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Dryland Agriculture and Secondary Salinization in Canal Commands of Arid Rajasthan

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Abstract

The drylands in India occupy about 80 million ha, and is spread over arid, semiarid and sub humid climatic zones presenting nearly 57% of the net cultivated area. The drylands are characterized by low precipitation, highly variable rainfall patterns, high evapotranspiration rates, inadequate available nutrients in native soils, poor quality of ground water, severe land degradation processes, short growing period and low crop yields. Despite these bio-physical constraints, the region has high human and livestock population, which mostly depend on agriculture and allied activities with limited natural resources resulting in over-exploitation of the resources. Presently degradation of natural resources (land, water, and biodiversity), decreasing farm profitability, low input-use efficiency (fertilizer, water, energy, and labor), environmental pollution (soil, water), climate change and scarcity of farm labour are threatening the sustainability of agricultural production in the drylands. Large-scale drive for modernization of agriculture in the northern and western parts of the Rajasthan, through IGNP and Narmada canal brought about considerable prosperity to the farmers. Some of the positive impacts of introduction of irrigation in the desert includes improvement in micro-climate, change in land use/ cropping pattern, improvement of soil and associated soil fertility and biological properties, but it has also brought in its wake the problems of water logging and secondary salinization. Lack of proper drainage, excess irrigation, seepage from the canals and poor planning under such situation have resulted in a rise in water table, followed by salinity build-up. In this perspective, some of the successful technologies on soil and water management in drylands provide a higher and stable crop yields and other associated profits like improving/maintaining soil quality, input use efficiency, environmental quality, well-being of farmers and reductions in land degradations, cost of cultivation, and help in climate change mitigation and adaptation. The present paper deals with the extent, significance, characteristics of and constraints of dryland agriculture along with suitable technological options to improve agricultural productivity with special reference to hot arid regions of India.

Key words: Dryland agriculture; Secondary salinization; Waterlogging; Canal command area; Poor-quality groundwater; Arid regions

Introduction

A key question facing agricultural scientists in the 21st century is how to produce sufficient amounts of food and feed and obtain good farm income while protecting and improving environmental quality (Robertson and Swinton, 2005). At present, depletion and / or degradation of natural resources (land, water, and biodiversity), decreasing farm profitability, low input-use efficiency (fertilizer, water, energy, and labor), environmental pollution (soil, water, air), climate change and scarcity of farm labour are threatening the sustainability of crop production systems. The problem of ensuring an adequate supply of agricultural produce along with protecting natural resources is particularly acute in dryland, which cover around 41% of the world's land area, and is home to about one third of the human population. These regions are characterized by low precipitation, highly variable rainfall patterns, high evapotranspiration rates, poor soils, severe land degradation processes, a short crop growing season and low crop yields. Interest in dryland

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and rain-fed farming system has increased markedly in recent years in many regions of the world because of the rapidly increasing human population coupled with low productivity gains, escalating water development costs for new irrigation projects, and high operational and maintenance costs associated with irrigated agriculture (Steiner *et al.,* 1988). In this context, development and adoption of dryland / rain-fed agricultural management practices, which provide a higher and stable yield and profits along with maintaining / improving soil-quality, input use efficiency, environmental quality, well-being of farmers and decrease soil erosion, cost of cultivation, and help in climate change mitigation and adaptation are essential. The objective of this review is to highlight the extent, significance, characteristics, and constraints of dryland agriculture along with suitable technological options to improve agricultural productivity with special reference to hot arid regions of Rajasthan.

Dryland: Concept and Extent

There are a variety of definitions of drylands based on the different criterion used. Among them the two definitions based on length of growing period of the annual crop, and an aridity index (AI) are widely accepted. The FAO has defined drylands as those regions which climatically classified as arid, semi-arid and dry sub-humid areas based on the length of growing period [number of days during a year when precipitation exceeds half the PET, plus a period required to use an assumed 100 mm of water from excess precipitation (or less, if not available) stored in soil profile] of annual crops. According to this criterion, the areas having a growing period between 1–59 days, 60-119 days and 120–179 days are classified as arid, semi-arid and sub-humid areas, respectively. Collectively, these regions account for approximately 45% (7, 20, and 18% of arid, semi-arid, and dry sub-humid regions, respectively). According to the aridity index (AI: ratio of P to PET) the regions having aridity index < 0.65 are drylands. The sub-types of dryland system along with their share in global areas and in the population, are presented in Table 1. In-fact, each classification scheme presented has advantages for specific purpose and locations, but subjective judgment is required for their interpretation. Oram (1980) listed some common climatic characteristics of dry lands and these are:

(i) Low total rainfall with at least one pronounced dry season (and sometimes two) so that lack of moisture puts a ceiling on year-round cropping even though it may be adequate for one crop;

(ii) Highly variable and unreliable precipitation during the rainy season, with large year-to-year differences in total rainfall and its distribution, and from month to month within seasons;

(iii) Increasing unreliability and variability with decreasing annual rainfall;

(iv) PET exceeding P for at least 7 months of the year; and

(v) Very high-intensity ocassional rainstorm leading to high runoff and erosion.

Overall low rainfall and the annual water deficit are the predominant features of drylands. The water deficit is attributed to the excess of ET

Table 1. The features of dryland systems in various regions

Sub-type	Aridity index	Share of global area (%)	Share of global population (%)	Rangeland %	Cultivated %	Others* %
Hyper-arid	<0.05	6.6	1.7	97	0.6	3
Arid	0.05-0.20	10.6	4.1	87	7	6
Semi-arid	0.20-0.50	5.2	14.4	54	35	10
Dry sub-humid	0.50-0.65	8.7	15.3	34	46	20
Total		41.3	35.5	65	25	10

*Includes urban
Source: Safriel *et al*. (2005)

over P due to an array of interacting factors that includes low and erratic precipitation, high temperature, low relative humidity, high winds etc. Drylands occur on all continents (between 63 ºN and 55º S), and are not spread equally between poor and rich countries: 72% of the global dryland area occurs within developing countries and only 28% within industrial ones.

Oram (1980) stated that dryland agriculture is crop husbandry under conditions of moderate to severe moisture stress during a substantial portion of the year, which requires special cultural techniques and adapted crops and systems for successful and stable agricultural production. ACIAR (2002) stated that dryland cropping refers to those agricultural areas where water supply to the crops limits potential yield to < 40% of full (water –unlimited) potential.

The terms "rain-fed" and "dryland" are often used synonymously, but in fact, they refer to vastly different physical and biological systems. Both systems exclude irrigation, but beyond that, they can differ significantly (Steiner *et al.,* 1988). Stewart and Burnett (1987) characterized dryland agricultural systems as those that emphasize water conservation, sustainable crop yields, limited inputs for soil fertility maintenance, and wind and water erosion constraints, whereas rainfed systems in more humid zones often emphasize disposal of excess water, maximum crop yields and substantial inputs of fertilizer.

The crop yield in drylands is lesser than irrigated lands – the average grain yield is about half of those in irrigated areas. The low productivity of dryland areas is attributed to numerous biophysical (drought, temperature extremes, salinity, marginal soils, loss of biodiversity, and high vulnerability to land degradation) and socioeconomic (poverty, social inequity, poor access to technology, underdeveloped markets, high population growth, and weak institutions) constraints.

Rainfed/dryland agroecosystems occupy a prime place in Indian agriculture, covering 80 million ha, in arid, semiarid, and sub- humid climatic zones, constituting nearly 57% of the net cultivated area. Rainfed area in India contributes 84–87% of coarse grain cereals and pulses, 80% of horticulture, 77% of oilseeds, 60% of cotton, and 50% of fine cereals including rice, wheat, etc. (Srinivasarao *et al.,* 2010, 2011a), and support 60% of livestock and 40% of human population and contribute 40% of food grains and several special-attribute commodities such as seed spices, dyes, herbs, gums etc. (Srinivasarao *et al.,* 2013). Thus, the dryland agriculture has and will continue to play a crucial role in India's food and livelihood securities (Singh *et al.,* 2007).

The climate of rainfed/dryland areas varies from arid, semiarid to sub-humid, with a mean rainfall ranging from 412 to 1378 mm $year^{-1}$. The Inceptisols, Alfisols, Aridosls, Entisols and Vertisols are the major soils of these regions. Drought stress, in conjunction with high temperatures reaching up to 45 ºC for 8–10 weeks in a year, coupled with low biomass productivity are common features of dry agroecosystems. The major constraints of crop productivity in dryland agroecosystem of India have been summarized by Srinivasarao *et al.* (2013).

Technological Options for Dryland Agriculture

Numerous technologies have been generated and refined over the years by various institutes and units of NARS of India. Some of the important technological options for improving productivity and resource utilization in dryland agriculture are as under:

Crops and cultivars

Majority of traditional crops grown in drylands are of long duration which does not match with water availability. The quantum and distribution of rainfall determines the effective growing season and crops/ cropping system for a given region (Singh *et al.,* 2007). In the regions receiving 350-600 mm rainfall with 20 weeks effective growing season, only single cropping is suitable in all soils except Vertisols. In deep Vertisols, having 350–600 mm rainfall with 20 weeks growing season single post rainy crop is possible. In regions having 650-750 mm rainfall with 20-30 weeks effective growing season, inter-cropping is possible. While in regions receiving > 750 mm rainfall with > 30 weeks growing season, double cropping is possible (Singh and Subba Reddy, 1986).

The efficient crops/ cropping systems for different dryland regions have identified. It has been shown that an increase in yields by 15-25% is possible with suitable crop diversification. A large number of improved cultivars which suit with moisture availability (depending upon rainfall amount, distribution and soil characteristics) have been developed for millets, cereals, pulses and oilseeds. The substitution of traditional cultivars by improved cultivars increased yields by 15–50% over traditional cultivars. The crop- growing period in hot arid Rajasthan ranged from less than 6 weeks to 12 weeks. The short duration legumes are suitable for the region having rainfall 250–300 mm year^{-1} with crop-growing period of 8-10 weeks; whereas, the pearl millet and short duration legumes are suitable for the region having 300–400 mm year^{-1} rainfall with 10–12 weeks of crop-growing period (Rao *et al.,*1994).Long-term studies indicated that 45, 23 and 32% area should be allocated to long duration millet (pearl millet, sorghum), pulses and grasses, respectively, for achieving stable crop production in hot arid region (Faroda *et al.,* 2007). Selection of suitable cultivar is an important consideration for getting better crop production in arid regions. The moisture availability period during *Kharif* season is ~ 50–60 days in the arid region; therefore, the cultivars that mature in this short period of moisture availability are suitable. The cultivars HHB–67, CZP 9802 (pearl millet), RMO–40, RMO–225, CAZRI moth–2 (moth bean), RGC–936, RGC 1003 (cluster bean) and RT-13, RT-46, RT-351 (sesame) are suitable for cultivation in hot arid region.

Cropping systems

Inter or mixed cropping is an important strategy to minimize the risk in crop production in arid and semi-arid regions. Mixed sowing of dryland crops is a common practice in arid and semi-arid regions to minimize the adverse effect of weather aberration and drought (Vittal and Bhati, 2009). Pearl millet + green gram+ moth bean + cluster bean+ sesame (48%) followed by mixture of same crops without sesame (24%) is the most common crop mixture of western Rajasthan. However, with the development HYV of these crops, the practice is fast diminishing and farmers prefer mono-cropping systems.

The suitable mixture ratio of the crop is important to achieve better yield and profits under mixed cropping. The intercropping is shown to increase yield, profits and resource use efficiency compared to sole crop in arid regions (Rathore, 1992; De and Singh, 1981; Bhati, 1997). Cereal / legume intercropping under rainfed condition increases dry matter production, equivalent yields and benefit: cost ratio more than their monocultures (Faroda *et al.,* 2007). Joshi (1999) recorded an additional yield of 265, 291, and 268 kg ha^{-1} of moth bean, green gram and cluster bean without any significant reduction in pearl millet yield in paired row planting of legume in interspace of pearl millet. Rathore *et al.* (2006) demonstrated higher pearl millet equivalent yield, land equivalent ratio and return with pearl millet + clusterbean intercropping in 2: 4 (pearl millet: clusterbean) ratio. Intercropping of *Cenchrus ciliaris* and *Lasiaruss indicus* with grain legumes (moth bean, cluster bean, green gram) recorded 20–30% higher yield of grasses compared to sole - grasses. Rao *et al.* (2009) reported that intercropping of sorghum with green gram in 2:1 row ratio at 50 kg N ha^{-1} recorded the highest land equivalent ratio (1.32), price equivalent ratio (1.23), relative crowding co-efficient (10.99), net returns (Rs 14 857ha^{-1}) and benefit: cost ratio (2.64) at Pali, Rajasthan. The available evidences suggest that in order to obtain maximum benefit in terms of resources utilization and yield, suitable mixed/ intercropping should be designed as per the availability of soil moisture, agro- climatic and socio-economic conditions prevailing in particular location. The component crops and their cultivars must be selected in accordance with rainfall pattern (amount, frequency, and intensity), rate of evapotranspiration, soil type.

Pearl millet – pearl millet is a traditional cropping system of the hot arid region of Rajasthan. Continuously following the sequence resulted in decline in yield. Singh (1985) demonstrated 11% higher yield of pearl millet in pearl millet–clusterbean cropping system than pearl millet – pearl millet rotation. Saxena *et al.* (1997) recorded a reduction of 17.2% in yield of pearl millet in pearl millet - pearl millet rotation compared to pearl millet-clusterbean rotation. Saxena and Lodda (2003) indicated that pearl millet – mustard and pearl millet-fallow- green gram- fallow is better cropping system under limited irrigated and rainfed conditions. Among the five cropping systems (moth bean-pearl millet, cluster bean-pearl millet, moth bean-cluster bean, pearl millet-pearl millet and pearl millet + cluster bean-pearl millet + cluster bean) at Bikaner, moth bean-cluster bean cropping system had 21-148%, 36-246% and 33-178% higher equivalent yields, return and water use efficiency, respectively than other cropping systems (Rathore *et al.,* 2014). Besides better productivity, profitability and water productivity efficient cropping system help to minimize weed infestations and improving soil properties.

Tillage

Tillage has a marked influence on the root growth, conservation of soil and rain water, and resource (water and nutrients) utilization by crops. Adequate tillage has been found to be highly useful in improving soil physical conditions, conserve soil and water, and facilitate crop growth (Lal, 2008) and crop yield without adverse effects on the edaphic environment (Gupta and Agarwal, 1991). Coarse textured soils developed under a hyper-thermic regime are characterized by low organic matter content, low water retention capacity, high permeability, high pore rigidity and can develop a sharp increase in strength with drying. High soil strength and pore rigidity restrict root growth and decrease the capacity of the plant for efficient utilization of water and nutrients (Gajri and Parihar, 1985; Parsad *et al.*, 1994). Because of the low water retention, high potential for nutrient leaching and restricted rooting, crops on these soils suffer from yield reduction. To achieve higher crop yields, management practices must improve conditions for root growth and help to provide a regular and adequate supply of water and nutrients. Saxena *et al.* (1997) assessed the effects of tillage on soil moisture balance, growth and yield of pearl millet at Jodhpur. Deep tillage improved the soil moisture storage, water use efficiency and grain yield of pearl millet. Total dry matter yield with deep tillage and conventional tillage was 23.2 and 10.2% higher than minimum tillage in the season 1, and the corresponding values for season 2 were 30.7 and 13.3%. Results of an experiment conducted to assess effects of different tillage systems i.e. no tillage (NT), shallow tillage (ST) and deep tillage (DT) on yield of mung bean in hot arid region of Rajasthan indicated that DT had a significantly greater grain yield (644 kg ha^{-1}) compared to ST (573 kg ha^{-1}) and NT (287 kg ha^{-1}). The DT had 12 and 125% greater yields than NT and ST, respectively (Gupta et al., 2000). A study conducted by CAZRI at Bikaner showed that yields of five cropping sequences (cluster bean – pearl millet, moth bean –pearl millet, cluster bean – moth bean, pearl millet – pearl millet and pearl millet + cluster bean – pearl millet + cluster bean) increased by 14-37% under deep tillage compared to that of conventional tillage (Rathore *et al.,* 2014).

Planting time, method and density

Sowing dryland crops with the onset of monsoon rainfall can significantly improve crop yield. The crop growing period in arid region of Rajasthan ranges from < 6 weeks to 12 weeks, therefore short duration crops i.e. pearl millet, cluster bean, green gram, moth bean, sesame are major crops of the region. The normal period of occurrence of sowing rains in western Rajasthan is 1-15th July. However, the sowing rains can be delayed as late as 1st week of August in western parts and 3rd week of July in the eastern part of western Rajasthan (Rao and Singh, 1998). Under timely rain conditions, pearl millet and sesame are preferred, while under delayed onset of rainfall, cluster bean, moth bean and green gram are preferred. Henry (2003) reported that cluster bean had better performance than other legume under late sown condition. Under delayed sown condition, the dry seeding and transplanting of millet has been tried. Transplanting of 21 – 25 days old seedling had 22– 36% greater yield than directed sown pearl millet under the onset of monsoon between mid-July to mid- August. The first fortnight of July for sesame, onset of monsoon to third week of July for cluster bean, second week of July for moth bean are the optimum time of sowing in western Rajasthan. The proper row spacing and plant population is a prerequisite for successful crop production in arid regions. The row spacing of 45 cm in moth bean, 30 -40 cm in cowpea, 45-60 cm in pearl millet, 30 cm in late sown cluster bean and 45 cm in early sown cluster bean are optimum. The 1.11 lakh plant ha^{-1} (45 × 20 cm or 60 × 15 cm spacing) is the optimum plant density for pearl millet. Cluster bean planted at 30 × 15 cm (2.22 lakh ha^{-1}) had highest seed yield which was at par with 45 cm × 10 cm (2.22 lakh ha^{-1}) but significantly higher than 45 cm × 15 cm (1.48 lakh ha^{-1}) and 30 cm × 10 cm (3.33 lakh ha^{-1}) in Jodhpur district of Rajasthan (ARS, 1994).

Soil moisture conservation

The rainfall is the sole source of water for dryland crops and its efficient uses is the key for successful crop production. The efficient utilization of rainwater comprises of increasing water storage in soil, *in-situ* moisture conservation, minimizing deep percolation, evaporation and transpiration. Joshi *et al.* (2009) gave a detailed account of different soil moisture conservation practices developed in arid and semi-arid regions. Contour bunding is an effective option to control soil erosion and increasing rain water storage in arable crops in areas having slope ranging from 1–6%. An array of variants of contour bunding in arid regions have been developed and refined. Singh (1984) reported that 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 recorded greater moisture conservation and produced higher forage yields than control/ bunding. Sharma *et al.* (1997) modified the contour bands partially and developed contour vegetative barriers (CVB), which comprises transplanting of fast growing grass species having extensive root system (*Cymbopogon jwarancusa, Cenchrus ciliaris, Cenchrus setigerus*) at 0.3 m apart on contour at 0.6 m -1.0 m vertical intervals forming a dense hedge. Compared to control, the CVB reduce runoff volume by 28–97% and increased soil moisture storage by 2.5 times that control and produced 37–51% and 19–40% greater yields of cluster bean and pearl millet, respectively. Similarly, vegetative barriers of grasses planted at a horizontal interval of 30 m. When alley was used for pearl millet planting, the moisture storage enhanced by 36–72% and yield of pearl millet by 39% (CAZRI, 1998). Vegetative barriers of *C. ciliaris* in combination with bunding on the field having 1–2% slope gave 40% greater yields of mung bean and moth bean (CAZRI, 2000). Numerous *in-situ* moisture conservation techniques like inter-plot, micro-catchment and inter-row have been developed and perfected for different soil, topographic and rainfall situations of hot arid region. The details of these techniques are described under water harvesting heading in this review.

The soils of arid regions are sandy having low moisture retention capacity and higher infiltration rate and hence prone to loss of soil moisture by deep percolation. CAZRI initiated work on potential of sub-surface moisture barriers. Bentonite clay, pond sediments, asphalt and vermiculite were studied for their efficacy in decreasing deep percolation of soil water. The placing of 5 mm thick bentonite clay and pond sediments at 60 cm were 50-70% effective in retaining total rainfall in the root zone. Gupta and Aggarwal (1980) found that use of asphalt as sub-surface barriers (2 mm thick at 60 cm depth) decreased deep percolation by 1/6 times and increase pearl millet by 40–50%. However, these interventions have found very little adoption at farmers' fields.

Apart from moisture stress, high thermal regimes of the soil are an important constraint for crop production in hot arid regions. Mulches have been reported to favorably modify the hydrothermal regimes of soil and suppress weeds. Evaporation from the soil surface is a major pathway of water loss; it accounts for 20–43% of ET in different crops in hot-arid region (Singh and Singh, 1993). The beneficial effect of mulch in hot arid region is reported by Gupta (1978, 1980) and Dauley and Singh (1980). Gupta and Gupta (1983) reported a significant increase in yield of green gram, moth bean and cluster bean with the application of grass mulch @ 6 t ha^{-1}. Mulches have been found suitable for winter crop raised on rainy season conserved moisture (Dauley and Singh, 1982). Besides reduction in evaporation loss, mulching helps in suppression of weeds (Gupta and Gupta, 1985), reducing surface runoff, increasing infiltration and moderating the thermal regimes. Non-availability of suitable materials and uneconomical operation restrict its large-scale adoption.

Water harvesting and supplemental irrigation

Water harvesting which is collection of runoff from treated or untreated catchment's area for its subsequent uses has been practiced since ancient times. The number of variants of water harvesting in accordance with their suitability to rainfall, soil, topography, runoff, crop and socioeconomic characteristics have been standardized. The inter-plot water harvesting having a ratio of 2/3 of cropping area to 1/3 of catchments area with 5% slope showed increased soil moisture and yield of several rain fed crops in arid region of India (Singh 1988; Singh, 1985). The in-situ water harvesting techniques i.e. inter-row water harvesting (IRWH) showed appreciable yield improvement of rain fed crops. Under inter–row system (ridge–furrow configuration), furrows (30–40 cm width, 15 cm deep) are made keeping the inter ridge space of about 60-90 cm. The ridges are constructed across slope to reduce runoff and increase concentration of water in furrows. This system is suitable for soil having medium to heavy texture with deep to moderate depth. In light textured soil, the crops are sown in furrows, while in case of medium to heavy textured soil the crops are sown in ridges to minimize the negative impact of water logging.

The collection of water in surface water collecting structures i.e. *Khadin* and farm ponds and using the collected water for supplemental irrigation to the crops during long dry spells showed considerable yield improvement and water productivity in rainfed arid region. The significance of supplemental irrigation in rainfed crops of arid region is well documented by Singh and Singh (1993), Kathju *et al.* (1993), and Rao and Aggarwal (1985). Singh and Singh (1997) reported that inter-plot water harvesting had 2425 and 1240 kg ha^{-1} yield as compared to 2320 and 400 kg ha^{-1} yield of pearl millet in good and low rainfall year, respectively.

Nutrient management

Soils of arid regions are low in N, low to medium in P and medium to high in K. Therefore, the adequate nutrient management is necessary for sustainable crop production in this region. Nitrogen plays an important role in getting better yield of crops in arid regions and response to N depends on rainfall. Aggarwal and Kumar (1996) reported that application of 80 kg N ha^{-1} increased yield of pearl millet in good rainfall year, but in a drought year the significant increase in yield was found up to application of 40 kg N ha^{-1}. Joshi and Singh (1985) reported linear increase in yield of pearl millet up to the application of 40 kg N ha^{-1}. Similarly, the significant increase in yield of legume, oilseed and grasses with N application has been reported. Daulay and Singh (1982) reported increased seed yield with N application (60 kg ha^{-1}) for sesame. The enhanced yield, protein yield of *Cenchrus setigerus* with 60 kg N ha^{-1} is reported by Bhati and Singh (1982). Phosphorus plays very important role in development of root system, seed setting, and nodulation in legume crops. The enhanced yield with P application in pearl millet (Singh and Singh, 2002), and legumes (Mali and Mali, 1991) has been reported from arid region. Mali and Mali (1991) reported that application of P @ 17.2 kg ha^{-1} gave highest grain yield of cowpea. Joshi and Mali (2004) indicated that application of 25 kg P ha^{-1} had greater protein and gum content in cluster bean. Among the secondary nutrients, S application significantly increased yield of crops in arid region. The significant increase in yield of cluster bean has been reported with application of S @ 20 kg ha^{-1} (Kumar *et al.,* 1999). Application of S is reported to increase protein content in moth bean (Jain and Raheja, 1980).

The escalating price of fertilizer and risk of using chemical fertilizer due to erratic rainfall, the use of chemical fertilizer in arid region is considered as risky. The use of suitable biofertilizer seems to be suitable option to supply the nutrient to crops in this region. Pearl millet seed inoculation with *Azospirillium* is reported to increase yield of pearl millet (Joshi and Rao, 1989). An 8 -15% higher seed yield for cluster bean and moth bean with seed inoculation *Rhizobium* has been reported from arid region (Faroda *et al.,* 2007). The P –solubilizing bacteria are found to effective to increase P availability to pearl millet, green gram and cluster bean in arid soils (Tarafdar *et al.,* 1991, 1995).

It is well recognized that integrated nutrient management is imperative to maintain sustainable crop productivity and soil health. Integration of 10 kg N along with 10 t FYM ha^{-1} for pearl millet gave greater yield than sole application of N through chemical fertilizer (Aggarwal and

Venkateswarlu, 1989). Yield of pearl millet with application of 40 kg N+ 10 t FYM was at par with 80 kg N ha^{-1} (Aggarwal and Kumar, 1996). Aggarwal *et al.* (1997) reported that addition of crop residues and FYM generally enhanced soil fertility status (N and P availability, organic matter, enzyme activity) of arid soils of Rajasthan. The cluster bean residues and FYM increased pearl millet grain yield 0.1 to 0.2 t ha^{-1}, compared with no residue. The use of cluster bean residues or FYM with fertilizer N improved N-use efficiency by 20 to 30%. Results indicate that incorporation of crop residues and FYM in arid tropical soils benefits soil water storage, soil nutrient availability, and crop yield. Saxena *et al.* (1997) reported that pearl millet-cluster bean rotation and monoculture of pearl millet with the application of 5 t ha^{-1} FYM gave 17.2 and 6.1% higher yield than monoculture of pearl millet, respectively. Different nutrient management strategies have been reported to increased water productivity by 13–37% for cluster bean in hot arid region (Rathore *et al.,* 2007).

Alternate land use system

Arable crop production in dryland regions is confronted by several bio-physical constraints, such as low and erratic rainfall, high evapo-transpiration, and extreme temperature variations. Therefore, the crop production is low and unstable. Under such situation, multi-species cropping system which integrate suitable under and ground storey crops with the perennial woody plants (trees) is suitable option. The woody perennials provide economic products (fruit, fodder, fuel), additional income, imparts stability in production, ameliorate microclimate, and improve soil productivity. Growing of trees with agricultural crops is an age-old practice in arid region. *Prosopis cineraria*, *Holoptelea integrifolia* and *Hardwickia binata* are suitable tree species for agri-silviculture system in rainfed hot arid regions (Muthana and Arora, 1977, Shankarnarayan *et al.,* 1987). Growing of suitable tree with arable crop increases productivity per unit of land compared to sole arable cropping in arid region (Harsh and Tewari, 1993). Bhati *et al.* (2008) reported that arable crops like cluster bean, green gram and pearl millet gave better yield in association with *P. cineraria.* Besides better yields of arable crops, bonus yield of dry leaves and twigs (650–1050 kg ha^{-1}) and fuel wood (1800–2500 kg ha^{-1}) could be obtained from tree through lopping. Besides, higher productivity the integration of trees improves soil properties. Tarafdar (2008) reported that integration of *P. cineraria*, *T. undulata* and *Z. mauritiana* had 13–53% higher microbial population and 18–77% higher microbial biomass compared to sole crop. At Pali, strip cropping of *Lawsonia inermis* and cluster bean (*Cyamopsis tetragonoloba*) (4: 2 rows) gave higher return compared to sole planting of component crops (Singh *et al.,* 2005). In arid Gujarat, cultivation of cowpea, green gram and cluster bean with *Azadirachta indica* and *Alianthus excelsa* trees gave 59.3% and 25.7% higher income than sole cropping. Besides higher income these systems provide fodder, fuel, timber and improve soil organic carbon (Patel *et al.,* 2008).

Horticulture-based production system is a suitable option for improving productivity, employment opportunities, economic condition and nutritional security in arid region (Chundawat, 1993; Pareek, 1999; Chadha, 2002). *Emblica officinialis*, *Punica granatum*, *Aegle marmelos*, *Phoenix dactylefera*, etc. are suitable fruit trees for areas having irrigation facilities, whereas *Capparis decidua*, *Salvadora oleoides*, *Cordia dichotoma*, *C. gharaf*, *Ziziphus nummularia* var. *rotundifolia*, and *Z. mauritiana* are suitable for areas receiving annual rainfall <300 mm. *Solanum melongena*, *Lagneria siceraria*, *Luffa acutangula, Luffa cylindrical, Citrullus lanatus, Citrullus lanatus var. fistulosus, Cucmis melo var. utillismus, C. melo var. momardica, C. callosus* and *Cyamopsis tetragonoloba* are suitable vegetables for horticultural- based farming system in arid region (Pareek and Awasthi, 2008). In order to mitigate the risk of total crop failure, suitable crop combinations in the interspace of orchard during initial years can generate extra income, improve productivity, ameliorate and improve the ecological situation (Awasthi *et al.,* 2008). In agri - horti system involving *Ziziphus* and *Vigna radiata*, in the year which had rainfall 51% less than long-term average (360 mm), the yield of *V. radiata* was 44% less whereas in sole crop the yield was 51% less. This indicates that the reduction in yield of arable crop in less rainfall year is less in agri-horti system compared to sole cropping. This system can provide year-round supply of fodder for 5 goats/sheep ha^{-1} and fuel wood for family of four members (Faroda, 1998). Green gram inter-planted with *Z. mauritiana* (400 plant ha^{-1}) gave Rs 2890 ha^{-1} higher return than sole cropping in year receiving 210 mm rainfall (Gupta *et al.,* 2000). Singh (1997) reported that interplanting of clusterbean, mungbean and sesame with ber had three-fold higher yields of *ber* fruit compared to sole *ber* plantations. Singh *et al.* (2003) could get 5–20% higher seed yield of legume in intercropped with *ber* compared to sole cropping of legumes. Pearl millet, green gram, isabgol (*Plantago ovata*) medicinal crop, sorghum and cumin are found suitable crops for inter-planting with pomegranate (*Punica granatum*) fruit tree in Jalore district (Gupta, 2000). The study of multi–species cropping systems at Bikaner shows that the growth and yield of perennial component were more under the multi-species cropping systems, i. e. *Emblica officinalis* + *Z. mauritiana* + *C. carandas* + *C. tetragonoloba* + *S. melongena* and *E. officinalis* + *Z. mauritiana* + *C. carandas* + *C. tetragonoloba* + fallow. Minimum yield was recorded in sole perennial crops (Arya *et al.,* 2010). An economic analysis of alternate land use systems by CAZRI clearly demonstrates that integration of perennial vegetation i.e. agroforestry, agri-horticulture, agri-pasture and silvo-pasture had 1.69, 1.46, 1.87 and 1.66 B: C ratio (Benefit: Cost ratio) compared to 1.24 from arable crop production (Bhati, 1997).

The strategies of cropping system will vary with the agro-ecosystem. Vittal and Bhati (2009) opined that the strategies for arid regions can be narrated in two broad groups:

1. For area receiving rainfall below 350 mm, management of *Khadins*, sand dunes and underlying cultivated fields, index catchments with the impeded drainage system need to be adopted. Stabilization of sand dunes/sandy, semi-rocky rugged wastelands be integrated with crops and cropping system diversification, wind break and shelterbelts, agri-pasture, top feed and fodder production systems. The cropping should be integrated with trees, shrubs and grasses to sustain the livestock husbandry which is the mainstay of the farmers in these areas. Development of value chain for animal products and by products is also very important for sustainability and economic stability of the area.
2. The strategies to be adopted for the area between 350 and 550 mm of rainfall are adoption of crop diversification, inter/mixed cropping in replacement series coupled with *in-situ* rainwater harvesting and recycling systems, crop rotations/cropping sequences and cropping patterns for SLM, in watershed/ IAD approaches. In this region, there are some areas of deep and medium soils and double cropping of pearl millet-chickpea, green gram-chickpea/mustard on conserved moisture in combination with fruit trees (*ber*) can help in income and employment generation. Livestock husbandry in this zone is also equally important and synergy of cropping system with this component of agriculture ensured with by fodder availability should be given due importance.

Secondary Salinity and Waterlogging

Salts, in variable amounts, are always present in irrigation waters. The input of salts through irrigation may reach more than 10 tonnes ha^{-1} in one year. Most of them remain in the soil when the water is lost by evapo-transpiration. When these salts are not leached to the subsoil and not lost through internal drainage, they will accumulate in the surface soil, reaching levels which may affect the plant growth. When the required leaching is not provided in arid and semi-arid climates, it is required to apply an excess of irrigation water for such purpose. If those excesses of water are not taken away by the natural or artificial drainage systems, probably the leached salts will come back to re-salinize the surface soil.

Water-table-induced salinization

In areas where the water table is hydraulically linked to bare soil evaporation or crop evaporation, water from the water table moves to meet the partial or total evaporative demand. When water is lost to the atmosphere as vapor, salts are left behind in the root zone, salinizing the root zone. The rate of water-table-induced salinization depends on:

- Atmospheric factors such as the evaporation demand and rainfall (intensity, amount and frequency);

- Soil factors such as texture, structure and its geologic origin;
- Water table factors such as depth and water quality; and
- Management factors such as crops grown and irrigation practices (intensity and amount).

Interactions among these factors are complex, and have been modeled (Robbins *et al.,* 1995). Although it would be difficult to prioritize factors influencing water-table-induced salinization, it is reasonable to conclude that a shallow water table is a key factor, because several studies confirm the link between water table-rise and water-table-induced salinization in the Indus basin irrigation system (IBIS) (Kuper, 1997; Rehman and Rehman 1998; Aslam *et al.,* 1999; Ejaz and Ahmad 1999).

Marginal-quality-water-induced sodicity

Many of the ground water resources in arid regions of Rajasthan are highly saline while water low in salinity often contains high residual sodium carbonate (RSC). Irrigation with such water results in sodification of land. As a result, sodicity with a pH 9.2 to 10.0 and ESP 40-50 percent has been developed. Even RSC water of 5 mel^{-1} has induced high sodicity in the rainfall zone of 200 to 300 mm (Joshi and Dhir, 1994). The soils under this situation acquire unusual hardness; water infiltration reduced to a greater extent and workability of soils becomes very difficult. The emergence of seedling, growth of crop and yield of harvest are severely affected under the described situation (Joshi, 1992). Large areas irrigated with high RSC water have gone out of cultivation. Even frequent ploughing during rainy season and application of higher dose of farmyard/ organic manure could not produce desired yield of restoring the productivity. However, the negative impact of high RSC water on infiltration SAR and nutrient availability could be mitigated, if irrigation is done after the gypsum treatment @ 50 and 100% of soil requirement. The improvements were also reflected in terms increased yields in loamy sand soils of Barmer and Jodhpur districts of Rajasthan (Joshi and Dhir, 1990; Mahesh Kumar *et al.,* 2016a).The quantity of gypsum required by soils plus to neutralize RSC in excess of 3 mel^{-1}, resulted an increase of 400-1600 kg ha^{-1} grain yield of wheat (Mahesh Kumar *et al.,* 2016a). The higher quantity of gypsum (100% GR) is more effective in lowering soil pH by 0.1 to 0.8 units and decrease of SAR by 6.4 to10.7 and improvement in nutrient status could be attained (Mahesh Kumar *et al.,* 2016a). Inadequate and unreliable canal water supplies (especially at the tail end of distributaries and water courses) and change in cropping patterns forced farmers to use this marginal-quality water for irrigation. Depending on the circumstances, groundwater meets 10 to 90 percent of the irrigation requirements (Kijne and Van der Velde, 1990). Kuper (1997) also reported that irrigation with groundwater, which is rich in sodium and bicarbonates leads to the sodification of the soil. Farmers indicate that the adverse effects of poor-quality irrigation water are felt by them quite rapidly. After two to three irrigations with such water, a surface crust develops. In addition to such a development, there is a likelihood of hard layers occurring in the soil within an irrigation season. Aslam and van Dam (1998) modeled the conjunctive use of canal water and groundwater of relatively high sodium content and found that a loam soil could become sodic within a short period of 3 years.

Secondary salinity mainly results from human activities, usually land development and agriculture. Common sources of secondary salinity include:

- irrigation—irrigated areas, either because of rising groundwater tables (from excessive irrigation) or the use of poor-quality water
- dryland—non-irrigated landscapes, generally because of clearing vegetation and changes in land use
- sea water intrusion—coastal aquifer systems where sea water replaces groundwater that has been over-exploited
- point source—large levels of salt in effluent from intensive agriculture and industrial wastewater

Water logging and secondary salinity in IGNP and Narmada canal commands of Rajasthan

The Indira Gandhi Nahar Pariyojna (IGNP) is one of the largest water resources projects in the world, aiming to transform the desert into an agriculturally productive region. The IGNP was conceived and executed to utilize 7.59 million acre feet water from Ravi-Beas to convert 1.96 million ha of land in the arid desert to agriculturally productive land. The project encompasses the districts of Sri Ganganagar, Hanumangarh, Churu, Bikaner, Jaisalmer, Jodhpur and Barmer and on completion will cover Culturable Command Area (CCA) of 19.63 lakh ha of land. The project has been divided into two stages. Stage I comprises a 204-km long feeder canal, having a discharge capacity of 460 m^3sec^{-1}. The stage I also consists of a 189 km long main canal and 3454 km long distribution system to serves 5.53 lakh hectare CCA. Stage II comprises a 256 km long main canal and 5,606 km long lined distribution system, and serves 14.10 lakh hectares CCA. The introduction of irrigation in desert area brought about considerable prosperity to the farmers. Some of the positive impacts of introduction of irrigation in the desert includes improvement in micro climate, change in land use/ cropping pattern, improvement of soil and moisture conditions and associated soil fertility and biological properties, but it has also brought in its wake the problems of water logging and secondary salinization. However, after few years of irrigation with canal water, some negative effects emerged such as rise in the water table, waterlogging, formation of marshy lands and soil salinity at few places. Lack of proper drainage, excess irrigation, seepage from the canals and poor drainage planning under such situation have resulted in a rise in water table, followed by salinity build-up. Under these situations two different sources of soluble salts are accumulated in irrigated soil; one is irrigation water itself, and the sub-soil or the parent rock impregnated with salts before irrigation began. The average rate of rise in water table in the command areas of IGNP 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 (Kar *et al.,* 2009). Introduction of canal irrigation in the Thar Deserts of Rajasthan has completed journey from one wasteland (water starved) to another wasteland (water soaked). At first instance, reduction in crop yield is observed which is followed by restrictions on the type of crop, and ultimately leads to the abandonment of previously productive land at few places. The current estimates indicate that about 0.208 million ha land is already affected by waterlogging and associated salinity in IGNP command area (Table 2). The salt affected and water logged soils in this command are mainly located in Anupgarh Branch, Suratgarh Branch and Charanwala branch.

The Narmada canal project was extended up to Rajasthan to provide irrigation to the drought prone areas in Jalore and Barmer districts. The Narmada Canal Project has been designed to utilize 0.50 MAF of Narmada water for a total of 2.46 lakh hectare CCA. Presently the Narmada canal through lift and flow systems providing irrigation facilities in about 2.39 lakh hectare area in both districts. With the available irrigation water

Table 2. Waterlogged area (ha) in IGNP commands of Rajasthan

Category	Years						
	2001-02	2002-03	2003-04	2004-05	2005-06	2006-07	2007-08
			Stage I				
Waterlogged area	10098	5755	2531	2968	3125	6875	1875
Critical area	11355	8750	9259	10625	11250	16875	12500
Potentially sensitive area	179170	164375	195000	168750	196875	202150	181250
			Stage II				
Waterlogged area	78	16	4	4	484	805	320
Critical area	1261	453	317	476	1129	2576	1120
Potentially sensitive area	18304	24572	13481	16018	18548	15906	11840

Waterlogged area (water table within 0 to 1 m), Critical area (water table within 1 to 2 m), Potentially sensitive area (water table within 2 to 6 m) (Source: CAD, IGNP, Bikaner) from Narmada canal, cultivating crops in this area have found its reality in the command areas. The crop production in the canal command areas has been increased by manifold with introduction of irrigation facility in arid areas, but it has also brought the problems of secondary salinization and water logging at some locations. The development of salinity in the newly developed command area of Narmada canal in Rajasthan has arisen chiefly from the pre-existing salt deposits in the sub-stratum rather than from the irrigation water (Mahesh Kumar *et al.,* 2016b). Sub-soil conditions, resulting in waterlogging, a rising water table and the resultant salinity has already rendered out of cultivation some parts of the Narmada canal command area in Sanchore tehsil of Jalore district. Saturation extract analysis of these soils revealed that the pH and EC of these soils varied from 7.7- 9.5 and 1.6 to 41.5 dS m^{-1}. Among the cations Na was dominant followed by calcium plus magnesium. While chloride followed by sulphate were by and large the dominant anions and were present in the range 16 to 156 and 12-126 me l^{-1}, respectively (CAZRI, 2015).

Management of secondary salinization

Improved irrigation practices

Although techniques such as laser leveling, furrow irrigation, corrugated basins, sprinkler irrigation and drip-irrigation had been introduced in the IBIS, only a few large landowners have adopted them. Most farmers are aware of the advantages of improved irrigation practices, but lack of exposure to and familiarity with such practices, along with existing constraints (labor, equipment, etc.), make them hesitant in trying them. Among several improved irrigation practices evaluated, the bed-and-furrow method is probably the most appropriate one for most farmers within the IBIS. Alberts and Kalwij (1999) reported that, on average, 17 percent less water was applied per irrigation event to the bed-and-furrow fields compared to the basin fields.

Deficit irrigation

Deficit irrigation refers to deliberate under-irrigation of a crop when compared to its evaporative and leaching needs. As a result, farmers are forced to utilize stored soil-water from the rains or preseason irrigation and capillary up-flow from the water table to irrigate their crops. This recommended concept by Rehman and Rehman (1998) was modeled by Prathapar and Qureshi (1999a). The modeling study showed that in areas where water tables are shallow, irrigation requirements could be reduced to 80 percent of the total crop evapotranspiration without reducing crop yields.

Change in crop selection

Kijne and Van der Velde (1990) found that farmers respond to secondary salinization by changing cropping patterns. They tend to grow more of salt-tolerant and low-water-consuming crops in saline areas.

Agroforestry and biological-drainage

In areas where undulated land topography does not permit gravity surface drains, and where ground waters are saline, water table control can be obtained by bio-drainage to some extent. The potential of certain tree species to draw more water than the agricultural crops because of their deeper root systems, higher transpiration rates throughout the year and the ability to minimize recharge from rain by intercepting it on their foliage, provides a technique for keeping water table under control. *Eucalyptus camaldulensis, E. tereticornis, Atriplex lentformis, Acacia nilotica*, and *Acacia ampliceps* are species that offer a great potential to work as bio-pumps (Tanwar, 1998; ACIAR, 1997; Dagar and Minhas, 2016). These plantations in fact work as biological pumps that can transpire large quantities of water. Studies conducted at the Forest Research Institute, Dehradun have sown that the average weekly transpiration rate of Eucalyptus species of one year age was between 2.5 to 11.5 gm of water per day per 100 sq.cm of leaf area. Experimental evidences from CSSRI, Karnal, show that both Eucalyptuses and poplar have very high potential for water consumption (Minhas *et al.*, 2015; Yadav et al., 2016). During 7-10 years of planting under low (163 trees per ha), moderate (517 trees per ha), and high (1963 trees per ha) density of *Eucalyptus*, the annual transpiration rate ranged between 418-473, 1373-1417, and 1567-1628 mm, respectively without any surface inundation or much ground water recharge. These solutions to waterlogging and secondary salinization appear slow responsive but in the long run would be certainly beneficial for the command areas.

Mechanical reclamation

Since evaporation from the water table deposits salt on the soil surface, breaking the hydraulic connectivity of capillary up-flow by cultivating abandoned soil prior to and in between monsoon rains would lead to the reclamation of saline soil. In this strategy, monsoon rains provide leaching, while cultivation breaks up the hydraulic connectivity.

Broadcasting soil amendments

Application of chemical amendments such as gypsum, calcium chloride dehydrate, sulfuric acid, hydrochloric acid and farmyard manure can reclaim sodic soil in the IBIS. Soil amendments are usually broadcast across the field, and ploughed in. Thus, treatment is limited to surface layers and the quantity of amendment needed is high.

Gypsum slotting

Reclamation of sodic soil requires an increase in the infiltration rates, so that water can flow through the soil matrix and leach the sodium ions. Short-term increases in the infiltration rate can be achieved mechanically by plowing. However, medium- to long-term solutions require the replacement of sodium by divalent (calcium or magnesium) ions. Therefore, an ideal solution to reclaiming sodic soils requires a combination of mechanical and chemical measures.

Conjunctive water use

The poor-quality of groundwater constrains its recycling and reuse as a means of crop irrigation, without proper management practices. Continuous recycling and reuse of saline-sodic ground water causes an imbalance in the salt balance of an irrigation system, in general, and in the crop root zone, in particular (secondary salinization). Direct use of saline-sodic tube well water cannot be made for crop production without having a proper soil, water and crop management system in place. Under these conditions, frequent light irrigations, use of chemical amendments (gypsum, H_2SO_4, etc.), along with adequate leaching, growing salt-tolerant and moderately salt-tolerant crops in proper cropping sequence are essential requisites, if saline-sodic tube well water is to be used for irrigation on a sustainable long-term basis (Chaudhary *et al.,* 1992; Ghafoor *et al.,* 1998; Ahmed *et al.,* 1998). Conjunctive use of good-quality and bad-quality waters through blending or cyclic application could be practiced to minimize the adverse effects of poor-quality waters on land and water resources. A blending strategy is useful under the conditions when fresh and saline water qualities are such that the mixed water would have less salinity than the threshold salinity of a given crop.

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