooling followed by packing.

Dehydrated Peelu fruits: Traditional way of preserving the fruits is drying them under the sun. Under improved drying, the fruits are sterilized in sulphur fumes for half-an-hour in a sulphur box to inactivate bacteria and enzymes, dehydrated to 15% moisture at 50°C for 48 hrs. The dried fruits are good in taste with long shelf life.

Fat from Peelu seeds: The inedible yellow fat extracted from peelu seeds is not preferred by the industry. Yellow colour of the fat is due to carotenoides. CAZRI developed a simple method of bleaching the yellow fat. The pulverised yellow fat was bleached in to snow white by spreading it on a Petri dish in thin layer and kept under direct sun-light for two days. The white fat could be used in soap industry, candle making and also as a base in ointments etc.

Many trees in the arid lands exude gum either naturally or through induced mechanism. The more important gum exuding trees are *Acacia senegal, A. jacquimontii, A. tortilis, A. nilotica* and *A. leucocepholea.*

Acacia senegal (Kumut) gum*: Acacia senegal* is the main source of gum Arabic. It is widely distributed in arid to hyper arid regions of Rajasthan, Gujarat, Madhya Pradesh and Haryana. Since natural gum production is quite low, CAZRI has developed a low cost technology for increased production (Khan *et al.,* 2000) by administering gum inducing ethephone solution into the tree stem through a small hole, which is plugged with clay after injection. The gum exudation begins within 5-10 days of ethephone injection and continues for one or two months. On an average 0.5 kg gum per tree is exuded against 20-30 g in natural way. The gum conforms to the specifications of Pharmacopoeias (Khan *et al.,* 1992, 1994). Ethephone cost is Rs. 10 tree^{-1}. Market value of the gum ranges from Rs.100- 400 kg^{-1}. Gum Arabic finds wide application in pharmaceuticals, textiles, paper, minerals, fertilizers, explosives, cosmetics, food beverages and confectionary industries.

Acacia senegal (Kumut) seeds: *A. senegal* seeds are one of the components of *Panchkutta,* a vegetable delicacy of the desert. The seeds from mature pods are extracted by threshing, boiled in water and dried. Dry kumut seeds are sold @ Rs. 20-40 kg^{-1}. However, green seeds if processed as Hema *matar* can fetch about Rs. 200 kg^{-1}.

Acacia tortilis gum: Under normal conditions, *A. tortilis* plant exudes 10-15 g gum, but with application of ethephone, the gum production increased to 400 g tree^{-1}. Other trees like A. *leucocepholea* and *A. jacquimontii* have also responded equally to ethephone injection and gum exudation increased manifold.

Prosopis juliflora bread and biscuits: *P. juliflora* pod flour (1000 g) mixed with wheat flour (3200 g), sugar (1000 g), sugar syrup (320 g), powder milk (160 g) and baked at 205°C for 15 minutes. About 6 kg biscuits of good taste and quality may be prepared from above quantity.

Prosopis juliflora coffee: Coffee is prepared by roasting pod flour for 1 hr at 120°C until it becomes dark brown. Roasted flour is reground and coffee is ready, which can be made either through filtration or expresso coffee machines. *Prosopis* coffee is good as it is not a stimulant and does not contain caffeine. CAZRI has made pods coffee by mixing 30% roasted coffee beans powder with *Prosopis* pods. The coffee beans + roasted pods mixture tastes good.

Prosopis juliflora cattle feed: 25% *P. juliflora* pods or powder were mixed in making a low cost concentrate feed for lactating cattle. The feed is relished by cattle. Increased milk yield and body weights have been observed in milch cattle fed on Prosopis *juliflora* cattle feed.

Azadirachtin indica (Neem) Products

The neem seeds can be used for pest management. Extraction from neem seeds is done though many processes such as; (i) Water extraction: crush or grind seeds, keep in water with regular stirring and filter after 8-10 hr. The extract may be used directly after proper dilution; (ii) Hexane extraction: seeds are grated and steeped in solvent Hexane, only oil is removed. The residue still contains active limonoids and can be removed on extraction with water or alcohol. (iii) Alcohol extraction: Alcohol is the best method for producing Neem based pesticides in concentrate form. Limonoids are highly soluble in alcohol. (iv) Pentane extraction: Solvent used for extraction of seed kernels but extract so obtained is different from azadirachtin.

Neem cake manure: The use of neem seed cake, obtained after the extraction of oil, particularly that of non-edible seed, as a manure not only provides nutrition to the plant, but also controls soil born pests. It also acts as a nitrification inhibitor, helps respiratory activity, increases the population of earthworms and produces organic acids, which help in removing the alkalinity of the soil.

Neem seed pallets: prepared from neem seeds by Central Arid Zone Research Institute, Jodhpur not only protect the crops from termite and white grub attack, but also provide nitrogen, P_2O_5, K_2O, crude protein, phosphorus, calcium, magnesium, iron, zinc, copper and manganese.

Neem oil soap: Untreated oil has awful odour and dark colour and bathing soap made of neem oil also has colour and smell. In making soap, neem oil can be incorporated upto 15% into the mixture of fatty oil along with cotton seed oil, coconut oil, etc. The cotton seed oil was found to mask the odour of neem oil. Alternatively, neem oil is boiled with water and caustic soda and cooled. This mixture of neem oil and caustic soda is further treated with other fatty oils to get a soap of the desired flavour and bactericidal properties.

Additional Products developed: Good quality jam and jelly of neem pulp are made in combination with mango, peach and ginger juices. Aggarbati and coils from neem seeds work as repellent for mosquitoes. Neem oil also checks multiplication of mosquitoes in ponds, pools and reserviors. On farm, undiluted neem oil can be sprayed with low volume sprayer (5-7 litre ha^{-1}) or as an oil in water suspension. In latter case, it as to be fortified with detergents and should not be applied in concentration more than 1-2% on crops, to avoid phytoxicity. CAZRI modules for use of neem as pest protection umbrella have been prepared for mothbean, cowpea, munbean, cumin, vegetables (cabbage and cauliflower) and stored pests (bruchids).

Products from Fruits and Vegetables

Ber products

Ber fruits are processed in to jam, jelly, pulp, juice, dehydrated products, powder, candy, tutti-frutti and wines. Juicy varieties are used for preparing unfermented beverages. Fruits are peeled and destoned followed by boiling in water for a few minutes and filtered through a muslin cloth. The juice is preserved by pasteurization or preservatives. The juice is blended appropriately with pomegranate and karonda juice in equal quantities for making flavoured squash, jam and nectar of good colour (Meghwal *et al*., 2007).

For making dry fruits, fully mature Umran, Banarasi Karaka, Mundia, Chhuhara, Katha, Bagwadi and Mehrun have been found good for drying. Blenching in boiling water followed by sulphuring gave better quality product for drying. Drying in solar dryer retained high SO_2 with less reduction in total sugars as compared to open Sun drying (Khurdia and Roy, 1986).

For preparing candy, ripe but hard fruits are blenched for 3-10 minutes. The blenched fruits are kept in sugar syrup of 40-70^{0}Brix, increased gradually to 65^{0}Brix. These are then immersed in hot water for a while to make them free of syrup and dried to 15% moisture. Candy prepared from variety Illaichi was adjudged the best in organoleptic rating. The by products of processing may be utilized for extraction of pectin.

Pomegranate products

While good quality pomegranate fruits are easily saleable, the low quality fruits including cracked, damaged, spotted, small size fruits as well as sour varieties are utilized for making squash, jelly and anardana (dehydrated arils). The anardana from sour fruits having deep red colour prepared by pre-treatment with burning sulphur fumes retain the colour and are used as acidulant material to replace tamarind or amchur in north Indian curries, chutneys and other culinary preparations.

Aonla products

Aonla is a rich source of vitamin C (400-900 mg per 100 g pulp), which is present in stable form. Aonla varieties are Chakaiya, NA7, Kanchan and Anand-2.The fresh fruit of aonla is sour and astringent, hence, not suitable as table fruit and used liberally in making dried products and chyawanprash. Also squash, carbonated juice, candy, jam, shredded aonla etc. are prepared from the fruits. Process for making aonla candy has been standardized with high B:C ratio (Meghwal, 2006).

Gonda products

Unripe gonda are used for pickles and vegetables along with unripe mango slices, since ripened fruits' pulp is highly mucilaginous and not fit for either pickles or vegetables. The acidity of unripe mango helps to reduce the mucilaginous nature of gonda fruits and enhances its delicacy. For preparing vegetable or pickle the green fruit with stalk intact are washed in water and blenched. This is very essential because entry of water into the fruits may result into off-flavours during pickling process. For dehydration and vegetable preparation, the blanched fruits are treated with sulphur fumes @ 2 g kg^{-1} for two hours, dried in a dryer up to 7-8% moisture content and then stalks and seeds are removed. To make gonda pickle, blanched whole fruits, without de-stoning, and unripe mango slices (3:1) are mixed with all usual spices and dipped under oil. Similarly vegetables are also prepared by mixing the gonda and mango in the same proportion.

Bael products

The importance of bael fruit lies in its marmelosin content, which has curative medicinal properties. Ideal genotypes for product processing should have high pulp content of orange colour and pleasant flavour, few seeds, less fibre and mucilage. Few selections such as Narendra Bael-5 and NB-9, have been found to be ideal for processing. Mature fruits may be used for making candy. Ripe fruits may be processed into quality beverages such as squashes, RTS, jam, toffee, powder and slabs.

Karonda products

Mature karonda fruits can be used for making pickle, chutney, preserve and candy. Fully matured fruits are de-stoned and cut into two halves, put in 2% salt solution containing 600 ppm SO_2 for 24 hours followed by washing in fresh water and blanching in 0.05% erythrosine and 0.25% citric acid solution until fruits become soft. The fruits are then kept in 40% to 70% sugar syrup increasing gradually. The sugar impregnated fruits are put into hot water for about a minute and dried under shade and packed air tight. Ripe fruits of maroon coloured variety may be processed into syrup and jelly. Fruits may also be dried for preparing condiments.

Jamun producst

Jamun fruit can be used to make products like jam, jelly, beverages, wine, vinegar and pickles. Roy *et al*. (1999) standardized a process for making jamun drink. Jamun is grated, heated to 60^{o} C and passed through a basket press. The jamun juice so obtained is heated again to 85^{o}C, cooled and then sodium benzoate is added as preservative. Jamun juice can also be pasteurized and stored. Pure jamun juice is highly acidic and unpalatable. Hence, ready to serve beverage is prepared with 25% juice, 18^{0} Brix and 0.6% acidity.

Kair products

Unripe fruits are highly valued for making vegetables and pickles either alone or in combination with others. It is very important to harvest the fruit with consideration of fruit size, rind colour, softness, ease of cutting with blade and seed and pulp colour (Meghwal, 2002). The unripe fruits are astringent due to tannins and other phenolic compounds. Astringency is removed by keeping kair in 4-5% saline solution for about a week with occasional replacement of saline water. After removing astringency, it is used for making vegetable curry, pickle or mixed with other dry vegetables to prepare panchkuta mixture vegetable (Meghwal and Tewari, 2002). The sweetened fruit can be blanched, sun dried and packed suitably for long term storage and marketing.

Phalsa products

Phalsa fruits are sweet to acidic and traditionally used to cure inflammation, heart and blood disorder, fever and constipation. Fruits ripe during May-June and contain 60-70% juice, 18-20% TSS, 2-3% acidity, 35-40 mg 100 g^{-1} vitamin C, 700-750 IU vitamin A and 0.4-0.6% minerals. Fruits may be utilized for quality beverages, squashes and syrup. The harvesting of fruits at appropriate stage is very essential as unripe fruits are highly acidic.

Mateera ***products***

Mateera is extensively grown in kharif as rainfed crop. The seeds of inferior varieties of *mateera* are mostly extracted during fruiting season and dried under the sun. After proper washing they are salted and roasted. The seeds are grinded in to flour and mixed @ 25% with bajra flour to prepare protein and fibre rich chapatti. The flour is also mixed with moth flour in the same proportion and chapattis locally called khakhra are made.

Date palm products

The date palm is an important upcoming fruit crop in hyper arid regions like, Jaisalmer, Barmer and Bikaner in Rajasthan. 10-15 year old plant produces 50-80 kg $plant^{-1}$ with a maximum yield of 200-300 kg $plant^{-1}$. However, the prospects date palm are diminished since only 185 hot days are available against 200-210 days required up to fruiting stage. Ripening of dates at *Doka* stage coincide with the onset of monsoon in July and consequently get infested by insects and other diseases due to lower temperature and high humidity. In order to avoid huge losses, the farmers in panic harvest Doka stage astringent fruits and sell at very low price. Farmers can, however, save losses by making value added products like, juice concentrates (jelly, spread, syrup and liquid sugar), fermented products (wine, alcohol, vinegar, organic acids) and date pastes (jams, ice creams, baby foods, bakery and confectionary), chutney, pickle and ioffee from unripe, overripe and low quality fruits.

Date palm Jelly: Under-ripen, over ripen dates with hard texture are used to make jelly. Its pulp is boiled in water followed by mincing and sifting through a cloth. Extract is then boiled with appropriate quantity of sugar to a consistency where microbes are not able to grow. Pectin is added to secure gelling and pH is adjusted by citric or tartaric acid. Hot jelly with 60 to 70°Brix density and 3.2-3.5 pH is bottled and pasteurized.

Date palm chutney: Chutney is made of date pulp, raisins, sugar, spices (ginger, garlic, onion, long pepper, cardamom, red chilli powder, turmeric powder, black pepper, fenugreek, cumin powder, coriander and cinnamon), vinegar/acetic acid and salt. Process consists of boiling the pulp and raisins with sugar, acetic acid in water initially for 15-20 minutes and then powdered turmeric, chilli and pepper and condiments are added and boiled further for 20 minutes or so till it becomes viscous. At this stage all the spices and salt are added. Chutney with Brix 52.2° density, pH 6.7 and total sugars 37.5% is pasteurised.

Date palm toffee: Pitted dates are boiled with butter and water, and then pulp is minced in a grinder with sugar and cooked till 85-90% TSS. The product is spread on tissue paper and wrapped in a suitable shape after cutting into desired shape. The toffee has granular texture, good taste and coffee colour with six months shelf life.

Date palm pickle: Date pickles are made on salt-oil preservation technique. Pitted dates are wrapped in a cloth and boiled for 5 minutes. Boiled date pieces are dried over night under the shade, mixed with appropriate spices, salt and kept in glass jar covered with muslin cloth for two days and then after dipped in boiled mustard oil. Pickles are cured under the sun for five days and then are ready for use with 12 months shelf life. The other processes of date palm pickling are "fresh brine pickling" and "salt-stock pickling". In "fresh brine pickling" process, the sliced dates are kept in 32° salometer brine (25% salt solution) and 2% vinegar in glass jars. After 90 days of fermentation, the brine and vinegar solution is renewed, jars' mouth sealed and pasteurized at 80°C for 15 minutes in hot water. In salt-stock pickling process, the fermentation is initiated with 32° salometer brine solution and then 2% salt is added at weekly interval for four weeks so that brine reaches to 60° Salometer. After 90 days the fruits are immersed in warm water for 8 hours at 50°C (repeated twice) and pasteurized at 80°C for 15 minutes in hot water. Lemon and till are added for flavour.

Products from Shrubs

Aloe vera products

Aloe vera gel and sap have been widely used in a number of cosmetics (shampoos, bubble baths, soaps, shaving cream and lotions), food and drug products. CAZRI has developed processes for making value added aloe products with longer shelf life. For making the products, the leaves are cleaned and sprayed with mild chlorine solution. Leaf skin is removed with a knife and gel is removed. Gel is decolorized, stabilised and processed for making various products.

Aloe crack cream: The product is highly effective for cracked feet, dry/ dehydrated skin. It moisturizes and softens the skin and helps in healing of skin lesions and skin cracks. Other than *Aloe* juice, it contains olive oil, glycerine, etc.

Aloe moisturizer: Moisturizer is most suitable for normal/ oily skin. It makes the skin smooth, shine and glow. It removes the black spot from the skin formed due to cold. Its main components are aloe juice and olive oil.

Aloe gel: This is a moisturizer, suitable for summer; regular use may improve the condition for growing new hair.

Aloe candy: Candy is made by treating fresh pulp with sugar under controlled conditions. The novel process developed here retains the active ingredients and shelf life is more than 6 months at room temperature.

Aloe jelly: is a novel edible product prepared by CAZRI. Aloe's active ingredients are retained with prolonged shelf life. The product is sugar free suitable for diabetics.

Aloe pickles: Made either in aqueous base or in oil base. Natural attributes including AVPS are intact. It has low salt content.

Haloxylon products

Soda and potash have traditionally been obtained in Asia from *Haloxylon*, *Salsola* ash (Goodall, 1982). In hot arid region (Anupgarh, Vijaynagar and Suratgarh tehsils of Sriganganagar and in large areas of Bikaner) *Haloxylon recurvum* locally known as *Saji or* barilla or *Khara Lana* grows along with chenopod shrubs like *Salsola baryosma* and *Suaeda fruticosa* in saline depressions. These plants are used for making *Saji* (a product of sodium carbonate) and *Choa* (pure form of *Saji*) and used in *Papad* making. Saji is also used as camel fodder (Watt, 1889-1896), in Auyrveda medicine (Singh *et al.*, 2006) and as a washing agent (Dagla and Shekhawat, 2006). Despite its multiple-uses, *Haloxylon* has not been used to its potential.

Saji is the soda ash obtained by burning air-dried foliage of *Haloxylon*, *Salsola* and *H. Suaeda.* However, best quality Saji is obtained from *Haloxylon* foliage. For making *Saji, Haloxylon* foliage is harvested after fruiting in December and stacked in circular heaps for natural drying for a month. Pit of 1 m diameter and 1 m depth is made. One rectangular pit is also made in the main pit and closed by placing bricks on two iron rods in the centre of the main pit. A hole is made in the brick placed in centre of the rectangular pit that allows movement of Saji inside the rectangular pit. The *Haloxylon* foliage is placed in circular mode continuously and burnt overnight. After 3-4 hr of burning the temperature inside furnace rises to a level that allows the Saji ash to convert in to semi-liquid, which finally solidifies to Choa after cooling for 3-5 days. *Saji is* collected at the surface and *Choa* is collected inside the rectangular pit.

Solubility of *Saji* and *Choa* was 47-60% and 75.5% respectively. Ionic composition of 15% solution of crude *Saji* has 1143-1391 meq Na L^{-1}, 97-153 meq K L^{-1} and 101-210 meq Ca + Mg l^{-1}. Among anions CO_3 , HCO_3 , Cl and SO_4 constitute 960-1180, 20-30, 315-420 and 31-202 meq L^{-1}, respectively. On dry weight basis, the Sodium in *Saji* and *Choa* was 31 and 36% and carbonate 34 and 33%, respectively.

Besides its use in Papad and Bhujia industry, green foliage of Khara lana can be fed to goats by mixing @ 25% in groundnut haulm (Mondal *et al*., 2005). Green foliage has 13.35% crude proteins, 0.88% ether extract, 22.84% total ash, 62.93% total carbohydrates, 20.69% crude fiber, 58.23% neutral detergent fiber and 25.19% acid detergent fiber.

Products from Creepers

Tumba (Citrullus colocynthis)

Though Tumba may provide food, oil and protein for human use, presence of cucurbitacins and other bitter ingredients restrict it's use for human consumption. CAZRI has developed process of removing bitterness of pulp by chemical treatment and made candy, pickle and digestive churn. Roasted seeds also taste good. The fresh fruit weighing about 500 g contain 74% pulp, 22% rind and 4% seeds. Since it is a weed, the cost of either pulp or seeds is very low and it can easily be made use for making products for generating additional income.

Cucumis melo (Kachra) and Cucumis callosus (Kachri)

Cucumis melo squash: The pulp of fruit is added in hot syrup to reduce bacterial count and flavour is added to final product. Citric acid class II preservative is added. Composition: Carbohydrate -575 g, Protein-2.34 g, Fat-5.6 g

Cucumis callosus chutney: *C. callosus*, sugar, salt, garam masala, red chilli, ginger, dried dates, resin are added in preparing chutney. Composition: Carbohydrate 582.24 g, Protein 13.94 g Fat 56.27 g.

Cucumis melo jam: Peeled and cleaned fruit, sugar, class II preservative and citric acid are added to prepare the product. The product comes out as delicacy over all types of jams. Composition: Carbohydrate -575 g, Protein-2.34 g, Fat-5.6 g

Cucumis melo laddu: Laddus are prepared by drying the fruit in oven and further processing. The product has long shelf life and is rich in minerals. Composition: Carbohydrate -44.75 g, Protein-5.68 g, Fat-26.01 g.

Products from Farm wastes

Mushroom

Mushrooms have high moisture (>90%), low calorie (30% fresh weight), low fat, high proteins (2.5-3.0%) with essential amino acids particularly, lysine, minerals (Phosphorus, Potassium, copper, iron, sodium, calcium and magnesium) and B-vitamins. Mushrooms are a good source of glycogen, chitin and hemicelluloses, but devoid of starch except sorbitol. They are an excellent source of Thiamine, Riboflavin, Niacin, Pantothenic acid, Biotin, Folic acid and Vitamin B_{12}. It is rich in Linoleic acid, an essential fatty acid and free from cholesterol. Interesting fact is that the K:Na ratio is very high and it is suitable for the people who are suffering from Hypertension (Rai and Arumuganathan, 2005). Out of available 20 genera, only 5 variants, button mushroom (*Agaricus bisporus*), oyster mushroom (*Pleurotus* spp.), straw mushroom (*Volovariella volvacea*), Milky mushroom (*Calocybe indica*) and Shiitake mushroom (*Lentinula edodes*) are grown in India. Mushrooms are highly perishable and get spoiled due to wilting, veil-opening, browning, liquefaction, loss of texture, aroma, flavours etc. making it un-saleable (Azad *et al.,*1987). Most of the mushrooms, being high in moisture and delicate in texture can't be stored for more than 24-48 hours at the ambient conditions prevailing in the tropics. Therefore, some post harvest practices have been developed to extend the shelf life of the fresh mushrooms and its value added products.

Sun drying: Oyster and Shiitake mushrooms are dried under direct sun on stainless steel trays or a clean cloth above 25^{0}C under low humidity and then at 55-60^{0}C for 4-6 hours in cabinet driers. Drying for short period minimizes discolorations. Faster drying at low temperatures is achieved through dehumidifying cabinet drier where in water vapour is removed by a desiccant or by recirculating air after passing through a chilling system. Mushrooms can be stored up to one year by this method.

Pickling: Mushrooms are sliced, blanched for 5 minutes in 2% Brine + 0.05% Potassium metabisulphite and washed in cold water for 2-3 times. After curing over night with 10% sodium chloride, preservatives (acetic acid and sodium benzoate), spices (turmeric, rai, red chilly, cumin, aniseed, black pepper, jaggery, ajwain, kalonji), mustard oil were mixed and good quality pickle made. It can be stored for one year in glass bottles.

Canning: Mushrooms with a stem length of one cm are preferable for canning. It can be canned whole or sliced longitudinally. Blanching is done with 0.1% Citric acid and 1% common salt for 5-6 minute to inhibit enzymatic and microbial activity and to remove air. Mushrooms are then kept in a brine solution with 2% common salt, 1% sugar and 0.05% citric acid in tin cans (Azad *et al.*, 1987) and sealed hermetically with double scanner. Then sterilized in autoclave at 15 psi pressure for 25-30 minutes.

Freeze-drying: Mushrooms are freeze dried under vacuum at -20^{0}C for 12-16 hours. Freeze dried mushrooms are packed in nitrogen packing for longer duration up to 6 months. It is a costly method as well as requires lot of energy.

Mushroom foods: Mushrooms can be processed into products like chutney, ketchup, soup, weaning foods, biscuits, soup powder, stuffed mushroom, mushroom curry, mushroom salad, mushroom omelette (Verma and Rai, 2005).

Mushroom Nuggets: Powder mushroom (10%) is mixed with urad dal (80%), salt (2%), red chilly (1%), sodium bicarbonate (0.01%), water (7%) and paste is prepared. Round balls of 2-4 cm diameter are made, spread over a steel tray and sun dried. The nuggets are either deep fried and used as snacks or in vegetable curry or alone.

Mushroom Biscuits: Biscuits are made by blending 100mg *maida*, sugar 30 g, vegetable oil 45 ml, baking powder 0.6 g, ammonium bicarbonate 0.3 g, salt 0.6 g, vanilla essence 0.02 g, milk powder 1.5 g, glucose 1.5 g, water 12 to 22% for 5 minute. Blended dough conditioned for 90 minutes at 30^{O}C in an oven and spread 2 to 4 mm thickness on a cleaned platform and cut into circular or required shape of 5 cm diameter and baked for 10-12 minute at 210^{0}C in baking oven.

Mushroom Ketch-up: Fresh button mushroom are washed in 0.05% KMS solution, sliced and cooked in a pressure cooker with about 50% water for 20 minutes. Mushroom paste is prepared in a grinder with 0.2% *arrarote*, 1.5% acetic acid and other ingredients (salt 10%, sugar 25%, acetic acid 1.5%, sodium benzoate 0.065%, onion 10%, garlic 0.5%, cumin 1.0%, black pepper 0.1%, red chilly powder 1%, ajinomoto 0.2%, arrarote 0.2%) and cooked to TSS to 35^{O}Brix and ketch up is filled in sterilized bottles.

Mushroom soup powder: Mushrooms dried at 60^{O}C for 8 hours in a cabinet air drier are pulverized. Powdered mushroom (16%) is mixed with corn flour 5%, milk powder 50%, refined oil 4%, salt 10%, cumin powder 2%, black pepper 2%, sugar 10%, and ajinomoto 2% and soup is ready.

Other mushroom products: Besides, mushroom candy, mushroom murabba, mushroom chips, mushroom curry, salads, snacks like mushroom pakora, mushroom vegetables and Chinese recipes are also prepared.

Trichoderma

Trichoderma harzianum is an antagonistic fungal organism highly effective for the control of seed and soil borne diseases of crops and trees. *Trichoderma* spp., as biofungicide formulation in farmyard manure (FYM) and Jaggary are excellent value added products in management of *Ganoderma* in *Prosopis cineraria* and *Acacia tortilis* affected trees. The formulations comprise of FYM + jaggary (3:1). Furthermore, many different classes of chemicals can be added to increase the value of *Trichoderma* products, which are good in controlling different diseases.

FYM talc based product: *Trichoderma* spores are concentrated by centrifugation or filtration, dried, milled and mixed with range of dusts, alginate granules, pellets, wettable powder, emulsifiable gels. FYM/compost/talcum based formulation improves the bio-efficacy of *Trichoderma* with and without fortification of C and N sources. They are nonphytotoxic and improve yield and growth of plants. Bio-fungicides can be used for coating seeds just before sowing, for nursery bed treatment, dipping cuttings or seedlings and soil application after multiplying on FYM and by soil drenching in case of perennial crops.

FYM with cake: Commercial bioagent (*T. viride*/*T. harzianum*) (1 kg ton^{-1}) is mixed with moist FYM along with 50 kg neem/pongamia oil cake. 15 cm high heap of the mixture is made under shade, covered by polyethylene sheet, incubated for 3 weeks at 25 ^{o}C to 30 ^{o}C and water sprayed regularly to maintain moisture. This colonized FYM can be used @ 6 g kg^{-1} soil in pot culture experiments, 5 tonnes ha^{-1} field soil before sowing of seeds or transplanting of seedlings, 2 kg $plant^{-1}$ for woody trees along with 400 g of neem/pongamia cake once in every 6 months after planting for controlling nematodes and other soil-borne pathogens. *T. harzianum* colonized compost significantly enhanced germination and growth of plants as compared to non-colonized FYM. A number of macro and micro-nutrients like P, K, S, Zn, Cu and Fe (both total and water soluble content) are significantly higher in *T. harzianum* colonized compost.

Carboxy methyl cellulose (CMS) based liquid culture: 100 ml mycelial discs of *Trichoderma* grown in potato dextrose agar medium are transferred to 250 ml conical flasks containing sterilized Jaggary/ molasses yeast medium (5 g yeast extract, 30 g Jaggary/Molasses, 1 litre distilled water sterilized at 1.42 kg cm^{-2} for 20 min) and incubated for 10 days. The mycelial mat along with the broth is homogenized and mixed with talc powder (500 mesh) at 1:2 ratio. CMS is added at 5 g kg^{-1} as sticker. The product is dried under shade until 12% moisture level. The clumps are broken, homogenized and 100 g polythene bags were made, with 28 x 10^7 CFU g^{-1} population having 4 months shelf life.

Application of Trichoderma products

Seed Treatment: Make slurry of formulation having $2x10^6$ CFU g^{-1} in 10-20 ml water for 1 kg seed just before sowing.

Drenching nursery beds: Use 5 g $litre^{-1}$ of water m^{-2} area.

Cutting and seedling dip: Mix 200 g in 15-20 litres of water and dip the cuttings/rhizomes/tubers/roots of seedlings for 10 minutes before planting.

Field application: Mix 1-2 kg in 100 kg in moist well decomposed FYM and keep under polyethene cover in shade for 10-15 days. Turn over the mixture every 3 days to enable uniform multiplication of biofungicides in FYM. Fortify FYM with 1kg molasses and broadcast over 1 acre before sowing.

Value Added Products from Crops

Guar pods: The immature pods of guar are used in various ways by the people in rural areas. The green pods are blanched and sun dried. The dried pods remain green and give a fresh look on re-hydration at the time of cooking. The immature ponds can also be salted and fried in oil to prepare a sort of *kurkura namkeen,* which is very delicious and rich in protein as well.

Pearl millet biscuits: The process for making biscuits is as under:

Bajra grain
6
Cleaning (Grain Cleaner)
6
Pearling (Pearler)
6
Size reduction (Grain mill)
6
Blending@ 50% Sugar (Manual)
6
Kneading (milk @ 50% & baking powder @ 1%) (Manual)
6
Rolling (3-4mm thick)
6
Moulding 25mmΦ
6
Baking (Oven) 140-150^{O}C (10-12 min.)
6
Tempering (room temperature 8-10 min.)
6
Pearled Bajra biscuits

Value Added Products from Livestock

Goat milk

The goat milk is organic in nature, free from pesticides, chemicals and oxytocin residues as the animals in general browse on bushes and tree fodder; and also not triggered through oxytocin hormone for milking. It has fine fat globules and hence digested within ½ hour against 2-3 hrs in case of cow milk by infants and adults equally. Generally the shelf life of goat milk is 6 hr (4.5-7 hr) during summer, 10.3 hr (9-13 hr) post monsoon and 11-14 hr (9-16 hr) during winter seasons (Khan *et al*., 2004a). However, it can be extended further by 4 hr by addition of ethanolamine (1500 ppm), 2 hr by hydrogen peroxide + sodium citrate (6 ppm H_2O_2 + 40 ppm Sodium citrate), 4.5 hr by sodium bicarbonate (0.2%) and 1 hr by mixing goat milk in cow milk (Khan *et al*., 2003). Work carried out at CAZRI has successfully removed its goatee odour and made delicious value added products like, paneer, kulfee and flavoured whey drink.

Kulfee: The kulfee is made by boiling and continuously stirring the goat milk till it is condensed to 35% of its original volume. Sugar 5 g, Saffron 1 mg, Cashew nut 1 g, Pistachio 3 g, Cardamom 25 mg and Vanilla essence 0.3 ml are added per 100 g milk while continuously stirring the boiling milk. The condensed milk (70 g) is placed in separate kulfee cones and kept in freezer overnight. Next day the Vanilla Kulfee is ready to serve.

Paneer: It is made by boiling the milk for about 10 minutes at 90 ^{0}C. Citric Acid granules are added @ 0.15 g for each 100 g milk while stirring the boiling milk. Whey is separated by filtration through a double layered muslin cloth. Paneer curd is flushed through chilled water for 5-7 minutes. It is then pressed @ 40% of paneer weight for 1-1.5 hr and fresh paneer is ready. Goat paneer is more compact than cow paneer. The paneer has 52% total solids, 21.5% protein, 25.5% fat; and minerals (Khan *et al*., 2004c).

Salty flavoured drink: is made by boiling the whey for 15 minutes and filtering through muslin cloth to remove impurities. To it 4 g black salt, 2 g common salt and 25 ml mint extract are added. Mint extract is made by grinding 50 g green mint leaves in 150 ml water and filtering. Sweet whey drink is made by adding 5% sugar and essence of pine apple or kewda or khas khas and permitted food colours. Whey has 0.94% protein, 0.93% fat, 6.7% total solids, 5.8% SNF and 0.71% Ash. Goat whey has all the essential vitamins like, Thiamine, Pantothenic Acid, Folic Acid, Biotin, Riboflavin and Vitamin B12 (Khan *et al*., 2004c). Also it has high quantities of essential minerals (Khan *et al*., 2004b).

Khoa: The yield of khoa from goat milk is significantly lower than from the cow milk. The goat khoa is slightly salty in taste. Total solids in goat khoa are significantly higher (68.9%) than cow khoa (62.7%). Fat and Protein in goat milk khoa are also higher than the cow milk khoa. 100 g goat khoa contains 0.30 mg thiamine, 0.24 mg riboflavin, 0.80 mg folic acid, 0.01mg biotin, 0.42 mg pantothenic acid and 0.11 mg pyridoxal hydrochloride. Cyanocobalamine was not detectable in the khoa while folic acid content was 800 µg 100 g^{-1}.

Curd: is made by boiling goat milk for 5 minutes, cooling to 40ºC, adding curd culture and incubating for 5 hours at 40ºC. Total solids, fat and SNF are significantly higher in goat *dahi* as compared to cow *dahi*. Panthothenic acid, folic acid and biotin are significantly high in goat dahi than in cow dahi whereas, pyridoxyl hydrochloride and thiamine contents are high in cow dahi.

Though collectively the goat milk production is roughly estimated to be about 0.3 million litres during 2003 contributing to about 3% of the total milk production with annual increments at the rate of 5-6% in arid Rajasthan, it has not yet been tapped for channelising towards income generation. Goat milk or its products like paneer, cheese and flavoured whey can very well find a place in our daily diets to supplement vital minerals, vitamins and amino acids. More over it is low in fat, high in protein and anti bacterial proteins with fine fat globules, it is easily digested equally by infants and elders. It may also be used as a medicine in cases of peptic ulcers, asthama, cough and digestive disorders. Health conscience people if made aware and convinced properly about its nutritional superiority and medicinal values with vital information that goat milk is totally free from pesticide and antibiotic residues because it forages on naturally grown top feeds and bushes and not milked using oxytocin as is the case with cattle and buffaloe milk, it will find an eager buyer in the open market. This will not only give due credit to this important animal of the arid ecosystem but also improve the rural livelihood, which is predominantly livestock based, particularly goats and sheep.

Camel milk

Camel milk is a valuable complete food as it contains all the essential nutrients. However, it is not liked by the consumer due its typical taste and smell and no products are made. In order to increase the income of the camel owners and to save camel from extinction, different camel products were developed.

Fermented milk (Lassi): Milk was boiled for 20-25 minutes, cooled to 30-37^{0}C, added starter culture @ 3-4% and incubated for 20-22 hours. Change in pH, acidity and DMC were recorded periodically during incubation. Composition in Lassi was 83-84, 16-17, 4.1-4.8, 3-3.3 and 0.6-0.8% for water, total solids, protein, fat and acidity, respectively.

Cheese: It is prepared by pasteurizing milk at 72.5^{0}C for 15 seconds. It is cooled to 2-5^{0}C, 4 ml HCl l^{-1} (0.02%) is added and heated to 21^{0}C. To it 50 mg rennet l^{-1} is added and kept for setting at 25^{0}C for one hour. It is cut and cooked at 42^{0}C and whey is drained out. The cheese is washed three times with water at 26^{0}C, 15^{0}C and 10^{0}C respectively followed by salting of cheese curd with 1-2% NaCl and stored at refrigerated temperature. The yield is 12%.

Camel flavoured milk: Fresh milk is heated at 45^{0}C to 60^{0}C and to it 0.04% carrageenan stabilizer, 5% sugar is added. The desired flavours i.e. pineapple, vanilla, and kesar is added @ 8-12 drops l^{-1}, chocolate flavour, 5 g powder l^{-1} followed by green, yellow or pink colour @ 2-3 drops l^{-1} (Raghvendar *et al*., 2003). After homogeneous mixing of above additions, it is pasteurized at 73^{0}C for 15 minutes and cooled to 5^{0}C. It is packaged and stored in refrigerated temperature for marketing. The camel milk of all the four flavors were evaluated as per hedonic scale and highest points in respect to taste, odour and colour was for vanilla flavor followed by pineapple, kesar and chocolate.

Kulfee: 8-10% sugar and 0.01-0.02% saffron are added in fresh camel milk and boiled to 2:5:1 ratio concentration (Raghvendar *et al*., 2004). To it crushed dry fruits @ 4-6% and 4 drops water based nutmeg solution are added. Mixture is cooled, filled in cones, kept overnight in freezer and kulfee is ready for sale. Kulfee is a rich source of calcium, phosphorus and other minerals.

Skin cream: Milk is centrifuged at high speed and upper creamiest layer separated. To the cream with appropriate moisture content are mixed glycerol, preservative (methyl and propyl paraben and BHA), sandal powder, perfume, deionised water and ethanol and homogenized evenly. Camel cream improves the shining and smoothness of skin and reduces the roughness for longer duration without any irritation, sensitization and reactions.

Sheep and goat meat

Hygienic production of meat, cost efficient processing technologies, sustained demand for value added products, innovative marketing approach, better utilization of by products and providing positive image to enterprise contribute for organized development of sheep and goat meat sector. So far importance of value addition products have not received due attention by the Government sector partly due to easy marketability of live sheep and goat. However, with newer practices in sheep and goat production (semi-intensive and intensive production systems) and socio-economic changes with increased awareness of meat products, it has become important to consider appropriate value addition to ensure demand driven growth in sheep and goat meat production and utilization.

At present about 2% of total meat is processed into products for trade while in developed countries it is above 60%. Due to prevailing practice of selling very young animals to the butchers at village level, a very large proportion of sheep and goat left are spent (aged) animals whose meat is generally tough and less palatable but more suitable for processing to products both on economic and quality considerations. Thus when low cost spent animals' tough meats are appropriately processed, benefits of value addition would be large.

Processes such as portioning, deboning, size reduction, seasoning (addition of spices and condiments), tenderization, tumbling, retorting, emulsion preparation, battering, breading and variety of cooking methods are utilized to produce a variety of value added products. Appropriate quality raw materials, correct formulation, optimum processing, right packaging, storage stability, flavour and colour changes, nutritional value, labelling requirements, product specifications and regulations etc are important factors in the success of processed meat products.

Sheep and goat meat processing technologies

Appropriate meat cutting is important for better utilization of different cuts. Meat from older (spent) animals is generally processed as ground meat to alleviate toughness problems in these meats. Use of polyphosphates (0.5% level) to produce better quality meat products with higher cooking yields from mutton and goat meat has been demonstrated (Agnihotri, 2004). Technologies for production of emulsion based products from these meats as well as combination with chicken have been developed (Anjaneyulu *et al*., 1990). This would facilitate incorporation of non-meat ingredients with advantage. Incorporation of mutton and goat fat which are 'hard type' in emulsion based products has been attempted with fair success. Some of the products developed from goat meat are: kababs, sausages, meat balls, patties, pickle, goat meat ham, keema, croquettes, tikka, intermediate moisture chunks, low fat products, meat blocks, nuggets etc. On similar lines mutton ham, sausages, patties, nuggets, kababs, meat balls etc. have been developed. Strategies for sheep and goat meat utilization are as foloows:

1. Production and processing heavier weight lambs and kids for better deboning yields and to promote value added products.
2. Hygienic meat production at rural, urban and peri-urban levels.
3. Production of variety products to cover a larger number of consumers to increase demand.
4. Production of convenience products for increasing per capita consumption.
5. Production of products using combination of meats for better marketability.

6. Incorporation of eggs, vegetables and other non-meat ingredients for a variety of benefits to processor and consumer.
7. Wider use of simple technologies with Indian Culinary Practices to increase consumer demand.
8. To produce a large variety of cured and smoked products to generate consumer demand.
9. Evaluation of rich traditional meat cooking practices to select products and processes of better promise to promote to the present day consumers with advantage.
10. Popularizing unique aspects of mutton and goat meat and developing technologies for overcoming deficiencies.
11. Organizing clubs and events related to value added sheep and goat meat products.
12. Processing products to sustain producer prices, when adversely affected.
13. Processing meat to meet a particular demand.
14. Processing technologies to promote sheep and goat into National Programs and goals.
15. To induct a variety of skilled and unskilled workers into the production and processing activities.
16. Technologies for promoting better utilization of tough meat and by products from spent sheep and goats.
17. Innovative marketing technologies to facilitate availability of products to a large variety of consumers.
18. Developing ready reckoner tables with growth rates, optimum slaughter weights and meat yields for different breeds of sheep and goat under different production systems to provide guidance to persons in the sheep and goat related ventures.
19. Introduction of grading live animals/carcasses to the benefit of producer/processor/consumer
20. Developing entrepreneur projects in sheep and goat meat sector for easy adoption by a variety of entrepreneurs.

Wool and Hair

The quality of wool available from different indigenous and cross-bred sheep varies with regard to annual produce, diameter, medulla %, staple length and lustre. On an average sheep produces around 1.3 kg yr^{-1} with 30 to 35 µ fibre diameter and 40-55% medullation. Magra and Chokla sheep produce soft and lustrous wool. New strain like Avikalin (Rambouillet X

Malpura half bred base) produces 1.7 kg wool with 27 µ diameter, 25% medullation and 4.75 cm staple length. Bharat Merino, a cross of Chokla/Nali sheep with Rarnbouillet/Merino rams with 75% exotic inheritance produces 2.5 kg wool with 19-20 µ fibre diameter and medullation less than one percent. The wool yield in German Angora rabbit was 900 g in 4 clips, with l2.0 to 12.7 µ fibre diameter, 5.0 to 6.0 cm staple length and guard hair of 2 to 3% (Shakyawar, 1997). Since lustrous wool is needed by the carpet industry, a lusture index was developed to screen wool samples (Parthasarathy *et al*., 1995). Magra and Chokla were found to be superior in lustrous index and at par with New Zealand wool (Mehta *et al*., 1998). Lustre can also be improved by dipping raw wool in Ginasul solution for 1 hour (Parthasarathy and Gupta, 1996). Wool scouring by sodium carbonate and surface-active agents is an important process for removing grease, saint and other extraneous matter from wool. Vegetable contaminants are removed by 3.5-5% H_2S0_4 and 0.2% sodium laurul sulphate treatment, baking at 140^{0}C for 2 mins followed by crushing and neutralizing with soda ash (Singh *et al*., 1983). Carpets, blankets, shawls, knitwear, suiting and felts have been developed with pure wool yarn or wool blended yarns. The design, colour combinations, higher insulation value and softness are some of the virtues considered in developing the products.

Blankets: Blanket is one of the important products of wool. In order to make quality blanket from indigenous wool with soft feel and prickle less effect on body, wool was blended with different synthetic and natural fibres. Fine Bharat Merino wool was blended with medium–coarse type of wool in different proportion. Pure Bharat Merino blanket gives highest bulk, colour value and thickness. However, the other blankets produced from blended yarns have no significant difference in bulk and value. All blankets meet strength criteria. When the blankets are prepared with blended yarns of sheep wool and other fibres i.e. viscose, acrylic and polyester waste, they are comparatively cheaper than pure wool blanket. Blankets of camel hair, which is not used commercially, blended with other fibres are fast in colour and cheaper. The fine wool of Merino sheep blended with viscose has shown potential for soft blankets of high value in the market.

Hand knotted carpet: The woollen products like carpets and durry have good demand for home as well as for exports. Coarse wool with high degree of medullated fibres can be blended with good quality wool to make high value carpets.

Hand knotted carpet made of medullated fibre of Chokla wool give best performance followed by Magra, Jaisalmeri and Nali. Their medullated fibres improved resiliency and visual appearance the carpet, while compressibility was retained. However a compromise of these characteristics with abrasion resistance must be sought while selecting a wool mix for carpet manufacture as abrasion loss and intensity of chalky whiteness increases with increase in the proportion of medullated fibres. Carpets made from Indian and New Zealand wool blends provide better abrasion resistance (Arora and Kalsy, 1982).

Handloom woven carpet: A new concept of carpet making by weaving on handloom was introduced (Arora *et al*., 1993). Handloom carpet is low cost with average life of the product is 3 to 10 years. Durability of handloom woven carpets depends on its pile density. The carpet piles having single-ply yarn exhibit better look because the spread of pile all over the carpet is more uniform. To get both virtues i.e. appearance and durability two-ply or three-ply yarn instead of single-ply yarn may be used. Carpets prepared from plied yarns require more force to withdraw a tuft.

Woollen Shawl: Woolen shawl is made using finer wool (52s-64s). The speciality fiber blended yarns are generally utilized in the preparation of shawls. The ends and picks per inch vary from 40-60 and the yarn count varies from 46/2 to 58/2 for warp and 42-48 double or single for weft. The khadi Amber charka has been successfully utilised for spinning rabbit hair-cotton blends, where as Ghantaria and Bhageswari Charkhas can be utilized for spinning rabbit hair-wool blends using normal khadi preparatory machinery. The shawl made out of 25/75 rabbit hair-wool blend is superior to the all wool shawl in respect of softness, feel, whiteness, fullness and warmth. The blended shawls have comparatively higher strength and undergo less abrasion loss.

Tweed fabrics

Wool obtained from crossbred sheep is very much suitable for worsted suiting purpose. Tweed fabric could be developed using these wool blending with polyester/Ramie, mohair, etc. Blends of Bharat merino wool blended with polyester is suitable for tweed type fabric for tropical environment (Shakyawar *et al*., 1996 and Behera *et al*., 2006).

Wool Polyester: Fine crossbred wool blends with polyester are optimised for worsted suiting, shirting and knitted products.

Wool Acrylic: Crossbred fine wool fibre mixes are optimised for knitting yarn. Bharat merino wool also blended with acrylic is found suitable for knitwear and shawl.

Wool-Ramie/Pine apple fibre: Blending of wool with ramie/pine apple fibre is optimised on worsted spinning system. Blended fabric is found lustrous and having good drape behaviour (Arora *et al*., 1985).

Non-woven felt manufacturing: The techniques were standardized for fibre selection, scouring, mixing, carding, hardening, felting and other chemical finishing treatment in developing apparel and technical felts. Inferior grade rabbit wool was blended up to 40% with short length crossbred sheep fine wool for making superior quality lightweight and extra white hand made felts. The felts of less than 4 mm thickness converted into value added products like, Jackets and women ruffles had desired consumer acceptability. These products had enhanced product quality and consumer acceptance with better luster, durability and thermal insulation value. Products with embroidery give better look and fetch much better price.

Medium type felt of 4-6 mm thickness was utilized in making medical textiles like; wound dressing, moisture absorption padding etc. Felts of fine cross bred wool- rabbit hair blends were made as per ASTM-D2475 standards and found suitable for orthopaedics surgical application as medical textiles. These felts possessed excellent softness, porosity or air permeability and absorbency. The products provided the patient with warmth, some impact resistance and protection against lateral shear. These felts when used as pads reduce pain in earth rite patients.

Dyeing wool with natural colour: Natural dyes were obtained from the Eucalyptus bark and Wattle bark by aqueous extraction (15 to 20%) of the dry weight of plant) and used to colour wool and wool blended products. Colour range could be widened by using different metabolic mordants like, Copper sulphate, Iron, chromium and alum at pH 6.5 (Verma *et al*., 1995). Besides, commercial available dyes such as Rust red, Mango, Kamala, Mud yellow, Manjith, Lac and madder red used for dyeing of woollen yarn in presence of mordants. The tone of the final colours of woollen products varies with kind of mordants (Gupta *et al*., 2004). Dyeing in presence of Cu^{2+} (1%) and Cr^{6+} (1.5%) gave lesser residual metal ion (%) in the dye discharge. CSWRI has standardized process for extraction of natural dye from Neem (*Azadirachta indica*), Red Sandal wood (Pterocarpous santalinus Linn), Bougainvillea, Beet sugar (*Beta vulgaris*) (Mathur and Bhandari, 2001 and Mathur *et al*., 2003) by soaking overnight with distilled water in 1:40 MLR followed by aqueous extraction at 97.5^{o}C for 20-30 minutes.

Natural dye @ 0.03 to 0.06 g per gram of wool was applied on woollen products at pH 4.5 (adjusted with acetic acid) for 45 to 60 minutes followed by mordanting with metal ion like, Al^{2+}, Cr^{4+}, Cu^{2+}, Fe^{2+} and Sn^{2+} and rare earth metal ions La^{3+} and Sm^{3+}. The mixed mordanting by La^{3+} and any transition metal ion show very good light and wash fastness properties without deteriorating quality of wool. It is observed that the use of earth metal like, La^{3+} first mordant and Cr^{4+} as second mordant reduces the quantity of Cr^{4+} in the spent dye bath and causes less damage to the wool fiber in comparison to the dyed yarn mordanted with Cr^{4+} alone (Mathur and Bhandari, 2001).

Utilization of speciality hair fibres

Angora rabbit hair: Angora wool has excellent whiteness, superb softness and high warmth with fibre diameter of 10.8 micron and linear density of 0.17 Tex. Angora wool blended with cashmere, superfine merino, natural silk, cotton, polyester, acrylic fibre in appropriate proportion makes the end product most attractive and high value demand (Patni *et al*., 1984).

Camel hair: Uutilisation of camel hair is limited to rural areas, tar carriage covers, animal clothing and floor coverings. After proper sorting, fine variety of brown coloured camel hair can be utilised for production of cloth for over coating, blankets, knitted goods and carpet (Gupta *et al*., 1986). Blending of camel hair with wool and acrylic fibres, polyester, wool and silk waste gives better end products. Moreover the products have more warmth, high durability, and can fulfil the demand of the indigenous as well as the export markets. Spinning of camel hair/polyester (80/20) was also conducted on the DREF-2 spinning system. It was observed that fiber breakage and slip in twist significantly increase at higher spinning roller speeds (Shakyawar and Gupta, 1996).

Equine Hair: Equine hair can be used as a textile raw-material for the manufacture of furnishing fabrics and carpets. Processing of this fibre in pure form is not advisable since it is very coarse (40-50 micron). However, when blended up to 30% imparts special effect to the product without affecting the carding and spinning processes. Further, the product does not need any dyeing since a natural colour is provided by the fibre itself. Sorting of the fibre into different categories according to colour, its carding, spinning, weaving, wet process etc. are standardised (Gupta *et al*., 2007).

References

Agnihotri, M.K. 2004. Effect of polyphosphates on quality and shelf life of shami kebabs prepared from spent goat meat. *Journal of Food Science and Technol.* 41(4): 439-442.

Anjaneyulu, A.S.R., Kondaiah, N., Salahuddin, M. and Panda, B. 1990. Quality of patties from chicken, mutton and combination of meats. *Journal of Food Sci. and Technol. India* 27(3): 184-185

Arora, R.K., and Kalsy, S.S. 1982. Indian and New Zealand wool blend trials, *The Indian Textile Journal* 92(10): 115-117.

Arora, R.K., Gupta, N.P. and Patni, P.C. 1985. Characteristics and performance of Pineapple leaf fibre. *Indian Journal of Textile Research* 10(3): 125-126.

Arora, R.K., Patni, P.C. and Dhillon, R.S. 1993. Handloom woven carpet- an introduction. *The Indian Textile Journal* 103(8): 86-88.

Azad, K.C., Srivastava, M.P., Singh, R.C. and Sharma, P.C. 1987. *Indian Journal of Mushrooms* XII-XIII: 21-29.

Bader, S., Carinelli, L., Cozzi, R. and Cozzoli, O. 1981. Natural hydroxyanthracenic polyglycosides as sun screens. *Cosmetic and Toiletries* 96: 67-74*.*

Behera, B.K., Shakyawar, D.B. and Mishra, R. 2006. Fabric values as influenced by spinning parameters. *Textile Asia* 17-23

Chundawat, B.S. 1990. *Cultivation Practices of Arid Fruit Species in Arid Fruit Culture,* Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi, 189.

Dagla, H.R. and Shekhawat, N.S. 2006. Little use of *Haloxylon* spp. in traditional food. *Natural Product Radiance* 5(2): 131-132.

Desikachar, H.S.R, 1975. Processing of maize, sorghum and millets for food uses. *Journal of Scientific and Industrial Research* 34: 231-236.

Duhan, Arti, Chauhan, B.M. and Punia, Darshan 1992. Nutritional value of some non-conventional plant food. *Plant Food for Human Nutrition* 42: 193-200.

Goodall, D.W. 1982. Chenopod shrublands communities-A global perspective. *International Journal of Ecology and Environmental Sciences* 8: 85-99.

Gupta, N.P., Shakyawar, D.B., Mathur, J.P., Dagur, R.S. 2004. New sources of Natural colour and their application on Wool, *Proceeding of National Conference on Traditional Knowledge System of India*.

Gupta,O.P., Ainsa, R.L., Chouhan, K.S. and Dhawan, R.S. 1986. Post harvest studies in ber fruits (*Ziziphus mauritiana* Lamk) IV. Comparison of sugars for the preparation of candies. *Haryana Agricultural University Journal of Research* XI: 369-392.

Gupta, N.P., Shakyawar, D.B. and Arora, R.K. 2007. Equine Hair: Properties, Processing and Product Development. *Journal of Textile Association* 7-8: 83-91.

Harsh, L.N., Khan, Hamid A., Meghwal, P.R. and Bohra, A. 2005. A study on economic potential of *Salvadora oleoides* Decne based agroforestry system in Araba area, District Barmer. *Journal of Non-Timber Forest Products* 12(4): 225-228.

Khan, Hamid A. and Harsh, L.N. 1992. Physico-chemical characteristics of ethephon induced gum from *Acacia senegal*. *Indian Drugs* 29(11): 507-508.

Khan, Hamid A. and Harsh, L.N. 1994. Quality of Ethephon Induced Gum from *Acacia senegal*. *Annals of Arid Zone* 33(1): 93-94.

Khan, Hamid, A., Harsh, L.N. and Bohra, M.D. 2003 Increased production of Gum Arabic from *Acacia senegal.* In *Human Impact on Desert Environment* (Eds. Pratap Narain, S. Kathju, Amal Kar, M.P. Singh and Preaveen Kumar), pp. 430-433. India and Scientific Publishers, Jodhpur.

Khan, Hamid, A., Meghwal, P.R. and Harsh, L.N. 2004. *Salvadora oleoides* Decne - an under-utilized economic plant of the desert. *Science Tech Entrepreneur* 12: 61-62.

Khan, M.S., Bohra H.C. and Panchal, R. 2002. Composition and quality of Marwari goat milk. *Indian Journal of Small Ruminants* 8(1):73-75.

Khan, M.S., Bohra, H.C. and Panchal, R. 2004a. Effect of storage on thiocyanate, Titratable acidity and Methylene blue reduction time in Indian desert cattle, sheep and goat milk. *Indian Veterinary Journal* 81(2): 213-215.

Khan, M.S., Bohra, H.C. and Panchal, R. 2004b. Minerals composition of milk, paneer and paneer whey of Marwari goat and Tharparkar cattle. *Proceedings of the National Seminar on "Opportunities and challenges in Nutrition and Feeding Management of Sheep",* pp. 355-356. Avikanagar: Indian Society for sheep and goat production and utilization & Central Sheep and Wool Research Institute, February 10-12, 2004.

Khan, M.S., Azam, M.M. and Panchal, R. 2004c. Hydrophilic vitamins in milk of Marwari goat. In *Proceedings of the National Seminar on Opportunities and challenges in Nutrition and Feeding Management of Sheep,* pp. 356. Avikanagar: Indian Society for sheep and goat production and utilization & Central Sheep and Wool Research Institute.

Khurdia, D.S. and Roy, S.K. 1986. Solar drying of fruits and vegetables. *Indian Food Packer* 40(4): 28-39.

Mathur, J.P. and Bhandari, C.S. 2001. Use of beet sugar as wool colourant. *Indian Journal of Fibre and Textile Research* 26: 313.

Mathur, J.P., Mehta, A., Karnawat, R. and handari, C.S. 2003. Use of neem bark as wool colourant-optimum conditions of wool dyeing. *Indian Journal of Fibre and Textile Research* 28(1): 94-99.

Meghwal P.R. and Tewari, J.C. 2002. Kair (*Capparis decidua*) a multipurpose woody species for arid region. *Forest, Trees and Livelihood* 12(4): 313-319.

Meghwal, P.R. 2006. Segmented aonla candy. *Science Tech Entrepreneur* 14(10):1-4.

Meghwal, P.R., Khan M.A. and Tewari, J.C. 2007. *Growing Ber for Sustainable Income and Employment in Arid and Semi-arid Regions.* Central Arid Zone Research Institute, Jodhpur.

Meghwal, P.R. 2002. Judging culinary maturity of Kair fruits (*Capparis decidua*). *Current Agriculture* 26(1-2): 75-76.

Metha, S.C., Singh, V.K., Parthasarathy, S. and Chopra, S.K. 1998. Subjective and objective lustre evaluation in Magra breed of sheep. *Indian Journal of Animal Science* 68(1): 91-92.

Mondal, B.C., Singh, J.P., Beniwal, R.K. and Rathore, V.S. 2005. Palatability of Khara Lana (*Haloxylon recurvum*) in goats. *Indian Journal of Small Ruminant* 11: 219-220.

Parthasarathy, S. and Gupta, N.P. 1996. Ginasul improves lustre in wool. *Asian Textile Journal* 5(5): 54-56.

Parthasarathy, S., Chopra, S.K., Kushwaha, B.P. and Rawat, P.S. 1995. Lustre index for wool. *The Indian Textile Journal* 105(12): 28-30.

Patni, P.C., Gupta, N.P., Arora, R.K. and Singh, U.S. 1984. Performance of Rabbit hair blended speciality fibre yarns. *Indian Journal of Textile Research* 9(2): 77-79.

Raghvendar, S., Shukla, S., Singh, A.K. and Sahani, M.S. 2003. Camel Milk Product-Flavored Milk. Technical Bulletin In Bilingual., Publisher National Research Center on Camel, Bikaner, India.

Rai, R.D., Chandrashekhar, V. and Arumugnathan, T. 2003. In *Current Vistas in Mushroom Biology and Production* (Eds. R.C. Upadhyay, S.K. Singh and R.D. Rai), pp. 289. Mushroom Society of India, Solan.

Roy, S.K., Pal, R.K. and Ramanjaneya, H.K. 1999. Jamun: A potential fruit for processing. *Indian Horticulture* 44(2):11.

Shakyawar, D.B. 1997. Angora Rabbit Hair: Production, properties and processing. *Wool Ways* 7(1): 15-18

Shakyawar, D.B. and Gupta, N.P. 1996. Spinning roller speed and feeding rate on friction spun camel hair blends and yarn properties. *Asian Textile Journal* 5(12): 66-69.

Shakyawar, D.B., Gupta, N.P. and Sinha, R.D. 1996. Bharat merino wool – Polyester fabric. *The Indian Textile Journal* 106(9): 48-52.

Singh, J.P., Rathore V.S. and Beniwal, R.K. 2006. Perennial medicinal plants for rainfed farming system in arid region. *Indian Journal of Arid Horticulture* 1: 8-14.

Singh, U.S., Arora, R.K., Patni, P.C. and Gupta, N.P. 1983. Performance of Rabbit hair-wool blend shawls, *Indian Journal of Textile Research* 8(4): 125-126.

Troup, R.S. 1921. *The Silviculture of Indian Trees* 2: 662. Oxford.

Verma, N. and Gupta, N.P. 1995. Wattle bark – a source of dye for woolen. *Colourage* 42(7): 27-32.

Verma, Shailja and Rai, R.D. 2005. *Mushroom Recipes.* NRCM, Solan, H.P. 73 p.

Watt, G. 1889-1896. *Dictionary of Economic Products of India*. Vol. 1-VII. Govt. Press Calcutta.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 411-457 pp.

Management of Pests, Diseases and Weeds in Arid Production Systems

M.P. Singh[1], Satya Vir[1], Nisha Patel[1], S. Lodha[1], R. Raj Bhansali[1], Arun Kumar[1], R.S. Tripathi[1], B.K. Soni[1], R.K. Kaul[1], Raj Singh[1], T.S. Rajpurohit[2], B.S. Rathore[2], S.I. Ahmed[3], K.K. Srivastava[3], Meeta Sharma[3], Neelam Verma[3] and Sangeeta Singh[3]

[1]*Central Arid Zone Research Institute, Jodhpur*
[2]*Agriculture Research Station, Rajasthan Agricultural University, Mandor, Jodhpur*
[3]*Arid Forestry Research Institute, Jodhpur*

The arid productions systems operate under several abiotic and biotic stresses, which limit their productivity. Whereas lack of moisture and nutrients form the major abiotic stress, biotic stress is exerted by invertebrate and vertebrate pests, diseases and weeds. The losses due to these invaders vary under different situations, but are considerable even under good rainfall years, calling for remedial measures. A major change in pest and disease scenario has been witnessed in the wake of increased irrigation in the arid regions due to Indira Gandhi canal, groundwater exploitation and changes in cropping pattern (Singh *et al*., 2003 Singh and Patel, 2003). The pest situation has also been influenced by the introduction of high yielding varieties and waning plant biodiversity in the landscape.

Substantial research work has been conducted on the pest and disease problems of different components of arid production systems. Cultivated crops have received a major share of research efforts targeted towards minimizing the losses due to pests, diseases and weeds. The major pests and diseases of the principal crops have been studied. Bionomical and epidemiological studies have been carried out to identify the predisposing factors for the pests and diseases. The germplasm of different crops have been tested for response to pests and diseases. Effectiveness of conventional and novel methods has been tested and synergy of their deployment worked out. Based on these, management strategies have been developed.

Pearl Millet

Pests

Pearl millet attracts fewer regular pests in the arid regions. Root grubs and termites affect the crop to limited extent. Red hairy caterpillar *Amsacta moorei* is a sporadic pest of many kharif crops, including pearl millet (Verma, 1982). *Cylindrothorax* and *Rhinyptia* beetles cause damage to milky and ripening grains (Pal and Sharma, 1973). The beetles may be collected and destroyed under light traps, while dusting of carbaryl 10% on the crop is effective. Shoot fly and stem borer are serious pests in Gujarat. Crop treatment at early stage with endosulfan 0.07% or methyl parathion 2% dust has been reported as effective for shoot fly, while for stem borer, a higher seed rate of 5 kg ha^{-1} and removal of dead hearts has been recommended.

Diseases

The infection of downy mildew or 'green ear' disease caused by *Sclerospora graminicola* is systemic and the environment and development stage of the host play an important role in the epidemic. Management entails deployment of cultural, chemical and biological control measures. Disease free or surface sterilized seed and field sanitation after harvesting the crop are among essential components of cultural control. The host resistance against downy mildew has been exploited to a large extent and the resistant varieties are now being used by the farmers. Exposure of surface sterilized seed to 55°C for 12 min., dried under shade and then treatment with metalaxyl at 2 g kg^{-1} seed effectively checks the disease. Early planting helps the crop escape sporangial inoculum resulting in low incidence of disease. Rouging of infected plants can reduce the level of infection. Seed dressing with Apron 35-SD (6 kg t^{-1} seeds) and foliar application of Ridomil MZ-72 (2 kg ha^{-1}) have been recommended. Foliar application of Cyazofamid (10 mg ml^{-1}) is also effective. A combination of raw cow milk as seed treatment and *Gliocladium virens* as seed and soil treatments resulted in the low disease incidence (Kumar *et al*., 2004). The protection is ascribed to induced systemic resistance based on the increase in resistance related enzymes (PPO, CA and PO) and metabolites (phenols, ODP) in the treated plants (Kumar and Mali, 2007).

Ergot, caused by *Claviceps fusiformis*, is another serious disease of pearl millet. Sclerotia sown with seeds, air borne conidia inoculum and insects contribute to the perpetuation of the disease. To reduce the primary inoculum load of the pathogen deep ploughing of field in hot summers is suggested. Spraying ear-head with fungicides like Ziram, (0.1-0.15%), Cuman-L (200 ppm) and Aureofungin have been suggested. A single spray of 8-Hydroxyqunoline (500 ppm) on ear-heads controlled the disease (Kumar *et al*., 1989).

Use of resistant cultivars is the most effective and economical way of controlling smut caused by *Tolyposporium penicillariae* in pearl millet. Deep ploughing prevents the germination of spores, while intercropping pearl millet with mung bean reduces the infection. Chemical control is not economic due to low value of the crop, but four sprays of capatafol (3 g l^{-1}) effectively manage the disease in field. A combination of seed treatment with raw cow/goat milk (50% dilution with water for 18 h) and *Gliocladium virens* (6 g kg^{-1}) along with soil treatment with *G. virens* (10 g m^{-2}) provides control in field (Dashora and Kumar, 2008).

Arid Pulses and Legumes

Pests

The arid pulses and the legumes *viz*., mung bean, moth bean, cowpea, pigeon pea and clusterbean are attacked by a number of regular and sporadic pests. The major pests are aphids (*Aphis craccivora*), weevils *Cyrtozemia* spp., flower thrips (*Megalurothrips sjostedti*), white flies *Bemisia* spp, jassids *Empoasca* spp, the pod borer (*Maruca vitrata* syn. *Maruca testulalis*), blister beetles and bugs *Clavigralla*, *Nezara* and *Piezodorus* spp. Different pest management aspects of mung bean have been covered by Singh (1985), Verma (1988) and Verma and Henry (1988). Investigations on pest complex of moth bean and cowpea, including varietal screening and control aspects, were carried by Vir (1983, 1984a, 1984c, 1986), Vir *et al.* (1984) and Vir and Singh (1985). Foliar damage by leaf weevils and their management have been covered by Singh (1985) and Verma (1988). Vyas (1996) gave an account of the insect pests in IGNP area.

Diseases

Occurrence of disease on arid legumes is a major constraint in realizing maximum output. In the past two decades, research organizations have also paid serious attention in developing strategies against important diseases. In all India coordinated research project, several multi-location experiments have been conducted in order to develop management strategies suitable for all the arid legumes growing regions or for a specific zone. Diseases of arid legumes, their epidemiology and management aspect have been recently reviewed by Pande (2008).

Blights caused by different pathovars of *Xanthomonas axonopodis* continue to remain serious problem in the arid legume growing regions.

Despite identifying resistant sources and breeding disease resistant varieties; large area still remains under cultivation of local strains. These strains are highly susceptible to blight causing 35-40% yield losses. Bacterial blight is favoured by spattering rains, high humidity (80-90%) and moderate temperature, which are usually available during August-September in arid regions (Singh and Swarup, 1987). In arid districts of Rajasthan, bacterial blight on guar occurs mostly after cluster initiation, thus number of pods are severely affected with increasing disease intensity (Lodha and Gupta, 1981), while in Haryana, it occurs before cluster initiation (Gandhi and Chand, 1985), therefore prophylactic measures need to be applied at vegetable stage of the crop i.e. 25-30 days after sowing. Recently this disease has become a serious problem in Karnataka also (Chakarvarty *et al.,* 2005). GAUG 63, an unbranched type was the best entry of guar showing moderate resistance to bacterial blight and high resistance against powdery mildew (Pandey *et al.*, 1993). Hot water treatment at 56°C for 10 min or seed treatment with streptocycline (0.025%) was found highly effective (Singh and Swarup, 1986; Lodha and Ananthram, 1993). Secondary spread of the disease can be checked by two sprays of streptocycline (0.01%) at 35 and 49 days after sowing.

Dry root rot caused by *Macrophomina phaseolina* affects all the arid legumes in mild to severe form. In spite of availability of sufficient inoculum load of *M. phaseolina*, development of dry root-rot is mainly dependent on critical stress condition of a crop or its variety. In arid regions, 15 days old seedlings were more susceptible to *Macrophomina* than 30 days old plants (Singh and Lodha, 1986; Lodha, 1998). Rotation with less susceptible crops like moth bean and Pearl millet reduced the population of *M. phaseolina* (Lodha *et al*., 1990). Certain genotypes like RGC 471 and Kutch 8 were found to be moderately resistant. Mulching of the soil with a layer of pearl millet Stover (3.5 ton ha^{-1}), low plant population (1.6 lakh ha^{-1}) and farmyard manure (10 ton ha^{-1}), singly or in combination effectively conserved the soil moisture and decreased the sclerotial counts and dry root rot incidence (Lodha, 1996). Amendment of soil with composts reduced *M. phaseolina* population and increased the antagonistic actinomycetes (Lodha *et al*., 2002). Soil solarization is a very effective technique but appeared too expensive for arid legumes. However, use of biological control agents like *Trichoderma* and *Bacillus firmus* holds promise in augmenting disease control if applied with other management strategies. Crop rotation, selection of healthy seeds, soil amendment with biocontrol agents, composts, effective weed residues or farm yard manure, adoption of moisture conservation practices, etc. are few of the proven management approaches, which can find place in rainfed agriculture.

Arid legumes also suffer from attack of several types of leaf spots. The intensity and losses may vary from crop to crop, variety to variety and season to season. In guar, Alternaria leaf spot caused by *Alternaria cyamopsidis* is seed borne in nature and survive as mycelium in debris and crop stubbles. Continuous rainfall, 80% RH, 25-31°C favors the development of disease. Many resistant varieties have been identified. Seed borne infection can be minimized by use of healthy seeds or treating seeds with fungicides. Secondary spread of disease can be checked by spray of mancozeb or other contact fungicides. In the regions where both the diseases are important a combination of contact fungicide with streptocycline is recommended for control of bacterial blight also. Neem or compost extract are effective in checking *Alternaria* species.

In addition to Alternaria leaf spot, several other leaf spots also occur on arid legume in mild to severe form. The pathogen includes *Cercospora*, *Myrothecium*, *Curvularia*, Anthracnose, etc. Among these, Cercospora leaf spot caused by two species viz., *C. cancescens* and *C. cruenta* are more important. In India, *C. cruenta* is more serious, which usually occurs during humid weather. The pathogen can survive in plant debris. Use of health seeds, seed treatment with fungicides and destruction of infected crop debris can minimize disease incidence to considerable extent.

Powdery mildew caused by *Leveillula taurica*, *Erysiphe polygonii* and *Sphaerotheca fuliginea* is favored by warm temperature (33°C and above), low humidity and bright sunshine. Early sown crop has been observed to escape the disease. Resistant cultivars of legumes have been identified particularly for Gujarat. Control of powdery mildew by sulphur dusting is common practice among farmer. A Biocontrol agent *Cicinnobolus cesatii* has been reported to be a natural fungal hyper parasite of powdery mildew (Venkatarayan, 1946).

Among arid legumes, viral diseases are major constraint in cowpea and moth bean. Seed borne viruses have epidemiological, ecological and quarantine implications. Viral diseases of economic importance in cowpea include mosaic, yellow mosaic, mild mottle, cucumo viruses, southern bean mosaic, tobamo viruses, etc. Large number of genotypes have been found to possess resistance against one or another viral disease. In addition to main legumes, certain weeds also act as alternative host. Therefore, weed free cultivation is recommended. Spraying the crop with endosulphan (0.2%) may check the insect vector. In moth bean, occurrence of yellow mosaic virus (YMV) transmitted by the white fly (*Bemisia tabaci*) is a regular feature in the entire moth been growing regions. Lack of resistance in available germplasm is the major constrain in this crop. Often due to late onset of rains, farmers grow moth bean in their fields in place of cereals. On late plantation, the vegetative stage of the crop coincides with multiplication of vector, which spread YMV on susceptible cultivars. These cultivars are planted in large areas as single crop favoring rapid spread of vector transmitted virus particularly at vulnerable stage. Intercropping or mixed cropping is one practical way to minimize losses. Moderately resistant cultivars should be cultivated.

Oilseeds

Pests

An account of the pests of oilseed crops in Rajasthan has been given by Srivastava *et al.* (1962). In the early sown seedling stage crop of raya mustard, grubs of sawfly (*Athalia proxima*) and the painted bug (*Bagrada cruciferarum*) cause considerable damage. Joshi *et al.* (1989) reported that September-October sown crop escaped aphid attack but suffered 27-70% loss in yield due to the painted bug (*Bagrada hilaris*) whereas November-December sown crop suffered 29-64% loss in yield due to aphids. Kumawat and Jain (1987) reported the host crossover of painted bugs in spring. *Lipaphis erysimi* is the major pest of mustard. Joshi and Kaul (1968) tested the efficacy of insecticides to various stages of the painted bug. Vir and Henry (1987) and Vir *et al.* (1990) recorded varietal difference in the susceptibility of different cultivars of raya mustard to the aphid *Lipaphis erysimi.* Vir *et al.* (1984b) gave economic evaluation of insecticides used to control aphids in mustard. Jat *et al.* (1993) also reported varietal differences in mustard cultivars against the aphid. Varuna and Durgamani were less preferred by the aphid whereas Rohini and Kranti were more preferred. Delayed sowings result in higher infestation by the aphids. Kanwat and Kumawat (1995) found September 30 to October 15 as the best sowing time of mustard for minimum infestation by aphids and maximum seed yield in protected as well as unprotected crops.

Castor is an important oilseed crop of arid and semi-arid regions. Castor semilooper *Achaea janata* is the most important pest and mites constitute another major pest of the crop. Several perennial plants are reported as alternative host of the semiloopers (Kavadia and Verma, 1973; Singh *et al.,* 1991). The moths are important as fruit sucking moths on guavas. Kapadia (1991) found that triple bloom varieties of castor were more susceptible to leaf miner than double or single bloom varieties.

Sesame suffers damage by leaf roller, sucking pests and sometimes suffers heavy damage by the death's head moth, *Acherontia styx*. Ahuja (1991) reported 12-68% loss in seed yield due to leaf roller, *Antigastra* *catalaunalis* in different cultivars. Kumawat and Kanwat (1995) recommended spraying of monocrotophos or phosphamidon for the control of gall fly, *Asphondylia sesami*.

Diseases

The oilseed crops cultivated in the arid regions *viz*.; sesame, castor, groundnut and mustard have been investigated for resistance to foliar, soil borne and root diseases and for their management. The minimum stem and root rot disease was observed in sesame intercropped with moth and mung bean (Rajpurohit, 2002). Seven genotypes viz. EC-770932, EC-351832, EC-370929, ES-379-3-84, IS-664-1, IS-97, IS-100B were found resistant to *Macrophomina* stem and root rot (Rajpurohit *et al.*, 2006a).

The morphology and taxonomy of *Alternaria sesami* and effect of carbon and nitrogen on its growth and sporulation have been studied (Rajpurohit, 1982; Rajpurohit and Prasad, 1982a,b). The entries EC-770929 and EC-770932 of sesame were found resistant to *Alternaria* leaf spot (Rajpurohit *et al*., 2006b). The effect of plant products, bio agents and fungicides on *Alternaria sesami* blight and phyllody disease of sesame have been studied by Rajpurohit (2003, 2004b). Foliar spray of 0.2% mancozeb, 0.1% propiconazole, AFF-3 and Neemgold were found highly effective and increased seed yield. Dithane M-45, Dithane Z-78, Auriofungin, Brestan inhibited the spore germination of *A. sesami*.

While carbendazim was found to be the best against *Cercospora sesami* leaf spot (Rajpurohit, 1998), seed treatment with carbendazim, carboxin, Captan and thiram and bioagents like *Trichoderma viride* were found highly effective against *Macrophomina phaseolina* in sesame (Rajpurohit, 1997, 2006). Soil drenching with 0.1% carbendazim reduced *Macrophomina* stem and root, while application of FYM, neem and tumba cakes were effective only at initial stage.

The occurrence of new powdery mildew (*Erysiphe orontii oidium* sp) disease on sesame has been reported from the region. The entries OMT-30 and DORS-101 were found to be tolerant to the disease while RT-225 was highly susceptible. Two sprays of Sulfex (0.2%) Bavistin, Karathane and sulphur dusting reduced powdery mildew in sesame (Rajpurohit, 1993).

The first evidence of mycoplasma like organism (MLO) transmitted by *Orosius albicintus* in sesame was confirmed by Purohit *et al.*, 1978. The incidence of phyllody was more in early sowing crop as compared to late sowing. Seventeen entries were observed free from phyllody viz. ES-29, ES-81-1-84, ES-111-1-84, ES-175-2-84, ES-222-2-84, ES-231-2-84, ES-231-3-84, ES-231-4-84, ES-233-6-84, ES-384-3-84, EC-343402, EC-343406, EC-355662,

EC-370663, EC-370716, EC-370721, EC-370920 (Anon.1997). Purohit *et al*. (1980) reported that hydrochlorides of tetracycline and oxytetracycline sprayed at 100, 200 and 300 ppm concentrations and applied to root zone at 500 and 750 ppm by drenching were effective in controlling the disease. The incidence of leaf curl virus on sesame could be reduced by applying methyl demeton @ 1 ml l^{-1} with other fungicides for controlling diseases (Rajpurohit, 2004b).

Foliar spray of mancozeb 0.2% + streptocycline 0.01% was found highly effective against *Alternaria* leaf spot and bacterial blight in sesame. Among 480 entries screened seven entries viz., IS-100B, IS-101-2 (A), IS-104-3, CST-783, Dhanera-1, GRT-8380 and GRT-8603 were found free from bacterial blight.

The integrated disease management modules tested for sesame revealed that seed treatment with *T. viride* + foliar spray of mancozeb, seed treatment with *T. viride* + intercropping of sesame + mung bean + foliar spray of neem formulations resulted in lower disease incidence and higher yields. Seed treatment with thiram 0.2% + carbendazim 50 WP 0.1% + foliar spray of mancozeb 0.2% + endosulfan 0.07% at 30-45 DAS and 45-55 DAS reduced *Macrophomina* stem and root rot, *Alternaria* leaf spot, phyllody and leaf curl diseases while increasing seed yield (Rajpurohit and Bishnoi, 2006).

Out of 130 entries of rapeseed and mustard tested against white rust seven entries were found free from white rust disease and three entries were tolerant while the rest were susceptible to highly susceptible. Seed treatment with metalaxyl and foliar sprays of mancozeb reduced white rust disease and increased seed yield of mustard (Rajpurohit, 2004a).

Out of the 127 entries of mustard screened against powdery mildew (*Erysiphe cruciferarum*) three entries exhibited field tolerance while 10 entries were moderately tolerant (Rajpurohit, 1996). Karathane (0.1%) has been found effective against this mildew.

Occurrence and control of stem rot of mustard (*Sclerotinia sclerotiorum)* was reported by Rathore *et al*. (1992). The disease was significantly reduced by amending soil with neem and castor cake @2 t ha^{-1}, Captan and Thiram @ 20 kg ha^{-1}). The parasite *Orobanche* in mustard could be reduced by spraying soybean oil @ 2 drops/shoot and glyphosate 0.2-0.4% (Rajpurohit *et al.,* 2005a).

In castor the variety GCH 4 was found resistant to *Fusarium* wilt and root rot, while GAUCH 1 was susceptible to wilt, root rot and *Alternaria* blight. Seed treatment with carbendazim 50 WP @ 2g kg^{-1} seed or with

Trichoderma viride @10g kg^{-1} seed + soil application of *T. viride* @ 2.5 kg ha^{-1} reduced wilt incidence (Rajpurohit *et al.*, 2005b, 2008).

An outbreak of bud necrosis disease on groundnut caused by peanut bud necrosis virus (PBNV) transmitted by thrips was observed in the region (Rajpurohit, 2005). *Digera arvensis* was observed as new host for bud necrosis disease. Inter cropping one row of pearl millet with 4 rows of groundnut and foliar spray of methyl demeton @ 1 ml l^{-1} water reduced BND incidence. Seed treatment with *Trichoderma* @ 10 g kg^{-1} seed + *Trichoderma* @ 2.5 kg ha^{-1} with FYM were effective in managing collar rot. Foliar spray of $FeSO_4$ @ 0.5% + citric acid @ 0.1% at 40 and 55 DAS was found effective in reducing yellowing in groundnut.

Spices and Medicinal Plants

Pests

The attack of insect pests and diseases is a major constraint in spice cultivation in the arid zone. There have been aspect-based studies on pests and diseases of spices and medicinal plants cultivated in the arid regions. Singh (2007b) and Patel (2007) reviewed the options available for managing insect pests of spices in fields and in storage. Lodha and Mawar (2007) have described the pathogens associated with seed spice crops and about their management.

The major pests of chilli are aphids, thrips (*Scirtothrips dorsalis*), mites (*Polyphagotarsonemus latus*), termites, white grubs and the fruit borer *Helicoverpa armigera*. Chilli leaf curl complex is one of the most destructive syndromes affecting chilli in this region and aphid, thrips and mites are considered to be the key causative agents for this malady. Chemicals are profusely used against the pests. Rathore (1990) determined the residues of select insecticides on chilli. Indiscriminate use of insecticides led to development of resistance in pests, increase in number of sprays and increased cost of cultivation (Singh, 2002). Use of neem and tumba (*Citrullus colocynths*) seed cakes (@ 500 kg ha^{-1} as soil amendment before transplanting) has been found to reduce infestation of termites and thrips and increase the yield of chilli (Patel and Bhati, 2005). Installation of pheromone traps (5 per acre) helps to monitor the adult moths. Ten days after spotting the moths in the traps, spraying with Nuclear Polyhedrosis Virus (NPV) @ 500 LE ha^{-1} in 4-5 rounds is effective against the early stage of the pod borers. Bird perches at 10-12 an acre reduce *Heliothis* population. The egg masses of *Spodoptera* borer may be collected and destroyed. Spraying of neem products and restricted use of *Bacillus thuringenisis* @ 1 kg ha^{-1} is reported beneficial. Soil application of phorate (15 kg ha^{-1}) or foliar application of dimethoate (0.03%), monocrotophos (0.04%), neem oil (1%) or neem cake extract (5%) is reported effective in controlling chilli aphids and thrips while for mites, dicofol 0.03% or Phosalone 0.07% has been recommended.

The major insects affecting cumin are aphids *Myzus persicae, Hydaphis coriandri* and defoliator *Spodoptera* sp. (Singh and Satyavir, 2003; Singh *et al*., 2003; Singh and Patel, 2006). Neem products have been investigated for their potential in managing pests of spices (Satyavir and Singh, 2003). Coccinellids predate over the aphids. The leaf-eating caterpillars respond to insecticides in early stages. On fenugreek, aphid *Acyrthosiphon pisum* is the major pest and responds to systemic insecticides.

In recent years henna has been observed infested heavily by the defoliator *Achaea janata* while termites, whiteflies, aphids and jassids are minor pests (Singh and Lodha, 2005). Deep ploughing, collection and destruction of larvae during early stage of infestation help in reducing the infestation of *A. janata.* Early instars respond to 0.05% monocrotophos and quinalphos. On senna injurious insects are defoliator *Catopsilia pyranthe,* pod borer *Phycita clientella*, jassid *Oxyrachis* sp., stink bugs *Nezara viridula*, termites *Odontotermes* sp. and whiteflies (Patel and Singh, 2001a,b). On isabgol aphid *Aphis gossypi* is the major insect pest, which can be managed with two sprays of 0.025% methyl demeton.

On jojoba, the castor semilooper *A, janata* has been reported as a defoliator (Singh *et al.*, 1991), while the guggal cuttings are prone to the attack of termites. Heavy infestation of whiteflies has also been observed on the leaves of guggal. On *Euphorbia antisyphilitica* plantation heavy infestation of *Denticera divisella* (Singh and Harsh, 1996) and *Homoeosoma* sp. has been reported (Singh and Satyavir, 1989).

Diseases

In cumin wilt caused by *Fusarium oxysporum* f. sp. *cumini* has been extensively investigated. Israel and Lodha (2004) studied the population dynamics of *F. oxysporum cumini* in presence and absence of the crop. So far wilt resistant strains are not available. Solarization of soil greatly reduces the incidence of wilt and weed populations (Lodha and Mawar, 2000). Combining summer irrigation with amendment of cruciferous residues was found highly effective in reducing *Fusarium* population in the field (Mawar and Lodha, 2002). Seed treatment with bioagents (*Aspergillus versicolor, Pseudomonas fluorescence*, *Trichoderma harzianum*) and application of organic amendments (farmyard manure/mustard cake) reduced wilt incidence in cumin (Israel and Lodha, 2005; Israel *et al.*, 2005; Chawla and

Gangopadhyay, 2009). Altering sowing time and rotation with non-host crops (mustard in winter and pearl millet in rainy season) has been found to be the most effective way of managing this disease (Rathore *et al*., 2004). Seed treatment with carbendazim @ 2 g kg^{-1} seed reduced wilt incidence significantly and was found economic (Rathore, 2004). Seed dressing with *Trichoderma viride* @ 6 g kg^{-1} followed by soil application of the same @ 2.5 kg ha^{-1} along with farmyard manure lowered disease incidence.

Powdery mildew of cumin caused by *Erysiphe polygoni* spreads rapidly under warm moist conditions. None of the genotypes tested possessed resistance against this pathogen. The disease can be managed in the field by timely application of fungicides like dusting of sulphur @ 20-25 kg ha^{-1} or spraying 0.1% dinocap (Rathore, 2004). Tridemorph has also been reported effective.

The blight of cumin caused by *Alternaria burnsii* spreads readily to the stem and blossoms under wet conditions. Seed treatment with carbendazim followed by 3 sprays of mancozeb first at 40 days after sowing and subsequently at 15 days interval were found effective to control blight as well as powdery mildew (Rathore, 2004). The disease can also be controlled by three sprays of Score 25 EC @ 0.5 ml l^{-1} water.

In coriander, the wilt caused by *Fusarium oxysporum* f. sp. *corianderii* can be managed by adopting the same measures as for cumin wilt. The incidence of stem gall disease caused by *Protomyces macrosporus* can be reduced by removal and destruction of gall bearing parts of the plant. It has been observed elsewhere that early and late sown crop contracted less incidence of stem gall than normal sown crop. A few cultivars have been found resistant to stem gall elsewhere. For powdery mildew of coriander caused by *Erysiphe polygoni* seed treatment with Thiram and foliar application of Cosan, sulphur, carbendazim have been reported effective.

In fenugreek, for powdery mildews (*Erysiphe polygoni*, *Leveillula taurica*) elsewhere a few cultivars have been found resistant and fungicides hexaconazole and welable sulphur are reported to be effective. Downey mildew (*Perenospora trigonellae*) in fenugreek is also reported be controlled by spraying of 0.2% difolatan.

In fennel, sulphur dusting is recommended for controlling powdery mildew caused by *Leveillula taurica*. Stem and root rot caused by *Sclerotinia sclerotiorum* and *Fusarium solani* could be prevented by seed treatment with carbendazim @ 2 g kg^{-1} and drenching of soil with 0.2% captan with crop rotation.

Stored Grain Pests

The World annually loses about 200 million tonnes of stored grain to pests. They invade various types of food grain in warehouses and food processing establishments. The common species associated with different storage structures in Thar desert are rice weevils *Sitophilus oryzae,* lesser grain borer *Rhizopertha dominica,* khapra beetle *Trogoderma granarium,* red flour beetle *Triboloium castaneum,* saw-toothed grain beetle *Oryzaephilus surinamensis,* moths *Sitotroga cereallela, Plodia interpunctella, Cadra cautella* and C*orcyra cephalonica*. Bruchids *Callosobruchus maculatus, C. chinensis* and *C. analis* are also the major stored pests of *Vigna aconitifolia, V. radiata, V. unguiculata, Cajanus cajan, Cicer arietinum, Lens culinaris, Dolicos lablab, Pisum sativum* etc. *Conicobruchus* sp. has been an established pest of seeds of *Cymopsis* sp. in arid region.

Field survey on the prevalence of various stored structures revealed that *R. dominica, S. oryzae* and *T. granarium* are the common pests recorded in storage structures of wheat, bajra, jowar and maize. Farmers generally store grain in bulk in structures namely Khattis, Kuthlas, Kothies, Kanda, Bhakar, Wooden boxes, Straw bins, Tin drums and Tin bins. Progressive farmers in Ganganagar and Hanumangarh districts also construct structure by using bricks and concrete where dried straw is not used.

Studies on multiplication of bruchids, infestation of seeds and loss in seed weight revealed that infestation of seeds varied from 31 to 81% with a loss of 24 to 58% in moth bean and 35 to 68% with loss of 18 to 38% in cowpea, respectively after six moths of storage. Although bright coloured smooth surface with greater seed volume were most preferred for oviposition but early development and fast emergence of beetles depend upon the nutritional value of seed. Mung bean is the most preferred host followed by moth bean, arhar, black gram, cowpea and Dolichos. In screening for identification of resistant strain of stored seeds to the attack of pulse beetle, IC-144 of rice bean was the only strain isolated resistant to the attack of pulse beetle and can be used as a donor allele in the breeding program for production of varieties resistant to beetle attack.

Studies have revealed some deleterious effects of bruchid beetles on the seeds of forest plants both in the field as well storage. *Caryedon serratus, Bruchus bilineatophygus, Bruchidius andrewesi,* and *Bruchdius uberatus* are the major field pests in the Thar-desert of India. *C. serratus* primarily a pest of *Tamarindus indica* has been found to establish on *P. cineraria, P. juliflora* and *A. lebbek*. Bruchid infestation on developing pods and seeds was highest in *P. cineraria* followed by *A. lebbek*, *A. senegal*, *A. tortilis* and *P. juliflora* resulting in a loss of 12, 55.9, 24.9, 9.3 and 9% in seed biomass, respectively.

Species specificity of bruchdae in different trees and their distribution in relation to environmental factors of arid region is reported. Use of neem and karanj oil in relation to other protection methods have been found to be safer while an indigenous storage structure with scientific modification in method of storage of leguminous seed is economical and safe.

Infestations can directly reduce grain weight and nutritional value, in addition to indirectly causing mold and other contaminations. Primary stored grain pests feed within intact kernels while secondary pests feed on broken kernels or grain dust. Examples of primary pests include rice weevil, granary weevil and maize weevil. Common secondary pests are red flour beetles, saw-toothed grain beetle, and Indian meal moth. Integrated pest management (IPM) of stored grain pests includes practices such as sanitation, empty bin treatment, grain cleaning and storage, grain protectants and top dressing, grain monitoring and fumigation.

Sanitation is the most important IPM practice for storing and protecting grain. Removing any potential pests and their food before filling grain bins will greatly enhance any subsequent management actions. New grain should never be stored on top of existing grain. Treating empty bins is most effective when insect activity is likely (temperatures over 30°C). The inside walls and floors should be treated with a residual insecticide (malathion or endosulfan) after thorough cleaning. The outside walls (up to 15 feet) and outside base of grain storage bins may also be treated.

Another invaluable IPM tool for stored grain pests is making sure the kernels are cleaned prior to storage. Dirty grain can prevent adequate airflow and uniform aeration. Any grain protectants (neem products, etc.), top dressings or fumigations will be more effective with clean grain. Temperature and moisture management of stored grain is vital. It is crucial that the grain mass temperature be reduced to 20°C and the moisture is below 9-11% soon after storage. Any time the grain mass is above 32°C, it should be inspected for insects every two weeks. Samples should be taken from several depths and locations, paying particular attention to the grain mass surface, central core, and any developing hot spots.

If grain is expected to remain in storage bins for over 12 months, use of protectant may be considered. These products are generally applied to whole grains as they are being augered, loaded, or turned into storage facilities. Application of grain protectants should be avoided before high temperature drying. Sometimes top dressing of insecticide is recommended instead of treating the entire grain mass. Applications should be made as soon as the grain bin is filled and the surface is level.

Fumigation is done for stored grain infested with internal feeders (e.g., weevils and lesser grain borer). Fumigants are extremely hazardous and should be applied by a professional. Fumigants have no residual activity and grain will become susceptible to reinfestation.

Horticultural plants

Pests

Insect pests take away a considerable portion of the harvestable produce from horticultural crops in the arid regions. They also induce other types of injuries that interfere with the growth and production potential of these crops. Preventive and curative measures have been developed for important pests of horticultural crops, besides studying the pollinators of a few fruit plants (Singh, 1984a).

The flies of *Dacus* genus attack a number of fruit and vegetable plants. Male annihilation and bait application techniques are effective against different species of *Dacus* flies. The former technique involves capturing and killing the male flies in traps containing pheromone analogue methyl eugenol and malathion in 3:1 ratio, while in the latter technique flies of both sexes are collected in traps containing yeast or protein hydrolysate.

The ber fruit fly *Carpomyia vesuviana* is confined to jujube. Different aspects related to the biology and management of this fruit fly have been studied in detail. The incidence period of the fly differs with the fruit-setting pattern of the host plant at the geographical location (Lakra and Singh, 1984, 1985; Bagle, 1992; Dashad *et al.,* 1999a). The oviposition pattern of the fly was studied by Lakra and Singh (1983) and emergence pattern by Singh (1983a), while Lakra and Singh (1989) and Sangwan and Lakra (1992) investigated other bionomical aspects. Losses due to bird damage in jujube have also been worked out (Lakra *et al*., 1979; Singh and Vashishtha, 1995). Sources of resistance among jujube germplasm to this fly have been located (Sachan, 1984, Singh, 1984b, Singh and Vashishtha, 1984). The physical, biochemical and physiological factors influencing fruit fly infestation in jujube have been studied (Singh, 2000; Singh and Vashishtha, 2002). Through crossing of susceptible and resistant varieties, hybrids were developed. The hybrids were backcrossed with the resistant parent to develop lines of jujube with low fruit fly incidence, good fruit size and early maturity (Faroda, 1996; Singh, 2000). The efficacy of insecticides against *C. vesuviana* has been tested (Singh and Pareek, 1981, Lakra *et al*., 1991; Patel *et al*., 1989, 1990; Dashad *et al*., 1991b; Saravaiya *et al*., 1998). The residues of insecticides on jujube fruits and other parts following foliar application have been determined under arid conditions (Popli *et al*., 1980; Yadav *et al.*, 1986 and Rathore, 1990). Singh (1989) reported *Biosteres vandenboschi* Fullaway as a new braconid parasite of *C. vesuviana* from the Indian desert.

As pollinators play a decisive role in fruit setting in jujube, timing of insecticide application has been standardized to ensure minimum hazard to pollinators while affording protection against the fruit flies. Application of endosulfan (0.05%) in mid October or when the developing fruit are of pea size, repeated three weeks later minimizes fruit fly attack on jujube. A few systemic insecticides have also been reported effective. Putting polyethylene sheet below the bush restricts the movement of maggots for pupation in soil and exposes them to natural enemies like birds and parasites. Incorporating dust formulation of contact insecticide in soil exposes larvae heading for pupation. Infestation of *ber* fruit borer though not common in northwestern part of the country, may be checked with the same measures.

The bark-eating caterpillar affects all arid fruit plants. The susceptibility of various jujube varieties to this pest was studied by Singh (1984c). The caterpillar can be killed by inserting an iron spike in the hole or by painting/spraying with 0.05% quinalphos/ monocrotophos or injecting dichlorvos solution in the hole through a syringe; or by inserting cotton swabs dipped in insecticide (Singh, 1983). The treated holes should invariably be plugged with mud or clay to prevent escape of the larva and to ensure its exposure to insecticide.

After the rains, chafer beetles defoliate the fruit plants heavily. The beetles could be collected during late evening by jerking the plant and destroyed by immersing in water containing insecticide or oil emulsion. The chafers could also be collected under light traps on a co-operative basis. For chemical treatment insecticides like methyl parathion in dust formulation and monocrotophos, fenitrothion and quinalphos (0.05%) in spray form are effective (Singh, 1982a).

For pomegranate butterfly (*Viracola isocrates*) fruit bagging is effective (also against the birds) or preventive spray may be done of 0.02% deltamethrin and 0.2% carbaryl in rotation at 21 day intervals starting from fruit set. Application of 2 sprays of acephate (0.05%), dimethoate (0.05%), fenvalarate (0.05%) or dimethoate (0.0015%) at fortnightly interval followed by 2 sprays of NSKE (5%) at 7 days interval proved effective in suppressing the thrips and anar butterfly on pomegranate.

On date palm, scales (*Parlatoria* sp) appear occasionally under arid conditions. Termites may infest the newly transplanted suckers, necessitating pretransplant treatment of the pits. Stored dates may be ingested by *Lasioderma* sp. Likewise aonla is generally free from pest attack. Occasional pests include bark eating caterpillar, mealy bugs and leaf rollers.

On fig, the midge infestation could be contained by spraying monocrotophos, fenitrothion or carbaryl.

Several caterpillars and weevils inflict injury to the foliage of arid fruit plants. Caterpillars of castor semilooper (*Achaea janata*) feed over the leaves of jujube, pomegranate and guava, which could be controlled with application of chemicals (Singh, 1982b) or *Bacillus thuringiensis* based formulations. In jujube caterpillars of blue butterfly and the tortoise beetles feed over the green matter of the leaves from the dorsal side, which respond to many contact and systemic insecticides. Sucking insects like lac (*Kerria lacca*), eriophid mites induced galls, mites and bugs like *Machaerota* and mealy bugs require repeated doses of systemic insecticides.

Diseases

Powdery mildew of ber caused by *Oidium erysiphoides,* f. sp *zizyphi* causes significant losses in ber (Lodha *et al.*, 1983). The weed *Euphorbia hirta* should be removed from orchards as fungus survives on them. Cultivars Safeda Rohtak, Sua, Noki, Chonchal, Sanaur-5 Kathaphal, Sanaur-1, Illachi-Jhajjar, Kakrola Gola Kala Gora, Pathani and Mirchia exhibit resistance to powdery mildew (Gupta *et al*., 1978; Jeyarajan and Cheema. 1972). CAZRI Gola, Jogia, Mundia, Rashmi and ZG-3 have shown greater tolerance to the disease in arid environment. Sulfex (0.2%) dinocap (0.05%), carbendazim (0.05%), wettable sulphur (0.2%) and Benlate at ten days interval between the second week of October and December have been reported effective. The time of spray could be related with increase in humidity (above 70%) with light rains or mist and temperature below 10^{o}C with cool nights.

Collar rot of newly grafted seedling of ber caused by *Colletotrichum, Fusarium* and *Rhizoctonia* could be managed by using sand, clay and farm yard manure free from disease propagules or formalin treated soil mixture for filling polythene tubes. Sterilized soil mixture and good drainage system of polythene tubes can minimize the mortality of grafted seedlings (Raj Bhansali, 1991). Drenching of copper oxychloride (0.2%) or carbendazim (0.1%) 2-3 times can control mortality of seedlings. *Alternaria* Leaf Spot can be effectively checked by spraying 0.2% dithane Z-78 (Nallathambi and Thakore, 2003). The sources of resistance in ber for *Alternaria* fruit rot have been reported by Nallathambi *et al*. (2000). Nallathambi and Umamaheswari (2001) reported the occurrence of a new disease on ber caused by *Torula herbarum*.

Fruit spots of pomegranate caused by *Colletortrichum, Alternaria, Cercospora, Dreshslera* and *Pseudocercosporella* are responsible for considerable damage to pomegranate trees in arid and semi-arid areas (Raj Bhansali, 1991; Pareek, 1997a,b). Bacterial leaf and fruit spots (*Xanthomonas campestriis* var. *punicae*) also cause heavy losses to pomegranate orchards. The diseases can be reduced by giving three sprays of 250-500 ppm streptomycin sulphate. Bacterial blight is incited by *Xanthomonas axonopodis* pv. *punicae*. Copper fungicides or Bordeaux mixture provide some protection against this disease. Effective control can be achieved by three sprays of paushamycin (0.05%) plus copper oxychloride (0.2%) at 15 days interval. *Phomopsis* leaf spot and fruit rot diseases can be controlled by 4-5 sprays of mancozeb or ziram or copper oxychloride (0.2%) starting from flower imitation or initiation of disease. Heavy rains, high temperature 35°C and high humidity (above 75%) favour disease development. *Glomerella* leaf spot and fruit rot disease can be reduced through sprays of 0.05% thiophanate methyl or carbendazim or 0.3% captan. *Aspergillus* fruit rot is common rot of pomegranate fruit. *Alternaria* rot is caused by fruit flies facilitating the entry of fungi. Control of fruit flies is therefore, one of the most important steps in management of the rot. Dip in propiconazole fungicide both pre and post inoculation treatment at 0.10% solution for 5 minutes is most effective in reducing fruit spoilage followed by dithane M-45. Cercospera leaf spot of pomegranate can be controlled by fortnightly spray of Topsin M (0.1%), Captaf (0.2%) or Dithane M-45 (0.2%); while Anthracnose in pomegranate was found to be controlled by 2 sprays with Blitox (0.3%) or Bavistin (0.1%) or Kavach (0.2%) at fortnightly interval commencing from second week of August.

In date palm, leaf spot (*Graphiola phoenicis*), black scorch (*Thielaviopsis paradoxa*) and off-shoot disease (*Botryodiplodia theobromae* and *Diplodia phoenicum*) cause significant losses (Raj Bhansali, 1989, 1989a; Chandra *et al*., 1994). Leaf pruning is the most common measure for combating leaf spot problem. However, removal of too many leaves reduces the vigour of trees and fruit yields. Application of copper-containing compounds at 15-day intervals beginning with the first signs of sporulation controls the disease in three to four sprays. Khadrawy, Bint Aisha, Barhee and Hayani cultivars have showed moderate resistance (Raj Bhansali, 1989b). Mortality due to off-shoot diseases can be minimized by regular spraying of copper oxychloride or Bordeaux mixture to detached suckers in nurseries.

Forest Plants

Pests

The insects and mites associated with woody species have been catalogued and their roles broadly defined. The injurious insects are defoliators, sap sucking insects, gall makers, twig girdlers, living wood borers, dead wood borers, seed borers and root feeders. Singh (1991) reported the pest complex of *Balanites aegyptiaca* and Kumar *et al*. (1994) provided an annotated list of insect pests of forest trees of arid regions, while Parihar and Kampantzov (1997) studied the faunal diversity and associated predators and parasites of wood boring Coleoptera of Rajasthan Desert. Parihar (1993) Parihar and Singh (1998) described the insects associated with khejri (*Prosopis cineraria*). Termite problem in desert planataions was studied by Parihar (1980). Ahmed and Singh (2007) gave an outline for integrated management of forest and agricultural insect pests in arid regions.

Chafer beetles, *Holotrichia consanguinea, Anomala* spp*, Adoretus* spp *Rhinyptia laebiceps* and *Schizonycha* spp feed on the foliage of a large number of trees and bushes in arid areas, while their grubs damage crops and nursery plants (Singh *et al*., 1989). Various species of *Myllocerrus* weevils infest nurseries and young plantations. Beetles and larvae of *Clytra succinata* feed on the tender leaves and buds. The larvae of *Taragama (=Streblote) siva* feed on foliage irrespective of any age group of plant in arid areas of India.

On khejri, 33 insect species have been reported from arid tracts. In nursery the gryllids *Gryllus domesticus* and *Brachytrypes portentosus* damage the foliage, at times also destroying the sown seeds. *Schistocerca gregaria* is recorded to feed on the foliage and may be a potential pest at the time of swarming. The aak grasshopper *Poekilocerus pictus* also attacks seedlings of *P. cineraria* and *P. juliflora*. Recently, a moderate attack of *Noorda blitealis* and *Achaea janata* has been noticed on *Prosopis* in arid region. *Taragama siva* is defoliator of many plants (Yousuf and Gaur 1998a,b). Among the sucking insects, *Oxyrachis tarandus, O. rufescens, Eurybrachys* sp, *Nezara viridula* and *Drosicha stebbingi* cause damage to seedling and young plants (Parihar, 1993, Kumar *et al.,* 1994). The nymphs and adults of *Frankliniella schutzei* and *F. dampfi* were reported to infest flowers of *P. cineraria and P. juliflora* (Parihar, 1993; Murugesan and Kumar, 1996). *Eurytoma* sp. is reported to cause gall formation in *P. cineraria* (Sachan and Pal, 1972). *Eurytoma settitibia* is a new pest record from Rajasthan. *Eriophyes prosopidis* is responsible to form leaf and inflorecence galls on *P. cineraria*. Among the pests of seeds, the most abundant are the bruchids *Caryedon serratus* (Satyavir, 1996), *Caryedon* *gonagra and Bruchus bilineatophygus*. *Bruchidus albizzae* has also been recorded to infest stored seed of *Prosopis cineraria*.

The woodborers impart injury to live and dead wood in khejri. *Acmeodera aurifera, Chrysobotheris laterallis, C. octicola and Stromatium barbatum, C. purvipuncata and Phradonoma nobile* (Parihar and Singh, 1998) have been reported to cause injury to *Prosopis* species in arid areas. *Acanthophorus serraticornis* is a major cause of premature drying of khejri trees (Singh *et al*., 2002; Singh, 2007a). Singh *et al.* (2007) described the measures tested in farmers' fields for containing mortality in khejri.

The parasite complex recorded on the insect pests of *Prosopis cineraria* include *Eupelmid* egg parasitoid on *Halys dentatus*, *Eurybrachus tomentosa* and *Homoecerus prominulus*. Eupelmus on gall forming *Contarinia prosopidis* and *Eurytoma settitibia*; Tetrastichus spirabilis on rachis gall midge *C. prosopidis*; *Apanteles* sp., on *Achaea janata*, *Noorda blitealis*, *Bruchidus uberatus* and *Caryedon serratus*; *Trichogrmma roi* and *Brachygrammatella aligarhensis* on *A. janata* and *Oxyrachis tarandus*; egg parasite *Ufens brevifuniculata* on *O. tarandus*. Field population of white grubs, Holotrichia consanguinea is frequently observed to be parasitised by *Scolia aureipennis*, *Campsomeria colloris* and Tiphia sp. The larvae of drywood borer *Acmeodera aurifera* were found parasitised by *Teretriosoma stebbingii*, Bracon sp., Chaoilta sp., and *Hacabolodes radiali*. *Carcellia buitenzorgiensis* has been recorded as a potential endoparasite of the larvae of Taragama siva.

The white fly *Acaudaleurodes rachipora* is attacked by spiders *Encarsia acaudaleyrodis*, Encarsia sp., Eretmocerus rajasthanicus, *Neoscona theis*, Theridon sp, Peucetia sp., Cyrtarachne sp., Parawixia sp. and Cheiracanthium sp. The green lacewing *Chrysopa scelestes* was found to be one of the most efficient predators of flower thrips *Frankiniella schultzei* and *F. dampfi*. The adults and nymphs of Canthocona blanchia and *C. furcellata* (Pentatomidae) were observed to predate on the immature stages of *Oxyrachis tarandus* and Eurybrachis tomentosa. Another pentatomid bug Clavata jugatoria attacks the larva of *Taragama siva*. Adult Halymorpha picus (Pentatomidae) were found feeding on the larvae of *Achaea janata*. The reduviid *Acanthaspis flavipes* predates over white flies, aphids and thrips. The green mantid Creoboter urbana predates over early stages of *Taragama siva* and *Achaea janata*, while *Diephobe infuscata* feeds on a number of minute insect pests of *Prosopis* spp.

The entompathogenic fungi *Beauveria bassiana* and *Aspergillus parasiticus* infect grubs of *Holotrichia consanguinea* attacking seedlings of *P. cineraria*. Larvae of defoliator *Taragama siva* were highly susceptible to the infection caused by a nuclear polyhedrosis virus (Ahmed and Kumar, 1998; Ahmed *et al.,* 1998). NPV- infection on *Achaea janata* has been reported by Ahmed and Murugesan (1995), Ahmed (1994) and Ahmed and Leather (1994).

Five species of mites, *Eutetranychus orientalus*, *E. maximae*, *E. phaseoli*, *E. bilobatus* and *Tetranychus* spp. injure nursery stocks of neem by sucking sap from the leaves. The adults and nymphs of thrips *Heliothrips haemorrhoidalis* and *Taeniothrips longistylus* also suck the sap of the foliage and shoots of seedlings. The oriental yellow scale, *Aonidiella orientalis*, neem scale, *Pulvinaria maxima*, *P. azadirachtae*, Indian wax scale, *Ceroplastes ceriferus*, Wax scale, *Ceroplastes pseudoceriferus*, shield scale, *Lecanium* sp., mealy bug *Pseudococcus* sp., the bug *Eurybrachus tomentosa* and the white fly *Dialeurodes almatus* were observed on tender leaves of neem at seedling stage. A pseudococcid *Pseudococcus* spp. was also recorded to cause severe damage in neem seedlings. Mirid bug *Helopeltis antonii* injects phytotoxin into the plant system. The nymphs and adults of grasshopper *Orthacris simulans* feed on mature leaves. The grubs of *Holotricha consanguinea* and termites *Odontotermes obesus*, *O. redemanni* and *O. gurdaspurensis* damage roots of saplings. The castor semilooper *Achaea janata,* semilopper *Boarmia variegat,* looper moth *Cleora cornaria*, *Eurema* spp. and *Thosea bipartita* form the defoliator complex on neem. The shoot borer *Laspeyresia koenigana* is the only one known from arid regions. The weevils *Myllocerus dorsatus*, *M. laetivirens, Cryptocephala aequalis* and chafers represent the coleopterans on neem. Two species of gastropod molluscs *Laevicaculis alte* and *Macrochlamys indica* are reported to cause damage to neem seedlings.

Apart from insecticide application, pruning and removal of infested parts of plant along with the insect colonies may check further attack. The molluscs can be hand picked or dropped in containers of salt solution. Studies on germplasm selection for insect resistance are under way. *A. janata* responds to nuclear polyhedrosis viruses and *H. consanguinea* to *Bacillus popilliae and* fungus *Aspergillus parasiticus* (Patel *et al.*, 1977; Ahmed, 1994; Ahmed and Leather, 1994).

Larvae of *Patialus tecomella* skeletonize the leaves of the Rohida (*Tecomella undulata*) whereas adults feed on the green matter. The adults of *Myllocerus dorsatus, M. laetivirens, M. maculosus* and *M. dalbergiae* feed on the foliage (Verma and Satyavir, 1995; Kumar *et at*., 1994). Beetles and larvae of *Amblyrhinus posicollis* feed on the tender leaves and buds while *Holotrichia consanguinea* and *Autoserica nathani* are pests of young seedling. *Amsacta moorie* and *Agrotis ipsilon* and *A. spinifera* caterpillars feed on foliage in the nursery. The castor semi-looper, *Achaea janata* and

Taragama siva feed on the leaves and growing shoots. The larvae of *Atteva fabriciella* cause moderate losses. Grasshoppers *Schistocerca gregaria, Pyrgomorpha brachycera, Poekilocerus pictus, Hieroglyphus banian* and *Locusta migratoria* are the new pest records on *T. undulata.* Leaf miner *Leucoptera sphenograpta* also occurs on rohida, besides many sap sucking insects. Infestation by *Stegmatophora* sp. in early stage is responsible for hollowing of the branches and stem.

Diseases

Both the natural tree stands and introduced tree plantations are exhibiting signs of stress in recent years. The instances of tree mortality are on an increase. Plant protection scientists of the arid region have taken a call on the phenomena and undertook investigations for the causal factors and endeavored to develop remedial measures. While abiotic factors such as moisture availability, carrying capacity of soils and climatic conditions have bearing on the establishment and development of trees, a conspicuous role of pests and pathogens has been recorded on the well being of trees in the arid regions. Added to this are the man made changes in cultivation practices and resource utilization.

The diseases associated with arid trees have been described by Srivastava and Verma (2008). Sun scorching and bark canker is common in neem, babul and rohida plantations. *Botryodiplodia theobromae* has been isolated from cankered portion. The disease could be managed by pasting of Chaubattia paste on affected portion or white washing with un-activated lime upto breast height for prophylactic treatment. Die back in neem caused by *Macrophoma collabense* could be managed through application of a paste containing copper carbonate, red lead and white petroleum jelly in 1:1:2 ratio. The sooty mould in neem developing on trees attacked by the sap sucking insect *Lasperasia koenigana* could be controlled through combined application of 0.02% dimethoate, 0.05% Blitox and growth regulator Vipul @2ml l^{-1}.

Ganoderma root rot affects a number of arid trees. The measures suggested for minimizing the disease include uprooting and burning of the dead tree, digging isolation trenches adjoining healthy trees, avoiding monoculture and planting the resistant varieties to break the continuity of fungus spreading. The trees in affected surfaces should be pasted with Bordeaux paste or Chaubattia paste. The heart rot in *Acacia* and khejri trees caused by *F. badius* can be minimised by avoiding injuries to trees and illicit lopping. Sporophores may be collected and destroyed manually. Gummosis in Su-babul (*Leucaena leucocephala*) was ascribed to the pathogen *Fusarium* sp.

In khejri, the borer attack is followed by a tertiary infection of fungal pathogens *Alternaria* sp; *Phoma* sp. and *Botryodiplodia* sp. which contribute in the die-back. For preventing the die back, the lopped portions/open wounds in the tree could be treated with Afri-paste (copper carbonate + red lead + white petroleum jelly or linseed oil in 1:1:2 ratio and 3 ml monocrotophos). For root treatment chloropyriphos (0.02%) + Bavistin (0.1%) + Leader should be applied at an interval of three months.

The rot in neem nursery caused by *Rhizoctonia bataticola* was first reported by Srivastava *et al*. (2004). Soil drenching with 0.1% Bavistin was fond effective. Mortality in *Acacia nilotica, Eucalyptus* and *D. sissoo* plantations in Hanumangarh and Sriganganagar districts was diagnosed to be due to heavy frost injury and acute drought conditions. Shisham plantation in canal side plantation was also found infected with wilt fungus, *Fusarium solani* in association with *Ganoderma lucidum*. Further rotting of roots due to canker nodules was impending the growth of roots.

Investigations were carried out to reveal the causes of hollowness of the main bole in *Tecomella undulata* trees. The malady was assigned to infestation of wood by borers and wood decaying fungi. Two species of imperfect fungi (*Phoma sp.* and *Botryodiplodia theobromae*) were primarily responsible for canker-rots, which subsequently attracted borers and heart rot pathogen (*Fomes* sp.). The problem of termite attack and cracking of bark has also been observed in Rohida. Mature trees treated with paste containing linseed oil, copper carbonate and red lead in 2:1:1 ratio exhibited reduced cankered area and healing of canker was observed due to formation of callus.

Nematode Problems in Arid Regions

Most of the nematode problems in arid lands relate to crops grown under assured irrigation conditions. Though a large number of nematode genera have been reported from arid lands, their population and severity on crops grown under rainfed conditions is low as compared to crops grown under irrigated conditions. Surveys of rainfed crops have revealed the presence of *Tylenchorhynchus* and *Pratylenchus* on pearl millet; *Hoplolaimus*, *Pratylenchus* and *Helicotylenchus* on *Cenchrus ciliaris*; *Heterodera cajani*, *Meloidogyne javanica* and *M. incognita* on guar and *M. javanica* and *M. incognita* on mung bean (Dutta *et al*., 1987; Jain, 1980; Gupta and Verma, 1990). In rainfed crops, soil populations of plant nematodes is generally low and starts building up with the onset of monsoon rains and increases to maximum during mid monsoon, which is also the peak growth period of crops. Under rainfed conditions, availability of moisture governs the population dynamics of plant nematodes and during evenly distributed rains, high build up of nematode population especially ectoparasitic nematodes is observed. On irrigated crops, mainly vegetables, pulses and spices, species of *Meloidogyne*, *Pratylenchus*, *Hoplolaimus*, *Tylenchorhynchus*, *Helicotylenchus* have been reported (Yadav *et al.*, 1970; Singh and Khera, 1978; Anon., 1985). Amongst the various genera of plant nematodes encountered on these crops, root-knot nematode has been observed economically most important nematode pest. In spite of regular irrigation, the nematode causes severe losses to crops in hot arid lands which are characterized by sandy nature of soils and extremely high temperatures.

Incidence of plant parasitic nematodes on fruit trees of arid region have shown occurrence of diverse species of plant nematodes. On Ber, *Tylenchorhynchus*; on date palm, *Tylenchorhynchus*, *Hoplolaimus*, *Pratylenchus* and *Meloidogyne*; on pomegranate *M. incognita* and *M. javanica*, *Tylenchorhynchus*; on citrus, *Helicotylenchus*, *Tylenchorhynchus*, and *Criconemoides* and on papaya, *Meloidogyne*, *Helicotylenchus* and *Tylenchorhynchus* have been recorded (Kaul, 2002). Amongst the fruit crops, lowest incidence of nematodes has been observed on Ber. Limited information is available on nematodes associated with forest trees of arid region. Difficulty in collecting samples from deeper zones of the roots has been a major limiting factor in precise estimation of nematode fauna. However, surveys of tree nurseries have revealed the presence of *Pratylenchus* and *Tylenchorhynchus* on *Prosopis cineraria*; *Meloidogyne* and *Pratylenchus* on *Accacia nilotica*; and *Tylenchorhynchus* on *Tecomella undulata*, *A. tortilis*, *A. samia*, *A. anura* and *A. salicinia* (Kaul, 1998). Similarly, arid shrub jojoba has also been found to support species of *Pratylenchus* and *Tylenchorhynchus*. Researches on tree based cropping systems have revealed the presence of low populations of plant nematodes in rainfed systems. In *Prosopis cineraria* based system moderate populations of *Tylenchorhyncus* have been reported on moth bean, guar and senna. Besides, this low population of *Pratylenchus* has also been recorded on moth bean and cowpea. In *Tecomella undulata* based cropping system low populations of *Hoplolaimus* and *Tylenchorhynchus* have been observed on moth, guar and senna. Ber based system however, has not been observed to support many genera of nematodes. Only low populations of *Tylenchorhynchus* have been reported to be associated with these crops (Kaul, 2002).

In irrigated vegetable crops root-knot nematode has been observed most severe nematode pest. The nematode is reported to cause 91.4 and 24% yield losses in okra, tomato and brinjal (Bhatti and Jain, 1977). Management of nematode diseases under arid conditions has mostly been achieved by the application of nematicides. On chillies, soil application of carbofuran @ 2-4 kg a.i. ha^{-1}, foliar spray application of carbosulfan or triazophos at 500 ppm, soil amendment with mustard/castor oil cakes 1000 kg w/w have been found effective in reducing the number root galls and soil and root population of *M. incognita* (Joshi *et al.,* 2008). Work done on bio control agents under arid zone conditions has revealed the promising potential of *Paecilomyces lilacinus* and *Pasteuria penetrans* especially on chilli. Survival studies on *P. penetrans* indicate the ability of the bacterium to survive for more than a year under natural field conditions (Kaul and Chaudhary, 2005). Survival studies on *P. lilacinus* suggest low viability of the fungus during high temperature months, however, application of the fungus during favourable temperature conditions can prove effective in management of root-knot nematode. A cost effective method for mass culture of fungus on a combination of locally available plant material in polypropylene bags has also been devised (Kaul and Khan, 2006). Application of nematicide carbofuran along with *P. penetrans* or *P. lilacinus* has not been observed to have any adverse effect on the efficacy of either of them (Kaul and Chaudhary, 2008). Similarly, combined application of *P. penetrans* and *P. lilacinus* has been found more effective for the management of *M. incognita* on chilli then their individual application (Kaul and Chaudhary, 2005). More reliable less cumbersome and simple methods for in vitro screening of plant germplasm against root-knot nematode have been developed (Kaul, 1997, 1999). Axenic seedling culture in sand supplemented with nutrients has been observed better for screening of chilli lines against *M. incognita* under aseptic conditions (Kaul, 2005). Amendment of soil with chopped leaves of *Tagetes patula* or su-babool or castor @ 40 kg ha^{-1} soil has been reported to cause significant reduction in egg masses and total population of this nematode on tomato, brinjal and okra (Pruthi *et al.*, 1987; Zaki and Bhatti, 1989; Walia and Gupta, 1997). Application of neem leaf extract @ 40 g kg^{-1} soil has also been found to reduce *M. javanica* population on chickpea (Kali Ram and Gupta, 1980). Intercropping of *Tagetes patula* with brinjal has been reported to suppress soil population of *M. javanica* (Jain *et al.*, 1990). Leaf extracts of *Calotropis procera* and *Withania sominifera* have been reported to inhibit egg hatching and extracts of *Tagetes* and *Citrullus* have been found to possess nematicidal properties against larvae of *M. incognita* (Kaul, 2001). Sensitiveness of plant nematodes to heat and drying has also been exploited variously for bringing down their population below threshold levels. Ploughing of fields during summer months has been found to reduce nematode population drastically. Three summer ploughings (10-15 cm deep) at an interval of 10 days during the months of May and June in combination with bare root dips in phosphamidon at 1000 ppm for 8 h has been reported to decrease *M. javanica* population by 92.3% in tomato (Jain and Bhatti, 1989). Similarly, in okra, normal ploughing (20 cm) or deep ploughing (20 cm) followed by fallow period of two months and application of alidicarb seed treatment and soil application of aldicarb @ 1 kg a.i. ha^{-1} has been found to cause 79.2 and 76.3% reduction in *M. javanica* population (Jain and Gupta, 1990).

Rodents

Rodents in Indian arid zone are represented by one species each of porcupine and squirrel, 4 species of gerbils, 7 species of rats and 5 species of mouse. Beside these, other species inhabiting the arid regions are of minor importance in agriculture. However, species like *Gerbillus gleadowi* and *Hystrix indica* may also acquire pest status occasionally. Like insect pests, there is no clear specificity of rodents for any particular crop. Generally speaking, *T. indica, M. hurrianae* and *R.meltada* may be considered as an important pest complex of arable crops of arid regions (Tripathi *et al*., 1992).

Indian gerbil (*Tatera indica*) is distributed throughout India. It is nocturnal and inhabits simple burrows. It breeds throughout the year and litter size varies from 1-9 (av. 4.78) with a gestation period of 28-30 days (Jain, 1970 and Prakash and Rana, 1970). Stomach content analysis revealed grasses, standing crops and insects as its food (Prakash, 1959; Parveen, 1992). It is found in association with *Meriones hurrianae* and *Gerbillus gleadowi* in eastern part of the desert and with *G.nanus* and *Rattus gleadowi* in western desert tract. In Haryana, Punjab and Gujarat this gerbil is found in association with *Bandicota bengalensis*, *R. meltada* and *Mus* spp. in crop fields.

Indian desert gerbil (*Meriones hurrianae*) inhabits exclusively the xeric regions of the country. Prakash (1981) has reviewed the CAZRI's findings on its taxonomy, distribution, population ecology, behavioural patterns, food, reproduction, adaptation for desert survival and the ventral scent marking gland of *M. hurriane*.

Soft furred field rat (*Rattus meltada pallidior*) usually occurs in irrigated fields and is regarded as submesic in nature. It is nocturnal and lives in simple burrows. In Rajasthan desert, it breeds during spring and monsoon with a litter size of 3-9 (Rana and Prakash, 1984). It is a serious pest of wheat, mustard, groundnut, sugarcane, cotton, pulses and other vegetations.

The mice include house mouse, *Mus musculus*, brown spiny mouse, *M. platythrix*, field mouse, *M. booduga* and fawn coloured mouse, *M. cervicolor*. *M. musculus* regarded as a commensal species has also been recorded from crop fields. Other three species are exclusively field mice and *M. booduga* is recognised as a pest of arable crops. *M. musculus* breeds round the year with a litter size of 3-6 in laboratory and 1-8 in the fields. *M. booduga* litters during October (Prakash, 1975) in Rajasthan and during September, October, February and June in other parts. Rana *et al.* (1993) trapped house mouse from cotton, sugarcane and wheat fields in Sriganganagar district of Rajasthan.

B. bengalensis, the lesser bandicoot rat, is considered a prime rodent pest of the country, however, this species is true mesic in the nature and was not found in western Rajasthan desert. With changes in landuse pattern and increase in irrigated agriculture due to the Indira Gandhi Canal, the bandicoots have invaded northern Rajasthan. They are found in the areas that are under canal irrigation for the last 60 years or more. *Nesokia indica*, the short-tailed mole rat, was first reported from Sriganganagar by Prakash *et al*. (1971). It is also a mesic rodent. It has now further spread up to Nagaur district (Jain and Tripathi, 1988a). The bandicoot is known to hoard up to 450 kg of food ha^{-1} in their burrows. It breeds all the year round with a litter size of 4-12. Both the species are nocturnal and make mole hills at burrow openings.

Estimates of rodent damage to arable crops have been variously reported by several workers (Table 2), but for want of a common methodology these figures are not comparable. However, these reports spread over three decades span, clearly reveal very high degree of damage to the standing crops.

Rana *et al.* (1993) reported that squirrels and gerbils eat even the sown seeds before germination. In western Rajasthan, *G. gleadowi* proved most destructive during 1970 at sowing stage, when farmers of 4 districts had to resow pearl millet 3-4 times (Prakash, 1976). At harvest, the bajra cobs from the field are heaped in the threshing yards near the huts. The gerbils mainly *M. hurrianae* and *G. gleadowi* follow the cobs, dig tunnels under the heaps and feed on bajra grains. In one such village, Prakash (1976) counted some 40 gerbils in a 15x40 m^2 area - a very high density of gerbil population. An upsurge in population of *T. indica* was noticed in 1989 during kharif in Rajasthan, which resulted in serious losses to bajra, mung and moth. Similarly, in chillies, *T. indica, M. hurrianae* and *R.m.pallidior* complex damaged 15-20 kg of fruits per ha per day at a very high population density of 142 burrows ha^{-1} resulting in about 40% damage to chilli fruits. In the rabi season, mustard is infested by rodents at vegetative growth stage when 33.2-45.2% plants are eaten away by rodents in the peripheral zones of the crops fields at a burrow density of 73.1 ha^{-1} (Jain and Tripathi, 1992). Three commonly grown wheat varieties, Kalyan sona, Kharchia and desi suffered an average damage to the tune of 16.29, 21.28 and 18.66%, respectively (Advani *et al.,* 1982, 1988). Advani and Mathur (1982) observed the highest damage to radish and tomato and minimum (less than 5%) to bottle gourd, sweet potato, okra and spinach. *Tatera indica* showed maximum preference for muskmelon and kachra seeds, however seeds of ridge gourd and carpet beans were not preferred (Jain *et al.,* 1995).

The work on rodent control techniques have been exhaustively reviewed by Prakash and Mathur (1987), Jain *et al*., (1993) and Rana *et al*. (1993). The techniques may be grouped as (i) non-chemical, and (ii) chemical measures.

Trapping can be effective on its own on a limited scale (Jain *et al*., 1992). Among cultural practices, reduction in bund size, light ploughing, flooding and removal of weeds have been reported to create stress for rodents leading to their migration from cropped areas (Prakash and Mathur, 1987; Pasahan and Sablok, 1987; Jain and Tripathi, 1994). Prakash and Mathur (1987) reported that *Opuntia* plantings on the bunds may also reduce the pest population. Similarly 20-30 m strip of unpalatable crop like guar or unpalatable grasses sown around the main crop would keep the immigrating rodents involved with the unpalatable crops and the main crop could be saved from rodent pests.

A large number of acute rodenticides viz., scilliroside, RH-787, strychnine sulphate, sodium monofluroacetate, barium carbonate and zinc phosphide have been evaluated in laboratory and fields against desert rodents (Prakash and Mathur, 1987). Among these, zinc phosphide is the most widely used rodent poison in India. It is highly toxic to a variety of desert rodents. Its LD_{50} is 35 mg kg^{-1} for *T. indica* and *M. hurrianae* and 250.0 mg kg^{-1} for *M. musculus* (Prakash *et al*., 1969; Rao and Prakash, 1981). It should be used at a concentration of 2.0% (W/W) in freshly prepared baits. Higher or lower concentration in baits results in induction of bait shyness among rodents due to sublethal consumption. This behavioural manifestation among rodents persists for 10-104 days in different species (Rana *et al.,* 1993). Aluminium phosphide fumigation of rodents burrows also yielded significantly higher control success in irrigated crops of arid zone (Soni *et al*., 1995). National Programme on Rodent Pest Management launched by Government of India and ICAR during 1975 also recommended aluminium phosphide fumigation as a follow-up measure after zinc phosphide baiting. CAZRI has evolved a new technique of bait preparation that is easy, simple and more economic than earlier techniques (Jain, 1986a). With the advancement in knowledge of anticoagulants several rodenticides have been evaluated against desert rodents. Warfarin, fumarin, chlorophacinone and coumatetralyl were found effective against a variety of rodent pests, however, these chemicals required multi feeding for 7-14 days for causing effective mortality of rodents (Mathur and Prakash, 1980, 1982, 1983). In eighties, single dose anticoagulants, referred to as second-generation anticoagulant rodenticides, were introduced. Bromadiolone and brodifacoum, both proved highly effective against arid rodents at 0.005% conc. (Jain, 1986b; Jain and Tripathi, 1988c). Later, in the same series, flocoumafion was also introduced as a potent rodenticide (Jain *et al.,* 1992).

Weed Management

Many weed species flourish under arid condition and complete the life cycle with in 60 to 70 days. The natural succession of weeds in dry land agriculture and in irrigated agriculture is quite different. The major weed flora of the region are presented in Table 1.

Weeds emerge in succession almost throughout the crop season and compete with crop plants for essentials like moisture, nutrients, space and light. Significant reduction in nutrient uptake was observed due to weedy check in mung bean compared to weed free (Yadav *et al.,* 1985). In a study Singh and Yadav (1994) observed that nutrient uptake (N and P) by weeds increased up to 60 DAS and it was brought down significantly due to two hand hoeing, atrazine at 0.5 kg ha^{-1} and terbutryne at 0.75 kg ha^{-1} in pearl millet. Competition studies carried on crops grown in arid zone revealed that crop yield loss varied to the extent of 60 to 90% due to crop weed competition (Saxena *et al*., 2003, 2004; Singh, 2006; Singh and Singh, 2004).

Since arid regions are already deficient in moisture and nutrients; effective weed management is of utmost importance. Weeds should be managed with in the critical period of weed crop competition. The critical period is the maximum period that weed competition can be tolerated by a specific crop without affecting final yield. This depends on the nature of weed and crop, environmental conditions and density of weeds and the period for which weeds are associated with the crops.

In pearl millet infestation of weed species can be minimized with three hand hoeing done at 15, 30 and 45 days after sowing (Dahiya *et al*., 1987). Integration of 2,4-D @ 0.50 kg ha^{-1} (post emergence) + one hand weeding at 30 DAS also effectively controlled the weeds at par with three hand weeding at Bikener (Sharma and Jain, 2003). Banga *et al.* (2000) reported that combined application of acetachlor 0.75 kg + atrazine 0.375 kg ha^{-1} significantly increased grain yield of pearl millet and was at par with atrazine at 0.50 kg ha^{-1} applied at 10 DAS under Hissar conditions. Deshveer and Deshveer (2005) reported that intercropping of cowpea and cluster bean with pearl millet significantly reduced weed population compared to weedy check. Further integrated application of oxyfluorfen at 0.3 or 0.2 kg ha^{-1} (pre-emergence) along with one hand weeding at 30 or 25 DAS resulted in very close weed control efficiency with sole manual hand weddings in pearl millet. Singh (1985) observed that pre-emergence application of atrazine at 1 kg ha^{-1} increased grain yield by over two fold under arid condition of Jodhpur.

Table 1. The major weed flora of the arid regions

Production system	Weed species
Kharif arable crops	*Amaranthus blitum, Borreria articularis, Celosia argentia, Cenchrus biflorus, Corchorus tridens, Cyperus rotundus, Dactyloctenium aegyptium, Digera muricata, Euphorbia indica, Heliotropium subletam, Rhynchosia minima, Tribulus terristris*
Rabi arable crops	*Asphodelus tenuifolius, Chenopodium album, C. murale, Fumeria parviflora, Medicago denticulate, Melilotus indica, Phalaris minor, Portulaca oleracea, Rumex dentatus*
Horticultural crops	*Achyranthes aspera, Aerva persica, A. pseudotomentosa, Amaranthus blitum, A. apinosus, Celosia argentia, Cenchrus biflorus, Cyperus rotundus, Crotalaria burhia, Cuscuta freflexa, Digera muricata, Eragrostis tremula, Euphorbia indica, Glinus lotoides, Indigifera argentea, Heliotropium sublatum, Leptadenia pyrotechnica, Mollugo cerviana, Pulicaria wightiana, Tephrosia purpurea, Tribulus terristris*
Forestry system	*Areva persica, Aristida histricula, Borreria diffusa, Calotropis procera, Cocculus pendulus, Indigofera cordifolia, Leptadenia pyrotechnica, Oligochaeta ramose, Phyllanthus niruri*
Fellow land	*Achyranthes aspera, Amaranthus blitum, Borreria articularis, Calotropis procera, Cenchrus biflorus, Crotolaria burhia, Eragrostis tremula, Euphorbia hirta, Heliotropium sublatum, Leptadenia pyrotechnica, Tephrosia purpurea, Tribulus terristris, Urochloa panicoides*

In moth bean, where yield reduction is recorded up to 75% under arid zone (Singh and Singh, 1979), one hand weeding at 30 DAS controlled most of the weed species effectively, but pre-plant incorporation of fluchloralin at 0.75 and 1.00 kg ha^{-1} were equally effective (Saxena *et al.* 2003, Shekhawat *et* *al*., 2003). Pre-plant incorporation of basalin or treflan @ 1.5 kg ha^{-1} control the weeds of moth bean effectively (Henry and Singh, 1985). Application of Fluchloralin at 0.75 kg ha^{-1} along with one hand weeding at 30 DAS provided excellent control of broad spectrum weeds and gave significantly higher seed yield and net returns over one hand weeding and fluchloralin at 1.0 kg ha^{-1} (Singh and Singh, 2005).

In green gram although manual weeding is effective in reducing weed competition, use of herbicides offers economic control. Singh and Faroda (1977) reported that pre-emergence application of alachlor at 2 kg ha^{-1} effectively controlled the weeds and gave significantly higher seed yield. Daulay and Singh (1982) reported that trifluralin, chloramben and alachlor were effective in controlling major weeds of green gram. To control broad-spectrum weeds herbicides application should be supplemented with manual, mechanical or cultural means.

In clusterbean pre-plant incorporation of fluchloralin 1.0 kg ha^{-1} has been found effective in minimizing the weeds and iscomparable to one hand weeding at 30 DAS, but monetary benefit was higher with fluchloralin than hand weeding (Singh and Singh, 2003). Application of alachlor, trifluralin and nitrofen proved effective in controlling weeds, giving a yield equal to that of the hand weeded treatment (Daulay and Singh, 1982).

In sesame pre plant incorporation of fluchloralin or pendimethalin 1.0 kg ha^{-1} and triflurain 1.0 kg ha^{-1} followed by one manual weeding at 4 WAS gave better seed yield compared to the herbicides application alone and two hoeing (Punia *et al*., 2001).

Among the Rabi crops, for wheat combined application of chlorsulfuron 20 g + isoproturon 170 g ha^{-1} and 4 g metasulfuron + 750 g ha^{-1} isoproturon provided satisfactory control of broad leaf and grassy weeds (Balyan *et al*., 2003). A study on low dose herbicides by Malik *et al*. (2005) indicated that application of sulfosulfuron @ 25 g ha^{-1} was most effective for decreasing maximum weed population and increasing grain yield. Singh and Singh (2004) reported that pre-emergence application of pendimethalin at 0.75 kg ha^{-1} followed by 2, 4-D (post emergence) at 0.50 kg ha^{-1} or one hand weeding at 30 DAS gave significantly higher yield over weedy check.

In mustard application of nutrients, irrigation and wider row spacing create conducive environment for profuse growth of weeds, which reduced mustard seed yield up to 50% (Singh, 2006). Pre-emergence application of oxyfluorfen @ 0.125 kg ha^{-1} significantly reduced the weed density and resulted in highest seed yield as well as minimum uptake of NPK and S by weeds (Sharma *et al*., 2001). Singh *et al.* (1999) observed that fluchloralin or pendimethalin at 0.50 kg ha^{-1} each supplemented with one weeding at 30 DAS gave maximum control of broad-spectrum weeds.

In seed spices uncontrolled weeds reduced the coriander, cumin, fennel and fenugreek yield 70 to 90% (Yadav and Dhama, 2003; Patel *et al.,* 2005; Singh *et al*., 2008). Integration of pendimethalin 1.0 kg ha^{-1} with one hand weeding at 30 DAS was found very effective for cumin crop (Parihar and Singh, 1994). Pre-plant incorporation of fluchloralin 0.50 kg ha^{-1} supplemented either with post emergence application of oxadiagryl 50 g ha^{-1} or one manual weeding at 25 DAS were as effective as two hand weeding in cumin. Crop rotation plays important role in controlling weeds like *Plantago pumila* (jiri), in cumin (Bhati *et al.,* 1999). Crop rotation is also very effective for reducing *Cuscuta* infestation in fennel (Bhati, 1994).

Looking Ahead

While many aspects of integrated pest, disease and weed management in arid production systems have been investigated, several issues need to address yet. The search for multiple resistance of crop varieties to pests and diseases should be intensified. Alternatives to toxic chemicals need to be developed. The approach thus far was largely isolated, targeting solution for individual problems. An integrated approach to tackle all the problems associated with different components of the production systems is the need of the hour. Devising modules that target management of biotic stresses of all types will be of great benefit to the cultivators.

References

Advani, R., Prakash, I. and Mathur, R.P. 1982. Assessment of rodent damage and yield losses in standing wheat crops in a desert village complex. *Zeitschrift fur Angewandte Zoologie* 69: 257-266.

Advani, R. and Mathur, R.P. 1982. Experimental reduction of rodent damage to vegetable crops in Indian villages. *Agroecosystems* 8: 39-45.

Ahmed, S.I. 1994. The use of entomopathogenic viruses in forestry: Potential for their use in developing nations. *Antenna* 18(1): 14-18.

Ahmed, S.I., Kumar, Seema and Sharma, Sangeeta 1998. Nuclear polyhedrosis of babul defoliator, *Taragama siva* Lefebvre (Lepidoptera : Lasiocampidae). *My Forest* 34 (1): 715-721.

Ahmed, S.I. and Kumar, Shivesh 1998. Role of natural epizootics of a NPV disease in controlling *Prosopis juliflora* defoliator, *Taragama siva* outbreak in north-west Rajasthan. *Indian Forester* 124 (11): 952-958.

Ahmed, S.I. and Leather, S.R. 1994. Suitability and potential of entomopathogenic micro organisms for forest pest-management some points for consideration. *International Journal of Pest Management* 40(4): 287-292.

Ahmed, S.I. and Murugesan, S. 1995. *Achaea janata* Linn (Noctuidae: Lepidoptera). A new pest record on Neem- Its management through Nuclear Polyhedrosis Virus. *Indian Forester* 121(1): 63.

Ahmed, S.I. and Singh, M.P. 2007. Integrated management of forest and agricultural insect pests in arid regions. In *Dryland Ecosystem: Indian Perspective* (Eds. K.P.R. Vittal, R.L. Srivastava, N.L. Joshi, Amal Kar, V.P. Tewari and S. Kathju), pp. 169-184. CAZRI-AFRI, Jodhpur.

Bagle, B.G. 1992. Incidence and control of fruit fly *Carpomyia vesuviana* Costa of ber *Zizyphus mauritiana*, Lamk. *Indian Journal of Plant Protection* 20(2): 205-207.

Balyan, R.S., Singh, Samunder, Malik, R.K. and Dhankar, R.S. 2003. Rate and application of chlorsulfuron for broadleaf control in wheat. *Indian Journal of Weed Science* 32(3-4): 173-176.

Banga, R.S., Yadav, Ashok, Malik, R.K., Pahwa, S.K. and Malik, R.S. 2000. Evaluation of tank mixture of acetachlor and atrazine or 2,4-D Na against weeds in pearl millet (*Pennisetum americana* L.). *Indian Journal of Weed Science* 32 (3-4): 194-198.

Bhati, D.S. 1994. Dodder *(Cuscuta reflexa Roxb.*) a severe parasitic weed of fennel (*Foeniculum vulgare* Mill). *Journal of Spices and Aromatic Crops* 3(2): 152-154.

Bhati, D.S., Jain, M.P. and Choudhry, G.R. 1999. Crop rotation an effective means to control resistant Jiri weed (*Plantago pumila* Wild.) in cumin (*Cuminum cyminum* Linn.). *Abstract VIII Biennial Conference of the Indian Society of Weed Science*, Varanasi. 78 pp.

Bhatti, D.S. and Jain, R.K. 1977. Estimation of loss in okra, tomato and brinjal yields due to *Meloidogyne incognita. Indian Journal of Nematology* 7: 37-41.

Chakravartry, C.N., Krishnappa, M. and Thippeswamy, B. 2005. Investigation on bacterial blight (*Xanthomonas axanopodis* pv. *cyamopsidis)* of clusterbean {*Cyamopsis tetragonoloba* (L.) Taub.}and *in vitro* control. *Journal of Mycology and Plant Pathology* Symposium Abstract pp. 119.

Chandra, A., Chandra, A. and Gupta, I.C. 1994. *Arid Fruit Research*. Scientific Publishes, Jodhpur. 50-61 pp.

Chawla, N. and Gangopadhyay, S. 2009. Integration of organic amendments and bioagents in suppressing cumin wilt caused by *Fusarium oxysprum* f *cumini*. *Indian Phytopathology* 62: 209-216.

Dahiya, S.S., Faroda, A.S. and Singh, J.P. 1987. Effect of weed control methods on growth yield of pearl millet under rainfed conditions. *Haryana Journal of Agronomy* 3: 13-16.

Dashad, S.S., Chaudhary, O.P. and Rakesh. 1999. Studies on the incidence of ber fruitfly (*Carpomyia vesuviana* Costa) in south-western Haryana. *Crop Research Hisar* 18(1): 115-118.

Dashad, S.S., Chaudhary, O.P. and Rakesh. 1999a. Chemical control of ber fruitfly. *Crop Research* Hisar 17(3): 333-335.

Dashora, K. and Kumar, Arun. 2008. Management of smut disease of pearl millet through bio-control agents. *Seed Research* 36: 238-240.

Daulay, H.S. and Singh, K.C. 1982. Chemical weed control in green gram and clusterbean. *Indian Journal of Agricultural Sciences* 52: 758-763.

Deshveer, C.L. and Deshveer L.S. 2005. Weed management in pearl millet (*Pennisetum glaucum*) with special reference to *Trianthama portulacastrum*. *Indian Journal of Weed Science* 37(3-4): 212-215.

Dutta, S., Trivedi, P.C. and Tiagi, B. 1987. Nematodes on guar and mung in some areas of Rajasthan, India. *International Nematology Network Newsletter* 4: 12-16.

Faroda, A.S. 1996. Developed resistance to fruit-fly in ber through hybridization. *ICAR News* 2(4): 23.

Gandhi S K and Chand J N (1985). Yield losses in guar due to bacterial blight caused by *Xanthomonas campestris* pv. *cyamopsidis*. *Indian Phytopathology* 38 516-519.

Gupta, P.C., Madan, R.L. and Grover, R.K. 1978. Occurrence of powdery mildew of ber in Haryana and its control. *Indian Phytopathology* 31: 440-443.

Henry, A. and Singh, R.P. 1985. Moth bean. In *Efficient Management of Dry land Crops*. CRIDA, Hyderabad. 199-207 pp.

Israel S. and Lodha, S. 2004. Factors influencing population dynamics of *Fusarium oxysporum* f. sp. *cumini* in the presence and absence of cumin crop in arid soils. *Phytopathologia Mediterranea* 43: 3-13

Israel S. and Lodha, S. 2005. Biological control of *Fusarium oxysporum* f sp *cumini* with *Aspergillus versicolor*. *Phytopathologia Mediterranea* 44: 3-11.

Israel S., Mawar, R. and Lodha, S. 2005. Soil solarization, amendments and bio-control agents for the control of *Macrophomina phaseolina* and *Fusarium oxysporum* f sp *cumini* in aridisols. *Annals of Applied Biology* 146: 481-491.

Jain, A.P. 1970. Body weight, sex ratio, age structure and some aspects of reproduction in the Indian gerbil, *Tatera indica indica* Hardwicke in Rajasthan desert, India. *Mammalia* 34 : 414-432.

Jain, A.P. 1986a. A simplified rodent baiting technique. *Indian Farming* 36(8): 33-34.

Jain, A.P. 1986b. Evaluation of second generation anticoagulants in India. I. Bromadiolone. AICRP on Rodent Control, CAZRI, Jodhpur pp 15 (Mimeo).

Jain, A.P. and Tripathi, R.S. 1992. Management of rodent pests in oilseeds crops. *Advances in Oil Seed Research* (Eds. D. Kumar and M. Rai), pp. 359-377. Scientific Publishers, Jodhpur.

Jain, A.P. and Tripathi, R.S. 1988a. Occurrence and incidence of short tailed mole rat, *Nesokia indica* in arid zone afforestation ecosystem. *National Seminar on Advances in Economic Zoology,* Jodhpur. p. 19.

Jain, A.P. and Tripathi, R.S. 1988b. Rodent pest management: A Training Manual. AICRP on Rodent Control, CAZRI, Jodhpur (Mimeo). p. 1-67.

Jain, A.P. and Tripathi, R.S. 1988c. Evaluation of second generation anticoaugulants in India. II-Brodifacoum. AICRP on Rodent on Control, CAZRI, Jodhpur. pp. 22 (Miemo).

Jain, A.P., Mathur, M. and Tripathi, R.S. 1992. Traps and Trapping. In *Rodents in Indian Agriculture.* (Eds. I. Prakash and P.K. Ghosh). pp. 585-594. Scientific Publishers, Jodhpur.

Jain, A.P., Parveen, F., Patel, N. and Tripathi, R.S. 1995. Preference of *Tatera indica indica* Hardwicke towards some vegetable seeds. *Geobios New Reports* 14: 151-152.

Jain, A.P., Rana, B.D. and Tripathi, R.S. 1993. Rodent Management : The State of Art AICRP on Rodent Control, CAZRI, Jodhpur, pp. 1-38.

Jain, A.P. and Tripathi, R.S. 1994. Current trends in rodent pest management. In *Himalaya, Ecology, Wildlife and Resource Development* (Ed. B.D. Sharma), pp. 275-308. Asian Publishing. House, Delhi.

Jain, R.K. 1980. Pathogenecity of *Helicotylenchus dihystera* to *Cenchrus ciliaris. Indian Journal of Nematology* 10: 236-239.

Jain, R.K. and Bhatti, D.S. 1989. An integrated approach for the management of root-knot nematode (*Meloidogyne javanica*) in *tomato. Indian Journal of Nematology* 19: 159-161.

Jain, R.K. and Gupta, D.C. 1990. Integrated management of root-knot nematode (*Meloidogyne javanica*) infecting tomato and okra. *Indian Journal of Nematology* 20: 14-18.

Jain, R.K., Pruthi, I.J. and Gupta, D.C. 1990. Influence of intercropping on the incidence of root-knot nematode (*Meloidogyne javanica*) in brinjal. *Indian Journal of Nematology* 20: 236-237.

Jat, M.C., Sharma, J.K. and Jat, B.L. 1993. A note on the relative incidence of aphid *Lipaphis erysimi* (Kalt.) on some mustard varieties/entries. *Indian Journal of Aplied Entomology* 7: 77-80.

Jeyarajan, R. and Cheema, S.S. 1972. Screening of ber varieties for resistant to leaf spot and powdery mildew diseases. *Indian Journal of Horticulture* 29: 353.

Joshi, M.L., Ahuja, D.B. and Mathur, B.N. 1989. Loss in seed yield by insect pests and their occurrence on different dates of sowing in Indian mustard (*Brassicajuncea* sbsp. *juncea*). *Indian Journal of Agricultural Sciences* 59: 166-168.

Joshi, Poonam, Rathore, Indira, Kaul, R.K. and Tarafdar, J.C. 2008. Effect of integration of *Glomus fasciculatum* and oilcakes on the management of root-knot nematode and nutrient uptake in chilli. In *National Symposium on Integrated Pest and Disease Management (IPDM) in Arid and Semi Arid Areas.* AFRI, Jodhpur. March 12-13, 48-49.

Joshi, H.C. and Kaul, C.L. 1968. Studies on the susceptibility of different stages of *Bagrada cruciferarum* Kirkaldy to some organic insecticides. *Indian Journal of Entomology* 30(2): 180-181.

Kali Ram and Gupta, D.C. 1980. A note on the efficacy of fresh neem leaf extract in the control of *Meloidogyne javanica* infecting chickpea *(Cicer arietinum). Indian Journal of Nematology* 10: 96-98.

Kanwat, P.M. and Kumawat, K.C. 1995. Effect of date of sowing on the incidence of aphid *Lipaphis erysimi* (Kalt.) on mustard. *Annals of Arid Zone* 34(1): 61-63.

Kapadia, M.N. 1991. Varietal susceptibility of castor to *Liriomyza trifolii* (Burgers). *Indian Journal of Aplied Entomology* 5: 79-81.

Kaul, R.K. 1994. Establishment of *Meloidogyne incognita* on callus induced roots of chilli, *Capsicum frutiscens*. *22nd International Nematgology Symposium*, Ghent, Belgium, August 7-12, 1994, pp. 79-80.

Kaul, R.K. 1997. A simple biotechnique for *in-vitro* screening of chilli against *Meloidogyne incognita. International Journal of Nematology* 7: 107-110.

Kaul, R.K. 1999. Establishment of callus induced roots of *Capsicum frutescens* and their response to *Meloidogyne incognita*. *International Journal of Nematology* 9: 95-97

Kaul, R.K. 2001. Screening of locally available plants of arid zone for toxicity against root-knot nematode. *Symposium on Impact of Human Activities on Thar Desert Environment*, CAZRI, Jodhpur, Feb. 15-17

Kaul, R.K. 2002. Nematodes associated with horti-silvicultural systems in arid zone. *Regional Workshop on Pest and Disease Scenario in Arid Agri-Silvi-Horti-Pastoral Systems*. Central Arid Zone Research Institute, Jodhpur, Sept. 3-4.

Kaul, R.K. 2005. Evaluation of different tissue cultures of chilli, *Capsicum annuum* for in vitro establishment of *Meloidogyne incognita*. *Indian Journal of Nematology* 35: 166-170.

Kaul, R.K. and Chaudhary, K.K. 2005. Viability of *Pasteuria penetrans* parasitising *Meloidogyne incognita* under different conditions. *Indian Journal of Nematology* 35: 174-177.

Kaul, R.K. and Chaudhary, K.K. 2008. Efficacy of single and combined application of *Pasteuria penetrans* and *Paecilomyces lilacinus* for management of *Meloidogyne incognita* on chilli. *National Symposium on Recent Advances and Research Priorities in Indian Nematology*. IARI, New Delhi. Dec. 9-10

Kaul, R.K. and Chaudhary, K.K. 2008. Effect of *Pasteuria penetrans* with carbofuran on the growth of chilli and the multiplication of *Meloidogyne incognita*. *National Symposium on Innovative Approaches for Disease Management in Arid Crops for Enhancing Export Potential*. Rajasthan Agricultural University, Mandore, Jodhpur, Nov. 2-3

Kaul, R.K. and Khan, Injela 2006. Efficiency of different substrates and their combinations for mass culture of *Paecilomyces lilacinus*. *International Journal of Nematology* 16: 79-84

Kavadia, V.S. and Verma, S.K. 1973. *Quisqualis indica* and *Dodonea viscosa* as new hosts of castor semilooper, *Achaea janata* L. *Journal of Bombay natural History Society* 70(1): 226-227.

Kumar, Arun, Bhansali, R. R. and Mali, P. C. 2004. Raw cow's milk and *Gliocladium virens* induced protection against downy mildew of pearl millet. *International Sorghum and Millets Newsletter* 45: 64-65.

Kumar, A., Kumar, A. and Nath, V. 1989. On the efficacy of 8-Hydroxyquinoline in pearl millet ergot control (Abst.). *Indian Phytopathology* 42: 292.

Kumar, Arun and Mali, P.C. 2007. Involvement of resistance induction by raw cow's milk and *Gliocladium virens* in the biocontrol of downy mildew of pearl millet. *Abstract National Symposium on Innovative Approaches for Disease Management in Arid Crops for Enhancing Export Potentials*. IPS (Central zone) and RAU, Bikaner. 3-4 pp.

Kumar Seema; Ahmed, S.I. and Kumar, Sahdev. 1994. Annotated list of insect pests of forest trees of arid and semi arid regions of Rajasthan and Gujarat. *Oikoassay* 11(1-2): 5-9.

Kumawat, S.R. and Jain, P.C. 1987. Spring movement of painted bug, *Bagrada cruciferarum* (Kirkaldy). *Indian Journal of Aplied Entomology* 1: 106.

Kumawat, S.R. and Kanwat, P.M. 1995. Effect of some insecticides against sesame gall faly, *Asphondylia sesami* Felt. *Annals of Arid Zone* 34: 151-152.

Lakra, R.K., Kharub, W.S. and Singh, Z. 1979. Relationship of shedding of ber fruits and the incidence of ber fruit fly and bird damage. *Indian Journal of Ecology* 6: 68-72

Lakra, R.K. and Singh, Zile 1983. Oviposition behaviour of ber fruitfly, *Carpomyia vesuviana* Costa and relationship between its incidence and ruggedness in fruits in Haryana. *Indian Journal of Entomology* 45(1): 48-59.

Lakra, R.K. and Singh, Zile 1984. Calender of losses due to ber fruit fly. *Carpomyia vesuviana* Costa (Diptera: Tephritidae) in different *Zizyphus* spp. in Haryana. *Indian Journal of Entomology* 46(3): 261-269.

Lakra, R.K. and Singh, Zile 1985. Seasonal fluctuations in incidence of ber fruitfly *Carpomyia vesuviana* Costa (Diptera: Tephritidae) under agro-climatic conditions of Hisar. *Haryana Agricultural University Journal of Research* 15(1): 42-50.

Lakra, R.K. and Singh, Zile 1989. Bionomics of *Zizyphus* fruitfly, *Carpomyia vesuviana* Costa (Diptera: Tephritidae) in Haryana. *Bulletin of Entomology* 27: 13-27.

Lakra, R.K., Sangwan, M.S. and Singh, Zile. 1991. Effect of application of some insecticides on the incidence of 'ber' fruit fly (*Carpomyia vesuviana* Costa). *Narendra Deva Journal of Agricultural Research* 6: 71-79.

Lodha, S. 1998. Effect of sources of inoculum on population dynamics of *Macrophomina phaseolina* and disease intensity in clusterbean. *Indian Phytopathology* 51: 175-179.

Lodha, S. 1996. Influence of moisture conservation techniques on *Macrophomina phaseolina* population, dry root rot and yield of clusterbean. *Indian Phytopathology* 49: 342-349.

Lodha, S. and Anantha Ram, K. 1993. Effectiveness of streptocycline spray schedules on the bacterial blight intensity and yield of clusterbean. *Annals of Arid Zone* 32: 237-240.

Lodha S and Gupta G K. 1981. The relationship between bacterial blight and loss in yield components of guar (Abstr.) In proceeding *Third International Symposium on Plant Pathology*, pp. 94-95.New Delhi. Dec. 13-17

Lodha, S. and Mawar, R. 2000. Utilizing solar heat for enhancing efficiency of cruciferous residues for disinfecting soil borne pathogens from arid soils. *Acta Horticulturae* 532: 49-52

Lodha, S. and Mawar, R. 2007. Integrated disease management in seed spices. In *Production, Development, Quality and Export of Seed Spices* (S.K. Malhotra and B.B. Vashishtha), pp. 119-138. NRCSS, Ajmer.

Lodha, S., Sharma, S.K. and Aggarwal, R.K. 2002. Inactivation of *Macrophomina phaseolina* propagules during composting and efficacy of composts on dry root rot and seed yield of clusterbean. *European Journal of Plant Pathology* 108(3): 253-261.

Lodha, S., Singh, S. and Singh, M.P. 1983. Alternaria blight of ber (*Zizyphus mauritiana*) and its control. *Indian Journal of Plant Protection* 11(1-2): 54-56.

Malik, R.K., Yadav, Ashok, Malik, R.K. and Punia, S.S. 2005. Efficacy of Flufenacet and metribuzin against weeds in wheat. *Indian Journal of Weed Science* 37(3-4): 171-174.

Mathur, R.P. and Prakash, I. 1980. Comparative efficacy of three anticoagulant rodenticides against desert rodents. *Protection Ecology* 3: 327-331.

Mathur, R.P. and Prakash, I. 1982. Laboratory evaluation of chlorophacinone against *Tatera indica* and *Meriones hurrianae*. *Tropical Pest Management* 28: 291-295.

Mathur, R.P. and Prakash, I. 1983. Toxicity of coumatetralyl to two gerbils *Tatera indica* and *Meriones hurrianae*. *Zeischrift fur Angewandte Zoologie* 70: 257-263.

Mawar, R. and Lodha, S. 2002. Integration of *Brassica* amendments and summer irrigation for the control of *Macrophomina phaseolina* and *Fusarium* in hot arid region. *Phytopathologia Mediterranea* 41: 45-54.

Murugesan, S. and Kumar, Shivesh 1996. New record and damage of flower thrips in the introduced tree species of arid region. *Indian Forester* 122 (9): 854-855.

Nallathmbi, P. and Thakore, B.B.L. 2003. Management of ber (*Ziziphus mauritiana* Lamk) fruit rot using fungicides. *Journal of Mycology and Plant Pathology* 33(3): 503.

Nallathambi, P. and C. Umamaheswari. 2001. A New Disease of Ber (*Ziziphus mauritiana* Lamk.) caused by *Torula herbarum* (Pers.) Limk. *Journal of Mycology and Plant Pathology* 31(1): 72.

Nallathambi, P., Umamaheswari C., Vashishtha, B.B. and Vishal Nath. 2000. Fruit rot (*Alternaria alternata*) and sources of resistance in ber germplasm under arid conditions. *Annals of Arid Zone* 39(4): 471-478.

Pareek, O.P. 1997a. Arid horticulture: its potential. *Indian Horticulture* 42: 42-46.

Pal, S.K. and Sharma, V.P. 1973. Occurrence of *Rhinyptia meridionalis* var. *puncticollis* Arr. (Scarabaeidae: Coleoptera) as a pest on bajra in western Rajasthan. *Journal of Bombay natural History Society* 70(3): 574-575.

Pande, R.N.. 2008. Legumes pp 133-196 In *Disease Management in Arid Land Crops* (Eds. Lodha *et al*.,) Scientific Publishers, (India) Jodhpur 430 pp.

Pandey, R.N., Pathak, A.R., Kher, H.R. and Bharodia, P.S. 1993. Evaluation of clusterbean (*Cyamopsis tetragonoloba*) germplasm for resistance to bacterial blight (*Xanthomonas campestris* pv. *cyamopsidis*) and powdery mildew (Leveillula taurica). *Indian Journal of agricultural Sciences* 63: 68-70.

Pareek, O.P. 1997. Indian Jujube and Pomegranate. In *50 years of Crop Science Research in India*. ICAR, New Delhi. 557-573 pp.

Parihar, D.R. 1980. Termite problems in desert plantations. *Annals of Arid Zone* 19 (2): 329- 339.

Parihar, D.R. 1993. Insect fauna of Khejri, *Prosopis cineraria* in arid zone. *Indian Journal of Forestry* 16: 132-137.

Parihar, D.R and Kampantzov, A.V. 1997. Faunal diversity and associated predators and parasites of wood boring Coleoptera of Rajasthan Desert. *Annals of Arid Zone* 36(4): 367-373.

Parihar, D.R and Singh, M.P. 1998. Insects associated with *Prosopis cineraria* in arid western Rajasthan, India. In *Prosopis Species in the Arid and Semi Arid Zones of India*, (Eds. J.C. Tewari, N.M. Pasiecznik, L.N. Harsh and P.J.C. Harris), pp. 99-102. *Prosopis* Society of India and the Henry Double day Research Association.

Parihar, G.N. and Singh, R. 1994. Effect of cultural and herbicidal weed management on yield of cumin (*Cuminum cyminum*). *Annals of Arid Zone* 33: 309-312.

Parveen, F. 1992. Food of the antelope rat, *Tatera indica indica* Hardwicke. In *Rodents in Indian Agriculture* (Eds. I. Prakash and P.K. Ghosh), pp. 427-432. Scientific Publishers, Jodhpur.

Pasahan, S.C. and Sablok, V.P. 1987. Effect of removal of wild vegetation on migration of field rodents. *Haryana Agricultural University Journal of Research* 27: 12-13.

Patel, B.H, Upadhyay, V.R, Murlidharan, C.M. and Judal, G.S. 1989. Comparative efficacy of different insecticides against 'ber' fruit fly *Carpomyia vesuviana* Costa. *Indian Journal of Plant Protection* 17(1): 39-45.

Patel, I.S., Upadhyay, V.R. Vyas, H.N; and Patel, A.T. 1990. Field bioefficacy of different insecticides for the control of ber fruit fly, *Carpomyia vesuviana* Costa (Tephritidae: Diptera). Gujarat Agricultural University Research Journal 16(1): 57-59.

Patel, Nisha. 2007. Management of storage pests of seed spices. In *Production, Development, Quality and Export of Seed Spices* (Eds. S.K. Malhotra and B.B. Vashishtha), pp. 149-161. NRCSS, Ajmer.

Patel, Nisha and Bhati, T.K. 2005.Organic soil amendments for pest management in chilli crop in the arid region. Abstracts *National Conference on Applied Entomology*. ERA, Udaipur. 288-289 pp.

Patel, Nisha and Singh, M P. 2001a. Insect pest fauna on senna (*Cassia angustifolia*). *Abstracts Symposium on Impact of Human Activities on Thar Desert Environment* AZRAI, Jodhpur. p 80.

Patel, Nisha and Singh, M P. 2001b. Incidence of Insect pests on Senna. *National Conference: Plant Protection- New Horizons in the Millennium*. Abstract No 14 p 5. (ERA, Udaipur).

Patel, R.H., Oliver, Judith and Usadadia, V.P. 2005. Influence of irrigation schedule and weed management practices on growth and yield of fenugreek (*Trigonella foenum-graecum* L.). *Indian Journal of Weed Science* 37(3-4): 237239.

Patel, R.M., Patel, C.B. and Vyas, H.N. 1977. Record and some observations on local milky disease in white grubs (*Holotrichia* sp. nr *consanguinea* Blanch.) in India. *Indian Journal of Entomology* 39: 181-182.

Popli, S. Kathpal, T.S. and Lakra, R.K. 1980. Note on dissipation of malathion residues from jujube fruits and leaves. *Indian Journal of Agricultural Sciences* 50(2): 191-192.

Prakash, I. 1959. Food of Indian Desert mammals. *Journal of Biological Sciences* 2: 100-109.

Prakash, I. 1975. The population ecology of the rodents of the Rajasthan desert, India. In *Rodents in desert envioronment* (Eds. I. Prakash and P.K. Ghosh), Dr. Junk b.v. Publishers, The Hague, pp. 75-116.

Prakash, I. 1976. Rodent pest management - Principles and Practices. CAZRI Monograph No. 4, Central Arid Zone Research Institute, Jodhpur, 28 p.

Prakash, I. 1981. Ecology of Indian desert gerbil, *Meriones hurrianae*. CAZRI, Monograph No. 10, Central Arid Zone Research Institute, Jodhpur, 86 p.

Prakash, I. and Rana, B.D. 1970. A study on the field population of rodents in the Indian desert. *Zeitschrift fur Angewandte Zoologie* 57 : 129-136.

Prakash, I., Gupta, R.K., Jain, A.P., Rana, B.D. and Dutta, B.K. 1971. Ecological evaluation of rodent population in the desert biome of Rajasthan. *Mammalia* 35: 384-423.

Prakash, I. and Mathur, R.P. 1987. *Management of Rodent Pests.* Indian Council of Agricultural Research, New Delhi, 133 p.

Prakash, I., Fitzwater, W.D. and Jain, A.P. 1969. Toxic chemicals and baits for the control of the gerbils, *Meriones hurrianae* Jerdon and *Tatera indica indica* Hardwicke. *Journal of Bombay Natural History Society* 66: 500-509.

Pruthi, I.J., Jain, R.K. and Gupta, D.C. 1987. Effect of different periods of degradation of su-babool leaves alone and in combination with nematicide on root-knot nematode incidence in okra. *Indian Journal of Nematology* 17 : 30-32.

Punia, S.S., Ral, Mayank, Yadav, Ashok and Malik, R.K. 2001. Bioefficacy of dinitroaniline herbicides against weeds in sesame (*Sesamum indicum* L.). *Indian Journal of Weed Science* 33(3-4): 143-146.

Purohit, S.D., Ramawat, K.G. and Arya, H.C. 1978. Light microscopic detection of micoplasma like organism(MLO)in sesame phyllody. *Current Science* 47: 866.

Purohit, S.D., Shekhawat, N.S. and Arya, H.C. 1980. Antibiotics in the control of sesame phyllody. *Indian Journal of Mycology and Plant Pathology* 10(2): 51.

Raj Bhansali, R. 1989. Early leaf spot disease of date palm shoots. *Indian Phytopathology* 42: 410-418.

Raj Bhansali, R. 1989a. Control of date palm disease. In *Biannual Report 5th National Workshop on Arid zone Fruit Research*. GAU, Sardarkrushinagar. 261 p.

Raj Bhansali, R. 1989b. Morphologically abnormal structures on Sewan grass infected with *Ustilago vilfae*. *Indian Phytopathology* 42: 592-594.

Raj Bhansali, R. 1991. Diseases of horticultural crops and their management. *Proceeding of Workshop-cum-Seminar on Arid Horticulture*. CAZRI, Jodhpur. 90-97 pp.

Rajpurohit, T.S. 1982. Morphology and taxonomy of sesamum *Alternaria*. *Madras Agricultural Journal* 68(10): 696-697.

Rajpurohit, T.S. 1993. Occurrence, varietal reaction and chemical control of new powdery mildew (*Erysiphe orontii* cast.) of sesame. *Indian Journal of Mycology and Plant Pathology* 23(2): 207-209.

Rajpurohit, T.S. 1996. Varietal resistance to powdery mildew in rapeseed and mustard. *Indian Journal of Mycology and Plant Pathology* 26(1): 132.

Rajpurohit, T.S. 1997.Management of *Macrophomina* stem and root rot of sesame through fungicidal seed treatment and varietal resistance. *Indian Journal of Mycology and Plant Pathology* 27(1): 98.

Rajpurohit, T.S. 1998. Integrated management of *Phytophthora* blight, *Cercospora* leaf spot and *Alternaria* leaf spot of sesame. *Indian Journal of Mycology and Plant Pathology* 28(1): 68.

Rajpurohit, T.S. 2002. Influence of intercropping and mixed cropping of sesame with pearl millet, green gram and moth bean on the incidence of stem and root (*Macrophomina phaseolina*) of sesame. *Sesamum and Safflower Newsletter* 17: 40-41.

Rajpurohit, T.S. 2003. Studies on fungicide, plant product and bioagent as spray in sesame disease management. *Journal of Ecophysiology* 6(3-4): 87-88.

Rajpurohit, T.S 2004a. Management of white rust of mustard through foliar spray. *Geobios* 31 :204-205.

Rajpurohit, T.S. 2004b. Studies on plant products and new chemicals as spray against Alternaria blight of sesame. *Geobios* 31: 64-65.

Rajpurohit,T.S. 2005. Occurrence of groundnut bud necrosis disease in arid region of Rajasthan. *Journal of Ecophysiology* 8(3-4): 39-40.

Rajpurohit, T.S. 2006. Seed treatment with chemicals and bioagents for the management of stem and root rot of sesame. *Geobios* 33:223-224.

Rajpurohit, T.S. and Bishnoi, H.R. 2006. Integrated disease management in sesame (*Sesamum indicum* L.). *Sesame and Safflower Newsletter* 21.

Rajpurohit, T.S., Bishnoi, H.R. and Solanki, S.S. 2008. Management of wilt disease in castor through bio-agent in Rajasthan. *Journal of Oilseeds Research* 26: 410-411.

Rajpurohit, T.S., Chandawat, M.S., Chaudhary, B.R. and Solanki, Z.S. 2005a. Management of *Orobanche* parasite in mustard. *Abstract Global conference II ISMPP* 292 pp.

Rajpurohit, T.S. and Prasad, N. 1982a. Effect of different media, temperature and levels of pH on the growth and sporulation of *Alternaria sesami. Geobios* 9(3): 142-144.

Rajpurohit, T.S. and Prasad, N. 1982b. Production of pectinolytic enzymes by *Alternaria sesami in vitro*. *Indian Journal of Mycology and Plant Pathology* 12(2): 220-221.

Rajpurohit, T.S., Solanki, S.S. and Bishnoi, H. R. 2005b. Management of wilt disease in castor through seed treatment and varietal resistance in Rajasthan. *J. Mycol. Pl. Pathol*. Vol. 35 No. 3:601-602.

Rajpurohit, T.S., Solanki, Z.S. and Ahuja, D.B. 2006a. Screening of sesame genotypes against stem and root rot, *Macrophomina phaseolina*. *Journal of Oilseeds Research* 23(1): 138.

Rajpurohit, T.S., Solanki, Z.S. and Chandawat, M.S 2006b. Identification of sources of resistance to Alternaria leaf spot in sesame. *Sesame and Safflower Newsletter* 21.

Rana, B.D. and Prakash, I. 1984. Reproduction biology of the soft furred field rat, *Rattus meltada pallidior (*Ryley, 1914) in Rajasthan desert. *Journal of Bombay Natural History Society* 81: 59-70.

Rana, B.D., Jain, A.P. and Tripathi, R.S. 1993. Fifteen Years of Coordinated Research on Rodent Control. AICRP on Rodent Control, CAZRI, Jodhpur, 141 p.

Rao, A.M.K.M. and Prakash, I. 1981. Rodenticidal evaluation of zinc phosphide against house mouse, *Mus musculus bactrianus. Indian Journal of Plant Protection* 13: 61-63.

Rathore, B.S. 2004. Management of cumin diseases and aphid through chemicals. *Abstracts National Seminar on New Perspectives in Commercial Cultivation, Processing and Marketing of Seed Spices and Medicinal Plants*. RAU, Bikaner. 67-68 pp.

Rathore, M.P.S. 1990. Determination of residues of endosulfan, monocrotophos and carbaryl in and on some arid zone crop and fruit plants. *Ph D Thesis*. University of Jodhpur. 186 pp.

Rathore, M.S., Chandawat, M.S., Rathore, B.S. and Singh, I. 2004. Appropriate time of sowing and plant population of cumin (*Cuminum cyminum* L) for arid western plains of Rajasthan. *Annals of Arid Zone* 43: 97-99

Rathore R.S., Rajpurohit, T.S., Solanki, J.S. and Bishnoi, H.R. 1992. Occurrence and control of *Sclerotinia sclerotiorum*. *Indian Journal of Mycology and Plant Pathology* 22(1): 95-96.

Sachan, J.N. 1984. Varietal susceptibility of ber fruits to the damage of fruitfly (*Carpomyia vesuviana* Costa). *Bulletin of Entomology* 25(2): 198-199.

Sacchan, J.N and Pal, S.K. 1972. Some observations on the gall formation in *Prosopis cineraria. Annals of Arid Zone* 12(1-2): 103-104.

Sangwan, M.S. and Lakra, R.K. 1992. Effect of temperature and soil depth levels on pupae of jujube fruit fly, *Carpomyia vesuviana* Costa. *Journal of Insect Science* 5(1): 80-81.

Saravaiya, S.N., Patel, M.B., Patel, C.B., Desai, H.R. and Patel, J.R. 1998. Bioefficacy of different insecticides against fruitfly *Carpomyia vesuviana* Costa (Tephritidae: Diptera). *Gujarat Agricultural University Research Journal* 24: 101-103.

Saxena, Anurag, Singh, Y.V., Singh D.V. and Singh, Raj. 2003. Weed management in moth bean (*Vigna aconitifolia*) in arid region of Rajasthan. *Annals of Arid Zone* 42 (2): 137-140.

Saxena, Anurag, Singh, Y.V. and Singh, Raj 2004. Crop weed competition in clusterbean in arid region. *Journal of Arid Legumes* 1(1): 41-43.

Sharma, O.L. and Jain, N.K. 2003. Integrated weed management in pearl millet (*Pennisetum glaucum*). *Indian Journal of Weed Science* 35(1-2): 134-135.

Sharma, R.P., Singh, P. and Nepalia, V. 2001. Effect of weed management and phosphorus levels on weed dynamics snd crop weed competition for nutrients in Indian mustard (*Brassica juncea* L.). *Indian Journal of Weed Science* 33 (3-4): 147-150.

Shekhawat, B.S., Shaktawat, R.P.S. and Shekhawat, P.S. 2003. Effect of fluchloralin on mothbean [*Vigna aconitifolia* (Jacq) Marechall] and associate weeds. *Indian Journal of Weed Science* 35(1-2): 141-142.

Singh, J. and Swarup, J. 1986. Control of bacterial blight of clusterbean by seed treatment and foliar spray. *Pesticides* 20: 23-24.

Singh, J. and Swarup, J. 1987. Epidemiology of bacterial blight of clusterbean caused by *Xanthomonas campestris* pv. *Cyamopsidis*. *Farm Science Journal* 2: 91-92

Singh, K.C. and Singh, R.P. 1979. Studies on weed control in grain legumes. *CAZRI Annual Report* 179 pp.

Singh, M.P. 1982a. Studies on the damage and chemical control of chafer beetles on grafted ber (*Zizyphus mauritiana* Lamk) cultivars. *Entomon* 7(2): 247-250.

Singh, M.P. 1982b. Studies on the damage of castor semilooper, *Achaea janata* Linn to some fruit plants and its chemical control. *Indian Journal of Plant Protection.* 10 (1&2): 37-39.

Singh, M.P. 1983a. Emergence pattern of ber fruitfly, *Carpomyia vesuviana* Costa under conditions of Jodhpur. *III National Workshop on Arid Zone Fruits*. 8-10 July 1983, Udaipur.

Singh, M.P. 1983b. Insecticidal control of Bark eating caterpillar, *Indarbela quadrinotata* Walker on ber. *Annals of Arid Zone* 22(4): 363-366.

Singh, M.P. 1984a. Studies on the activities of some insect pollinators on jujube (*Zizyphus mauritiana* Lamk). *Entomon* 9(3): 177-180.

Singh, M.P. 1984b. Studies on the field resistance of different jujube cultivars to the fruitfly, *Carpomyia vesuviana* Costa. *The Madras agricultural Journal.* 71(6): 413- 415.

Singh, M.P. 1984c. Field screening of some jujube cultivars against the attack of bark eating caterpillar, *Indarbela quadrinotata* (Walker). *The Madras Agricultural Journal* 71(6): 416-417.

Singh, M.P. 1985. Studies on the damage and chemical control of the weevil *Cyrtozemia dispar* Pasc. on some legume crops. *Entomon* 10: 261-266.

Singh, M.P. 1989. *Biosteres vandenboschi* Fullaway- a new braconid parasite of *Carpomyia vesuviana* Costa from the Indian desert. *Entomon* 14(1-2): 169.

Singh, M.P. 1991. Observations on the pest complex of *Balanites aegyptiaca* (L) Delile in the arid zones of India. *Entomon* 16(3): 249.

Singh, M.P. 2000. *Final Report*. AP Cess Fund project "Biochemical basis of resistance to the fruit fly *Carpomyia vesuviana* Costa in ber, *Zizyphus mauritiana* Lamk. CAZRI. 46 p.

Singh, M.P. 2002. Impact of indiscriminate use of pesticides in chilli growing belt. *Landschaftsokologie und Umweltforchung* 38 : 236-244.

Singh, M.P. 2007a. The phenomenon of mortality in *Prosopis cineraria* trees in some arid districts of Rajasthan. In *Mortality in Agroforestry Trees* (Eds. D.P.S. Nandal and J.C. Kaushik), pp. 67-76.CCS HAU, Hisar.

Singh, M.P. 2007b. Integrated pest management in seed spices. In *Production, Development, Quality and Export of Seed Spices* (S.K. Malhotra and B.B. Vashishtha). NRC on Seed Spices, Ajmer. 139-148 pp.

Singh, M.P. and Harsh, L.N. 1996. *Denticera divisella* Duponchel (Pyralidae: Lepidoptera) infesting *Euphorbia antisyphilitica* in the arid zones. *Entomon* 21 (3-4): 263- 264.

Singh, M.P., Harsh, L.N., Lodha, S.K. and Bohra, M.D. 2002. Mortality in *Prosopis cineraria* in the arid districts of Rajasthan. In *Mortality of shisham and kikar in India* (Eds. S.S. Gill, Sanjeev Chauhan, H.N. Khajuria, R.S. Dhanda and Rajni Chauhan), pp. 65-67. Punjab Agricultural University, Ludhiana.

Singh, M.P. and Lodha, S. 2005. Plant Protection in Henna and Henna for Pest and Disease Management. In *Henna Cultivation, Improvement and Trade* (Eds. M. Singh, Y.V. Singh, S.K. Jindal and P. Narain), pp. 35-38. CAZRI, Jodhpur.

Singh, M.P., Lodha, S. and Harsh, L.N. 2007. On farm testing of IPM measures to contain mortality of *Prosopis cineraria* in Indian Arid Regions. In *Mortality in Agroforestry Trees* (Eds. D.P.S. Nandal and J.C. Kaushik), pp. 77-82. CCS HAU, Hisar.

Singh, M.P., Nawal, S.K. and Singh, D. 2003. Outbreak and control of *Laphygma exigua* on cumin in western Rajasthan. In *Proceedings of National Symposium on Frontier Areas of Entomological Research*, pp. 179-180. IARI/ESI.

Singh, M.P. and Pareek, O.P. 1981. Chemical control of Ber fruit fly, *Carpomyia vesuviana* Costa. *Indian Journal of Plant Protection* 9(2): 180-182.

Singh, M.P. and Patel, Nisha. 2003. The widening pest spectrum of the arid production systems in western Rajasthan. In *Proceedings of the National Symposium on*

Frontier Areas of Entomological Research, pp. 642-643. IARI/Entomological Society of India.

Singh, M.P. and Patel, Nisha. 2006. Population Dynamics of Aphid Complex in Cumin under Arid Conditions. In *Proceedings 9th National Symposium on Recent Advances in Aphidology,* pp. 22-24. Aphidology Society of India, BHU, DDUGU.

Singh, M.P. and Satyavir 1989. *Homoeosoma* sp. (Pyralidae:Lepidoptera) as a pest of *Euphorbia antisyphilitica* Zucc in the Indian desert. *Indian Journal of Plant Protection* 17(2): 293.

Singh, M.P. and Satyavir 2003. The menace of insect pests to spice cultivation in western Rajasthan. *Abstracts National Seminar on New Perspectives in Spices, Medicinal and Aromatic Plants* (ISS/ICARRCG/IISR). 183 pp.

Singh, M.P., Satyavir and Parihar, D.R. 1989. A note on the Coleopterous pests of forest plants in the Indian desert. *Indian Journal of Forestry* 12(4): 330- 331.

Singh, M.P., Satyavir and Verma, S.K. 1991. Castor semilooper and other insect pests of jojoba in the arid regions of Rajasthan. *Transactions of Indian Society of Desert Technology* 16: 105-106.

Singh, M.P. and Vashishtha, B.B. 1984. Field screening of some ber cultivars for resistance to ber fruitfly, *Carpomyia vesuviana* Costa. *Indian Journal of Plant Protection* 12: 55-56.

Singh, M.P. and Vashishtha, B.B. 1995. Losses due to bird damage in different jujube cultivars. *Annals of Arid Zone* 34(4): 305- 307.

Singh, M.P. and Vashishtha, B.B. 2002. Factors influencing infestation of fruit fly (*Carpomyia vesuviana*) in Indian jujube (*Zizyphus mauritiana*). *Indian Journal of Agricultural Sciences* 72(9): 543-547.

Singh, R. and Yadav, S.K. 1994. Effect of method of weed control on nutrient uptake in pearl millet. *Annals of Arid Zone* 33: 81-82.

Singh, Raj. 2006. Effect of cropping sequence, seed rate and weed management on weed growth and yield of Indian mustard in western Rajasthan. *Indian Journal of Weed Science* 38(1-2): 69-72.

Singh, Raj, Saxena, Anurag and Tripathi, K.P. 2008. Weed dynamics, resource use efficiency and yield of cumin (*Cuminum cyminum*) as influenced by crop weed competition. *Extended Summery National Symposium on New Paradigms in Agronomic Research*, Navsari. 360-61 pp.

Singh, Raj and Singh, Bhagwan. 2003. Effect of sowing methods and weed management on weeds and yield of clusterbean. In *Advances in Arid Legume Research* (Eds. A. Henary, D. Kumar and N.B. Singh), pp. 229-232. Scientific Publishers (India). Jodhpur.

Singh, Raj and Singh, Bhagwan. 2004. Effect of irrigation time and weed management practices on weeds and wheat yield. *Indian Journal of Weed Science* 36(1-2): 25-27.

Singh, Raj, Singh, Bhagwan and Chauhan, KNK. 1999. Productivity and economics of Indian Mustard (*Brassica juncea*) as influenced by varieties and different weed control treatments. *Indian Journal of Weed Science* 31(3-4): 138-141.

Singh, Raj and Singh, Bhagwan 2005. Response of cultivars and weed management practices on the weeds and yield of moth bean. *Journal of Arid Legumes* 2(1): 28-31.

Singh, R.C. and Faroda, A.S. 1977. Chemical weed control in mung bean. *Indian Journal of Weed Science* 9: 33-37.

Singh, R.P. 1985. Pearl millet. In *Efficient Management of Dryland Crops*. CRIDA, Hyderabad. 51-62 pp.

Singh, S. and Lodha, S. 1986. Varietal resistance of cowpea to *Macrophomina phaseolina* (Tassi.) Goid. causing dry root rot and its control. *Indian Journal of agricultural Sciences* 56: 552-555.

Soni, B.K., Rana, B.D. and Jain, A.P. 1995. Field trials of some rodenticides to control rodents in various crop fields of western Rajasthan desert. *Pestology* 9: 25-27.

Srivastava, B.K., Vyas, H.K., Rathore, Y.K. and Khan, R.M. 1962. Survey of injurious insects of oilseed crops in Rajasthan and suggestions for the control of major pests. *Uttar Bharti J. Res.* 8(3): 111-117.

Srivastava, K.K and Verma, Neelam 2008. Trees. In *Disease Management in Arid Land Crops* (Eds. Satish Lodha, Ritu Marwar and B.S. Rathore), pp. 311-351. Scientific Publishers, Jodhpur.

Srivastava, K.K., Verma, Neelam and Thangamani, D. 2004. Charcoal Root Rot - a serious disease of Neem. *My Forest* 40: 65-67.

Tripathi, R.S., Jain, A.P., Kashyap, N., Rana, B.D. and Prakash, I. 1992. North-western desert : Special problem areas. In *Rodents in Indian Agriculture* (Eds. I. Prakash and P.K. Ghosh), pp. 357-395. Scientific Publishers, Jodhpur.

Venkatarayan, S.B. 1946. A natural fungus parasite of powdery mildew on C. psoraloides DC. *Current Science* 15: 319

Verma, S.K. 1982. Hairy Caterpillars and their Control. Directorate of Extension, Ministry of Agriculture and Cooperation, New Delhi, 23 p.

Verma, S.K. 1988. Assessment of insecticidal bioefficacy against *Cyrtozemia cognata* Marshall (Curculionidae: Coleoptera) in mung bean using Cumulative Insect Days. *Abstracts*, National Seminar on Advances in Economic Zoology, University of Jodhpur, Jodhpur, December 20-22, 1988.

Verma, S.K. and Henry, A. 1988. Intensity of insect pests on mug bean cultivars in arid Rajasthan. *Annals of Arid Zone* 27(1): 71-74.

Verma, S.K and Satyavir. 1995. Field insect pests of Rohida (*Tecomella undulata*) in Arid Zones of Rajasthan. *Annals of Arid Zone* 34: 54-55.

Vir, S. 1983. Efficacy of some important insecticides for the control of leaf hopper, *Empoasca kerri* Pruthi on moth bean crop. *Indian Journal of Plant Protection* 11: 130-133.

Vir, S. 1996. Bruchid infestation of leguminous trees in the Thar Desert. *Tropical Science* 36 (1): 11-13.

Vir, S.. and Singh, M P. 2003. Potential of neem based formulations for managing serious insect pests of important spice crops in arid region. Abstracts

National Seminar on New Perspectives in Spices, Medicinal and Aromatic Plants (ISS/ICARRCG/IISR). Abst# 212 p 168.

Vir, S. 1983. Efficacy of some important insecticides for the control of leaf hopper, *Empoasca kerri* Pruthi on moth bean crop. *Indian Journal of Plant Protection* 11: 130-133.

Vir, S. 1984a. Assessment of yield loss due to yellow mosaic virus infection in moth bean. *Pesticides* 6: 33-34.

Vir, S. 1984b. Evaluation and economics of some insecticides for the control of mustard aphid *Lipaphis erysimi* Kalt. on raya. *Annals of Arid Zone* 23(1): 25-29.

Vir, S. 1984c. Effectiveness of some important insecticides for the control of leaf hopper *Empoasca kerri* Pruthi on moth bean crop. *Indian Journal of Plant Protection* 11: 130-133.

Vir, S. 1986. Studies on the bionomics of Bemisia tabaci, a vector of yellow mosaic virus, extent of damage and the control of moth bean. In *Recent Advances in Development Biology of Animals* (Eds. S.C. Goel and C.B.L. Srivastava), pp. 124-129. Rastogi & Co., Meerut.

Vir, S., Jindal, S.K. and Lodha, S. 1984. Screening of moth bean cultivars against jassids, whiteflies and yellow mosaic virus. *Annals of Arid Zone* 23: 99-103.

Vir, S. and Singh, M. 1985. Influence of dates of sowing on the incidence and extent of damage by insect pests in moth bean and cowpea. *Annals of Arid Zone* 24: 329-333.

Vyas, H.K. 1996. Insect pests in Indira Gandhi Canal region of the Thar desert In *Faunal Diversity in the Thar Desert: Gaps in Research* (Eds. A.K. Ghosh, Q.H. Baqri and I. Prakash), pp. 203-214. Scientific Publishers, Jodhpur, xi+ 410 p.

Walia, Kum Kum and Gupta, D.C. 1997. Management of root-knot nematode, *Meloidogyne javanica* on vegetable crops with *Tagetes* sp. *Indian Journal of Nematology* 27: 18-24.

Yadav, B.S., Verma, M.K.and Naik, S.M. 1970. A note on the prevalence of *Meloidogyne incognita* (Kofoid and White,1919) Chitwood, 1949 in various parts of Rajasthan. *Current Science* 39: 470-471.

Yadav, G.S, Kathpal, T.S, Singh, G., Gupta, S.P. and Lakra, R.K 1986. Persistence of dimethoate and oxy-demeton methyl in jujube fruits and leaves. *Indian Journal of Agricultural Sciences* 56(2): 127-130.

Yadav, R.S. and Dhama, A.K. 2003. Effect of Planting data, irrigation and weed control method on yield and water use efficiency of cumin (*Cuminum cyminum* L.). *Indian Journal of Agricultural Sciences* 73: 494-496.

Yadav, S.K., Bhan, V.M. and Kumar, A. 1985. Weed management in mung bean. *Indian Journal of Weed Science* 17: 1-5.

Yousuf, M. and Gaur, Meeta 1998a. Some note worthy insect pests of *Prosopis juliflora* from Rajasthan. In *Prosopis Species in the Arid and Semi Arid Zones of India* (Eds. J.C. Tewari, N.M. Pasiecznik, L.N. Harsh and P.J.C.

Harris), pp. 91-94. *Prosopis* Society of India and the Henry Double day Research Association.

Yousuf, M. and Gaur, Meeta. 1998b. Record on complete defoliation and host range of *Taragama siva* Lefebvre (Lepidoptera: Lasiocampidae). *Bioscience Research Bulletin* 12(2): 85-88.

Zaki, F.A. and Bhatti, D.S. 1989. Effect of castor (*Ricinus communis*) leaves in combination with different fertilizer doses of *Meloidogyne javanica* infecting tomato. *Indian Journal of Nematology* 19: 171-176.

Trends in Arid Zone Research in India
(Eds. Amal Kar, B.K. Garg, M.P. Singh and S. Kathju),
Central Arid Zone Research Institute, Jodhpur, 458-478 pp.

Livelihood Opportunities and Socio-Economic Issues

D.K. Saha, Y.V. Singh, B.L. Gajja, Raj Singh, Khem Chand, Amtul-Waris, Bhagawan Singh and B. L. Jangid

Central Arid Zone Research Institute, Jodhpur

From time immemorial people are living in the Great Indian Desert despite harsh climatic conditions. A greater part (62%) of the Thar Desert falls in western part of Rajasthan covering twelve arid districts. This region has diverse problem with socio-economic and infrastructural backwardness. Drought is a common phenomenon where every second or third year becomes a drought year, which has an impact on livelihood. Farmers have, however, evolved some judicious means of resource utilization to cope up with drought conditions since long. Recent studies on drought vulnerability conducted in arid region found that disadvantageous group of population were vulnerable to drought whose livelihood derived from outside employment (Saha *et al.* 2008). The population in arid region is sedentary as well as semi- nomadic or nomadic. Excessive biotic interference (human and livestock) in this region has caused natural resources degradation. With the increasing population more and more marginal and sub-marginal lands have been put under cultivation, disturbing the entire ecosystem.

Realizing the intricacies of various facets of human resources which are essentially required for development and planning of the vast arid region, the socio economic researches at Central Arid Zone Research Institute were initiated in the early nineteen sixties as a benchmark to help in integrated natural resources management and fast adoption of improved technologies.

Although agriculture is a big gamble here in the absence of assured irrigation, cultivation and its allied activities are the principal sources of livelihood of the majority of population besides animal husbandry, pastoralism wage earnings, household industries and manufacturing other than household industries. However, a majority of population living in the arid region is, by and large, dependent on subsistence and rain- fed agriculture. The rate of adoption of various improved technologies is poor barring a few. For minimizing the risk of climatic vagaries farmers persist with some traditional system of cultivation like mixed cropping, crop rotation, fallowing of land, fragmentation of land, livestock migration, etc. Since the rainfall is less and erratic, farmers keep mixed type of herd for their survival to assure that in the event of crop failure they would get something from livestock. The livestock population far exceeds the human population resulting an enormous pressure on land (livestock per hectare increased from <1 in 1956 to 1.13 in 2003).

The prevalent socio-cultural and economic practices have aggravated the deteriorating land conditions. Farmers still follow the traditional way of life primarily due to limited occupational base, widespread illiteracy especially the female illiteracy, social customs and taboos, factionalism, scattered settlements, knowledge gap, etc. The nomadic people in this region, by and large, lead migratory life with all socio-economic backwardness. The nomads are not a separate ethnic group and do not have a separate territory, with exclusive rights and economic framework. The socio-economic conditions of the nomadic population have continuously been changing with the agrarian development and availability of various infrastructural facilities. The sedentary population is no longer dependent on nomads for their services. The pastoral nomads who practice semi-nomadic life frequently move with their livestock and cover a long distance. The pastoralists in arid and semi arid regions have permanent settlements and on the onset of monsoon they return to their villages and follow cultivation with their meagre land holding. The concentration of scheduled tribe population in arid Rajasthan is negligible (3%) who are primarily dependent on wage earnings and to a little extent on agriculture and livestock activities.

Demographic Features and Sources of Livelihood

The growing trend of population is more serious in arid region of Rajasthan considering the limited livelihood opportunities. The demographic features showed an expansive growth of population in all the census years. However, the situation has slightly improved as decennial growth rate has marginally declined from 29.86 in 1991 to 28.56 in 2001 which is a positive indication for arresting the growth of population. Although the region is sparsely populated, it has higher density of population with 108 persons km^{-2} compared to other deserts of the world. The decennial growth of population in Kachchh region of Gujarat, on the other hand, is lower than in arid Rajasthan.

Demographic studies carried out in this region primarily focused on population growth, trend, structure and implications, social, economic and cultural dimensions etc (Bose, 1962, 1966a; Malhotra and Gupta, 1980; Saha, 1993; Saha and Bhandari, 1998; Saha *et al.*, 2003, 2004; Patel, 1990). The higher growth of population may be viewed as the prevalence of early marriages, traditionalism, female illiteracy, lack of livelihood opportunities, gender preference in favour of male children, declining mortality, scattered settlements, poor infrastructural facilities, lack of health care and hygiene, limited knowledge in family welfare measures, etc. The family welfare program initiated in this region is slowly making its impact felt. There has been a vast gap between fertility (30.6) and mortality (7.7) rate in the state compared to national average (25.0 & 8.1, 2002). Malhotra (1977) reported that immigration from other states and emigration from this region was less for lack of pull and push factors. The concentration of population in the lower age (0-14 yrs) group is still large (30 to 35%) which would definitely enhance the population in near future. The traditional large sized joint families are disintegrating to small sized nuclear families which is causing increasing fragmentation of land and pressure of livestock on land besides lack of care of the aged population. Anantharam *et al.* (1999) reported that inheritance law for subdivision of land holdings caused shrinkage of holding size and shortage of food grains of small farmers. Saha *et al.* (1999) reported that in Pokaran *teshil* of Jaisalmer district the infrastructure facilities were so poor that 77% villages lacked basic minimum health facilities and 17% villages had no primary schools.

The level of literacy in this region is low compared to the state and country as a whole despite National Literacy Mission. During the last decade the situation, however, has improved with the increase of both rural and female literacy (fom 36.0 to 56.0% & 18.0% to 39.0% from 1991 to 2001). Although the government is trying hard to make hundred percent literacy with the new education policy, will take some time particularly in arid region considering the socio- cultural, economic and geographical conditions of the region (Saha and Sen, 1993).

With the increasing population there has been a problem of urban agglomeration as urban population in India has increased from 21% in 1975 to around 28% in 2003 and it is expected that by 2015, around a third of India's population will be an urban resident. The rapid urbanization is a serious problem as the urban areas are becoming congested and require basic necessities like drinking water, sewerage and sanitation, housing and environmental protection. A similar pattern is also evident in the arid region where a number of hinterlands are coming up rapidly, affecting plan development processes.

Livelihood Sources

A shift in livelihood sources has been observed in recent times, as wage labour activities have increased. Livelihood is a set of economic activities through which a household meets its basic needs and earns some cash income. Carried out on a repetitive basis, these tend to become a way of life. Agriculture is one of the rural sectors in which government has given more attention for achieving self-sufficiency in food grain demand of the country. Of the total 56 million population in Rajasthan (Census 2001), labour force was 23.8 million and growing by 2.2% annually about 6 lakh additional persons are seeking work annually. Under the dryland condition the uncertainty in rainfall leads to variation in agricultural production over the time. With the rising population and declining man: land ratio, people are not able to meet their family needs from agriculture alone. The shift from over-crowded agriculture to a diversified rural non-farm sector (RNFS), though happening, is not adequate to absorb the growth in the labour force. Thus the urban informal sector becomes the "employment of last resort". A large part of rural population from arid Rajasthan also migrates every year to cities and neighbouring states for work in construction, transport, miscellaneous activities, retail shops, etc.

Although there has been an increase in number of workers in the arid region of Rajasthan their share has declined from 45.17% of total population in 1961 to 41.48% in 2001. This is because of a rise in old age population.

The workers are classified as cultivators, agricultural labourers, workers in household industries and other workers (Census, 2001). Census data reveal that although the absolute population of cultivators increased in arid region since 1961, its share in total workers has been reduced from 74.84% in 1961 to 58.04% in 2001. Some cultivators with very low size of land holdings have either become agricultural labourers or have migrated to urban areas as wage labours/ industrial workers. During the period 1961 to 2001 the population of agricultural labourers increased from 1.4 lakh to 9. 6 lakh in arid Rajasthan. The rise in population of agricultural labourers indicates that some cultivators with very low land holdings have lost their land and become agricultural labourers. In arid region agricultural labourers are generally required for weeding and harvesting operations as sowing is mainly done now through tractors.

In case of household industry workers the absolute numbers are almost the same as in 1961 and 2001 but their share has also come down from 7.54% to 2.80%, due to high labour cost, lack of modern machinery, rising opportunity of alternative employment in organized industrial sectors, and inability to compete in the market that have started closure of many units. The other workers include government and municipal employees, teachers, factory workers, plantation workers, people engaged in trade, commerce, transport, banking, mining, construction, political or social work, and priests, entertainment artists etc. There has been significant growth in absolute number of other worker. Their share has increased from 13.57% to 28.87% in total workers. The increase in composition of other workers indicates that people in arid region are not getting sufficient employment from farm sector and opportunities for livelihood earnings are rising in industrial and service sectors. It is a positive sign for the arid zone economy as it will help in reducing pressure on already limited land and common property resources.

The socio-economic situation is improving gradually with the introduction of many development programmes and better infrastructural facilities, both at *teshil* and district level. However, there is a need to study the factors responsible for people's apathy in participating in development programmes, which is, nevertheless, essential for long-term sustainable development.

Diffusion and Adoption of Improved Technologies

Since independence lot of extension approaches/ strategies such as National Demonstration Programmes, Front Line Demonstration, Operational Research Project, Lab to Land Programme, Training & Visit (T&V), Krishi Vigyan Kendra, Institute Village Linkages Programme and very recently Agricultural Technology Information Centre (ATIC) were initiated for proper dissemination of technologies and its adoption. In spite of that the rate of diffusion and adoption of various improved farm practices could not make much headway particularly in the arid Rajasthan primarily for socio-psychological, communication, input and situational constraints.

Diffusion is a process by which an innovation spreads. The diffusion process is the spread of new ideas from its source of invention or creation to its ultimate users or adopters. The essence of the diffusion process is the human interaction in which one person communicates a new idea to another person. Adoption is a decision to continue full use of an innovation. The adoption process is the mental process through which an individual passes from first hearing about an innovation to final adoption. The adoption process differs from the diffusion process. Adoption process deals with adoption of a new idea by one individual while the diffusion process deals with the spread of new ideas in a social system or with the spread of innovations between social systems or societies (Rogers, 1962).

A majority of farmers in this region, who are resource-poor, still depend on rainfed agriculture. Their participation in improved farm practices is, nevertheless, essential to enhance the food production. However, with the incoming of the Indira Gandhi canal and availability of wells to a limited extent, farmers are gradually shifting to modern methods of farming. The impact of the green revolution has, however, not been uniform in the desert region. The maximum benefits went to better-endowed areas, having irrigation potentialities.

Studies carried on diffusion and adoption of improved agricultural practices in western Rajasthan since mid-sixties found that the adoption of various improved farm practices was poor. Bose and Saxena (1965), Bose (1966b), Bose and Jain (1966) and Malhotra *et al.* (1974) found that socio-economic factors played an important role in adoption of improved farm practices and innovators take least time to adopt an innovation whereas laggards take maximum time. Studies carried out by (Saha *et al.* 1981, 1982, 1983, 1987, 1991; Saha and Vyas, 1991; Malhotra *et al.,* 1983) discussed extent of adoption, factors affecting the adoption, rate of diffusion, effectiveness of communication channel, constraints in communication, key-communicators and their role, etc. The key communicators/opinion leaders played an important role in the dissemination of technologies and their adoption. The key communicators were identified on the basis of socio-metric techniques. It is observed that the key communicators, in other words change agents are from higher socio-economic status, exposed to greater mass media sources, contact with the outside through visits to urban centers, innovative in nature, more education and had contacts with extension personnel. On the contrary, the followers or information seekers are lagging. Key communicators are more progressive than followers in farming. Information provided by the key communicators to the followers will be effective and more scientific than what the average farmer already possessed. When the information and advice emanate from a more powerful source the impact on decision-making is likely to be greater. The key communicators occupy higher position in formal and informal organizations than their followers. The followers not only provide information on agricultural matters but also consult for some other affairs like credit, marketing and day-to-day political life with the key communicators. Thus the key communicators are polymorphic.

Further studies carried out on status of adoption of improved dry farming *Kharif* crops like pearl millet, oil seeds, legume crops discussed about the level of adoption and constraints in adoption of various improved practices. It was found that the level of adoption was medium to low and farmers hardly go for any seed treatment although a majority of farmers follow the recommended seed rate. However, a very few farmers use chemical fertilizer and adopt plant protection measures (Achariya and Gupta, 1982; Kunnal *et al.*, 1984; Singh 2000, 2001, 2004a, 2004b, Singh and Chouhan, 2006, 2008; Singh and Chouhan, 2000, Singh *et al.*, 2003;, Saha, 2008; Sharma and Sharma, 2007; Singh, 2008). Saha (2007) reported that adoption of sprinkler system of irrigation was need based besides water and labour saving.

The poor adoption of improved farm practices in this region raises many questions. Whether the improved technology was suitable for the farmers of this vast arid region or farmers' lack of knowledge/interest? Chambers *et al.* (1989) pointed out that the interest of resource poor farmers has not been served well by the green revolution. In the 1950s and 1960s, non-adoption was attributed to farm level constraints. The gaps in yield between research stations and farms were analyzed and suggestion was to try to make the farms more like the research stations. In the 1980s it was felt that the problem is neither the farmer nor the farm but of the technology.

Participatory approach

The farming systems approach prioritizes farmers' needs and for their involvement in the research programmes especially the resource poor farmers. The basic philosophy upon which the model is based holds that successful agricultural research and development must <u>Begin</u> and <u>End</u> with the farmers. In practice, this means obtaining information, about and achieving understanding of the farmers perception of the problem and finally to accept the farmer's evaluation of the solution.

Interpretation of the whole research in operational and socioeconomic mode is very essential for its significant impact. Development and dissemination of technologies with the involvement of users can reduce the possibility of non-acceptance of the technologies. Moreover, peoples' participation reduces the risk of project failure by improving the quality of planning and decision making (Singh and Jain, 2002). Top down approach is being shifted even in developed countries to a collaborative bottom-up approach for the effective results (Griffin, 1999). In simplest term participation is as public or people's involvement in the project decision making (Singh and Jain, 2002). However, a participatory approach implies a major, but not exclusive role for local populations in exercising responsibilities and receiving benefits (Kausik *et al.,* 2007). In agriculture, farmers participatory approach instruct them on the principles and techniques of advances in technological practices which helps to improve productivity and returns from land, animal, labour and other resources.

Faroda *et al.* (2007) reported that the concept of low input-low risk-low yield, needs to be revolutionized using the technologies developed by the research institutes working in the arid region. Sinha (1995) evaluated the impact of watershed development programme and found that lack of participation in watershed development is one of the principal reasons for its disappointing impact in spite of the huge investments made. Kolavalli and Kerr (2000) found that in the states of Rajasthan, Karnataka and Orissa NGO's commitment to participation resulted in higher levels of collective action. In fact poor identification of the needs of stakeholders and inadequate assessment of the social impacts is the key reasons for the failure of project or technologies.

Impact of participatory approach in arid zone

The livelihood security in the arid region is the primary concern for policy makers, researchers and administrators. Agriculture being directly related to livelihood security is influenced by environmental, biotic and socio-economic factors. Small, fragmented production units, low risk bearing capacity and lack of alternate occupational base other than cropping and animal husbandry are the other important constraints. Further, inadequate exposure to adoption of improved agricultural technologies tends to the low productivity and instability. A major challenge in securing livelihood in the arid region is to stabilize the productivity. To make the sustainable system more productive and remunerative, adoption of new technologies is nevertheless, essential, for which public private partnership in an integrated mode can play a vital role. Various studies conducted in Indian arid region and elsewhere observed the importance of participatory approach i.e. farmers' involvement in developmental activities like watershed programme, tree plantation, higher yield in agricultural production due to adoption of new techniques, application of IPM practices in controlling diseases and pests (Khan *et al.*, 2006; Prasad *et al.*, 2003; Dhaka and Mann, 2002; Ghewande *et al.*, 2002; Salem and Smith, 2008 and Mapfumo *et al.*, 2001).

The improvement in the agricultural productivity in the arid region can be achieved through maximizing the usefulness of available resources including natural, industrial and biotic. There is also a need to refine and shift the traditional methods into improved and productive techniques with the participation of the farmers. The farmer is the best judge of his needs and therefore, should be responsible for finalizing the operational plan.

Future perspectives

Increasing biotic pressure will put more pressure on the arid lands to enhance the production vertically. Therefore, emphasis should be given to the holistic approach to maintain the balance between resource, quality and productivity. Strengthening and expanding researcher and farmers' understanding brings together for conflict resolution and collaborative decisions. It is necessary to refine the approach for research and transfer of technologies so that the objectives of a productive and sustainable agriculture can be attained. This would require identification of areas where efforts are necessary to develop acceptable, profitable and sustainable technologies. Collective action taken by researchers, extension workers and farmers seems to assure more usefulness of the technologies.

For sustainable adoption of any technology the assessment of farmers' need is a sine- qua-non in the transitional phase of agrarian development. And for proper dissemination of technologies, Village Resource Centre (VRC) could play an important and effective role as farmers and technologists can interact simultaneously, besides already available mass media and interpersonal sources. In this direction very recently a VRC has been established at Central Arid Zone Research Institute by Indian Space Research Organization for the benefit of the farmers.

Gender Issues, Women Empowerment, Micro credit and Livelihood Security

Gender issue has assumed importance in the transitional phase of socio economic development. The term 'gender analysis' in agriculture refers to the determination of who does what, why and with what resources towards improving their overall production and the standard of living. It is the most effective tool to open up the farm household and to understand its behavior (Poats, 1989).

Gender is essential for our understanding of economic, social and environmental processes and changes and there are direct linkages between women's and men's roles in social and economic processes on the one hand, and natural resources and the environment on the other. An understanding of the gender issues in farming systems requires a look at the different roles and relations of men and women as a part of their overall livelihood resources.

Gender differences in participation in agriculture and livestock-based activities in arid Rajasthan

In small farming systems, women farmers are largely responsible for the selection, improvement and adaptation of plant varieties. They are also responsible for the management of small livestock. Empirical studies carried out in this region (Anon., 2000) observed that out of 19 livestock-based activities, men exclusively carried out five activities like breed selection (95%), purchase of animals (91%), purchase of feed (92.5%), vaccination (100%) and sale of milk (74%). Higher participation of men in these activities has been reported by Mishra and Sasmal (1997), Tamilselvi *et al.* (1999) and Sharma and Khandelwal (2002). Certain activities like fodder collection and care of sick animals are jointly carried out by men and women. Women perform the more tedious and time consuming activities such as feed preparation (88%), feeding animals (80%), cleaning yard (95%), care of pregnant animals and care of newborn calves (74%), milking (86%) and product preparation (96%). Saha and Mathur (2001) reported that the women share equal burden with their male counterparts irrespective of their status with little variation. Tewari *et al.* (1996) concluded that the participation of women in livestock based activities in the arid region was upto 90%. Similarly, high participation of women in agricultural activities in semi-arid region of Andra Pradesh was reported by Waris (2008).

It is imperative therefore, that women should form the focus of any livestock development program as they are the main caretakers. Literate and interested women may be trained as para-veterinarians. Extension personnel, policy makers and administrators may plan and design training programs on scientific management of livestock exclusively for women to improve their knowledge and skills.

Gender mainstreaming for women's empowerment

Gender mainstreaming denotes, making women's concerns and experiences integral to the design, implementation, monitoring and evaluation of policies and programs in all political, economic, and social spheres. Its goals are gender equity through empowerment of women as well as men (Linda Mayoux, 2005).

Empowerment of women

As such empowerment is something to do with getting power and also sharing the power and remaining in power, exercising power, controlling power leading to a democratic and inclusive growth. More so, it is for social, political, economic and spiritual strength, both individually and collectively. It further includes addressing the discrimination that exclude women from decision making processes, not only for reasons of equality but for the insights they could bring to the process addressing marginalization by way of implementing equal pay for equal work and equal rights in the family. Saha and Rani (1992) reported that in decision making processes particularly in agriculture, livestock and socio-religious matters, women are consulted by male heads although the extent of discussion varied depending on socio economic status. Information seeking behavior of rural women found that irrespective of the educational status, women consulted informal sources (family members/relatives friends neighbors), followed by formal sources (extension personnel/bank officials/*panchayat* members) and mass media respectively for both agricultural and livestock based activities. The male members and older women of the household need to be sensitized to share technical information related to agriculture, livestock and other welfare activities with younger women members of the family. Considering the low literacy status of rural women, it is imperative to popularize the rich traditional folk media for the dissemination of technical information (Amtul-Waris 2004).

Women's empowerment cannot be achieved through economic independence alone. It should also be accompanied by other socio- political empowerment to attain Millennium Development Goal 3, Gender Equality. Social empowerment of women includes changes in the socialization process, without any discrimination on gender in day-to-day affairs, gender sensitization and inculcating a feeling of equality among women.

Livelihood security through entrepreneurship development

Alternative income generation for farm women can be made possible through entrepreneurship development for which women have to become more confident and assertive. To gain confidence it would be helpful to get organized into small Self-help groups (SHG's).

SHG's are small informal associations created for the purpose of enabling members to reap economic benefits out of mutual help and solidarity. The benefits include basically obtaining savings and credit facilities, and pursuing group enterprise activities. The group-based approach not only enables the poor to accumulate capital by way of small savings but also helps them to have easy access to formal credit facilities. These groups by way of joint liability enable the poor to overcome the problem of collateral, which is a major hurdle in gaining access to formal credit. The special characteristics of SHG's like small size and homogeneity in composition bring about cohesiveness and effective member participation in the working of the groups.

Strategies for entrepreneurship development

Adequate training in an area where the women have natural abilities and understanding

Provide technical support in their area of interest

Access to information and materials

Sharing of resources among group members

Creation of financial assets through savings

Enterprises for income generation

Farm women in the initial stages of enterprise selection need professional guidance. Entrepreneurship development comprises of three stages of stimulation, support and sustenance. The role of skill is crucial in enabling the women to select an appropriate enterprise along with their technical training. The farm women as members of groups can take up income earning enterprises like animal feed making, food preservation, vermi-compost, collection, processing and marketing of minor forest products, nursery raising and spices grinding unit etc.

Entrepreneurship development in the rural women leads to more income in the hands of women that is invariably spent for improving the quality of life of family members and the women themselves feel a sense of pride in being able to contribute meaningfully for the family welfare.

Micro credit is linked with women's empowerment. The National policy for empowerment of women 2001, conceptualizes empowerment as social, economic and inclusive of gender justice. Economic empowerment highlights poverty alleviation and micro-credit thereby connecting micro-credit to both poverty reduction and empowerment goals. The tenth five-year plan made a specific commitment to women's empowerment, based on the prescription of the National Policy for Empowerment of Women.

Women's empowerment is a continuum of several interrelated and mutually reinforcing components. Specific strategies or methods, which can be utilized, to bring out this would be ranging from changing the attitudes of people, motivating them, enhancing facilitating factors, providing institutional framework which is gender sensitive. Improving women's access to resources and increasing their participation in decision-making.

Capacity building is the most important and basic strategy one could employ to initiate the process of empowerment. It will result in enhancing their self-esteem and confidence. The specific programs may include skills development especially the ability to plan, make decisions, organize, manage and carry out their life activities. Capacity building of members of two selected self-help groups in Jodhpur District of Rajasthan was envisaged through dissemination of selected technologies. A technology package of feeding and health management of dairy animals and cultivation of dual-purpose crop varieties to meet the food and fodder needs of the family was provided. The components of the technology package that would be continually adopted by the trained farmwomen are regular de-worming of dairy animals, incorporation of mineral mixture and feeding of balanced concentrate mixture to dairy animals (Anon. 2005a,b, 2007).

The holistic and universal development of women must concentrate on the aspects of literacy, education, health and nutrition, water and sanitation, skills, technology, credit and marketing. Technology must be proactive and facilitate women. Technological development in education, health and nutrition, water and sanitation and skills development must reach all women particularly at grass roots. Credit support, along with new technological input with assured marketing support will be the necessary inputs for development in general and women empowerment in particular.

In arid Rajasthan empowering of women through various means as discussed above is essential as women are suppressed in society. The vulnerable section of population, especially the disadvantageous group of women who derive their livelihood through labour activities could be empowered through SHGs with micro-finance. There is a need to study the sustainability of SHGs for long term gain.

Impact Assessment of New Technology

Economic impact assessment is a process of measuring development objectives, such as increases in production, income and improvements in the sustainability of production systems. It is important to demonstrate that the changes observed are due to a specific intervention. The new technologies transferred to farmers' field also raised many issues like production, employment and income generation. James (1994) defined the impact assessment of new environment (new technology) on the basis of following criteria:

- Change in output
- Change in employment
- Change in unit cost of production and
- Change in profitability status

However, the positive impact can be assessed by the increase in output per hectare, increase in employment opportunity, decrease in unit cost of production and increase in farm income and net income.

The introduction of modern technology has positive impact on agricultural production and additional employment generated by crop. With the introduction of modern technology of crop, it is essential to know how much additional production and employment can be attributed to technical change. What proportion of change in production and employment can be attributed due to increase in complementary inputs? The impact of any technology can be assessed only by per hectare production, per unit cost of production, net returns and employment generation.

The impact can be decomposed to know the contribution of the technology as well as the increase in complementary inputs. The productivity difference between modern and traditional technologies was disaggregated into its constitutions i.e. sources of technological and inputs components used with the help of the decomposition model as suggested by (Bisaliah 1977).

Impact of technological changes on production

Quantitative assessments of the contribution of various factors including technological change were studied by many researchers. Empirical studies attempted to isolate the influence of input growth (movement along production function) and technical change (shift of the production function) found that technical change contributed in increased output, conjunctive use of both canal and tube well irrigation and changes in input increased production and income level, minimized water logging, and reclamation technology improved land productivity (Bisaliah, 1977; Gajja and Sharma, 1994; Gajja *et al.*, 1997). Singh *et al.* (2004) reported that productivity of *Moth* bean and cluster bean in arid region of Rajasthan can substantially be increased (67% and 60%) by introducing HYVs (RMO-40 and RSG-936).

Impact of technological changes in employment

The implications of modern technologies on employment has been an area of considerable importance and number of studies were carried out in past to examine the impact of new technology on economic development and labour employment (Billings and Singh, 1971; Sindhu, 1974; Rao, 1975; Raju, 1967; Vaidyanathan, 1978). Although these studies have shown the impact of new technology on production and employment, have not mentioned the contribution of individual components of new technology on total employment growth. Very few studies are available on the decomposition analysis of the employment growth due to improved technology.

Raj Krishna (1974) studied direct employment effects of new technology for wheat crop and for wheat and rice. For wheat, it was observed that the total change in labour employment from 1968-69 to 1973-74 is -91.61 man-hours per hectare. Decomposition of this change revealed that the contribution of irrigation and variety effect is almost equal, being 16.28 and 17.35 man-hours respectively. Mechanization of threshing and irrigation has negative employment effect of the order of 70.58 man-hours and 34.59 man-hours per hectare respectively. The tractor ploughing effect is also negative but small in magnitude. For rice and wheat combined the employment of human labour declined by 64.07 man-hours per hectare. Technology and interaction element have a negative employment effect while crop mix and cropping intensity have positive effect for wheat and rice taken together. Bisaliah (1978) found that introduction of new technology in the form of Mexican wheat increased labour employment by 41%. The contribution of new technology, normalized wage rate and complementary inputs to the employment growth was estimated as 12%, -14.8% and 53.7% respectively. Gajja *et al.* (1996) found that conjunctive use of tube well and canal water as an alternative to canal irrigation had potential in employment generation and enhanced agricultural production. Gajja *et al.* (1995) estimated decomposition analysis of hired labour employment by irrigation class and soil degradation level and found that complementary inputs such as family labour and fertilizer use have a direct positive employment effect. Gajja and Sharma (1998) also studied the changes in labour demand between irrigation classes and between soil degradation levels and found that land irrigability class and soil degradation levels had a negative relationship with crop yield. The use of other inputs had positive effects on yield. Complementary inputs like family labour and fertilizers used had a direct positive effect. Gajja (2000) reported that the change in labour demand was guided by change in irrigation class and soil degradation level. The magnitude for change in labour depends upon the land irrigation class and soil degradation levels as technical changes. The technological changes contributed for more than 50-80% variation. Fertilizers contributed more in comparison to other complementary input.

Impact assessment in arid region

In the arid region of Rajasthan very limited information is available on impact of new technology on production and employment generation. Decomposition analysis revealed that the total changes in yield of pearl millet crop with different variety over local variety and with *thumba* cake was more than 85%, 78% and 83% at the resources utilized under old technology while the remaining contribution was due to change in complementary inputs under local, HHB-67 and MH-169 pearl millet variety. Similarly, cumin crop with *thumba* cake (new technology), increased yield by 91% while the other complementary inputs by 9% only. In case of chilli crop, the two technologies like application of *thumba* cake and milk spray contributed 81% and 86% in enhancing yield of chilli crop. The remaining contribution was by complementary inputs.

The application of *thumba* cake with local, HHB-67 and MH-169 has generated more than 85% additional employment over the resources used under old technologies. The remaining contribution was from complementary inputs. Similarly, cumin crop with *thumba* cake indicated that 92% additional employment generated at resources used under local technology while the remaining contribution was due to change in complementary inputs in generation of additional employment. Singh and Gajja (2003) found that increase in labour employment due to adoption of new technology of *moth* and cluster beans were 57.44 and 47.61% respectively.

Gajja *et al.* (2008) reported that the agricultural return increased to the extent of 430.8% in net returns due to shelterbelt plantation. Shelterbelt technology has contributed 399.4% and increase in use of complementary inputs was 31.4%. Total additional employment generated by shelterbelt technology was 106.4%. Out of 106.4, 76.5% employment was generated by shelterbelt alone and remaining 29% by complementary inputs. Therefore, by adoption of shelterbelt technology employment opportunity could be increased.

The above discussion clearly indicates the importance of impact assessment of new technologies which not only find out the impact of various inputs in production potential but also help in to assess the employment potential. There is more scope of impact assessment studies in arid region which could tell about the factors affecting technological changes.

References

Acharya, S.S. and Gupta, J.P. 1982. Production of pulse crops: Performance constraints and prospects. *Indian Journal of Agriculture Economics* 373: 408-409

Anantharam, K., Tsunekawa, A., Saha, D.K. and Miyazaki, T. 1999. Subdivision and fragmentation of land holdings and their implication in desertification in the Thar Desert, India. *Journal of Arid Environments* 41: 463-477.

Anonymous. 2000. *Annual Progress Report*. Central Arid Zone Research Institute, Jodhpur.

Anonymous. 2005a. *Annual Progress Report*. Central Arid Zone Research Institute, Jodhpur.

Anonymous. 2005b. *Annual Progress Report*. Central Arid Zone Research Institute, Jodhpur.

Anonymous. 2006. *Annual Progress Report*. Central Arid Zone Research Institute, Jodhpur.

Anonymous. 2007. *Annual Progress Report*. Central Arid Zone Research Institute, Jodhpur.

Bose, A.B. 1962. The population problem in the Jaisalmer desert region. *The Journal of Family Welfare* 9: 1-7.

Bose, A.B. 1966a. Population trends in the arid zone of Rajasthan. *The Journal of Family Welfare* 7(3): 23-27.

Bose, A.B. 1966b. The process of adoption of agricultural innovations in Western Rajasthan. *The Journal of Social Work* 27(3): 263-268.

Bose, A.B. and Saxena, P.C. 1965. The diffusion of innovations in a village in Western Rajasthan. *The Eastern Anthropologist* 18(3): 138-151.

Bose, A.B. and Jain, M.B. 1966. Relative importance of some social- economic factors in the adoption of innovations. *Indian Journal of Social Research* 7(1): 8-13.

Biggs, S.D. 1986. *Resource-poor Farmer Participation in Research*. OFCAR comparative study. ISNAR, Netherlands.

Bilings, Martuin, H and Singh, Arjan 1971. The effect of technology on farm employment in India. *Development Digest* 9(1): 98-107.

Bisaliah, S. 1977. Decomposition analysis of output change under new production technology in wheat farming: some implications to returns on research investment. *Indian J. Agr. Econ* 32(3): 193-201.

Bisaliah, S. 1978. Decomposition analysis of employment change under new production technology in Punjab agriculture. *Indian J. Agr. Econ.* 33(2): 70-80.

Dhaka, B.L. and Mann J.S. 2002. Participatory way to increase production. In Extended summaries Vol.2: 2nd International Agronomy Congress, New Delhi: 1490.

Faroda, A.S., Joshi N.L., Singh, Raj and Saxena, Anurag. 2007. Resource management for sustainable crop production in arid zone-A review. *Indian Journal of Agronomy* 52(30): 181-193.

Gajja, B.L. 2000. Labour decomposition analysis under different soil and land irrigability environments in the Mahi Right Bank Canal Irrigation Project in Gujarat State. *Current Agriculture* 24(1&2): 49-56.

Gajja, B.L. and Sharma, Vijay Paul 1994. Impact of conjunctive use of surface and ground water on tobacco crop in Mahi Right Bank Canal Command area in kheda district of Gujarat' *The Bihar Journal of Agri. Marketing* 2(20): 171-177.

Gajja, B.L., Sharma, Vijay Paul and Joshi, P.K. 1995. Labour decomposition analysis under different environment in Ukai-Kakrapar irrigation project in Gujarat State. *The Bihar Journal of Agri. Marketing* 3(1): 25- 33.

Gajja, B.L., Sharma, Vijay Paul and Parshad, R. 1996. Impact of land degradation on agricultural production and income in the Ukai-Kakrapar Canal Command area in Gujarat. *Indian Journal of Agricultural Sciences* May: 41-43.

Gajja, B.L., Sharma, Vijay Paul and Parshad, R. 1997 Impact of salinity and water logging on Agricultural Production and Employment in irrigation project; A case study A. Ukai -left Bank Carnal Command Area. *The Bihar Jn. Agri. Marketing* 5(2): 217-227.

Gajja, B.L. and Sharma, Vijay Paul 1998 Labour decomposition analysis under different soil and land irrigability environments in the Kakrapar Left Bank Canal Irrigation Project in Gujarat State. *Annals of Arid zone* 38(2): 186-193.

Gajja, B.L., Prasad, Rajendra, Mertia, R.S., Khem Chand and Samra, J.S. 2008. Impact of shelterbelts on net returns from agricultural production in Arid Western Rajasthan. *Agri. Econ. Research Review* 21: 118-122.

Ghewande, M.P., Andagopal, N., Devidyal,G.D., Kumar, Satish, Sojitra, V.K. and Cavda, V.N. 2002. Farmer's participatory assessment and refinement of integrated pest management technology for sustainable groundnut (*Arachis hypogaea*) production. In *Extended Summaries*, Vol.2: *2nd International Agronomy Congress*, New Delhi 3:1501.

Griffin, C.B. 1999.Watershed councils: an emerging form of public participation in natural resources management. *Journal of American Water Resources Association* 35(3): 505-518.

James, D. 1994. The application of economic techniques in environmental impact assessment. Kluwer Academic Publisher, London.

Kaushik, P.K., Panday, B.K. and Tripathi, Y.C. 2007. Participatory approach to watershed management in India. *Indian Forester* 133(12): 1659-1667.

Khan, M.A., Tewari, J.C., Singh, Raj and Narain, Pratap 2006. Structure, production attributes and management strategies in a traditional extensive agroforestry system in an arid region watershed of India. *Forests, Trees and Livelihoods* 16: 227-246.

Kolavalli, S. and Kerr, J. 2000. Mainstreaming Participatory Watershed Development. Mimeo.

Kunnal, L.B., Itnal, C.J. and Krishnaswami, N.K. 1984. Adoption of new technologies in dry land sorghum crop production. *Indian Journal of Extension Education* 20(3&4): 60-62.

Linda, Myoux 2005. Gender equity, equality and women's empowerment: principles, definitions and frameworks. Aga Khan Foundation website on microfinance for women's empowerment. http//:www.genfinance.net

Malhotra, S.P. 1977. Socio-demographic factors and nomadism in the arid zone. In *Desertification and its Control,* pp. 310-323. Indian Council of Agricultural Research, New Delhi.

Malhotra, S.P and Gupta,B.S. 1980. Spatial distribution of population in Rajasthan. *Samaj Vigyan Jagat* 3(1&) 21-28.

Malhotra, S.P, Joshi, P.L. and Rao, J.S. 1974. Relative importance of some socio-economic factors in the adoption of agricultural innovations. *Indian Journal of Extension Education* 10(1&2): 62-64.

Malhotra, S.P., Saha, D.K. and Krishna, G.V.S.R. 1983. Factors influencing information sources -A study of causal relationship. *Annals of Arid Zone* 22(4): 313-317.

Mapfumo, P., Campbell, B.M., Mpepereki, S. 2001. Legumes in soil fertility management: The case of pigeon pea in smallholder farming systems of Zimbabwe. *African Crop Science Journal* 9(4): 629-644.

Patel, Tulsi 1990. Modernisation and changing fertility behaviour: a study in Rajasthan village. *Sociological Bulletin* 38(1&2): 53-73

Prasad, Rajendra, Gupta, R.K. and Lohra, R.R. 2003. Participation of farmers in tree plantation in Western Rajasthan. In Human Impact on Desert Environment (Eds. S. Kathju, A. Kar, M.P. Singh and Praveen-Kumar), pp. 618-626. Arid Zone Association of India & Scientific Publishers:

Rogers, H.M.1962. Diffusion of Innovations, Free Press of Glencoe, New York.

Raj, Krishna 1974. Measurement of the direct and indirect employment effects of agricultural growth with technical change. In *Employment in Developing Nations* (Ed. E.O. Edwards), Columbia University Press, New York.

Raju, V.T. 1967 The Impact of New Farm Technology on Human Labour Employment, Indian *Journal of Industrial Relations* 1(4): 493-510.

Rao, Hanumantha, C.H. 1975. Technological change and Distribution of Gains in Indian Agriculture, The Macmillan Company of India Limited. Delhi.

Saha, D.K. 1993. Population dynamics in Indian arid zone. *Man and Life* 19(3&4): 153-162.

Saha, D.K. and Sen, M.L.A. 1993. Status of education in some arid villages of Jalor district in arid zone of Western Rajasthan. *Current Agriculture* 17(1&2): 89-96.

Saha, D.K. and Bhandari, C.S. 1998. Desert dwellers and family planning measures-some socio-cultural issues. *Man & Life* 24(3&4): 192-197.

Saha, D.K., Mathur, Y.N., Khan, W.A. and Singh, Roopendra 1999. Indicators of Development in Pokaran Teshil in Jaisalmer District, Rajasthan. *Annals of Arid Zone* 38(1): 63-68.

Saha, D.K., Tsunekawaka, A., Anantha Ram, K. and Miyazaki, T. 2003. Socio-cultural practices and peoples' perception in desertification processes in an Indian arid village. In *Human Impact on Desert Environment* (Eds. Pratap Narain, S. Kathju, A. Kar, M.P. Singh and Praveen-Kumar), pp. 597-608. Arid Zone Research Association of India and Scientific Publishers, Jodhpur:

Saha, D.K., Narian, Pratap and Patwa, F.C 2004 Socio-economic conditions of pastoral nomads-Raikas under changing agrarian situation in an arid district of Western Rajasthan, India. In *A study on dominant factors in a recent transformation of Livestock keeping in India* (Ed. Nakasato Tsuguo), pp. 145-175. Fukuoka University of Education, Japan,

Saha, D.K., Kar, Amal, Rao, A.S. and Soni, V.K. 2008. Disadvantageous groups of population and drought vulnerability in some arid villages of Western Rajasthan. In *Youth, Globalization and Social Transformation*, pp. 153-154. 34th AISC, University of Rajasthan, Jaipur.

Saha, D.K. Malhotra, S.P. and Krishna, G.V.S.R. 1981. Diffusion and adoption of agricultural innovations in arid villages of Western Rajasthan. *Annals of Arid Zone* 20(4): 271-275.

Saha, D.K., Malhotra, S.P. and Gadewar, A.U. 1982. Differential characteristics of key-communicators and followers in arid villages of Western Rajasthan. *Indian Journal of Social Research* 23(2): 107-114.

Saha, D.K., Malhotra, S.P. and Krishna, G.V.S.R. 1983. Factor analysis in adoption of agricultural innovations in arid areas of Western Rajasthan. *Annals of Arid Zone* 22(4): 307-312.

Saha, D.K., Malhotra, S.P., Mathur Y.N. and Singh Ugam 1987. Pattern of communication and constraints in disseminating modern agricultural technologies in arid villages. *Annals of Arid Zone* 26(4): 235-240.

Saha, D.K., Gupta, B.S. and Mathur, Y.N. 1991. Factors affecting adoption of improved farm technologies in an arid village of Western Rajasthan. *TISDT* 16: 175-180.

Saha, D.K. and Vyas, D.L. 1991. Improved farming - Its implications in arid Rajasthan. *Man and life* 17(3&4): 125-132.

Saha, D.K. 2007. Farmer's need and adoption of technologies in some arid area of western Rajasthan. *Journal of Arid Legumes* 4(117-120.

Saha, D.K. 2008. Arid legume crops and its adoption of modern varieties in some arid areas of Western Rajasthan. *Journal of Arid Legumes* 5(2): 132-135.

Saha, D.K. and Rani, Usha 1992. The role of rural Women in decision-making processes in arid Rajasthan. *Annals of Arid Zone* 31(4): 295-297.

Saha, D.K. and Mathur, Y.N. 2001. Differential characters and work participation of women in an arid village of western Rajasthan. *Man in India* 81(3&4): 305-311.

Salem, H.B. and Smith, T. 2008. Feeding strategies to increase small ruminant production in dry environments. *Small Ruminant Research*77(2&3): 174-194.

Sharma, B.L. and Sharma R.N. 2007. Adoption and impact of recommended technology in *kharif* pulse crops in Agro-climatic Zone II A of Rajasthan. *Rajasthan Journal of Extension Education* 15:122-128.

Sidhu, S.S. and Heady, B.O. 1974. Technological change and Relative Factor Share in Indian Agriculture : An Empirical Analysis , *American. J. Agr. Econ*. 55(3): 509-514.

Singh, V.P. and Jain, S.K. 2002. Watershed Management New Approach and Paradigms. *Annals of Arid Zone* 41(3&4): 233-262.

Singh, Bhagwan 2000. Constraints in fertilizer use in arid zone of Western Rajasthan. *Current Agriculture* 24(1-2): 93-95.

Singh, Bhagwan 2001. Note on adoption and constraints of improved practices of mung crop in Arid Zone. *Current Agriculture* 25(1&2): 131-133.

Singh, Bhagwan. 2004a. Adoption of guar production technology in arid zone of Rajasthan. *Journal of Arid Legumes* 1(2): 122-124.

Singh, Bhagwan. 2004b. Adoption of sesame production technology in arid zone of Rajasthan. *Asian Journal of Extension Education* 23(1): 181-187.

Singh, Bhagwan and Chauhan, K.N.K. 2000. Adoption and constraints of improved practices of guar in arid area of Rajasthan. *TISDT* 25:13-138.

Singh, Bhagwan and Chauhan, T.R. 2006. Factors influencing the adoption of moth bean production technology in arid zone of Rajasthan. *Journal of Arid Legumes* 3(1): 34-38.

Singh, Bhagwan and Chauhan, T.R. 2008. Adoption of moth bean production technology in arid zone of Rajasthan. *Annals of Arid Zone* 47(1): 95-101.

Singh, B and Gajja B.L. 2003 Labour Decomposition analysis under new technology in legume crops. *Annals of Arid Zone* 42(1): 79-83.

Singh. B, Gajja, B.L., Khem Chand and Beniwal, R.K. 2004. Impact of Modern Technology of Legume crops in arid zone of Rajasthan' *Annals of Arid Zone* 43(1): 91-95.

Singh, R.N. 2008. Adoption of improved agriculture practices among arid zone farmers. In *Diversification of Arid Farming Systems* (Eds. Pratap Narayan, M.P. Singh, A. Kar, S. Kathju and Praveen-Kumar), pp. 440-446. Arid Zone Research Association of India and Scientific Publishers, Jodhpur:

Singh, Bhagwan, Singh, Raj and Chauhan, K.N.K. 2003. Adoption and constraints in moth bean production technology in arid zone of Rajasthan. In *Advances in Arid Legumes Research* (Eds. A. Henry, D. Kumar and N.B. Singh), pp. 510-14. Indian Arid Legumes Society & Scientific Publishers, India, Jodhpur.

Sinha, M.S.1995. Review and status of rain fed farming and watershed management in India. The *Status of Watershed Management in Asia* (Eds. P.N.Sharma and M.P. Wagley). Kathmandu Nepal:UNDP/FAO

Vaidyanathan A. 1978. Labour use in Indiana Agriculture: An analysis based on Farm Management Survey. ILOARTEP, Bangkok.

Mishra and Sasmal, S. 1997. Gender implications in livestock production and management in animal based farming systems. *Journal of Extension Education* 11:126-129.

Poats, S.V. 1998. Gender analysis in farming systems research and extension projects. In *Proceedings of Farming Systems Research Extension Symposium*. University of Arkansas and Winrock International Institute for agricultural development.

Sharma, K.C. and Khandelwal, Suman 2002. Role of farm women in animal management. *Rajasthan Journal of Extension Education* 10:126-129.

Tamilselvi, G., Somasundaram, D. and Thyagarajan, S.1999. Role performance of farm women in varied farming systems. *Indian Journal of Extension education* 34(3&4): 251-245.

Tewari, Pratibha. Amtul Waris and Singhal Savita. 1996. Rural women's participation in agriculture and livestock activities in arid areas of Rajasthan. *Current Agriculture* 20(1-2) 91-95

Waris, Amtul. 2004. Utilization of information sources by farm women in arid Rajasthan. *Indian Journal of Extension Education* 40(1&2) 75-77.

Waris, Amtul. 2008. Farm women's participation in agricultural activities in semi arid region of Andhra Pradesh. *Green Farming* 2(2) 137-138.

Author Index