From Research Station to Farmer's Field: Nutrient Management Research for Millet-based Cropping Systems of Western Rajasthan

International Crops Research Institute for the Semi-Arid Tropics

Central Arid Zone Research Institute

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Abstract

A multidisciplinary team of scientists from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the Central Arid Zone Research Institute (CAZRI) and representatives of the Rajasthan Department of Agriculture and Rajasthan Agricultural University met to plan the transition from on-station to on-farm research in nutrient management. This volume reviews nutrient management research for rainfed pearl millet-based cropping systems; past and current on-farm research and extension in western Rajasthan; and the application of cropping systems models in on-farm research. The final section summarizes the discussions and recommendations of the workshop.

These research activities were partially supported by the Japanese Official Development Assistance and the Australian Centre for International Agricultural Research.

Cover *Farmers map the soils of their village. This participatory exercise serves the selection of sites for nutrient management experiments.* (Photo Bjorn Seeling).

From Research Station to Farmer's Field: Nutrient Management Research

for Millet-based Cropping Systems of Western Rajasthan

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1997

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Preface

ICRISAT's Integrated Systems Project 1 (ISP1), "Strategies for enhanced and sustainable production in rainfed short-season (60-100 days) millet/legume/ livestock based production systems," has a broad research agenda. It aims at improving millet production systems in Sahelian Africa and the southern and eastern margins of the Thar Desert in Asia. Areas of research include crop improvement; genetic diversity; fodder production; integrated pest disease, and weed management; integrated resource management; soil and water conservation; nutrient and water management; and communication techniques.

Although environments and cropping systems may be similar across the target regions, successful nutrient management research requires a focus on the constraints of a particular region. To better structure our research in the Asian target region of ISP 1, a planning workshop was held 20-22 May 1996 in Jodhpur, Rajasthan, India, with participants from the Central Arid Zone Research Institute (CAZRI), Rajasthan Agricultural University (RAU), the Rajasthan State Department of Agriculture, and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

The national agricultural research organizations represented at the workshop have a long tradition of nutrient management research. Although research initially focused on irrigated crops, regional fertilizer recommendations are today available for all major dryland crops. Fertilizer recommendations established for the highly variable and less productive arid environments of western Rajasthan and Gujarat give profitable yield increases on research stations. In spite of these promising results, however, farmers seldom use fertilizer on dryland crops of the arid environments.

During a workshop on nutrient management issues, held earlier in 1996, we had found that farmers perceive the fertility status of their soils and manage it through legume rotations, crop mixtures, application of farmyard manure (FYM), animal penning, and fallowing.

Several issues arose during that first workshop:

- What constraints prevent farmers from using purchased nutrient inputs, even though they perceive a need to restore soil fertility by applying nutrient sources from their own farms?
- How much do legumes, FYM, and animal droppings actually contribute to nutrient supplies in farmers' fields?
- Can farmers improve their nutrient management through supplemental use of purchased nutrients?
- What would be the best strategy to guide such applications?

CAZRI and ICRISAT scientists who participated in the first workshop realized that participatory on-farm research would be a promising approach to answering these questions. Consequently, this second workshop was held to exchange information on nutrient management research conducted in western and central Rajasthan and to plan future collaborative on-farm research. Specific workshop objectives were to

- review the existing knowledge relevant to nutrient management for dryland cropping in the region;
- identify promising nutrient management strategies that might lead to improved technology;
- determine the scope for collaboration in future research;
- evaluate the scope for using cropping systems models in on-farm nutrient management research;
- develop and/or coordinate on-farm research plans involving the organizations represented at the workshop; and
- identify suitable research locations.

The workshop discussions, summarized in the last chapter, brought to light important issues that need to be addressed in nutrient management research.

Reducing the risk of fertilizer application is the key to wider acceptance of nutrient management recommendations. Promising results of on-station experiments suggest that response application schemes for fertilizer may be the way to achieve this goal, if farmers' participation in the process of technology development is assured. The collaborative research plans developed during this workshop are based on these experiences and will contribute to greater food security and sustainable land use in the harsh arid environment of western Rajasthan.

B Seeling

Opening Address

A S Faroda[1]

Distinguished participants:

It gives me great pleasure to welcome you all to CAZRI and to this planning workshop for on-farm nutrient management research in Rajasthan. This time of year is normally very dry and hot in Jodhpur, but this year it has rained a little, and this hopefully will make your stay comfortable here in this Sun City, the gateway to the Indian desert.

Western Rajasthan, occupying nearly 62% area of the Indian arid zone, is the most thickly populated desert in the world, with meager, overexploited natural resources and a predominantly agrarian base. Farming is almost entirely rainfed. The rainfall has a high coefficient of variability in this zone. Even the onset and recession of the monsoon play hide-and-seek with the farmer. The poor physicoedaphic characteristics, coupled with frequent and intermittent droughts, create a gloomy scenario. Perhaps in no other habitat are plants subjected to such rigors of fluctuating weather and adverse edaphic conditions as in these arid regions.

Farming in this zone, therefore, is for sustenance and survival. Farmers grow crops that have withstood these conditions for centuries: pearl millet among cereals and cluster bean, moth bean, and mung bean among legumes. Thus we have some choice of legume crops but none of cereals. Pearl millet is the only crop for arable farming, beyond which we move to pastoral activities and even less intensive forms of agriculture. Pearl millet has been a measure component of arid land cropping systems followed here in India and in the Sahelian countries.

Despite differences in locations and cultures of the peoples who inhabit them, these areas have striking similarities. They represent one of the poorest resource bases for cropped areas in the world. Subsistence agriculture predominates, and risk of crop failures is high, with drought and poor soil nutrient status significantly limiting production. Soils in these areas contain more than 90% sand and little organic matter; yet surface crusting is common. This problem is further compounded by low-input management strategies that are sustainable only at very low production levels.

The participation of ICRISAT in our effort to improve the productivity of the arid zones, therefore, is not only logical but imperative, considering our common interests. We made a beginning last year in this direction through our collaboration on ICRISAT's Integrated Systems Project 1 (ISP1). I am happy that this workshop is organized to further strengthen the links between us by planning for the nutrient management research to be taken up in coming seasons. I am

1. Director, Central Arid Zone Research Institute (CAZRI), Jodhpur 342 003, Rajasthan India.

confident that this will help develop strategies for enhanced and sustainable production in rainfed areas with short growing seasons.

Considerable work has been done at CAZRI on various aspects of nutrient management strategies. I am sure the participating scientists from CAZRI will present a complete review, so that future research needs are well defined and decided.

As you are aware, nutrient application promotes root and shoot growth and confers other advantages, resulting in increased water-use efficiency. Since water is the most severely limiting factor in arid areas, water-use efficiency can be considerably increased if soil and crop management is good and fertilizers are used bearing weather data in mind. Without a proper awareness of weather and soil conditions, fertilizer use may be beset with difficulties. In my considered opinion, however, if application rates and carriers of nutrients are decided with full appreciation of soil and weather conditions and if time and method of application are properly determined, the chances of improving production with fertilizer use in arid areas are good. I understand that the modeling component of our collaborative research program will be of help in this direction. I am happy that on-farm trials are also being planned to meet these objectives.

I thank ICRISAT for hosting this workshop at CAZRI. I hope that all of you will contribute fully to the discussions and think hard about what needs to be done and how we can work together to improve the productivity of arid lands. Finally, I wish you all success in your deliberations, which I am confident will be constructive and fruitful.

Thank you.

Response of Pearl Millet-based Cropping Systems to Nitrogen in the Arid Region

N L Joshi[1]

Abstract

Western Rajasthan includes 62% of the 31.7 million hectares of the Indian arid zone. Farming is almost entirely rainfed, and the highly variable rainfall (CV 40%) is the major climatic factor influencing agriculture. Pearl millet is the main crop, grown either alone or in mixtures with different legumes. Fertilizer is applied in small quantities in these areas, and is largely limited to nitrogen. Considerable variation has been observed between seasons and among varieties in the N response of sole pearl millet. The optimum N dose ranged from 23 kg ha^{-1} for local varieties to 84 kg ha^{-1} for hybrids, and varied with the amount and distribution of rainfall during the season. Results suggest that as little as 24 kg N ha^{-1} could be used without seriously reducing pearl millet yields. The application of N increased water use marginally in a good rainfall season, but the consequent increase in water-use efficiency was significant. Balanced application of N, P, and K gave the maximum yields. Response to micronutrients (Fe and Zn) was more marked during a drought than in a normal season. In legume-pearl millet cropping sequences, cluster bean preceding pearl millet was more productive than mung bean or moth bean. Inoculation with Azospirillum brasilense *was found to contribute an amount equivalent to 13 kg ha^{-1} of the N requirement of pearl millet in a sole-cropping system; however, this effect decreased with increase in external N application, and at 40 kg N ha^{-1} the inoculation ceased to increase grain yield.*

Introduction

In the arid regions of India, farming is almost entirely rainfed, and pearl millet is the predominant crop. The arid regions occupy 31.7 million hectares (12% of the geographical area of India), and western Rajasthan includes 62% of the arid area. Pearl millet yields are very low in this region, principally due to recurring droughts. Farmers apply 12-24 t ha^{-1} farmyard manure (FYM) once in 3-4 years, but seldom apply fertilizer—chiefly nitrogen—to pearl millet. Deficiency of N in this zone is considered universal, but the economic benefits of fertilizer application in drought-prone areas has always been debatable. On the one hand,

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Joshi, N.L. 1997. Response of pearl millet-based cropping systems to nitrogen in the arid region. Pages 5-23 *in* From research station to farmer's field; nutrient management research for millet-based cropping systems of western Rajasthan; proceedings of a planning workshop, 20-22 May 1996, Jodhpur, India (Seeling, B. and Joshi, N.L, eds.). Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics and Jodhpur 342 003, Rajasthan, India: Central Arid Zone Research Institute.

where soil moisture is limited, nutrient deficiency may reduce yield, and the addition of some fertilizer is warranted. On the other hand, the fertilizer-induced increases in water use during the early vegetative period may reduce yield by increasing crop water deficit at critical later stages. The reduced availability and utilization of nutrients under dry conditions vis-a-vis fertilizer-induced drought tolerance make the problem even more complex. This paper reviews the response of pearl millet to applied N in different moisture availability situations in the various cropping systems practiced in India's arid areas.

Rainfall and Soil Moisture Variability

Climate is the major factor determining >75% of the variability in the land-use pattern of a region, although other factors, such as soils, topography, and water quality are also important. The efficiency of the agricultural production systems in the arid region is determined mainly by the local climatic conditions. Of these, rainfall is the most important, as it defines the length of the growing season and the availability of moisture within the season for the success of the crop (Ramakrishna 1986).

The hot arid regions of the Indian subcontinent receive the major part of rainfall during the southwest monsoon, from June to September. The mean annual rainfall ranges from 400 mm in the eastern part of the arid zone to <100 mm at Jaisalmer, on the western border (Fig. 1). Rainfall also varies widely from year to year—for example, in Jodhpur, where the highest annual rainfall recorded was 1178 mm in 1917; the lowest, 38 mm in 1918 (Ramakrishna 1988). The coefficient of

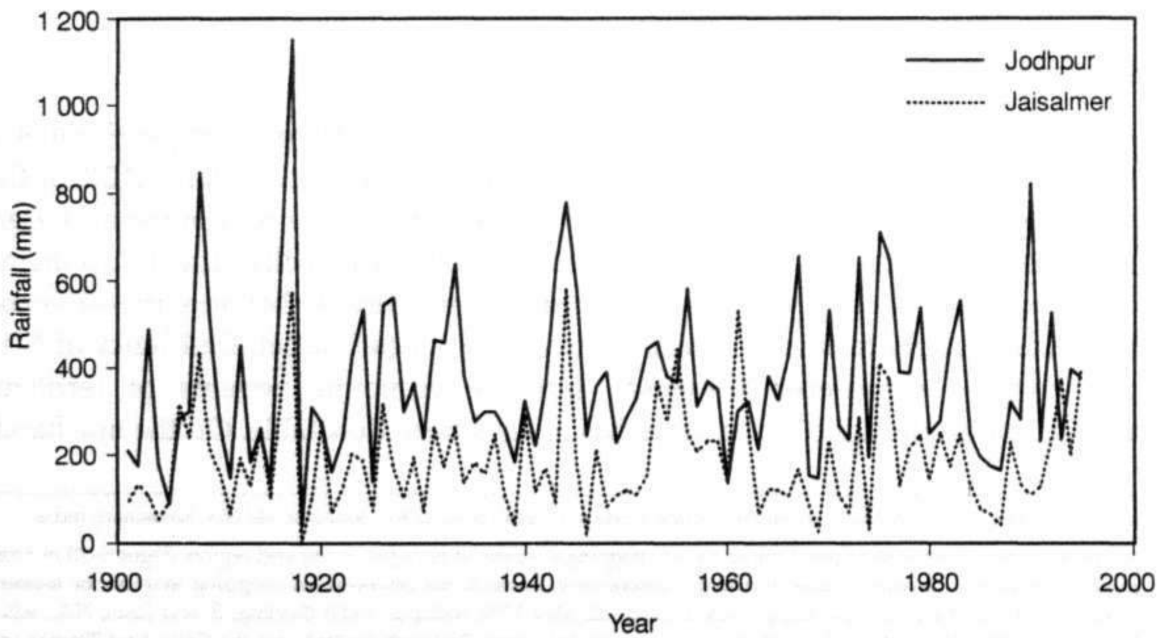


Figure 1. Annual variability in rainfall at two arid-zone stations, Rajasthan, India.

variation (CV) of annual rainfall in the arid region is normally >40%; the seasonal variability is still higher (Fig. 2).

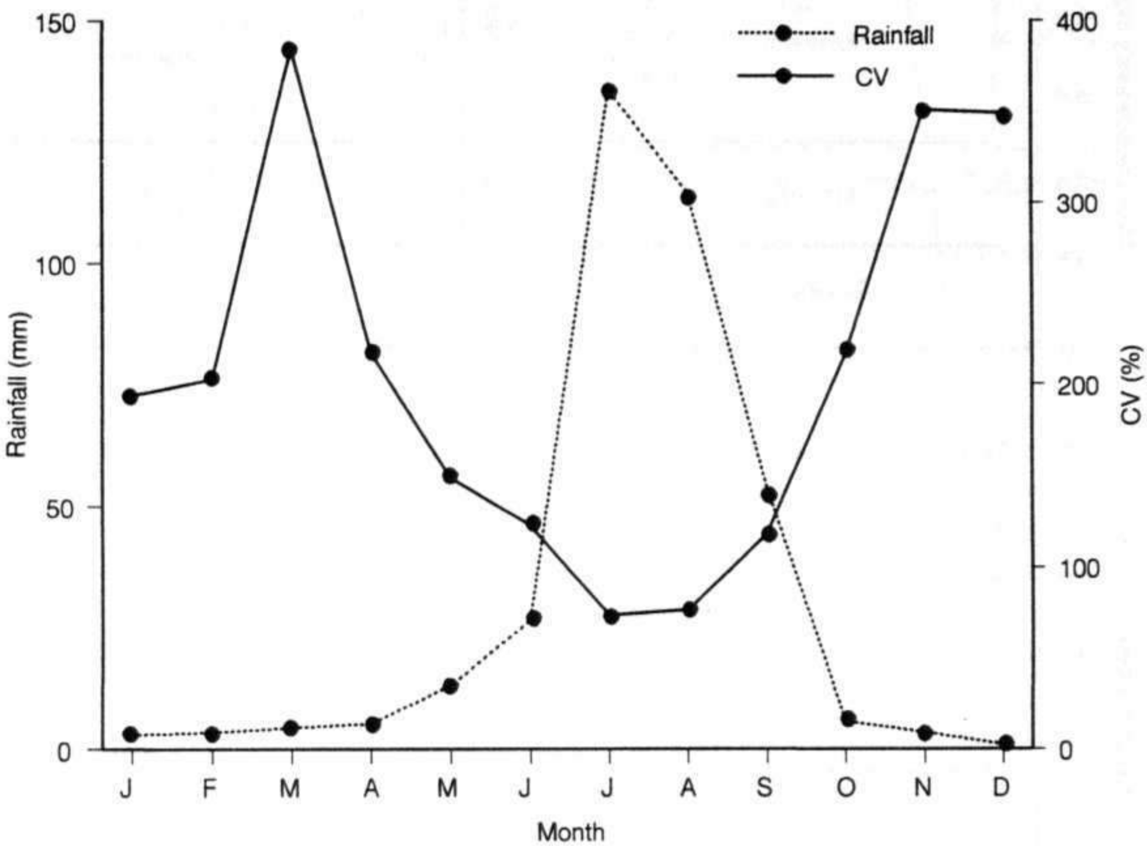


Figure 2. Rainfall in relation to variability in the arid zone, Rajasthan, India.

Pearl millet is generally sown during the first half of July, when the mean precipitation is high, with a low CV. Maximum precipitation is during July-August, after which there is a sharp decline in rainfall, with a higher CV, in September. Rainfall is negligible between October and June. With this distribution, it is normal for crops to suffer water deficit during the critical reproductive phase.

Successive dry years are common, particularly in lower rainfall areas. For example, the region of Jaisalmer has recorded up to 7 consecutive years of below-normal rainfall.

Wide departures from the average pattern of rainfall are common (Fig. 2); consequently, unpredictable moisture deficits can be seen in the patterns of soil moisture encountered during the cropping period in different years (Fig. 3). Despite this variability, we can visualize four situations of moisture availability: normal season (no major stress), moderate stress, severe stress, and extreme stress (Fig. 3). The results discussed in this paper are limited to these situations.

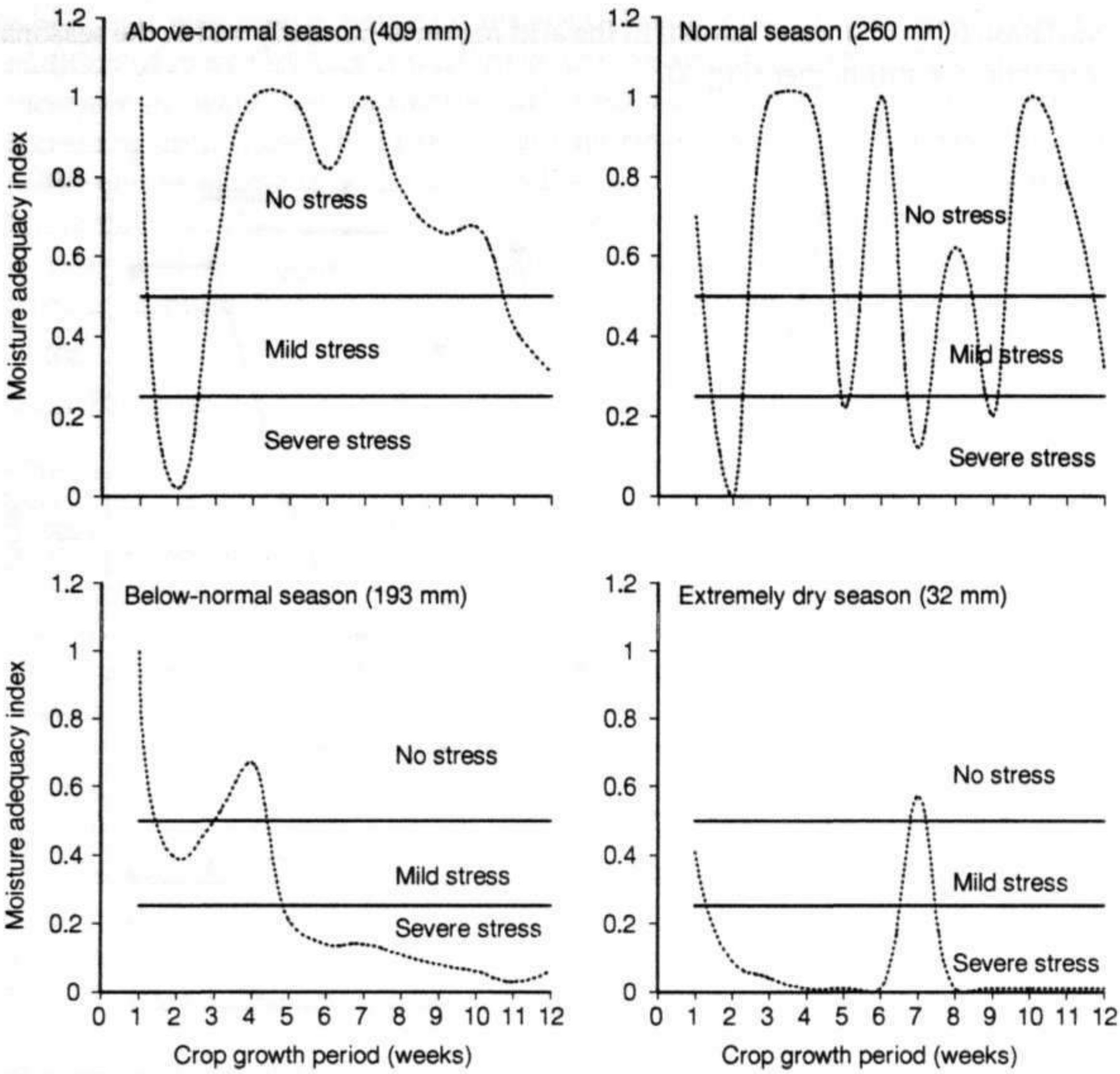


Figure 3. Different moisture availability situations in the arid zone, Rajasthan, India.

Cropping Systems in Arid Regions

Western Rajasthan has been divided into four agroclimatic zones (Ia, Ib, IIa, and IIb), based on rainfall, topographical features, and cropping patterns. Zone Ib (consisting of the districts of Sriganganagar and Hanumangarh) has large areas under canal irrigation and therefore is not included in this paper.

Zone Ia, the Arid Western Plain, covering a geographical area of 12.4 million hectares, includes Jaisalmer, Barmer, Bikaner, and parts of Jodhpur district. In this zone, rainfall imposes serious restrictions on arable farming. Despite rigorous ecological selection over a long period, only a few crops, such as pearl millet, mung bean, cluster bean, moth bean, sesame, and castor are grown in various proportions. Pearl millet is the most important crop; sole-cropped pearl millet or a pearl millet-fallow rotation is common.

Cluster bean, moth bean, and mung bean are legume crops of the rainy season. In irrigated pockets, wheat, barley, chickpea, and mustard are important crops, but yields are fairly low. The majority of farmers in zone Ia prefer mixed cropping to sole cropping, mixing pearl millet, mung bean, moth bean, and sesame. The proportion of pearl millet in the mixture is reduced if sowings are delayed beyond the first fortnight of July Cluster bean is usually sole-cropped and seldom put in mixtures. Table 1 shows the most commonly practiced cropping patterns in this zone.

Table 1. Existing cropping patterns in agroclimatic zone Ia, western Rajasthan, India.

First year		Second year	
Rainy season	Postrainy season	Rainy season	Postrainy season
Pearl millet	Fallow	Fallow	Barley
Moth bean	Fallow	Pearl millet	Fallow
Pearl millet	Chickpea	Fallow	Fallow
Cluster bean	Fallow	Pearl millet	Fallow
Sesame	Fallow	Fallow	Fallow
Pearl millet + grain legumes	Fallow	Sesame	Fallow
Fallow	Fallow	Grain legumes	Wheat
Fallow	Mustard	Cluster bean	Fallow

Silviagripastoral cultivation with production of pearl millet, moth bean, mung bean, cluster bean, and sesame has the potential for increasing incomes and stabilizing crop production in this zone, provided row spacing is wider than presently practiced.

Zone IIa is a transitional plain of inland drainage, with a geographical area of 3.7 million hectares, comprising Nagaur, Sikar, Jhunjunu, and parts of Churu districts. Zone IIb is classified as a transitional plain of the Luni basin, with an area of about 3 million hectares, comprising Jalor, Pali, and parts of Sirohi and Jodhpur districts. Since these zones are transitional between arid and semi-arid, pearl millet, mung bean, cluster bean, and cowpea are the principal rainy-season crops, with mustard, chickpea, wheat, and barley grown in pockets in the postrainy season.

Our experience over several years is that only one crop can be grown in zones IIa and IIb. Rainy-season crops, such as pearl millet, mung bean, and cluster bean can be grown without irrigation if techniques for harvesting water in-situ are adopted; in the absence of such arrangements to augment water supply during the postrainy winter season, only one crop per year is possible. Thus, a mustard-based cropping system, chickpea/barley-based system, and a pearl millet-wheat rotation offer better prospects in irrigated areas. Average yields of mustard, chickpea, and pearl millet are about 0.5 t ha^{-1}, and of wheat, 2 t ha^{-1} in this zone.

The common cropping patterns in zones IIa and IIb are similar to those of zone I, but yields are relatively higher, and the risk of crop failure is lower. In contrast to farmers of zone Ia, those of zone IIa prefer sole crops of pearl millet and legumes to mixtures. Pearl millet is mixed with legumes only when sowings are delayed beyond the third week of July

Most of the crops are well adapted in these subzones, but yields are poor because of fertility depletion in already impoverished soil. Fertilizer use is <15 kg ha^{-1} $year^{-1}$ in some areas, while actual net requirement is about 40 kg ha^{-1}. Most farmers at present are reluctant to use inorganic fertilizers in arid areas, relying instead on FYM to partly meet the nutritional requirements of crops.

Nutrient Management in Cropping Systems

Agriculture in this area of Rajasthan has been traditional, essentially subsistence, agriculture, the most common practice being sole-cropping of pearl millet. The use of fertilizers is meager, and, based on their years of experience and observations, farmers have used fallows to let soil productivity recuperate. However, weeds in fallow lands grow unchecked, and farmers do not till the land for fear of severe wind erosion; therefore, recuperation is inadequate. The practice of fallowing is also declining, with the decrease in land holdings. Pearl millet-based intercropping and cereal-legume rotations are also practiced in some areas. Not much work has been done on integrated nutrient management based on cropping patterns of the region; hence, the emphasis in the succeeding paragraphs is on the most commonly practiced patterns of the arid zone.

Nutrient management in sole pearl millet

Fertilizer is an important input for increasing crop productivity, even in rainfed lands. Nitrogen influences pearl millet yields more than other nutrients (Misra 1964). Better response of pearl millet to nutrients could be obtained if other factors, such as timely weeding, were adopted, to allow maximum uptake of nutrients (Joshi and Panjab Singh 1981, 1985).

Several pearl millet varieties and hybrids have been developed and released. Varietal response to N has been studied at CAZRI from time to time. For local varieties, 23.3 kg ha^{-1} N is optimum (Vyas et al. 1972). The improved varieties are more responsive to N application (Singh et al. 1974; Panjab Singh 1977). The optimum N dose, however, varies considerably between years and among varieties in the arid region (Table 2). Better responses could be expected, even in low-rainfall seasons, because crop yield response is influenced not only by the amount but also by the distribution of rainfall during crop growth. Because of improved N-use efficiency, a marginal fall in optimum dose is expected when rainfall during crop growth is well distributed. Considering the high variability of response in arid areas due to high risk conditions, the use of lower-than-optimum doses has been suggested (Joshi et al. 1984).

Table 2. Production response and economic optimum for nitrogen application to three pearl millet varieties in two rainfall distribution situations.

Seasonal rainfall (mm)	Rainy days	Distri-bution	Variety	Production response	Optimum N (kg ha^{-1})	Expected yield (kg ha^{-1})
280	23	Good	BJ 104	$Y = 5.57 + 0.2623\,X - 0.0020\,X^2$	57.14	1403
			Improved Local	$Y = 4.80 + 0.0920\,X - 0.0005\,X^2$	58.25	846
			BD 111	$Y = 3.56 + 0.1584\,X - 0.0009\,X^2$	69.25	1022
698	16	Bad	BJ 104	$Y = 4.67 + 0.1839\,X - 0.0012\,X^2$	62.57	1148
			Improved Local	$Y = 2.85 + 0.1517\,X - 0.0009\,X^2$	65.53	892
			BD 111	$Y = 4.69 + 0.1147\,X - 0.0005\,X^2$	80.95	1070

Source: Joshi (1984).

The recommendations for using physical or economic optima for optimum yield of pearl millet (Singh et al. 1974; Panjab Singh, 1977; Joshi 1984) presupposed no constraint on the availability of fertilizer. In fact, however, the country is now facing a shortage of fertilizer N. Joshi and Kalla (1986) proposed the use of pragmatic levels of N. For this, a schedule should be worked out to curtail N application without impairing the production potential: the quantities of N are allowed to diminish at a fixed interval, and the cost reduction and consequent net payoff incidental to the reduction in the quantities of fertilizer are iterated until the loss in net payoff is equivalent to the gain in the cost of reduction of fertilizer. This is termed a "pragmatic" level of N.

The results of such studies indicate the possibility of N curtailment of about 24 kg ha^{-1} for pearl millet variety CM 46 and hybrid PHB 12 (Table 3). From the point of view of N economy, it would be desirable to popularize such varieties and hybrids: the N saved on every 3 ha of these can be used for about 1 ha additional area that otherwise may not have received N application at all. Such N savings need to be worked out from time to time for new releases.

Some studies have been made on balanced application of nutrients to effect efficient use of applied inputs and to increase pearl millet yields. Higher yields have been obtained on sandy soils with the combined application of N and P than with N or P alone (Misra 1971). Application of 40 kg ha^{-1} N plus 17.5 kg ha^{-1} P has given 35-150% yield increase in good rainfall years (Mann and Singh 1977). Over 3

Table 3. Relationship of nitrogen applied (kg ha^{-1})[1] to grain yield (kg ha^{-1})[1] in pearl millet in the Indian arid zone.

Variety/ hybrid	N_{max}	Y_{max}	N_{opt}	Y_{opt}	Pragmatic N level	N saving from use of pragmatic N level (kg ha^{-1})
Improved						
Local	84.4	921	63.9	893	39.4	24.5
BJ 104	76.5	1367	66.0	1353	50.2	15.8
BD 111	91.7	1106	74.4	1082	55.0	19.4
CM 46	104.3	1195	84.2	1168	59.5	24.7
PHB 12	101.5	1261	82.5	1250	59.4	23.1

1. N_{max} = maximum N applied; Y_{max} = maximum yield; N_{opt} = optimum N; Y_{opt} = optimum yield.

Source: Joshi and Kalla (1986).

years, the maximum grain yield of pearl millet was obtained with a combined application of 60 kg N, 13 kg P, and 12.5 kg K ha^{-1} (CAZRI 1978).

Few studies have been made of the effect of micronutrients on pearl millet yield in the arid zone. Beneficial effects of trace elements were observed in 1 year during a 4-year study (Misra and Bhattacharya 1966). Application of Fe, Zn, and Mg has given a 15-21% yield increase in traditional varieties (Table 4). With a hybrid, Zn application increased yield up to 13% (Joshi and Panjab Singh 1985). The response to Fe and Zn was confined to the development stage, with significant increases in kernel weight, whereas response to Mg could be seen at all stages of plant growth and development. Responses to micronutrients were more pronounced in a drought year than in normal rainfall years (Misra 1971).

Work on the relations among nutrients applied to pearl millet is also limited. Application of major nutrients (N, P, and K) at times may reduce the Cu uptake by pearl millet (Jain et al. 1967). The H_2PO_4 may reduce the uptake of Cu by some process external to the plant that may result in Cu immobilization. The increased concentration of NH^+_4 and K+ ions due to application of N, P, and K cause retention of available Cu in the soil, indicating antagonistic effects of these ions on the uptake of copper (Misra and Hwari 1964).

Research conducted on different aspects of fertilizer use— i.e., optimum and pragmatic levels of N, balanced use of major nutrients, response to micro-nutrients, etc.—shows the responsiveness of pearl millet to fertilizers. Application of fertilizers under arid conditions should therefore be given greater emphasis, as hungry plants transpire water without producing food. However, fertilizers will not invariably increase crop yield under arid conditions. For example, if the average and anticipated rainfall (on the basis of the previous several

Table 4. Effect of micronutrients on grain yield of pearl millet over four seasons in the Indian arid zone.

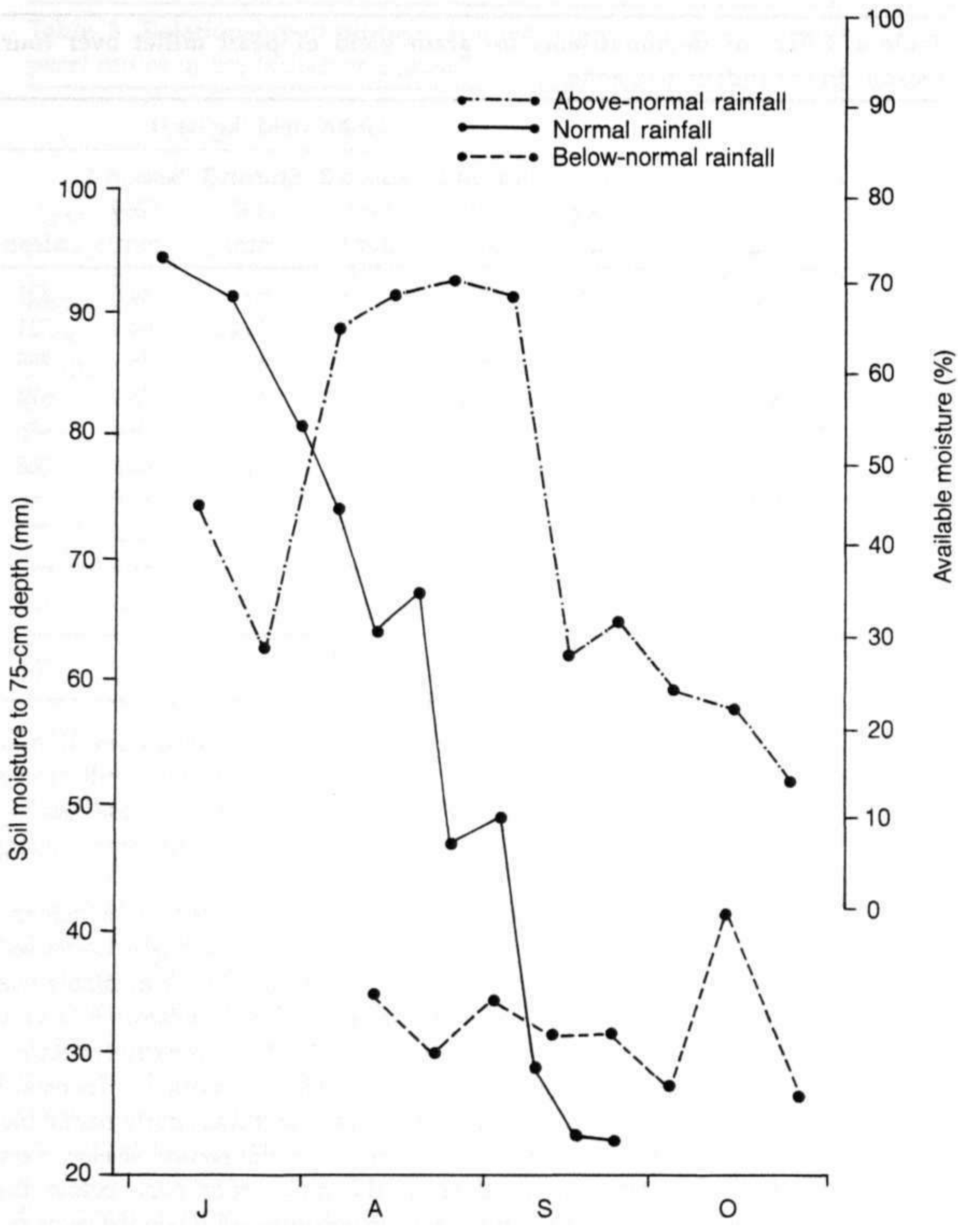
			Grain yield (kg ha^{-1})				
Element	Source	Rate (kg ha^{-1})	Season 1 (450 mm)[1]	Season 2 (355 mm)	Season 3 (137 mm)	Season 4 (269 mm)	Mean
Fe	$FeSO_4$	32.6	970	813	657	847	821
Mn	$MnSO_4$	16.8	840	1028	334	648	721
Zn	$ZnSO_4$	11.2	997	491	473	755	798
Cu	$CuSO_4$	11.2	844	809	459	584	674
B	$Na_2B_4O_7$	5.6	768	795	73	764	675
Mo	$(NH_4)_6Mo_7O_{24}$	0.1	790	704	484	694	668
Mg	$MgSO_4$	163.0	880	872	512	857	780
Mixture			1114	900	415	686	778
Control			853	866	415	564	675
LSD (5%)			NS	NS	141	NS	NS

1. Figures in parentheses show total seasonal rainfall.
Source: Misra and Bhattacharya (1966).

years) is not received and fertilizer applied is used to the maximum, it may accelerate the initial growth of the crop to the extent that almost all stored moisture is exhausted by the time the crop enters the reproductive phase, leaving little or no moisture to support subsequent crop growth and thereby causing complete crop failure.

This situation is better explained by Lahiri's studies (1980), in which the moisture content in the 75-cm soil profile in the first season gradually decreased from 95 mm at sowing. By 30 days after sowing (DAS), 50% of available soil moisture was removed, and continued removal reduced soil moisture to a very low level toward the end of the growing season (Fig. 4). Thus the early vegetative growth consumed most of the moisture, and dry-matter production increased significantly due to N application; however, the grain yield was nearly negligible, and the influence of N was nonsignificant (Table 5). In the second season, very low precipitation kept the soil moisture of the major root zone below the minimum availability (Fig. 4). Such situations are encountered when the rains fail completely in arid areas, and neither dry-matter production nor grain yield shows a response to N application (Table 5). The third season was a favorable one, in which the soil moisture was readily available for the first 50 DAS, and the crop faced only a mild terminal drought. Both dry matter and grain yields increased significantly with increasing N levels up to 40 kg ha^{-1}.

Variation in seasonal rainfall and crop growth influence the water use and water-use efficiency. In a very low rainfall season, the water use may be



Month

Figure 4. Moisture availability in three typical rainfall seasons of the arid zone, Rajasthan, India.

approximately half that in a good rainfall season (Table 6), but water-use efficiency for grain production is drastically reduced. The application of N has been found to increase the water use a little, but the increase in water-use efficiency was conspicuous (Lahiri 1980) (Table 6).

Table 5. Effects of fertilizer nitrogen on grain yield and dry-matter production of pearl millet in four seasons with different soil water availability.[1]

N applied (kg ha^{-1})	Grain yield (kg ha^{-1})			Dry-matter yield (kg ha^{-1})		
	Season 1	Season 2	Season 3	Season 1	Season 2	Season 3
0	25	0.5	1680	720	66	5080
20	22	0.5	1850	1170	70	5560
40	26	0.6	2480	1460	73	6860
60	-	0.5	2310	-	81	7020
LSD (P = 0.05)	NS	NS	390	162	NS	730

1. Total annual rainfall: season 1 = 179 mm; season 2 = 93 mm; season 3 = 595 mm.
Rainfall during cropping period : season 1 = 43 mm; season 2 = 76 mm; season 3= 442 mm.

Source: Lahiri (1980).

Table 6. Grain yield, water use, and water-use efficiency of pearl millet at four levels of nitrogen fertilizer in a drought year and a good rainfall year in the Indian arid zone.

	Season 1[1]			Season 2[1]		
N applied (kg ha^{-1})	Grain yield (kg ha^{-1})	Consumptive water use (mm)	Water-use efficiency (kg ha^{-1} mm^{-1})	Grain yield (kg ha^{-1})	Consumptive water use (mm)	Water-use efficiency (kg ha^{-1} mm^{-1})
0	0 3	79	0.0038	1970	163	12.08
20	0.5	-	-	2500	171	14.62
40	0.6	81	0.0074	4070	174	23.39
60	0.5	75	0.0067	3280	199	16.48

1. Total annual rainfall: season 1= 93 mm; season 2 = 595 mm.
Rainfall during cropping period: season 1= 76 mm; season 2 = 442 mm.

Source: Lahiri (1980).

Response to nitrogen in relation to planting geometry

In sole-cropped pearl millet, planting geometry has been found to influence the response to N. In a study of three different rainfall situations, it was found that in above-normal and normal rainfall seasons, the yields of pearl millet planted in uniform rows and in a "triplet" system—skipping every fourth row to get border effects—were about the same. However, when rainfall was below normal, the triplet system gave significantly higher yields (Table 7).

High fertility (90 kg ha^{-1} N) gave significantly higher yields than low fertility (no N), irrespective of rainfall. At similar levels of N, triplet planting gave higher

Table 7. Grain yield (kg ha^{-1}) of pearl millet as influenced by planting geometry and fertility level in three seasonal rainfall situations, Indian arid zone.

			Grain yield (kg ha^{-1})		
Planting geometry	Plant population ('000 ha^{-1})	Fertility level	Above-normal rainfall (409 mm)	Normal rainfall (260 mm)	Below-normal rainfall (193 mm)
Uniform rows	166	Low	2268	1548	314
		High	3065	2198	620
Triplet[1]	166	Low	2312	1690	426
		High	2895	2384	790
Triplet	100	Low	2280	1637	374
		High	2820	2052	668
CD (5%) Planting geometry			NS	232	92
CD (5%) Fertility level			445	290	119
CD (5%) System fertility			NS	NS	NS

1. 'Triplet" planting = set of three rows followed by a vacant row.

yields than uniform planting (Table 7), indicating that better N-use efficiency can be achieved by manipulating pearl millet planting geometry.

Response to nitrogen in intercropped pearl millet

Growing one or two legumes with pearl millet as a mixed crop has been a traditional practice in the arid zone, primarily to reduce the risk of complete crop failure in poor seasons. No specific row arrangements are followed in this system, which leads to low yields of both components in the mixture. Nutrient management of the mixed system is also difficult, because of very close association of crops with different nutrient requirements. Studies conducted to assess the response to N in an intercropping system showed that application of N favorably influenced the yield of pearl millet (both with paired rows and alternate planting), regardless of rainfall. Although the interaction of planting system with N application was nonsignificant, response to N was greater with the paired-row planting. In a good rainfall season, the response per kg applied N was higher than in a season with rainfall below normal.

Although N was applied to the principal crop, pearl millet, it reduced the yield of the legume component in the system. Increasing N application to the principal crop steadily reduced the yield of mung bean, irrespective of rainfall. Perhaps at higher N levels increased vegetative growth of pearl millet suppressed the growth of the intercrop.

Sustainable Yield Index in Relation to Nitrogen

Sustainable yield index (SYI) helps in identifying the treatment that gives the maximum sustainable yield under arid conditions. The SYI is computed as follows:

$$SYI = \frac{Y - \sigma}{Y_{max}}$$

where Y is the mean yield of crops over years, σ is the standard deviation, and Y_{max} is the maximum yield obtained.

The assessment of various cropping systems (sole-cropping, intercropping, etc.) in relation to N application showed that increasing N application increased the sustainability of both sole-crop and intercrop systems (Table 8). Application of 90 kg ha^{-1} N gave the highest SYI (0.31) with paired-row (30/70 cm) intercropping. This suggests that at least 31% of the maximum observed yield over years is assured with high probability in this system, compared with 23% in the same system without N application.

Table 8. Effect of nitrogen application (kg ha^{-1}) on sustainable yield index of three cropping systems in the Indian arid zone.

Cropping system	Sustainable yield index at N level of			
	0	30	60	90
Intercrop (paired rows 30/70 cm)	0.23	0.24	0.27	0.31
Intercrop (alternate rows 1:1)	0.24	0.22	0.23	0.26
Sole-crop pearl millet	0.09	0.13	0.16	0.17

Nutrient Management in Cereal-Legume Rotations

Crop rotation occupies an important place in conservation farming. A crop sequence that reduces loss of soil and gives good returns per unit area is suitable for adoption in arid areas. Growing the same crop continuously on the same piece of land may have adverse effects on soil fertility, because it continuously depletes nutrients from a particular depth. Adverse effects of such systems have been observed even under good soil fertility management

In a continuous pearl millet system, grain yield was about 62% lower than in a mung bean-pearl millet rotation (Mann and Singh 1977). In traditional cropping, pearl millet is either grown after fallow in a 2-year rotation or sole-cropped every year. Of the single-crop systems studied, the pearl millet--fallow rotation proved the most remunerative, in both yield and monetary returns (Singh 1980).

Among double-crop systems, cluster bean-pearl millet gave the highest returns per unit area. Results of a longterm study (Singh et al. 1985) also support this rotation, in which pearl millet yield was 11% higher than in a continuous pearl millet system. The cereal-legume rotation also increased soil organic carbon by up to 12% and available soil phosphorus by up to 25%.

Studies on nutrient requirements of crop sequences showed that when 17.5 kg P was applied to mung bean, pearl millet grown in the next season yielded 200-500 kg ha^{-1} more with added N (20 kg ha^{-1}) and 200-350 kg ha^{-1} more without N (Singh et al 1981). The P can also be applied once in 2 years to the legume for sustained pearl millet production (Singh et al. 1985). For a pearl millet-wheat rotation, Singh (1985) suggested that it was not necessary to apply FYM or P to both crops. A single application of 26 kg P ha^{-1} plus 120 kg N ha^{-1} to wheat and only 60 kg N ha^{-1} to pearl millet in the rotation was enough to give good grain yields and maintain soil organic matter at a desirable level.

The role of legumes in stabilizing the yield of cereals grown in sequence or rotation is well known. In a longterm study, cultivation of mung bean in rotation with pearl millet supplied with 20 kg N ha^{-1} gave yields similar to those obtained with 40 kg N ha^{-1}; that is, the legume supplied the equivalent of 20 kg ha^{-1} N to the following millet crop (Singh et al 1981). However, different grain legumes have different effects. For instance, Singh et al. (1985) found cluster bean benefited succeeding pearl millet more than either moth bean or mung bean. The relative beneficial effect of legumes depends on the amount and quality of crop residues added to soil and is related more to hydrolyzable NH_4-N than to total N (Table 9). Thus cluster bean, although a low N-fixer, benefits the succeeding pearl millet more than do the other two legumes (Kathju et al. 1987).

Table 9. Changes in nitrogen status of soil after cultivation of legumes for 3 years at two levels of phosphorus application in the Indian arid zone.

P_2O_5 (kg ha^{-1})	N_2 fixed (kg ha^{-1})	Increase in total N over initial status (%)	NO_3-N and NH_4-N (mg kg^{-1})	Hydrolyzable and NH_4-N (kg ha^{-1})
Mung bean				
0	131.6	9.5	32.0	39.2
40	273.0	34.0	35.7	85.8
Moth bean				
0	84.6	4.7	35.8	43.1
40	247.5	34.0	44.8	95.8
Cluster bean				
0	75.6	8.3	47.0	81.4
40	145.7	19.4	48.2	105.8
Initial status	-	-	15.7	11.7

Source: Kathju et al. (1987).

Biological Nitrogen Fixation

In arid areas where little N fertilizer is applied to crops, the role of various N-fixing bacteria in improving the soil N status offers considerable potential. Since the identification of *Azospirillum brasilense* as an N-fixing bacterium for cereals, there has been much interest in this organism and the N economy of pearl millet. Use of biological sources of N is a possible method of increasing millet production, especially when application of chemical fertilizers is risky (Joshi and Panjab Singh 1981).

An inoculated crop may yield up to 39% more than a noninoculated one (Fig. 5). Response was better in a season with an even distribution of rainfall than in one with erratic distribution. Root dry weight of pearl millet increased significantly with inoculation; this has been attributed to the production of various growth-regulating substances, such as indoles, gibberellins, and cytokinins by *A. brasilense* (Venkateswarlu and Rao 1983).

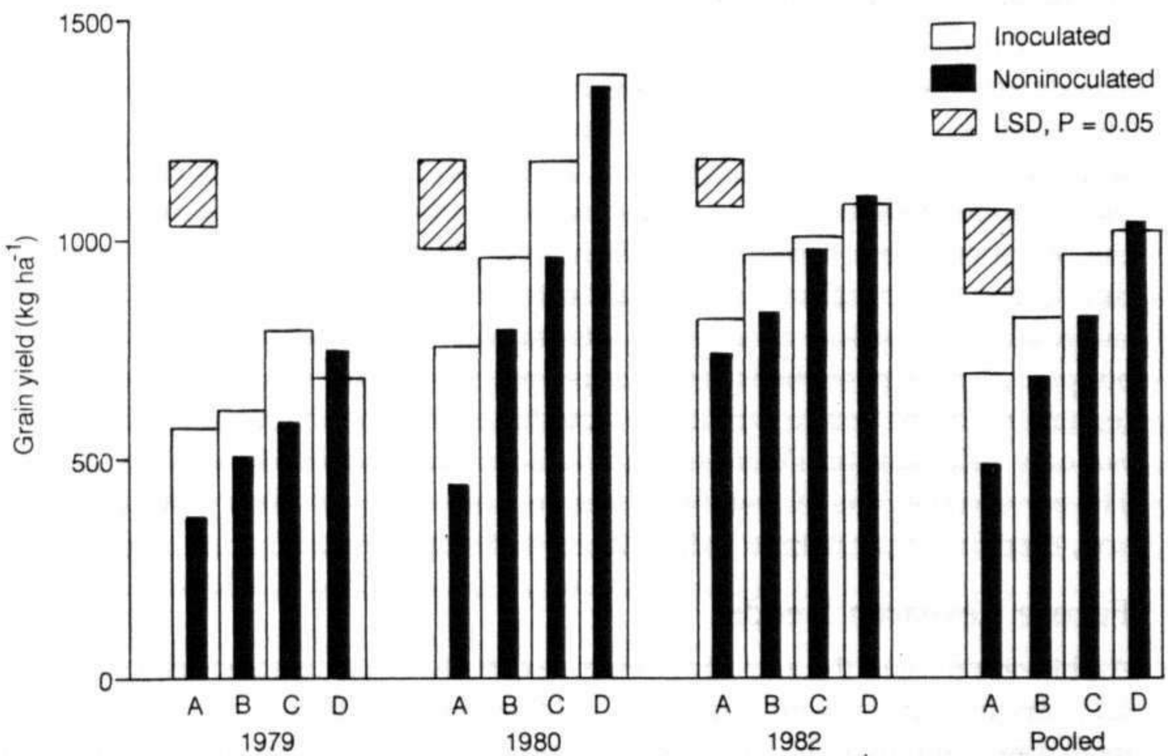


Figure* 5. *Response of pearl millet to* Azospirillum brasilense *inoculation in the arid zone, Rajasthan, India. A=0 kg N; B=13 kg N; C=20 kg N; D=40 kg N ha^{-1}.

The results (Fig. 5) indicate that inoculation with *A. brasilense* could contribute the equivalent of 13 kg ha^{-1} N to the crop requirement: pearl millet yield obtained with the application of 13 kg ha^{-1} N (716 kg ha^{-1}) was similar to that with inoculation alone (718 kg ha^{-1}). The inoculation effect decreased with the increase in N application, and at 40 kg N ha^{-1}, the inoculation ceased to increase grain yield (Joshi and Rao 1989). This could be due to inhibition of the N_2-ase activity of

A. brasilense at such N rates (Rao and Venkateswarlu 1982). Thus N fertilizer, beyond a threshold concentration, inhibits the activity of *Azospirillum* and its beneficial effects.

Although the amount of N contributed by this bacterium (13 kg N ha^{-1}) may appear low, it is significant under arid conditions, where farmers' inability to use purchased inputs is a major constraint to increasing farm output (Joshi et al. 1984). Therefore the use of *Azospirillum* inoculation as a biological N source could be advocated.

Conclusions

The fertilizer management studies hitherto conducted on sole pearl millet and cereal-legume systems have generated valuable information. It can be concluded that pearl millet responds favorably to application of N in most rainfall situations, except in seasons of extremely low rainfall, where there is terminal drought. Split application may be beneficial, and the part of N earmarked for topdressing should be withheld if droughts are anticipated in the later part of the crop season. Manipulation of planting geometry may also help improve response to applied N. The pearl millet/legume intercropping system also responds to application of N. However, the yield of the legume component declines with increasing N levels; thus N inputs should be kept at a low level. The possibility of associative biological N fixation in pearl millet could be further explored and integrated into the N management schedule. Application of FYM and organic manures should find a place in pearl millet cultivation to maintain longterm productivity and improve soil physical conditions. Integrated fertilizer management should be adopted, where phosphatic fertilizer is applied only to legumes in pearl millet-legume rotations and to wheat in a double cereal rotation. Such practices would not only help save fertilizer but would also ensure better fertilizer-use efficiency The beneficial effects of micronutrients are particularly evident in drought years and, therefore, may help to reduce the risk of crop failures.

Future Research Needs

Arable cropping in the arid zone being essentially of a subsistence nature, studies on nutrient management, especially with respect to different cropping patterns, have been minimal. A large knowledge gap exists in this area. Some broad research needs, with special reference to nutrient management in arid areas, are outlined here:

- Specific nutrient deficiencies in different parts of the arid zone need to be identified, along with other constraints, and yield levels that can be sustained by native nutrient supply systems determined in relation to soil physical and chemical characteristics.
- Specific studies to work out integrated nutrient requirements of different cropping patterns on a subzonal basis would provide a base for efficient management of the systems.

- Strategies need to be worked out for harnessing biological N fixation in cereals and its integration with adequate supplies of other nutrients for different cropping systems. Such studies should be aimed at the N economy of sole and intercropping or mixed cropping systems.
- Fertilizer use in arid areas will have to be associated with careful management of organic manures. Studies are needed not only on the agronomic value of FYM and residue management but also on the net availability of this resource. Such studies should include analysis of the role of organic manures in eliminating existing deficiencies of Zn and S in specific arid areas, improving efficiency of organic manures, and scheduling application intervals to improve productivity of sandy soils.
- Validated models sensitive to management practices are needed to improve prediction of plant nutrient requirements and soil fertility management, manures, and soil organic matter dynamics in cropping sequences.
- Besides various measures to increase the productivity levels of rainfed crops in the arid region, efforts are also needed to increase the cropping intensity in rainfed areas, where generally a single crop is taken during the year. Cropping intensities could be increased by intercropping (i.e., growing more than one crop together in regularly spaced rows). The row ratio could vary between the base crop and the companion crops and, if integrated nutrient management is worked out, it would be possible to improve productivity and sustainability in the arid zone. Such studies should also include (1) the pathways of N losses from cereal-legume intercropping systems to maximize N use and reduce wastage of an expensive input; (2) the amounts of fixed N in below-ground parts of component crops to permit accurate estimates of N balances in cereal/legume intercropping systems; (3) methods of improving the production efficiency of cereal/legume intercropping systems by giving high priority to maintaining the legume component. This could be achieved through manipulation of the inter- and intra-row spaces of the taller associated cereal, which would also minimize interspecies competition.

References

CAZRI (Central Arid Zone for Research Institute). 1978. Annual report 1977. Jodhpur, Rajasthan, India: CAZRI. 191 pp.

Jain, G.L., Misra, D.K., and Raheja, P.C. 1967. Uptake of copper with and without NPK by bajra (*P. typhoides)* and moth *(Phaseolus aconitifolius).* Labdev Journal of Science and Technology 5:154-155.

Joshi, N.L. 1984. Economics of fertilizer application in pearl millet production in arid areas. Fertilizer Marketing News 15(3):1-4.

Joshi, N.L., and Kalla, J.C. 1986. Economising nitrogen use of pearl millet in the Indian Arid Zone. Annals of Arid Zone 25:321-325.

Joshi, N.L., and Panjab Singh, 1981. Towards higher bajra yields in arid Rajasthan. Indian Farming 31(7):17.

Joshi, N.L., and Panjab Singh. 1985. Additive and complementary effects of various agronomic inputs on the yield of pearl millet. Annals of Arid Zone 24:218-222.

Joshi, N.L., and Rao, A.V. 1989. Response of pearl millet to *Azospirillum* as influenced by N fertilizer under field conditions. Annals of Arid Zone 28:291-297.

Joshi, N.L., Verma, S.K., and Gupta, G.K. 1984. Technology for higher bajra production in arid zone. Indian Farming 34(7):33-35.

Kathju, S., Aggarwal, R.K., and Lahiri, A.N. 1987. Evaluation of diverse effects of phosphate application on legumes of arid area. Tropical Agriculture 64:91-96.

Lahiri, A.N. 1980. Interaction of water stress and mineral nutrition on growth and yield. Pages 341-352 *in* Adaptation of plants to water and high temperature stress (Turner, N.C., and Kramer, P.J., eds.). New York NY, USA: John Wiley.

Mann, H.S., and Singh, R.P. 1977. Crop production in the Indian arid zone. Pages 215-234 *in* Desertification and its control. New Delhi, India: Indian Council of Agricultural Research.

Misra, D.K. 1971. Agronomic investigations in arid zone. Pages 165-169 in Proceedings of the Symposium on Problems of Indian Arid Zone. Jodhpur, Rajasthan, India: Arid Zone Research Association of India.

Misra, D.K. 1964. Bajra supplement. Indian Farming 14(2):31-40.

Misra, D.K., and Bhattacharya, B.B. 1966. Agronomic studies on crops in arid zone IV. Response of *Pennisetum typhoides* to micronutrients. Indian Journal of Agronomy 11:178-184.

Misra, S.G., and Tiwari, R.C. 1964. Effect of fertilizers and pH on retention of copper by soils. Journal of the Indian Society of Soil Science 12:295-298.

Panjab Singh. 1977. Levels and time of nitrogen application in rainfed bajra. Madras Agriculture Journal 64:80-83.

Ramakrishna, Y.S. 1986. Climatic constraints to crop production in the Indian arid zone. Transactions of Indian Society of Desert Technology 11:41-47.

Rao, A.V., and Venkateswarlu, B. 1982. Nitrogen fixation by *Azospirillum* isolated from tropical grasses native to Indian desert. Indian Journal of Experimental Biology 21:316-318.

Singh, K.C., and Singh, R.P. 1977. Intercropping of annual grain legumes with sunflower. Indian Journal of Agricultural Sciences 47:563-567.

Singh, R.P. 1980. Cropping systems for drylands of the Indian arid zone. Annals of Arid Zone 19:443-447.

Singh, R.P., Daulay, H.S., and Prasad, M.V.R. 1974. Hungry drylands of western Rajasthan need a new technology. Indian Farming 23(12):5-6.

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 Sciences 51:498-503.

Singh, S.D, 1985. Direct, residual and cumulative effect of manure and fertilizer phosphate in pearl millet-wheat rotation. Indian Journal of Agricultural Sciences 55:104-109.

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

Venkateswarlu, B., and Rao, A.V. 1983. Response of pearl millet to inoculation with different strains of *Azospirillum brasilense.* Plant and Soil 74:379-386.

Vyas, D.L., Singh, S,D., Daulay, H.S., and Misra, D.K. 1972. Comparative study of nitrogen sources for fertilization of rainfed pearl millet. Annals of Arid Zone 11:145-153.

Nitrogen in Arid Soils: Availability and Integrated Management for Increased Pearl Millet Production

Praveen-Kumar and R K Aggarwal[1]

Abstract

The status of nitrogen in arid soils is generally low (0.021-0.056%), with amino acid-N and NO_3-N the predominant organic and inorganic fractions. The content of NO_3-N fluctuates seasonally, with surface accumulation during the summer and at lower depths during the rainy season. Nitrogen deficiency generally limits pearl millet yield. This deficiency can be corrected with fertilizer, but because of low fertilizer-use efficiency and lack of residual effect, the application of fertilizer considerably increases risk. Split application of fertilizers is the first step towards reducing risk. Other steps include (1) avoiding basal application of fertilizer to pearl millet if a legume has been grown in the preceding year; (2) use of farmyard manure and crop residues in conjunction with fertilizer N; and (3) incorporation of legumes in the cropping system. Growing of legumes alters the content of different fractions of organic N, promoting better pearl millet growth. Farmyard manure and crop residues also improve soil quality, albeit slowly.

Introduction

In arid regions, limited water resources and low crop productivity have discouraged the widespread use of nitrogenous fertilizers, although most arid soils are deficient in N (Table 1). However, with the ever-increasing demand for food, production levels in the arid regions must be increased. The introduction of improved crop varieties that are responsive to better management has made N application a prerequisite to achieving good crop yields and sustainable soil productivity.

Soils

Soils of the arid areas of Rajasthan have been classified into 17 major series (Table 1). They are generally sandy in texture, poorly structured, and moderately alkaline. Their productivity potential ranges from low to medium. Their organic

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Table 1. Major soil series of the Indian arid region.

Series/FAO classification	Surface characteristics[1] Texture	Structure	pH	OC (%)	Total N(%)	LCS[2]	pp3	Area[4] ('000 ha)
Chandawal Eutric Cambisols	fsl	sbk	8.3	0.10	0.028	HI	M	61.7
Chirai Calcaric Cambisols	lfs,fsl	sbk	8.0	0.11	0.035	VI	L-M	eank
Dhaber Haplic Calcisols	sl	sbk	8.1	0.12	0.032	III	H	41.6
Dune Eutric Arenosols	s	sg	8.4	0.08	0.021	VIII	L	4283.3
Gajsinghpura Eutric Cambisols	sicl	sbk	8.3	0.30	0.049	III	M	98.7
Jadan Eutric Cambisols	l,cl	sbk	8.3	0.54	0.063	III	M	392.0
Jaitaran Haplic Arenosols/ Eutric Cambisols	sl	sbk	8.5	0.40	0.051	III	M	eank
Kolu Petric Calcisols	ls,sl	sg	8.2	0.18	0.042	IV	L	eank
Masitawali Eutric Fluvisols	fsl	gr	8.0	0.16	0.044	IV	M	eank
Molasar Eutric Arenosols	ls	sg	7.9	0.12	0.032	IV	L	654.8
Pal Eutric Cambisols	sl	sbk, gr	8.4	0.22	0.042	IV	L	136.9
Pali Calcaric Cambisols	1	gr	8.1	0.37	0.056	IV	M	58.3
Panchroli Calcaric Cambisols	ls	sbk	8.2	0.29	0.031	IV	L	99.9
Parbatsar Eutric Cambisols	sl	sbk	7.4	0.22	0.034	IV	M	99.7
Pipar Calcaric Cambisols	sl	sbk	8.1	0.23	0.029	IV	L-M	127.0
Shobhasar Eutric Cambisols	s	sg	8.5	0.08	0.016	III	M	eank
Thar Eutric Arenosols	ls	sg	8.0	0.10	0.021	Vic	L-M	eank

1. Texture: s = sand; ls = loamy sand; lfs = loamy fine sand; sl = sandy loam; 1 = loam; fsl - fine sandy loam; cl = clay loam; sicl = silty day loam. Structure: sbk = subangular blocky; gr = medium granular; sg = single grain OC = organic carbon.
2. LCS = land capability subclass.
3. PP = productivity potential: L = low; M = medium; H = high.
4. eank = extensive but exact area not known.

matter content is low, and they are often deficient in N. Phosphorus is generally in the range of medium to adequate; potash and available micronutrients often adequate.

Content and form of nitrogen in soils of the arid zone

The content of organic carbon and total N in arid-zone soils was reported to be low; C ranged from 0.16-0.34%, and N from 0.021-0.056% in surface soils, decreasing with depth (Joshi 1993). Aggarwal et al. (1977, 1990) reported that the major part of N in the Aridisols of Rajasthan was in the organic form, of which acid-hydrolyzable N constituted about 62-87%. The different N fractions were distributed in the order amino acid >unidentified N >ammoniacal N >hexosamine N. The content of different fractions varies among different soil series (Fig. la). In comparatively fine-textured soils, the amino acid and hexosamine fractions contributed more to total hydrolyzable N than the unidentified fractions did (Fig. la). Although the absolute amount of the hydrolyzable fraction decreased with depth, when expressed as a percentage of total N, it generally followed the opposite trend.

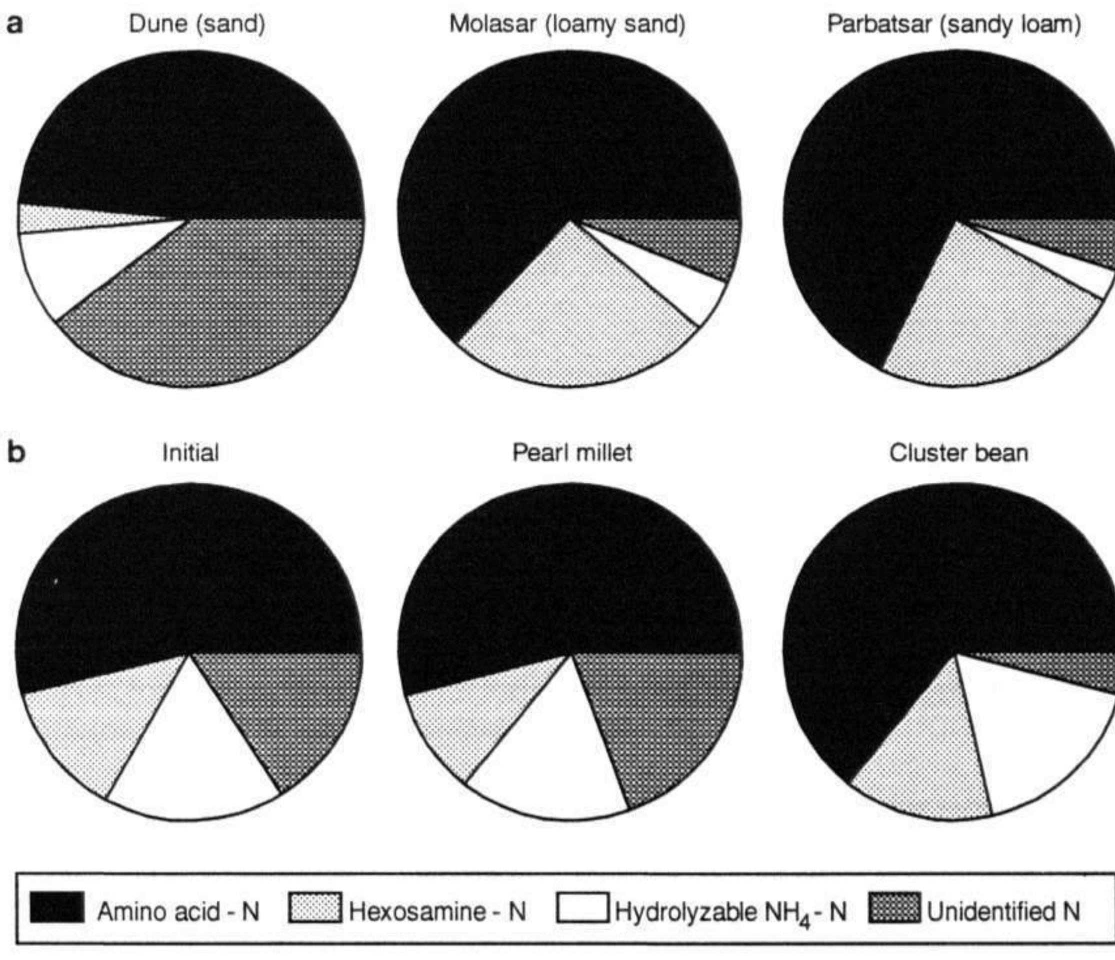

Figure 1. Changes in organic fractions of nitrogen (% of total hydrolyzable-N) in arid soils: A. Effect of soil texture. B. Effect of pearl millet or cluster bean cultivation for 3 years. (Source: Aggarwal et al. 1975, *1990; Praveen-Kumar et al. 1996a.)*

Crops also influence the distribution of N fractions: legume cultivation results in a higher contribution of amino acid and hexosamine N to the total hydrolyzable pool, while cereal cultivation results in the opposite trend (Fig. lb). The level and distribution of NO_3-N in the soil profile is subject to seasonal fluctuations, and the Birch effect is commonly observed. In Jodhpur, the concentration of NO_3-N in the upper layer of soil increased from nearly 3 mg kg^{-1} in winter to 5 mg kg^{-1} in summer (CAZRI 1990). Fluctuations in the concentration in the lower depths were minimal until the rainy season.

The vegetation contains only 5-10% of total N found in the arid ecosystem, but even in such a small quantity, biotic N can remarkably influence the horizontal and vertical distribution of N in arid soils (West and Klemmedson 1978). Figure 2 shows a typical vertical distribution pattern of N beneath a mesquite *(Prosopis)*

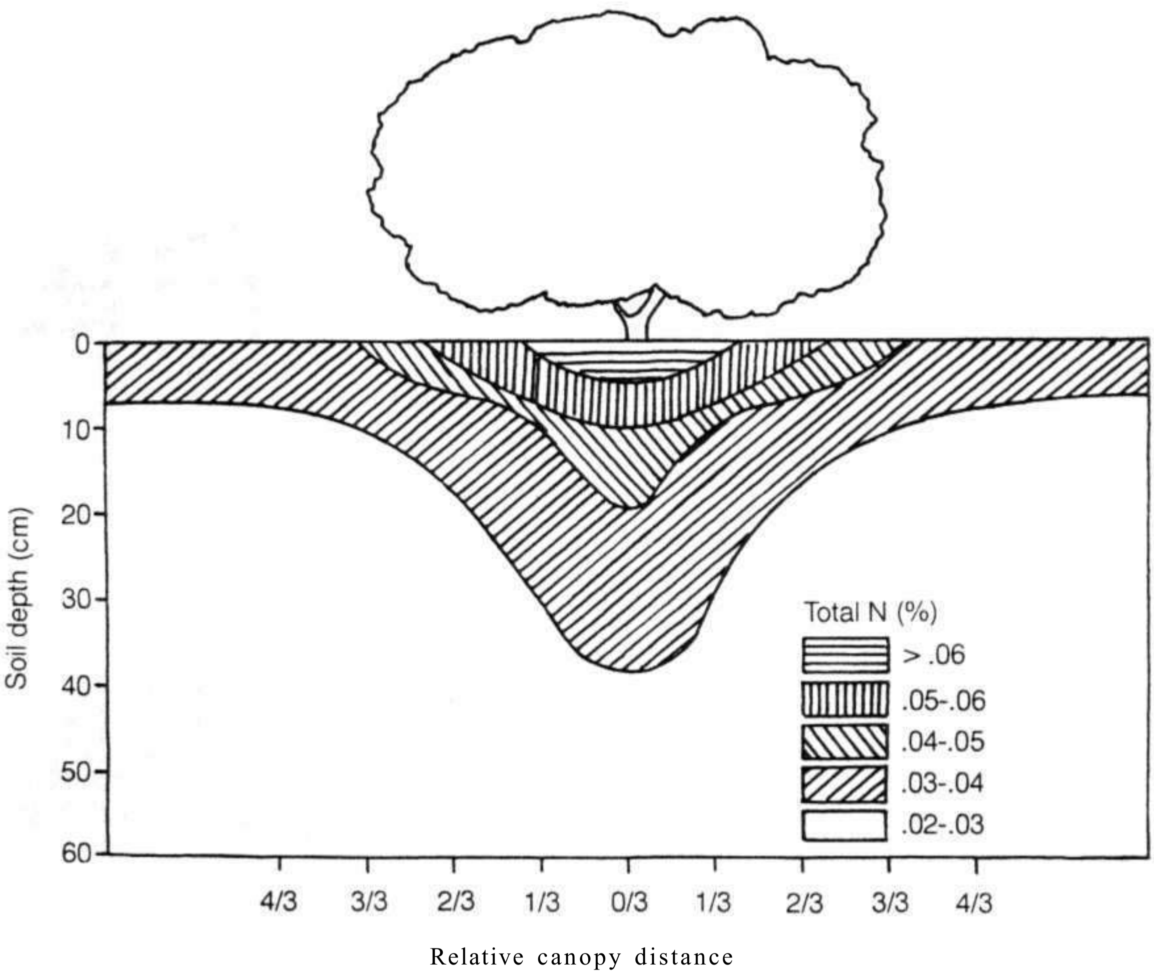

Figure 2. Total soil nitrogen (%) beneath an average-size mesquite* (Prosopis) *canopy. (Source: West and Klemmedson 1978.)

canopy, where N is shown to be concentrated in the upper part of the profile. This pattern is expected to be most pronounced where the vegetation has a high shoot:root ratio. Horizontal patterns are striking in desert situations where scattered vegetation results in "islands of fertility" (Garcia-Moya and McKell 1970).

These patterns result largely from plants absorbing nutrients from lower soil depths and redisposing them as mulch on the soil surface. Decomposition is enhanced by the moderate temperature and increased retention of moisture under the shade of trees and shrubs. Aggarwal and Praveen-Kumar (1990) and Aggarwal et al. (1993) have reported higher fertility status of soils underneath *Prosopis cineraria* than in the adjacent open soils (Table 2).

Table 2. Chemical characteristics of surface soils (0-15 cm) below *Prosopis cineraria* canopy and soil away from canopy.

Characteristic	Soil below canopy	Adjacent open soil
pH	8.0	8.2
OM (%)	0.57	0.37
N(%)	0.038	0.020
S(%)	0.028	0.016
P(%)	0.038	0.028
Available nutrients (kg ha^{-1})		
N	250.0	190.0
P	22.4	7.7
K	633.0	370.0

Source: Aggarwal et al. (1993).

Nitrogen input in an arid ecosystem

Ecosystems in arid regions depend to a great extent on N inputs from the atmosphere to compensate for the losses of N from the soil-plant system. The most important mechanisms of atmospheric N input are N deposition through precipitation and biological N_2 fixation.

Precipitation. West (1975) estimated that the N deposition in the arid regions worldwide was 12.5 kg ha^{-1} $year^{-1}$. Nitrogen deposition in arid areas of the USA has been reported to be generally <5 kg ha^{-1} $year^{-1}$ (Vlek 1981). Aggarwal et al. (1982) reported that N deposition as precipitation ranged from 5.47 to 10.06 kg ha^{-1} $year^{-1}$ in the arid regions of India. In Israel, rainfall has been reported to contribute 4-20 kg N ha^{-1} $year^{-1}$ (Yaalon 1964).

Biological N_2 fixation. Leguminous plants are the most important N-fixers in the arid region, and the N contributions from microorganisms such as *Azotobacter* (0.3 kg ha^{-1} $year^{-1}$) and *Clostridium* (0.1-0.5 kg ha^{-1} $year^{-1}$), plant algal associations such as *Azolla, Gunnera,* and lichens are small. Of the total of 135×10^9 kg N returned to earth each year through biological N_2 fixation, about 65% (89×10^9 kg) is contributed by nodulated legumes (Stevenson 1986). West (1975) estimated that the N contribution of biological N_2-fixers in the arid zone was nearly 3.6 kg ha^{-1} $year^{-1}$.

Transformations of nitrogen

Ammonification. Ammonification of organic N in soil is affected by several factors, many of which are related to biological activity. The minimum temperature limit for ammonification is generally around freezing (Stanford et al. 1973) and the maximum, about 50° C (Myers 1975). Stanford and Epstein (1974) suggested that the effect of temperature on ammonification is generally uniform among soils. Optimum water potential for ammonification is 10-50 kPa (Stanford and Epstein 1974), and the process virtually stops at the permanent wilting point (1.5 MPa) (Robinson 1957). However, Miller and Johnson (1964) and Reichman et al. (1966) found that ammonification proceeds at matric suction exceeding 1.5 MPa. Kowalenko and Cameron (1976) demonstrated the importance of a ratio of temperature:water content in quantifying microbially mediated ammonification. In the arid-zone soils of India, a favorable ratio is observed mainly after rains and results in a sudden burst of mineralization. Ordinarily, the ammonium thus formed is converted to nitrate. However, in the relatively alkaline soils of the arid region, a substantial part of NH_4-N is converted to ammonia and escapes to the atmosphere, because nitrification starts after a long delay.

Nitrification. The population of nitrifiers is generally low in arid soils. Sims and Collins (1960) reported the maximum number of nitrifiers to be 800 g^{-1} in an arid Australian soil. In contrast, the number in cultivated soils may reach millions per gram (Alexander 1961). Skujins and Fulgham (1978) reported that the nitrification potential of arid soil decreased with depth and became zero in the layers not reached by precipitation. Alexander (1961) found seasonal variation in the population of nitrifiers, the largest number being found in the warm rainy season. The *Nitrosomonas* population generally remained more stable than that of *Nitrobacter.*

The optimum temperature for nitrification in soil is 25-35° C. The rate of nitrification drops rapidly below 15° C to almost zero at 0° C (Alexander 1965). The optimum soil water potentials for nitrification are very close to those for ammonification. Nitrifiers also exhibit a remarkable ability to survive desiccation (Alexander 1965). Kowalenko and Cameron (1976) demonstrated the existence of a temperature x water content interaction on nitrification in soils subjected to a range of mesophyllic temperatures and water potentials above -1.5 MPa.

Denitrification. Few denitrification studies have been made on arid lands, possibly because of the general notion that anaerobiosis is rare in these soils. However, it was recognized two decades ago that under field conditions, poor O_2 supply to soil aggregates could result in localized anaerobiosis and denitrification (Dowdell and Smith 1974; Virginia et al. 1982). Such a situation in arid soils may develop after heavy rainfall. High activity of denitrifying enzymes and considerable denitrification losses have been shown by Peterjohn (1991) in desert soils. Praveen-Kumar and Uday Burman (1996) have also reported considerable activity of the denitrifying enzyme, nitrate reductase, in Indian arid soils. The activity of denitrifying enzymes was many times higher in the rhizosphere of many crops and trees than in nonrhizosphere soil.

Ammonia volatilization. Ammonia volatilization worldwide is estimated to be 170×10^6 t annually, or an average of 10 kg N ha^{-1} $year^{-1}$ (Burns and Hardy 1975). Measurements of NH_3 volatilization from natural arid ecosystems are lacking, possibly reflecting an inadequacy of suitable techniques and the general notion that NH_3 volatilization under these conditions is not an important N-loss mechanism (Husz 1977; Noy-Meir and Harpaz 1977). Heavy losses of N as NH_3 have been observed by Aggarwal et al. (1987) after the application of various NH_4 and NH_4-forming fertilizers in the arid sandy soils of Rajasthan.

Management of nitrogen

The N requirement of crops varies with crop type and yield level. Longterm estimations of the N requirement of crops under arid conditions may be difficult, because yield levels vary considerably with variations in rainfall. Stewart (1992) observed that under such conditions, crop yields may vary from zero to three times the average yield. Tucker (1988) concluded that using average yields to estimate N requirements in semi-arid regions is too conservative and actually lowers average yields with time, because of insufficient N supply in favorable years. However, the 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 environmental degradation from excess N also makes this alternative unacceptable.

Tucker (1988) presented several ground rules to arrive at logical yield goals. These include choosing yield goals based upon (1) highest yield within the past 5 years, provided crop management was good; (2) yield goal set at 1.5 times of longterm average; and (3) yield goal based on soil capabilities as defined in Standard Soil Surveys, using yields of top growers in the vicinity on the same kind of soil.

Pearl millet responded favorably to N additions (Aggarwal and Venkateswarlu 1989); response ranged from 7.0 to 18.0 kg grain per kg N applied, with higher values in years of good rainfall. Venkateswarlu and Hegde (1992) reported that, in the long term, the application of N as either organic or inorganic fertilizer reduces the year-to-year yield variation.

Nitrogen uptake by pearl millet. The pearl millet crop takes up the major quantity of N—up to 70% of the total N uptake—within the first 30 days of growth. Thereafter, N uptake slows down, continuing gradually until the grain-filling stage. The total quantity of N taken up varies with the yield level (Table 3). Factors that affect yield, such as soil fertility and previous crop, also affect total N uptake.

Table 3. Nitrogen uptake by pearl millet (var. MH 179) at different yield levels.

Grain yield (kg ha^{-1})	N uptake (kg ha^{-1})
720	28.13
860	28.39
930	51.48
1560	64.55

Addition of nitrogen. A good crop of pearl millet takes up around 65 kg ha^{-1} N (Table 3). Of this, the contribution from soil organic matter, rainfall, and biological N_2 fixation may amount to 25 kg N ha^{-1}. Therefore, to achieve a good yield, N needs to be added to the soil from other sources, to make the remaining 40 kg N ha^{-1} available to the crop.

Singh et al. (1979, 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 7-year study, reported a significant response of pearl millet to application rates of 80 kg N ha^{-1} only in years of good rainfall. A comparison of different N fertilizers showed that maximum yields were obtained with ammonium sulfate (Table 4), but due to the high cost of of this fertilizer, urea has become the major source of N in arid regions, even though the use efficiency of urea-N by pearl millet is very low.

Table 4. Effect of different nitrogen sources on pearl millet yield, ammonia volatilization, and nitrogen-use efficiency.

N source	Grain yield (kg ha^{-1})	NH_3 volatilization (% applied N)	N-use efficiency (%)
Control	520	-	-
Urea	610	16	5
Ammonium sulfate	740	12	32
Urea mixed with sulfur	880	8	48
Diammonium phosphate	610	3	18
Calcium ammonium nitrate	660	0.1	24
CD (P=0.01)	40	0.7	

Source: Aggarwal et al. (1987).

Various studies at CAZRI have revealed that mixing elemental sulfur with urea (Table 4) (Aggarwal et al. 1987) or applying a small quantity of ammonium sulfate before applying urea (Praveen-Kumar and Aggarwal 1988) increases the efficiency of urea. Praveen-Kumar and Aggarwal (unpublished data) also showed that the $NH_4:NO_3$ ratio in an N fertilizer affects its use efficiency and found that the optimum ratio, which gave the highest yields and use efficiency, was 3:1.

Besides ammonia volatilization, denitrification is now considered an important pathway of N loss (Peterjohn 1991). Due to different loss mechanisms, a major part of applied N, if not used by the crop, is lost from the soil. As a result, no residual effect of fertilizer N is observed (Aggarwal and Praveen-Kumar 1996). This was demonstrated in a field experiment (Praveen-Kumar and Aggarwal, unpublished data) in which 20, 40, 60, and 80 kg N ha^{-1} was applied to different plots at the time of sowing, and the crop was harvested after 20, 40, and 60 days of growth, representing complete crop mortality at early, medium, and late stages of drought. The next year, pearl millet was again grown in these plots without added N fertilizer. Yields were compared with yields from other plots where 0, 20, and 40 kg N ha^{-1} was added. Yields from plots being studied for residual N effects were comparable to those from control plots where no fertilizer was added (Fig. 3). This suggests that fertilizer N applied the previous year did not show significant residual effect at any level of fertilizer application or stage of crop harvest. Since droughts occur frequently in arid regions, farmers consider N fertilizers a risky input; hence there is a need for better management.

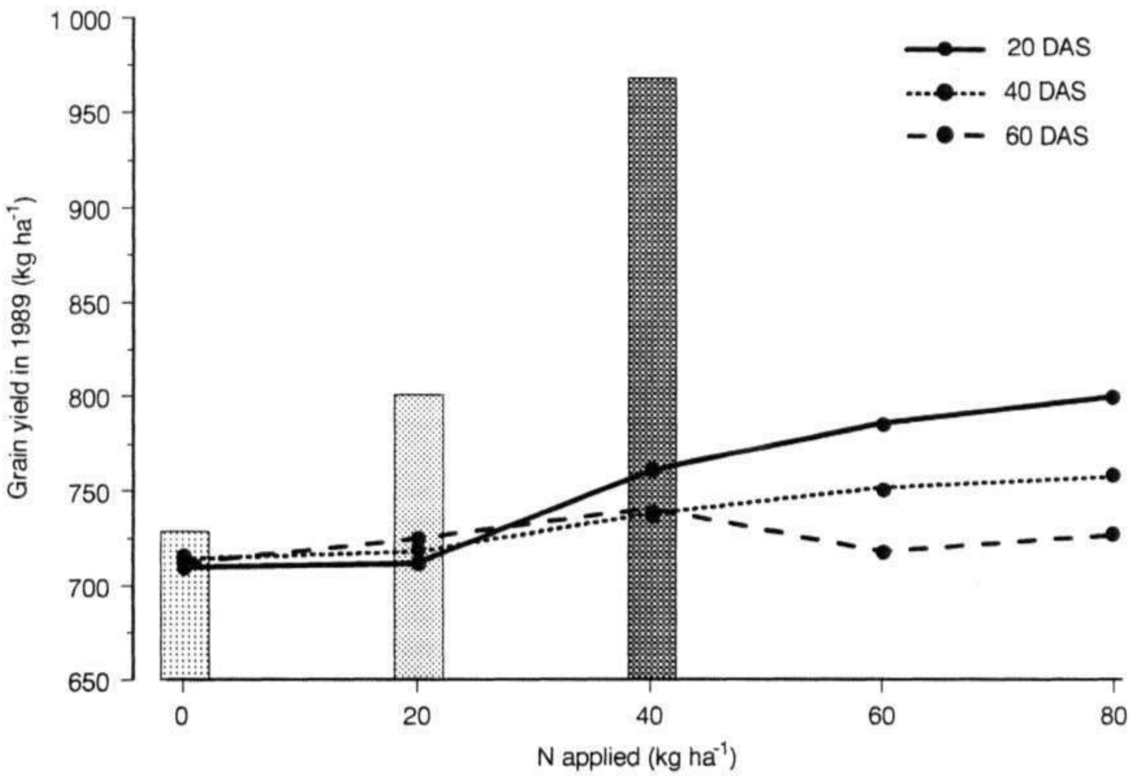

Figure 3. Residual effect of nitrogen applied to pearl millet crops harvested 20, 40, and 60 days after sowing to simulate drought conditions. Lines indicate residual effect of fertilizer applied in 1988 on the pearl millet crop grown in 1989; bars indicate grain yield after fertilizer application in 1989. (Source: Praveen-Kumar and R.K. Aggarwal, unpublished.)

Split application of N fertilizer gives higher yields than a single application, increases N-use efficiency, and reduces risk due to impending droughts. Six ways of splitting fertilizer N application to pearl millet, with various proportions of basally applied and topdressed fertilizer, were compared for two cropping systems—pearl millet-pearl millet and cluster bean-pearl millet (see Fig. 4). Our results suggested that for both systems

- split application of fertilizer was better than a single application;
- application of 40 kg N ha^{-1} either as two or three splits (treatment b, c, or e) gave yields that were at par with one another;
- at 80 kg N ha^{-1}, yields obtained with either treatment c or e were higher than those obtained with treatment b;
- yields obtained with treatment d—no basal N application—were lower than those obtained with any other treatment at the same N level.

Comparing the pearl millet yields in the two cropping systems, we found that with treatment d, i.e., without basal N application, yields were much higher in the cluster bean-pearl millet than in the pearl millet-pearl millet system.

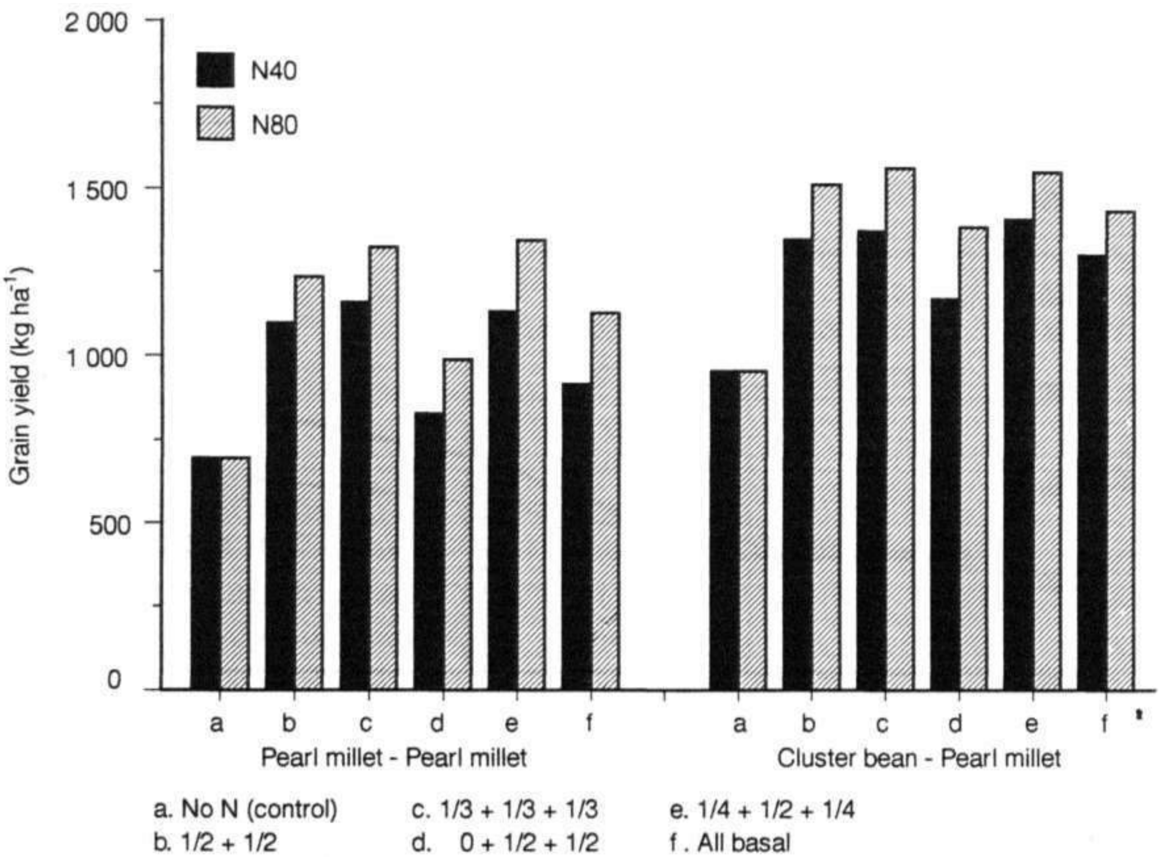

Figure 4. Effect of different methods of split application of fertilizer N (40 and 80 kg ha^{-1}) on pearl millet yield in two cropping sequences. (Source: Praveen-Kumar and R.K. Aggarwal, unpublished.)

Our results suggested that, although basal application is necessary to achieve high pearl millet yields, it can be avoided to reduce risk, without much loss of yield, if cluster bean was grown in the previous year.

Integrated use of Fertilizers, Manures, Crop Residues, and Legume-based Cropping Systems

In view of the high cost of chemical fertilizers and the characteristic uncertain yield levels in this arid zone, Aggarwal and Venkateswarlu (1989) suggested supplementing chemical fertilizers with bulky organic manures.

Fertilizer nitrogen and farmyard manure

Singh et al. (1981) observed that, under the arid conditions of Jodhpur, continuous application of sheep manure in general gave substantially higher pearl millet yields than the application of urea alone. Rao and Singh (1993) showed that substituting FYM for 50% of the fertilizer requirement gave yields nearly similar to those obtained with the full fertilizer dose. Aggarwal and Praveen-Kumar (1996), on the basis of a 7-year study on arid soils, showed not only a beneficial effect of FYM alone but also a synergistic effect on crop yield of FYM applied with inorganic fertilizers. Application of FYM increases the use efficiency of fertilizer N; however, improvement of soil fertility with FYM application is a very slow process (Table 5).

Table 5. Effect of continuous cropping of pearl millet and addition of farmyard manure (FYM) ($t\ ha^{-1}\ yr^{-1}$) on fertility status of soil.

		Final value (1989)	
		FYM addition	
Soil fertility status	Initial value (1983)	0	10
Organic C (%)	0.27	0.25	0.33
Available nutrients			
P ($mg\ kg^{-1}$)	6.31	5.68	8.00
Mn ($mg\ kg^{-1}$)	5.54	5.60	5.86
Fe ($mg\ kg^{-1}$)	2.00	2.09	2.18
Cu ($mg\ kg^{-1}$)	0.16	0.16	0.19
Zn ($mg\ kg^{-1}$)	0.13	0.37	0.45
N ($kg\ ha^{-1}$)	140.0	138.6	144.3

1. *Source:* Aggarwal and Praveen-Kumar (1996).

Crop residues and fertilizer nitrogen

Crop residues are an important source of soil nutrients. In India, 1.24 million tons of N, 0.16 million tons of P, and 2.0 million tons K of can be added to the soil if only one-third of the estimated crop residues (185.3 million tons per year) were returned to the soil (Bharadwaj 1981). Residues can be left on soil as mulch cum manure, can be incorporated into soil, or can even be burnt in the field and the ashes incorporated into the soil. But research on this aspect of nutrient management has been rather limited in arid regions.

Gupta and Gupta (1986) reported that under arid conditions, mulching with local weeds increased soil moisture content from 3-7% to 4-9%, but was more effective in a no-tillage system. Gupta (1984) reported that mulching reduced the mean maximum temperature at 10-cm depth by 1-6° C in fields of cowpea and pearl millet. The addition of crop residues also improves soil aggregation (Venkateswarlu 1987). This is mainly attributed to increased microbial activity during decomposition (Elliot and Lynch 1984; Elliot and Papendick 1986), adhesive action of decomposition products (Elliot and Lynch 1984), or increased earthworm populations. Venkateswarlu (1984) and Gupta (1986) have reported a decrease in bulk density and increase in hydraulic conductivity in soils where residue management is practiced.

Retaining the crop residues on the soil generally has a positive effect on grain yield (Hadimani et al. 1982; Hegde et al. 1982; Venkateswarlu 1984; Dhillon and Dhillon 1991; Aggarwal et al, in press). Rao and Singh (1993) have reported that crop residues are as efficient a source of nutrients as other organic materials, such as cattle manure and compost. However, Aggarwal et al. (in press) did not find any significant change in the yield of the succeeding crop of pearl millet after the addition of crop residues with a wide C:N ratio, whereas yield increases were significant after the incorporation of residues with a narrow C:N ratio (Table 6). Incorporating crop residues into the soil has been reported to increase the organic

Table 6. Effect of crop residues, farmyard manure (FYM), and fertilizer N on grain yield and nitrogen-use efficiency of pearl millet in the Indian arid zone.[1]

Fertilizer N ($kg\ ha^{-1}\ yr^{-1}$)	Control without organic amendments	Added crop residue[2] ($t\ ha^{-1}\ yr^{-1}$)[1] CB 1.7	PM 1.4	MB 2.7	FYM ($t\ ha^{-1}\ yr^{-1}$)[1] 2.0
Grain yield ($kg\ ha^{-1}$)					
0	335	515	430	435	530
20	505	625	540	545	635
40	550	715	585	655	770
N-use efficiency (% of applied N)					
20	30.10	57.52	38.71	30.71	56.52
40	20.03	35.93	18.49	26.26	39.87

1. Average of 2 years.
2. CB = cluster bean; PM = pearl millet; MB = mung bean.

matter content (Hooker et al. 1982; Aggarwal et al., in press). Hegde et al. (1982) reported higher organic C and available P and K in soils after 5 consecutive years of maize residue incorporation. Increases in the organic C and available N, P, and K after the application of residues have also been reported by Dhillon and Dhillon (1991).

Legume-based crop rotation

Mann and Singh (1977) observed that pearl millet yield was 62% lower with a pearl millet-pearl millet rotation than with a mung bean-pearl millet rotation. Singh (1980) reported that, among sole crop systems, the pearl millet-fallow rotation proved the most remunerative in both yield and monetary returns. Among rotations, pearl millet-cluster bean gave the highest returns per unit area (Misra 1964). Based on a longterm study, Singh et al. (1985) reported that in arid soils of Jodhpur, pearl millet yield was 11% higher from a cluster bean-pearl millet rotation than from continuous pearl millet. Similar results were also obtained by Oswal et al. (1989) in rainfed soils of Haryana. The beneficial effects of legume cultivation may be attributed to improved soil fertility (Das and Rao 1986; Oswal et al. 1989; Praveen-Kumar et al. 1996). In a longterm study, Singh et al. (1985) found a 12% increase in soil organic C and a 25% increase in available soil P as a result of legume cultivation.

Singh and Singh (1977), also on the basis of a longterm study, reported that the cultivation of mung bean in rotation with pearl millet supplied with 20 kg N ha^{-1} gave yields similar to those obtained with application of 40 kg fertilizer N ha^{-1}. In other words, growing legumes had an effect equivalent to that of 20 kg N ha^{-1}. However, this legume effect differs with different grain legumes. For instance, Singh et al. (1985) observed that rotation of pearl millet with mung bean or cluster bean was better than its rotation with moth bean. Praveen-Kumar et al. (unpublished data) reported a higher pearl millet yield when the preceding crop was cluster bean than when it was mung bean. The beneficial effect of legumes on pearl millet also depends on the number of seasons they are cultivated prior to pearl millet.

Legume cultivation improves the fertility status of soils. Praveen-Kumar et al. (in press) have shown that the changes in the concentration of total N after legume cultivation are very small compared with changes in the distribution of different organic N fractions. The intercropping of pearl millet and legumes in arid soils has also shown promising results (Misra 1971; Singh and Joshi 1980; Singh et al. 1978).

Conclusion

Soils of arid regions are generally deficient in N, which is a major reason for low productivity. Because of variable yield levels and the farmers' lack of resources, there is need to build up and maintain soil N through integrated nutrient management. This can be achieved in part by mobilizing the organic sources of N available on the farm. Research on rainfed agriculture has shown the beneficial effect of integrating organic sources with inorganic N sources. Better management of fertilizer N by regulating the ammonia volatilization processes helps enhance its efficiency. Further research is needed on (1) establishing fertilizer N rates on the basis of total nutrient requirements for a given cropping system under variable moisture conditions, availability of N, and organic and biological resources, while taking into account fertilizer efficiency; (2) identifying the potential of on-farm organic sources (plant and animal) and their management for higher N availability and fertility maintenance.

References

Aggarwal, R.K., and Praveen-Kumar. 1990. Nitrogen response to pearl millet *(Pennisetum typhoides* S&H) grown on soil underneath *Prosopis cineraria* and open site in an arid environment. Annals of Arid Zone 29:289-293.

Aggarwal, R.K., and Praveen-Kumar. 1996. Integrated use of farm yard manure and fertilizer nitrogen for sustained yield of pearl millet *(Pennisetum glaucum)* in a desert sandy soil. Annals of Arid Zone 35:29-36.

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

Aggarwal, R.K., Dhir, R.P., and Kaul, P. 1977. Study on N fractions in some arid zone soils differentially managed under normal rainfed farming and saline water use. Annals of Arid Zone 25:112-117.

Aggarwal, R.K., Kaul, P., and Lahiri, A.N. 1982. Ammonia and nitrate in rain water over arid and semi-arid areas of western Rajasthan. Annals of Arid Zone 21:299-305.

Aggarwal, R.K., Praveen-Kumar, and Power, J.F. (In press.) 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.

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

Aggarwal, R.K., Praveen-Kumar, and Sharma, B.K. 1990. Distribution of nitrogen in some arid soils. Journal of the Indian Society of Soil Science 38:430-433.

Aggarwal, R.K., Raina P., and Praveen-Kumar. 1987. Ammonia volatilisation losses from urea and their possible management for increasing nitrogen use efficiency in an arid region. Journal of Arid Environments 13:163-168.

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.

Alexander, M. 1961. Introduction to soil microbiology. New York NY, USA: John Wiley. 471 pp.

Alexander, M. 1965. Nitrification. Pages 307-343 *in* Soil nitrogen (Bartholomew, W.V., and Clark, F.E., eds.). Madison WI, USA: American Society of Agronomy.

Bharadwaj, K.K.R. 1981. Potential and problems of recycling of farm and city wastes on land. Pages 57-76 *in* Recycling residues of agriculture and industry (Kalra, M.S., ed.). Ludhiana, Punjab, India: Punjab Agricultural University.

Burns, R.C., and Hardy, W.F. 1975. Nitrogen fixation in bacteria and higher plants. New York NY, USA: Springer Verlag.

CAZRI (Central Arid Zone Research Institute). 1990. Annual report 1989-90. Jodhpur, Rajasthan, India: CAZRI. 49 pp.

Das, S.K., and Rao, A.C.S. 1986. Effect of preceding crops on nitrogen management for rainfed sorghum in black soil. Journal of the Indian Society of Soil Science 34:510-513.

Dhillon, K.S., and Dhillon, S.K. 1991. Effect of crop residues and phosphorus levels on yield of groundnut and wheat grown in rotation. Journal of the Indian Society of Soil Science 39:104-108.

Dowdell, R.J., and Smith, K.A. 1974. Field studies of the soil atmosphere. II. Occurrence of nitrous oxide. Journal of Soil Science 25:231-238.

Elliot, L.F., and Lynch, J.M. 1984. The effect of available carbon and nitrogen in straw on soil and ash aggregation and acetic acid production. Plant and Soil 78:335-343.

Elliot, L.P., and Papendick, R.I. 1986. Crop residue management for improved soil productivity. Biological Agriculture and Horticulture 3:131-142.

Garcia-Moya, E., and McKell, C.M. 1970. Contribution of shrubs to the nitrogen economy of a desert-wash plant community. Ecology 51:81-88.

Gupta, J.P. 1984. Effect of mulches on hydrothermal regimes of soil and crop yield. Pages 143-147 *in* Annual report 1984. Jodhpur, Rajasthan, India: Central Arid Zone Research Institute.

Gupta, J.P. 1986. Effect of tillage and mulch on soil and the growth and yield of cowpea grown in arid tropics. Arid Soil Research and Rehabilitation 1:161-172.

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

Hadimani, A.S., Hegde, B.R., and Satyanarayana, T. 1982. Management of red soil. Pages 689-702 *in* Review of soil research in India, Part II. Transactions of the XII International Congress of Soil Science, 8-16 Feb 1982, New Delhi, India. New Delhi, India: Indian Agricultural Research Institute.

Hegde, B.R., Havanagi, G.V., Reddy, M., Venugopal, N., Viswanath, A.P., and Satyanarayana, T. 1982. Studies on incorporation of maize residue on soil properties and yield of maize under rainfed conditions. Indian Journal of Agronomy 27:254-258.

Hooker, M.L., Herron, G.M., and Penas, P. 1982. Effect of residue burning, removal and incorporation on irrigated cereal crop yields and soil chemical properties. Soil Science Society of America Journal 46:122-146.

Husz, G. St. 1977. Agro-ecosystems in South America. Agro-ecosystems (Special issue. Frissel, M.J., ed.) 4:244-276.

Joshi, D.C. 1993. Soil resources of Rajasthan. Pages 77-92 *in* Natural and human resources of Rajasthan (Chouhan, T.S., ed.). Jodhpur, Rajasthan, India: Scientific Publishers.

Kowalenko C.G., and Cameron D.R. 1976. Nitrogen transformations in an incubated soil as affected by combinations of moisture content and temperature and absorption-fixation of ammonium. Canadian Journal of Soil Science 56:63-70.

Mann, H.S., and Singh, R.P. 1977. Crop production in Indian Arid Zone. Pages 215-234 *in* Desertification and its control. New Delhi, India: Indian Council of Agricultural Research.

Miller, R.D., and Johnson, D.D. 1964. Effect of soil moisture retention on carbon dioxide evolution, nitrification and nitrogen mineralization. Soil Science Society of America Proceedings 28:644-647.

Misra, D.K. 1964. Agronomic investigations in arid zone. Pages 165-169 *in* Proceedings of the Symposium on Problems of Indian Arid Zone, 23 Nov-2 Dec 1964, Jodhpur, India. New Delhi, India: Government of India Ministry of Education.

Myers, R.J.K. 1975. Temperature effects on ammonification and nitrification in a tropical soil. Soil Biology and Biochemistry 7:83-86.

Noy-Meir, I., and Harpaz, Y. 1977. Agro-ecosystems in Israel. Agro-ecosystems (Special issue. Frissel, M.J., ed.) 4:143-167.

Oswal, M.C., Bakshi, R.K., Kumar, V., and Kumar, S. 1989. Response of dryland pearl millet to fertilizer under two cropping sequences. Journal of the Indian Society of Soil Science 37:337-342.

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

Praveen-Kumar and Aggarwal, R.K. 1988. Reducing ammonia volatilization from urea by rapid nitrification. Arid Soil Research and Rehabilitation 2:131-138.

Praveen-Kumar, Aggarwal R.K., and Power, J.F. (In press.) Cropping systems: effect on soil quality indicators and yield of pearl millet in arid Rajasthan. American Journal of Alternative Agriculture.

Praveen-Kumar and Uday Burman. 1996. Visual evidence of nitrate reductase exudation from plant roots. Current Science 71:585-586.

Rao, V.M.B., and Singh, S.P. 1993. Crop responses to organic sources of nutrients in dryland conditions. Pages 287-304 *in* Recent advances in dryland agriculture (Somani, L.L., ed.). Jodhpur, Rajasthan, India: Scientific Publishers.

Reichman G., Grunee D.L., and Viets, F.G., Jr. 1966. Effect of soil moisture on ammonification and nitrification in two northern plains soils. Soil Science Society of America Proceedings 30:363-366.

Robinson, J.D. 1957. The critical relationship between soil moisture content in the region of the wilting point and mineralization of native soil nitrogen. Journal of Agricultural Sciences 49:100-105.

Sims, C.M., and Collins, F.M. 1960. The numbers and distribution of ammonia-oxidizing bacteria in some Northern Territory and South Australian soils. Australian Journal of Agriculture Research 11:505-512.

Singh, K.C., and Singh, R.P. 1977. Intercropping of annual grain legumes with sunflowers. Indian Journal of Agricultural Sciences 47:563-567.

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

Singh, R.P. 1980. Cropping systems for drylands of Indian Arid Zone. Annals of Arid Zone 19:443-447.

Singh, R.P., Singh, H.P., Daulay, H.S., and Singh, K.C. 1979. Pages 22, 27 *in* Annual report 1979, Jodhpur Centre. Jodhpur, Rajasthan, India: All India Coordinated Research Project on Dryland Agriculture.

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

Singh, R.P., Singh, K.C., and Ramakrishna, Y.S. 1978. Effect of systems of planting of pearl millet on yield, total productivity, moisture use and money returns. Indian Journal of Agriculture Sciences 48:138-142.

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 legumes. Indian Journal of Agricultural Sciences 55:274-278.

Skujins, J., and Fulgham, P.T.Y. 1978. Nitrification on great basin desert soils. Pages 60-74 *in* Nitrogen in desert ecosystem (West, N.E., and Skujins, J., eds.). Stroudsburg: Dowden, Hutchinson, and Ross.

Stanford, G., and Epstein, E. 1974. Nitrogen mineralization water relations in soils. Soil Science Society of America Journal 38:103-107.

Stanford, G., Frere, M.H., and Schwaninger, D.H. 1973. Temperature coefficient of soil nitrogen mineralization. Soil Science 115:321-323.

Stevenson,E.J.1986. Cycles of soil. New York NY, USA: John Wiley.

Stewart, B.A. 1992. Strategies for managing nutrients in stressed environment. Pages 115-124 *in* Nutrient management for sustained productivity: proceedings of an International Symposium, 941 Feb 1992, Ludhiana, India. Ludhiana, Punjab, India: Punjab Agricultural University

Tucker, B.B. 1988. Soil fertility assessment and management and management strategies in dry land system. Pages 361-366 *in* Proceedings of the International Conference on Dryland Farming, 15-19 Aug 1988, Amarillo TX, USA. Amarillo TX, USA: Texas Agricultural Experiment Station.

Venkateswarlu, J. 1984. Nutrient management in semi-arid red soils. Part II, Project Bulletin 8. Hyderabad, Andhra Pradesh, India: All India Coordinated Research Project on Dryland Agriculture.

Venkateswarlu, J. 1987. Efficient resource management for drylands of India. Advances in Soil Science 7:165-221.

Venkateswarlu, J., and Hegde, B.R. 1992. Nutrient management for sustainable production in coarse textured soils. Pages 188-194 *in* Nutrient management for sustained productivity: proceedings of an international symposium, 9-11 Feb 1992, Ludhiana, India. Ludhiana, Punjab, India: Punjab Agricultural University.

Vlek, P.L.G. 1981. Accession, transformation and loss of nitrogen in soils of the arid region. Plant and Soil 58:133-175.

Virginia, R.A., Jarrell, W.M., and Franco-Vizcaino, E. 1982. Direct measurement of denitrification in a *Prosopis* (mesquite) dominated Sonora Desert ecosystem. Oecologia 53:120-122.

West, N.E. 1975. Short term ecosystem dynamics in arid lands. London, UK: Cambridge University Press.

West, N.E., and Klemmedson J.O. 1978. Structural distribution of nitrogen in desert ecosystem. Pages 1-16 *in* Nitrogen in desert ecosystem (West, N.E., and Skujins, J., eds.). Stroudsburg: Dowden, Hutchinson, and Ross.

Yaalon D.H. 1964. The concentration of ammonia and nitrate in rain water over Israel in relation to environmental factors. Tellus 16:200-204.

Nutrient Management Research on Pearl Millet for the Arid Western Plain Zone of Rajasthan

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Abstract

This paper reviews research done at the Agricultural Research Station of Rajasthan Agricultural University at Mandor, Jodhpur, on the response of pearl millet to nutrients supplied through organic and inorganic sources. Pearl millet yields increased with nitrogen up to 40 kg ha^{-1}, applied as a split dose, half at sowing and half topdressed 30-40 days after sowing, when rainfall was normal Under intermittent drought, N was beneficial only up to 20 kg ha^{-1}, applied basally. However, when adequate soil moisture was maintained with supplemental irrigation, 80 kg ha^{-1} N significantly increased yields—grain by 72.1% and stover by 33.1%—over the unfertilized crop. Sulfur fertilization (50 kg ha^{-1}) had no significant effect on grain yield, even when available soil S was below the critical soil test value, indicating that pearl millet uses S efficiently. Studies on crop rotation and fertilizer management showed that continuous sole-cropping of pearl millet reduced grain yields. Moth bean-pearl millet emerged as the most productive rotation, giving a gross monetary return of Rs. 3802 ha^{-1}. Leguminous crops did not respond to N fertilization, but phosphorus applied to the cereal, legume, or oilseed crop in alternate years appeared to supply sufficient P for the succeeding pearl millet crop. Farmyard manure applied at 10 t ha^{-1} in alternate years considerably increased grain and stover yields of pearl millet and organic carbon content and water-holding capacity of the soil

Introduction

Pearl millet is the traditionally grown cereal food crop of the dry farming systems in Rajasthan. It is grown on 4.8 million hectares and is the single rainy-season cereal grown in six of the nine agroclimatic zones of Rajasthan. However, average yields of pearl millet have fluctuated between 223 and 562 kg ha^{-1} in the last two decades because of the arid environment, which subjects the crop to severe abiotic stresses, especially deficiencies of soil moisture and nutrients. Application of fertilizer, particularly N, depends on the intensity and distribution of the southwest monsoon. Hence, there is a need to determine the optimum rate and

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time of fertilizer application, either alone or in combination with farmyard manure (FYM), in varying rainfall situations. Nutrient management studies on pearl millet done at the Agricultural Research Station, Mandor, Jodhpur, are reviewed in this paper.

Nitrogen Management

Field studies over 5 years to determine the optimum dose and timing of N application under dryland conditions showed that in seasons with normal rainfall (300 mm ± 60 mm), pearl millet responded up to 40 kg ha^{-1} N applied in two equal splits, half at sowing and half topdressed 30-40 days after sowing (DAS) (Table 1). Mean increase in grain yield was 60.3% over yield of the untreated crop. Under intermittent drought, however, pearl millet responded only up to 20 kg ha^{-1} N, applied basally (ARS 1991).

Table 1. Effect of nitrogen level (kg ha^{1}) and time of application on grain yield of pearl millet (kg ha^{-1}).

Treatment		Year					
Basal	Top-dressed	1988 (M)[1]	1989 (PM)[1]	1989 (M)	1990 (M)	1991 (M)	Mean
0	0	282	846	974	528	315	589
0	10	296	878	1139	567	454	667
0	20	351	936	1079	822	491	736
10	0	318	909	1120	767	481	719
10	10	348	911	1278	972	546	811
10	20	356	894	1130	1100	500	796
20	0	360	857	1051	1139	528	787
20	10	388	855	1009	1264	500	803
20	20	468	939	1231	1371	712	944
CD (5%)		78	NS[2]	NS	283	186	-

1. M = monsoon sowing, PM = premonsoon (June) sowing,
2. NS = nonsignificant.

Another field study over 3 years showed that with supplemental irrigation, grain and stover yields of pearl millet increased significantly with N applications up to 80 kg ha^{-1}, applied in two equal splits, half at sowing and half topdressed at 30 DAS (Table 2); grain yield was 72.1% higher than that of the untreated control and stover yield was 33.1% higher. Yield increases were attributed to the cumulative effect of significant increases in yield attributes.

In the same study, S application had no significant effect on grain yield, although available S content of the soil was below the critical limit (8.5 mg kg^{-1}).

Table 2. Effect of nitrogen and sulfur on yield of pearl millet with adequate moisture supply, Rajasthan, India, 1989-91.

	Yield (kg ha^{-1})							
	Grain				Stover			
Treatment	1989	1990	1991	Mean	1989	1990	1991	Mean
N applied (kg ha^{-1})								
0	1125	1788	1170	1361	4548	4471	3804	4274
40	1274	2531	2187	1997	4868	5293	4834	4998
80	1329	3037	2661	2342	5744	6064	5262	5690
120	1270	3032	2710	2337	5817	6466	5524	5936
CD (5%)	91	209	173	156	303	229	196	232
S applied (kg ha^{-1})								
0	1215	2586	2138	1980	5223	5524	4810	5186
50	1284	2609	2226	2040	5266	5623	4901	5263
CD 5%	65	NS	NS	NS	NS	NS	NS	NS

This may be due to the existence of an efficient mechanism for S uptake and translocation in pearl millet.

Crop Rotation and Fertilizer Management

Field studies were undertaken for 8 consecutive years (1988-95) on a permanent site to test crop rotations of rainfed pearl millet with legume and oilseed sole crops and the amount of fertilizer required for these cropping sequences (ARS 1995).

Pearl millet yields in the legume-pearl millet rotation were higher than those of continuous pearl millet (Table 3). This may be due to a marginal increase in the organic carbon content of the soil from legume leaf litter. Under the legume-pearl millet rotation, organic C content of the soil at the end of 8 years was 4.1-5.0% higher than that under continuous pearl millet.

The moth bean-pearl millet rotation was economically the most remunerative, giving a mean gross return of Rs. 3802 ha^{-1} (Table 4). Applying 100% of recommended N every season and of P every alternate season was found as effective as applying 100% N and P every season. From this we conclude that P could best be applied to the cereal, legume, or oilseed crop in the sequence once in two seasons and pearl millet grown in rotation on the residual fertility.

Longterm Effect of Manure

Field studies using longterm manurial treatments showed a significant effect of FYM application on grain and stover yields of pearl millet in all years. The

Table 3, Effect of crop rotation and fertilizer application on yield of rainy-season crop, Rajasthan, India, 1988-95.

	Yield (kg ha^{-1})							
Treatment	1988	1989	1990	1991	1992	1993	1994	1995
Crop rotation[1]								
PM-PM	377	917	1046	930	525	143	1769	200
MB-PM	-	1178	845	1134	645	167	706	351
CB-PM	576	1081	357	1125	400	168	322	256
S -PM	92	1271	113	1097	149	149	73	210
Fertility level[2]								
	373	1191	655	1194	469	168	758	269
F_2	384	1180	609	1097	441	160	703	264
F_3	288	962	507	923	371	142	690	230

1. PM = pearl millet; MB = moth bean; CB = cluster bean; S = sesame.
2. F_1 = 100% N and P applied every season; F_2 = 100% N applied every season and P in alternate seasons; F_3 = 75% N applied every season and P in alternate seasons. For pearl millet and sesame 100% = 40 kg N + 17.2 kg P ha^{-1} and for legumes 100% = 20 kg N + 17.2 kg P ha^{-1}.

Table 4. Effect of crop rotation and fertilizer application on gross monetary returns from pearl millet and legume or oilseed crops, Rajasthan, India.

	Gross returns (Rs ha^{-1})								
Treatment	1988	1989	1990	1991	1992	1993	1994	1995	Mean
Crop rotation[1]									
PM-PM	2489	2314	3159	4620	1993	918	8507	1435	3204
MB-PM	567	2961	4561	5560	5922	1071	7876	1890	3802
CB-PM	3185	2773	2323	5876	2479	1073	2516	1677	2713
S-PM	787	3207	1594	5481	2164	978	1352	1448	2126
CD (5%)	277	513	338	689	271	112	744	245	452
Fertility level[2]									
F_1	2582	3029	3231	5882	3447	1083	5363	1693	3289
F_2	2524	2975	2979	5427	3196	1036	4947	1660	3093
F_3	2122	2434	2521	4694	2783	911	4878	1484	2728
CD (5%)	240	444	293	597	235	109	NS	NS	NS

1. PM = pearl millet, MB = moth bean, CB = cluster bean; S = sesame.
2. F_1 = 100% N and P applied every season; F_2 = 100% N applied every season and P in alternate seasons; F_3 = 75% N applied every season and P in alternate seasons. For pearl millet and sesame 100% = 40 kg N + 17.2 kg P ha^{-1} and for legumes 100% = 20 kg N + 17.2 kg P ha^{-1}.

application of FYM at 10 t ha^{-1} increased grain yields by a mean of 101.6% and stover yields by 82.9% over the control (Table .5), There was no significant difference in yields between applications made every year and in alternate years, except in 1990. Thus, applying FYM once in 2 years seems sufficient for obtaining higher pearl millet yields.

Table 5. Effect of farm yard manure (FYM) on pearl millet yields, Rajasthan, India, 1988-92.

	Yield (kg ha^{-1})									
	Grain					Stover				
Treatment	1988	1989	1990	1992	Mean	1988	1989	1990	1992	Mean
Control	107	77	664	671	380	3458	400	2527	958	1836
FYM (10t ha)										
Every season	130	267	1583	1084	766	4375	1398	4213	1292	2820
Alternate seasons	130	268	1280	1101	695	4236	1051	4185	1236	2677
CD 5%	NS	43	103	195	-	NS	329	130	137	-

The application of FYM also significantly increased soil organic C and water-holding capacity during all seasons (Table 6). Mean organic C content increased by 43.8% with the yearly and 25% with the alternate-year applications; water-holding capacity increased by 7.6% and 4.7% over the control (ARS 1992).

Table 6. Effect of farm yard manure (FYM) on soil organic carbon content and water-holding capacity, Rajasthan, India, 1988-92.

	Organic carbon (%)					Water-holding capacity (%)			
Treatment	1988	1989	1990	1992	Mean	1989	1990	1992	Mean
Control	0.17	0.17	0.17	0.15	0.16	27.2	27.6	28.5	27.8
FYM (10 t ha^{-1})									
Every season	0.21	0.23	0.24	0.24	0.23	29.5	30.2	30.0	29.9
Alternate seasons	0.20	0.22	0.22	0.18	0.20	28.8	29.2	29.4	29.1
CD 5%	0.02	0.02	0.01	0.02	-	0.63	1.07	1.60	-

Conclusions

Nitrogen application increases grain yields of pearl millet in the arid western plains zone of Rajasthan when rainfall is normal. Topdressing of N should be done only when there is sufficient rainfall, during the peak growth period of the crop. The moth bean-pearl millet rotation was the most remunerative and productive cropping sequence tested. Applying P to the preceding cereal, legume, or oilseed crop was found sufficient for the succeeding pearl millet crop. Application of FYM at 10 t ha^{-1} once in 2 years was sufficient to maintain soil fertility

References

ARS (Agricultural Research Station). 1991. Pages 25-27 *in* Annual *kharif* progress report, Mandor, Jodhpur 342 304, Rajasthan, India: Rajasthan Agricultural University,

ARS (Agricultural Research Station). 1992. Pages 33-38 *in* Annual *kharif* progress report. Mandor, Jodhpur 324 304, Rajasthan, India: Rajasthan Agricultural University, India.

ARS (Agricultural Research Station). 1995. Pages 30-33 *in* Annual *kharif* progress report. Mandor, Jodhpur 324 304, Rajasthan, India: Rajasthan Agricultural University.

Economic Issues in Nutrient Management

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Abstract

This paper discusses economic issues in nutrient management involving applications of inorganic fertilizer and use of organic materials in sole- and mixed-cropping systems in the arid zone of India. Most nutrient response studies calculate the benefits of fertilizer application in terms of grain yields. In arid areas, however, crop byproducts also fetch good prices. In subnormal rainfall years, grain and straw together can cover fertilizer costs. Therefore, straw yield should form an indispensable part of every economic analysis. In the arid zone, all animal waste, agrowaste, and litter is used as farmyard manure. In mixed cropping, the proportion of seed of each crop varies, depending on the time of onset of the monsoon; therefore, it is difficult to determine the product proportion and thereby the economic feasibility of fertilizer application in such systems. Nutrient management in alternative land-use systems is thought to be important, yet very little information is available on the economic feasibility of these systems.

Introduction

Economic issues in nutrient management involve increasing productivity per unit area by applying inputs on a sustainable basis. Sustainability means optimizing productivity over time rather than maximizing production at one point in time. It emphasizes continued physical accessibility to agricultural products through economic feasibility.

"Sustainable agriculture" is a loosely defined term that encompasses many approaches to alternative agricultural systems. It implies a time dimension and the capacity of a farming system to endure indefinitely (Loakeretz 1988). The ultimate goal of sustainable agriculture is to develop farming systems that are productive and profitable, conserve the natural resource base, protect the environment, enhance health and safety, and do so over the long term (Parr et al. 1990). In essence, it emphasizes ecofriendly agricultural management that will ensure that natural resources are available to future generations.

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Nutrient Management in Cropping Systems

The nutrient supply in a sole-cropping system does not provide ideal conditions for soil improvement and aeration and for moisture and nutrient use. In systems such as mixed cropping, crop rotations, and crop-tree or crop-livestock combinations, nutrient management is easier and may be both economical and ecologically friendly. Nutrient management in agriculture concerns

- Application of inorganic fertilizers—nitrogen/phosphorus/potash, and trace elements.
- Use of organic materials—agrowaste, animal waste, forest waste, etc.
- Crop mixes and various enterprise mixes.
- Crop rotations and cultural practices, such as breaking of surface crust, preventing crop burial from wind drift, etc.
- Management of crop residues and their effects on the nutrient status of the soil.
- Alternative land use—agroforestry, silvipastoral, hortipastoral, and agro-horticultural systems.
- Use of biofertilizers—such as *Rhizobium* and *Azotobacter*—and of vermiculture.

Application of inorganic fertilizer

As arid-zone soils are inherently poor in fertility, applying inorganic fertilizer is usually beneficial, although it adds to the costs of cultivation. More fertilizer is needed to enhance production if rainfall is normal, when 40 kg ha^{-1} N is considered appropriate. However, this rate is reduced by 50% when rainfall is subnormal, and the optimum N dose mostly recommended is only 20 kg ha^{-1}.

Different crops show different yield responses (calculated as kg grain yield increase per kg nutrient applied) to fertilizer. On research or demonstration farms, pearl millet, sesame, and grasses have shown better responses to fertilizer than legumes, such as moth bean, mung bean, and cluster bean. Yield response of pearl millet to N fertilizer was 7.5-18 kg; of sesame, 4.0-14.7 kg. Aggarwal and Venkateswarlu (1989) found the following yield responses to P application: 4.2-5.3 kg in cluster bean; 1.4-4.1 kg in mung bean; 0-0.09 kg in moth bean; 1.3-17.1 kg in pearl millet; and 1.0-2.7 kg in sesame.

Generally, crop response to nutrients is considered solely in terms of grain yield; however, in arid areas, crop byproducts also fetch good prices and, even in years of subnormal rains, grain and straw together can cover nutrient costs. Straw yield should therefore form an indispensable part of any economic analysis for computation of nutrient-use efficiency of the dryland crops of this region.

Use of organic material

The most important practice in indigenous nutrient management is the use of farmyard manure (FYM). Besides increasing crop yields, FYM improves soil physicochemical characteristics, enabling the crop to withstand unfavorable weather conditions and also benefiting succeeding crops.

Farmyard manure contains about 0.3% N, 0.2% P, and 0.3% K. The arid region as a whole has the potential for producing about 19 million tons of dung annually, containing approximately 3.5 million tons of organic matter and 0.02 million tons of soil nutrients (Kalla et al. 1978). Of the 19 million tons, 12.4 million tons are used for manure, 5.57 million tons for dung cake, and 0.56 million tons to plaster mud walls and floors of the *jhupas* (huts).

Singh et al. (1981) observed the effect of FYM on grain yield of pearl millet over 5 years (1975-79). A grain yield of 1.5 t ha^{-1} was obtained with 20 t of FYM alone; however, the same yield was obtained with only 10 t of FYM when it was combined with 10 kg ha^{-1} N.

The practice of biannual FYM application is very old and is followed by farmers who have enough animals to provide the dung. Farmyard manure has longterm residual effects; thus, its incorporation in the nutrient application schedule may help evolve a sustainable system of nutrient management.

Other animal waste from slaughter houses, dried blood, bone meal, etc., are not generally used as organic manure in this region, because of religious sentiments. Oilcakes are seldom used as manure but are utilized as concentrates for cattle feed.

Crop Mixes and Various Enterprise Mixes

Mixed cropping is the sowing of one main crop and one or two subsidiary crops, the seed being mixed and sown together in the same field. In rainfed conditions, pearl millet is usually sown together with mung bean, moth bean, and sesame. In the postrainy season, wheat + chickpea, mustard + chickpea, wheat + barley, etc., are also grown as mixed crops.

In this mixed-cropping context, different rooting patterns and maturity periods of various crops assume importance. In the mixed system, crops will better utilize the available nutrients and soil moisture because of reduced competition effects. The farmer's seed mix generally changes from tract to tract due to different soil types and other associated ecological factors. The proportion of different crops in the seed mix is not fixed, and it varies according to the anticipated season. It is difficult to determine the proportion of the product in relation to the proportion of the seed in the seed mixture. A clear understanding of the process involved in mixed cropping and the logic behind this age-old practice can provide valuable insights into nutrient management and its economic feasibility.

Crop Rotations and Cultural Practices

Legumes have always played an important role in cropping systems in the agriculture of most ancient civilizations (e.g., Indian, Greek, Egyptian, Roman, Chinese). Inclusion of legume crops in rotations helps fix atmospheric N and build up organic reserves in the soil. Legumes followed by pearl millet in a normal rainfall period fix 20 kg ha^{-1} N, which can help reduce the quantity of fertilizer required the next year.

Sometimes heavy rains that occur just after sowing may hamper seedling emergence, requiring cultural operations (locally known as *rhode)* to break the soil crust and help the seedlings emerge. Formation of a surface crust can be checked by applying FYM over the seed, which keeps the surface layer moist and porous. The recommendation for this purpose is 2 t FYM ha^{-1}; however, this is often not available. Again, by erection of physical barriers against the wind, soil erosion can be checked and burial of seedlings (locally called *relana)* prevented. The traditional systems, such as *math* (stabilized field boundary with natural vegetation) and *carta* (small vegetative barriers with dead bushes) bunding, can help to achieve this objective. All these practices can help in better nutrient management in this region.

Management of Crop Residue and Nutrient Residual Effects

Utilization of crop residues is part and parcel of nutrient management. Crop residues plowed into the field add to soil organic matter, benefiting the growth of subsequent crops. Even weeds, such as *Digera muricata* and *Cleome viscosa,* have a high N (4.5%), P (0.25%), and K (3.5%) content and, if buried, can help to enrich soil fertility. However, to improve nutrient-use efficiency, it is imperative to avoid weed-crop competition at critical crop phases.

Alternative Land-use Systems

Agroforestry, silvipastoral, hortipastoral, and agrohorticultural systems and animals within the systems all help in nutrient management of soil and are often complementary. It is worthwhile collecting data on these alternative land uses, for they help maintain soil fertility and will eventually bring prosperity and economic stability to the rural masses of this region.

Biofertilizers and Vermiculture

Biofertilizers, such as *Azotobacter* and *Rhizobium* cultures, are cheap sources of nutrients for maintaining soil fertility. One packet of biofertilizer, which will increase production by 10-15%, costs only about Rs. 10. The cost:benefit ratio in this application was 1:10.

Vermiculture uses earthworms to pulverize the soil, making it more friable. Earthworms add humus to the soil, thereby increasing its water-holding capacity.

Conclusion

Nutrient management can be defined as nourishing of biomass under natural resources (soil, water, and air) for integrated farming systems that would foster an ecofriendly environment and, used with newly developed technologies, would enable sustainable agricultural production.

References

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

Loakeretz, W. 1988. Open questions in sustainable agriculture. American Journal of Alternative Agriculture 3:174-181.

Kalla, J.C., Joshi, B.R., and Mehta, A.C. 1978. A strategy to meet energy demands in Arid Area of Western Rajasthan. Urja 3(3):73-76.

Parr, J.F., Stewart, B.A., Hornet, S.B., and Singh, R.O. 1990. The sustainability of dry land farming systems—global perspective. Advances in Soil Science 13:1-8.

Technology Transfer in Rajasthan through the Department of Agriculture

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Abstract

The role of the Rajasthan State Department of Agriculture in the transfer of technology from research station to the farmer is reviewed. The state is divided into nine agroclimatic zones to facilitate area-specific recommendations for cropping systems involving cereal pulse, and oilseed crops. Research results are tested at the adaptive trial centers of the state government and in on-farm trials. The area under improved varieties of pearl millet, pulses, and oilseeds has increased significantly in the arid region.

Introduction

The arid regions of Rajasthan are characterized by extreme temperatures, low relative humidity, severe drought, erratic and low rainfall, and high wind velocities. The mean aridity index in these areas is 78%, with a mean wind velocity of 20 kmph during April, May, June, and July, which causes significant wind erosion. Mean annual rainfall ranges from 424 mm in Pali on the eastern border of the arid zone to 185 mm in Jaisalmer on the western border. Of the total rainfall, 91-96% is received during the southwest monsoon, from June to September.

Three types of aberrant weather create problems in cropping tinder these conditions: delayed onset of monsoon, long gaps in rainfall, and early termination of rains. Some important measures to counter these problems are (1) the use of suitable crops and crop varieties; (2) cultural operations, such as thinning, hoeing, and weeding; (3) topdressing and spraying of urea; (4) moisture conservation; and (5) efficient use of precipitation and stored soil moisture.

Yields obtained from rainfed lands are low and highly unstable. It is important to increase productivity during good rainfall seasons and to stabilize production in years of normal and subnormal rainfall.

Development of Fertilizer Recommendations

The state of Rajasthan has been divided into nine agroclimatic zones (Table 1), so that area-specific recommendations can be made for various cropping systems,

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Table 1. Agroclimatic zones of Rajasthan, India.

Agroclimatic zone		Areas covered
Ia	Arid Western Plain (Area 1 243 700 ha)	All tehsils of Bikaner, Jaisalmer, and Barmer districts; Phalodi, Shergarh, Osian, and Jodhpur tehsils of Jodhpur district; Dungergarh, Sujangarh, Ratangarh, and Sardarshar tehsils of Churu district
Ib	Irrigated North Plain (Area 206 300 ha)	All tehsils of Sriganganagar district
IIa	Transitional Plain of Inland Drainage (Area 369 300 ha)	All tehsils of Nagaur, Sikar, and Jhunjhunu districts; Taranagar, Churu, and Rajgarh tehsils of Churu district
IIb	Transitional Plain of Luni Basin (Area 294 200 ha)	All tehsils of Jalore and Pali districts; Reodhar, Sirohi, and Sheoganj of Sirohi district; Bilara and Bhopalgarh tehsils of Jodhpur district
IIIa	Semi-arid Eastern Plain (Area 2 948 000 ha)	All tehsils of Ajmer, Jaipur, and Tonk districts
IIIb	Flood Prone Eastern Plain (Area 2 368 000 ha)	All tehshils of Alwar, Bharatpur, and Dholpur districts; Mahauwa, Toda-Bhim, Hindun, Nadautim Bamanwas, Gangapur, Karoli Sapotra, and Bonli tehsils of Sawaimadhopur district
IVa	Sub-humid Southern Plain and Aravalli Hills (Area 3 359 000 ha)	All tehsils of Bhilwara and Rajsamand districts; all tehsils except Dhariyavad, Salumbar, and Sarada of Udaipur district; all tehsils except Chhotisadri, Pratapgarh, Arnod, and Badisadri of Chitorgarh district; Abu Road and Pindwara tehsils of Sirohi district
IVb	Humid Southern Plain (Area 1 721 000 ha)	All tehsils of Banswara and Dungarpur districts; Chhotisadri, Badisadri, Pratapgarh, and Amod tehsils of Chitorgarh district; Dhariyavad, Salumbar, and Sarada tehsils of Udaipur district
V	Humid South Eastern Plain	All tehsils of Bundi, Kota, Bara, and Jhalawar districts; Khandar and Sawaimadhopur tehsils of Sawaimadhopur district

and microfarming systems can be developed. The Directorate of Research, Rajasthan Agricultural University, and the State Department of Agriculture jointly formulate research programs of direct utility to the farmers in different zones. Research results from various stations are tested at the adaptive trial centers (ATCs) of the state government at Rampura (Jodhpur) for agroclimatic zone Ia and at Sumerpur (Pali) for zone IIb. Results are also tested in farmers' fields. Finally, they are translated into recommendations for farmers.

Pearl millet is sown on about 2.5 million hectares in Jodhpur division, only 16 284 ha of which are irrigated. Similarly, maize is sown on 53 843 ha, of which only 5101 ha are irrigated. Mean yield of pearl millet in 1993/94 was 115 kg ha^{-1}; in 1994/95, it was 431 kg ha^{-1}. Maize yields were 338 kg ha^{-1} in 1993/94 and 512 kg ha^{-1} in 1994/95. The mean yield of rainy-season pulses during 1993/94 was 87 kg ha^{-1}; yield forecast for 1994/95 was 338 kg ha^{-1}.

In these harsh agroclimatic conditions, the Department of Agriculture is trying to stabilize the productivity of cereal, pulse, and oilseed crops by distributing high-yielding, short-duration varieties and by promoting fertility management and balanced use of fertilizer, based on soil test and water management.

In the last 5 years, 27 pearl millet varieties have been under test at the ATCs and in farmers' fields; Table 2 summarizes the performance of the leading varieties. In general, the hybrids outyield the composites, despite their generally

Table 2. Grain yields of pearl millet cm-station and in farmers' fields in two agroclimatic zones of Rajasthan, India, 1991-95.

	Yield (kg ha^{-1})					
	Zone Ia		Zone IIb			
Pearl millet variety	ATC(R)[1]	Minikit demons-trations[2]	ATC(R)[1]	Minikit demons-trations[2]	Range	Duration (days)
Hybrid						
MH 179	874	858	849	1125	430-1812	80-85
MHB 67	903	570	964	965	405-1784	60-65
RHB 30	743	-	768	-	33- 149	70-75
HHB 60	934	-	-	-	555-1956	60-65
Composite						
MP 171	811	-	489	-	38- 174	80-90
WCC 75	685	-	486	-	26-1589	80-90
RCB 2	720	-	-	-	353-1465	80-90

1. ATC = Adaptive Trial Centre, Rajasthan Department of Agriculture: R = Rampura, Jodhpur district (35 locations); S = Sumerpur, Pali district (30 locations).
2. Farmers' fields.

longer duration. *In* zone IIb, HHB 67 and MH 179 perforated best; in zone Ia, HHB 60 and HHB 67-which mature in 60-65 days, thus satisfying the farmers' requirement for a fast-maturing, high-yielding variety—did well.

Of the composites, MP 171 did best in both zones Ia and IIb, while RCB 2 and WCC 75 also performed well. The minikit demonstrations confirmed the superiority of MH 179 and HHB 67, Thus overall, HHB 60, HHB 67, and MH 179 were the best-performing varieties, with the differences between them attributable to soil fertility and moisture variations.

Adaptability Testing of Legume and Sesame Varieties

Promising varieties of three legumes—moth bean, cluster bean, and mung bean—and one oilseed (sesame) have been tested over the last 5 years.

Of the eight varieties of moth bean tested, RMO 40 performed best, combining good grain yield (385 kg ha^{-1}) and early maturity (60-65 days) (Table 3).

Table 3. Grain yields of eight moth bean varieties, Rajasthan, India, 1991-95.

Variety	Yield (kg ha^{-1}) Average (1991-95)	Range (30 locations)	Duration (days)
RMO 40	380	314-473	60-65
Maru	307	240-474	65-70
Jawala	290	287-485	75-80
RM0 256	334	-	65-70
RM0 257	300	-	68-70
IPCMO 880	371	288-507	70-75

Suvidha was the best of the six cluster bean varieties in zone Ia and RGC 936 in zone IIb. Both varieties are early-maturing (65-70 days) and gave good yields in both zones. Variety Naveen also yielded well in both zones (Table 4).

Table 4. Grain yields of six cluster bean varieties in two agroclimatic zones of Rajasthan, India, 1991-95,

Variety	Average yield (kg ha^{-1}) Zone Ia	Zone IIb	Range (kg ha^{-1})	Duration (days)
D Safed	305	288	138-338	80-85
D Jai	328	-	200-394	80-85
Suvidha	342	340	13-488	65-70
RGC 936	316	407	65-626	65-70
Naveen	416	333	7-550	75-80
Mona	271	-	17-256	75-80

The mung bean variety K 851 had the highest average yield, followed by RMG 11(R) (Table 5). All three of the varieties tested are higher yielding than the local cultivar.

Table 5. Grain yields of improved mung bean varieties, Rajasthan, 1991—95.

	Yield (kg ha^{-1})	
Variety	Average[1]	Range
RMG 11(R)	494	287-720
RMG 286	481	259-703
K 851	559	305-800
Local	*444*	250-638

1. Over 15 locations.

Five sesame varieties were tested, and RT 46 was the best in terms of yield (503 kg $ha^{-1)}$ and early maturity (70-75 days) in zone Ia (Table 6). Extra-short-duration varieties are needed to match the short rainfall season.

Table 6. Yields of five sesame varieties in two agroclimatic zones of Rajasthan, India, 1991-95.

	Average yield (kg ha-[1])		Range	Duration
Variety	Zone Ia	Zone IIb	(kg ha^{-1})	(days)
TC 25	447	447	172-767	90-100
RT 46	503	366	198-593	70- 75
RT 125	128	260	172-580	75- 80
RT 103	168	146	131-428	75- 80
RT 54	380	376	214-428	75- 80

Performance in Adaptive Trials

There was a clear response of pearl millet to added nitrogenous fertilizer during the period 1991-94 (Table 7). The highest yields were from split applications totaling 40 kg ha^{-1} N. A demonstration was laid out in 1993 over a range of sites, with 20 kg N ha^{-1} applied basally. Yields are reported, although the responsiveness and economics are not.

Sole-cropped pearl millet variety HHB 67 gave the highest yield (2375 kg ha^{-1}) when rows were spaced at 60 cm; however, data are for 1 year only, at one location.

When pearl millet was intercropped with mung bean, a 2:1 ratio was found the most productive, though less so than sole-cropped pearl millet. The best mixture

Table 7. Response of pearl millet to nitrogen in two agroclimatic zones of Rajasthan, India, 1991-94.

N applied (kg ha^{-1})	ATC Ia[1]	Demonstration	
	HHB 67	HHB 67	MH 179
0	662	-	-
20 (1/2 B + 1/2 TD)[2]	869	-	-
20 (TD)	795	-	-
10(B)	765	-	-
20(B)	-	570-1093	750-975
40 (1/2 B + 1/2 TD)	1099	-	-

1. ATC = Adaptive Trial Centre.
2. B = basal application; TD = top dressing at 30-40 days after sowing.

for pearl millet, which did not reduce yields, was with either moth bean or mung bean.

The recommendations resulting from this work are that in light soils with scanty rainfall pearl millet variety HHB 67 should be grown, at a 60-cm spacing. For zone Ia, pearl millet should be mixed with moth bean; for zone IIb, on heavy soils, pearl millet should be mixed with mung bean.

The highest gross income (Rs. 9500 ha^{-1}) was obtained from sole-cropped pearl millet sown at a row spacing of 60 cm; the second highest (Rs. 6908 ha^{-1}), from a pearl millet + moth bean mixture. Pearl millet sown in a mixture with moth bean, cluster bean, mung bean, and sesame gave the lowest income (Rs 4569 ha^{-1}).

Fertilizer Management in Relation to Soil Test

Fertilizer application based on specific soil-test recommendations was more productive than that based on generalized departmental recommendations: pearl millet, moth bean, and mung bean yields were all higher—pearl millet more markedly than the legumes—when fertilizer was applied according to soil test recommendations.

Implementation of Program

The extension wing of the Department of Agriculture, under various central and state government schemes, organizes demonstrations of early-maturing, high-yielding hybrid and composite varieties of pulses, oilseeds, small millets, and coarse cereals.

For alkaline soils/gypsum is distributed to farmers as required, through a subsidy scheme. Higher yields have been obtained from plots treated with gypsumthanfromuntreatedplots.

A major problem farmers face in this region of Rajasthan is that of soil crusting. This hampers seedling emergence, so that farmers often have to resow pearl millet and sesame two or three times in a season. This problem needs to be addressed.

Scientists from Rajasthan Agricultural University and officers of the State Department of Agriculture develop various recommendations in the form of packages of practices to be followed for each season (rainy and postrainy). Instruction booklets for these are printed and distributed before the start of each season to the officers and field workers to help them guide farmers regarding the best recommendations to follow.

The region has two mobile soil-testing laboratories and one stationary one, and farmers are encouraged to apply fertilizers on the basis of soil tests. Another laboratory testing soil and water for salinity also provides recommendations to farmers for remedial measures.

Impact of Work by the Department of Agriculture

The Department of Agriculture has been making consistent efforts to popularize the use of improved high-yielding varieties, fertilizers, and plant protection measures. These have resulted in increased adoption of high-yielding varieties of pearl millet to 1628.7 t, of rainy-season pulses to 212 t, and of edible oilseeds to 65.2 t during the 1995 rainy season. Fertilizer use has also increased from an average 1.28 kg ha^{-1} in 1990 to 3.84 kg ha^{-1} in 1995.

On-farm Research: Development of Sustainable Farming Systems for an Arid Ecosystem

H P Singh[1]

Abstract

On-farm farming systems research is considered as an approach to controlling desertification in the Indian Thar Desert through participatory technology development and transfer Livestock management is emphasized as the central component of the farming system for increasing productivity on a sustainable basis. The paper stresses the need to use indigenous technical knowledge and to integrate all components of the system—arable farming, alternative land-use systems, and management of livestock, wastelands, and common property resources—to develop prototype models of desert agriculture that can be replicated in developmental programs.

The Scenario

The Thar desert in northwestern India represents one of the harshest agroecological environments in the country. Low rainfall, shifting sand dunes, sandy hummocky soils, wind erosion, and recurring droughts have been driving the farmers to total despondency Many smallholders appear resigned to living at or below the poverty line, practicing subsistence farming on a fragile resource base. The scenario has become worse in some situations due to natural resource constraints on the one hand and land abuse on the other. People in their quest for livelihoods are driven to look at what is available today, with complete disregard for posterity. Extending cultivation to marginal and submarginal lands, overgrazing of village commons, and indiscriminate cutting of vegetation for fodder and fuel are the easiest options available. All of these accelerate the process of desertification in many locations of the Thar. If these practices continue without suitable interventions, the damage may become irreversible (Singh 1995). Thus the present production system is not sustainable. As Figure 1 shows, there was no perceptible increase in the yields of dryland pearl millet, the principal crop of this region, over a 30-year period.

Animal husbandry has been the traditional source of livelihood in the Thar desert This region was endowed with productive and hardy breeds of cattle, such

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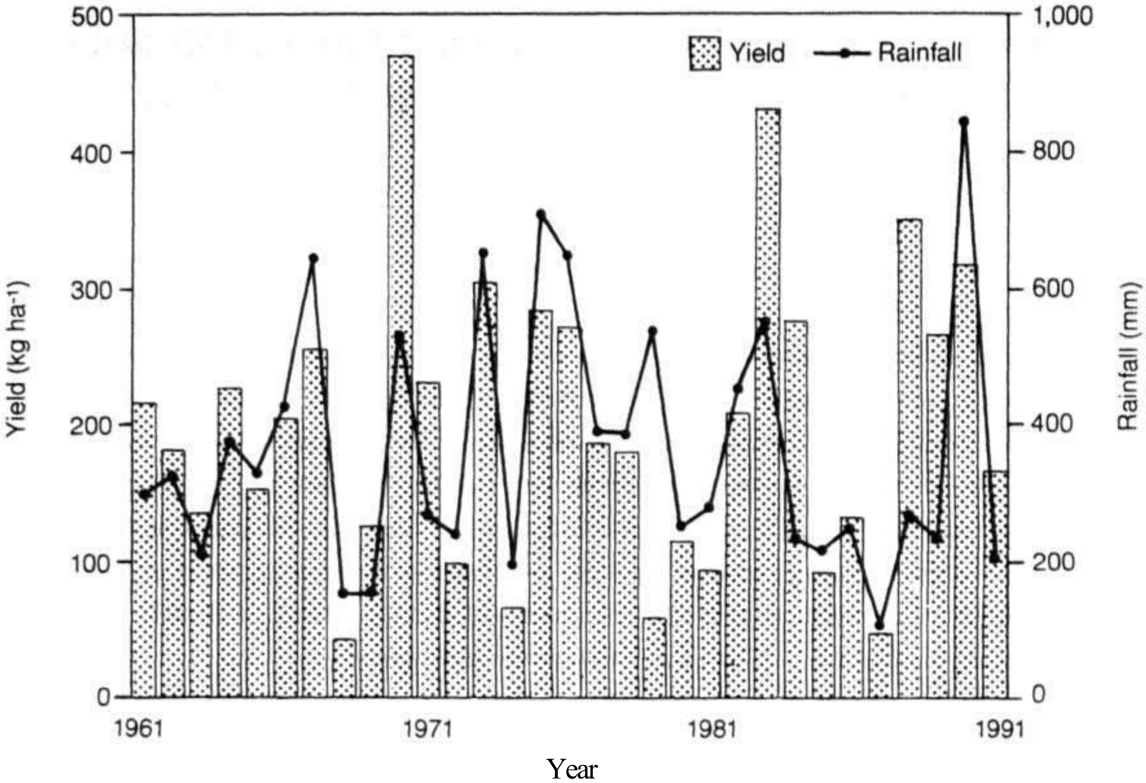

Figure 1. Yield of pearl millet in the Thar Desert region, Rajasthan, India, 1961-1991.

as Tharparkar, Kankreg, and Rathi, which, with proper management, could yield as much as 8-10 liters of milk per day.

Fallowing was a traditional practice. Until the 1950s, land holdings were generally large, and farmers left 20-25% of their holdings as temporary fallows, using them as private grazing lands. The associated benefit was the enhanced soil fertility from the addition of animal excreta and plant residues. Invariably, crop yields increased when the fallows were used for croplands after 3-5 years. This was the local wisdom that provided a degree of complementarity between arable farming and animal husbandry.

Since the 1950s, however, this traditional farming system has been under increasing strain because of the constant growth in population (human and livestock) and the subdivision of land holdings. Overgrazing of village commons has become a way of life. Smallholders and landless pastoralists now constitute a large sector of rural society. The purity of local breeds has gone down as low as 10-25%; coupled with poor forage supply, this has reduced milk yields to 2-4 liters per day. Once-rich grazing lands are now a pathetic sight, with hardly anything to graze. Besides degrading pasture lands, uncontrolled grazing has become a formidable barrier to the development of permanent vegetal resources of trees and grasses to serve as forage to sustain and upgrade livestock husbandry and to control desertification.

Rural communities therefore need to be mobilized to recognize the gravity of this situation and develop a new social order to ensure sustainable land use

(Singh 1996). Developing an appropriate strategy for such mobilization calls for a critical review of past extension efforts to identify gaps in delivery

Extension and Development Efforts

Extension

Agricultural extension programs have been run for several decades in western Rajasthan by the Rajasthan State Departments of Agriculture and Animal Husbandry. The initiation of the lab-to-land program in the mid-1970s marked the beginning of organized efforts by the Indian Council of Agricultural Research (ICAR) institutes in this area. The All India Coordinated Research Project for Dryland Agriculture (AICRPDA), which began in 1970 with a network of 24 centers located in different agroecological regions of the country, had a built-in extension mechanism of simultaneous testing and dissemination of technology through a state-run pilot project.

Operational research

Organized operational research was initiated at CAZRI in 1974. The main objectives were

- Testing of technology under real field situations to identify technological, operational, and socioeconomic constraints to its adoption.
- Demonstration of proven technology.
- Creation of a multiplier effect through close involvement of farmers, local bodies, and the state extension network in the program.

This on-farm effort, however, could serve only one of the objectives; i.e., demonstration. This approach had been successfully used in irrigated areas of the country; however, this model did not work for the smallholders in poorly endowed dryland areas in arid and semi-arid regions, because of the small gains from component technologies under the uncertain and inadequate water supply.

Training

Recognizing the pivotal role that training can play in upgrading farm productivity, it was started as a regular activity at Rajasthan Agricultural University (RAU) and many other state agricultural universities in the late 1960s and early 1970s. Regular courses for extension personnel started at CAZRI in 1981. Training has critical significance in this desert area, where literacy is low and where effective mass media intervention is still in the takeoff stage. Greater efforts are required in this area, with a focus on client participatory methods.

Area development programs

Considering drought management as a national priority, the Government of India initiated a major developmental effort called the Drought Prone Areas

Programme (DPAP) in 1972 (earlier known as the Rural Works Programme). As many as 54 districts in the country, with parts of another 18 contiguous districts, were identified as drought-prone and included in the program, covering nearly 12% of the country's population and 20% of its geographical area. The National Commission on Agriculture in 1974 made a strong plea for planned development of desert areas. This led to the launching of the Desert Development Programme (DDP) in 1977/78, focusing on afforestation, pasture development, soil and water conservation, and development of water resources for agriculture and drinking water.

Impact of Extension and Development Programs

As stated earlier, the extension model used in the desert was essentially the demonstration approach successfully applied in irrigated areas associated with the green revolution in this country. In those areas, the synergistic effect of improved crop varieties, fertilizer use, and water management led to a quantum jump in productivity The National Demonstration Programme, coupled with the training and visit (T&V) system, produced dramatic results that led to instant adoption of the technology package over large areas.

This extension model, however, failed to produce encouraging results in risk-prone and resource-poor dryland areas. The farmers' interest was limited to receiving free inputs; once the program was withdrawn, the farmers reverted to their original ways.

The area development programs, DPAP and DDP, were designed to restore the agroecological balance by controlling desertification and adopting a watershed management approach; however, except at a few locations, the achievements were dismal (GOI 1994). Besides the lack of an adequate research backstop, the National Committee on DPAP and DDP, set up in 1988, listed the following shortcomings in the programs (GOI 1990):

- Lack of conceptual clarity about longterm and shortterm objectives.
- Isolated and segmented program planning and implementation.
- Lack of intersectoral coordination and linkages with other area development programs.
- Spreading of programs thinly over a wide area.
- A top-down approach resulting in poor involvement of the stakeholder in program planning and implementation.
- Lack of a multidisciplinary approach in program planning and implementation.
- Inadequate extension network at grassroots.
- Limitations to backup from research and training.
- Bureaucratic bias towards shortterm gains, with less appreciation of the longterm goal of ecosystem sustainability.

From the inception of these programs up to 1993, Rs. 14 709 million had been invested under the DPAP, covering 5 million hectares, and Rs 4685 million under the DDP, covering 0.4 million hectares. Despite these huge investments, however, ecological degradation has continued unabated in many such areas. From 1995/96 onwards, into the Ninth Five Year Plan (beginning 1997/98), an annual outlay of Rs. 15 billion is planned for these programs. Considering the gaps in these programs identified by the two National Committees constituted in 1988 and 1993, steps need to be taken to realize the fullest gains from such investments on drought proofing and sustainable development of dryland ecoregions.

Farming Systems Research

Of late, it has been increasingly recognized that it is extremely difficult to develop sustainable technology for the heterogeneous agroecological and socioeconomic conditions of smallholders in arid and semi-arid regions (von der Osten et al. 1989). The failures in technology development and transfer in these regions stem, in part, from the inherent difficulty of the task; in part, from the lack of farmers' participation.

The problems are complex and characterized by a host of environmental and socioeconomic issues. Addressing only a single component of the farming system, e.g., crop variety, fertilizer use, or crop husbandry, cannot bring about the dramatic increase in productivity witnessed in irrigated areas. Dryland farmers are not interested in anything less.

The extension strategy should therefore match this challenge. Mixed farming, comprising crop production and animal husbandry, has been the mainstay of subsistence of dryland farmers. Technology must therefore fit the whole farming system rather than solve individual and isolated problems. The recognition of this fact in the 1970s marked the beginning of farming systems research (FSR) on-farm.

On-farm FSR is essentially an extension of on-station research to synthesize and develop technologies from research results relevant to improving the whole farming system. Hence, research station backup is necessary for FSR, which should be undertaken on farmers' fields, with the full cooperation and involvement of the farmers. Such FSR should be complementary to the on-station research, adopting a problem-solving approach that is fundamentally oriented to farmers as the primary clients of research.

Planning of FSR requires some understanding of the farmers' situation. Initiating FSR in real field situations requires three sets of information (Singh 1995) on the following:

- socioeconomic conditions of people, their perceptions, priorities, requirements, and indigenous technical knowledge;
- resource conditions; and
- technology (research information) developed at the research stations.

All this information must then be carefully analyzed to effect a balance between resource conditions and farmers' requirements in the choice of component technologies to be tested as treatments. To begin with/the focus should be on refining indigenous technical knowledge. Strict prescriptions of component technologies developed at the research stations should be avoided. Necessary adjustments should be incorporated to offer baskets of options to suit clients' requirements and priorities (Chambers 1991). If required, alternative technologies for farmers sharing common problems can be developed by conducting experiments on their fields. The farmers' complete involvement is absolutely necessary in both planning and execution of a program. The farmer thus functions as the real executor of the program; the researcher and extension worker serve as facilitators. This is the basic philosophy of on-farm FSR.

The cultivated area in the Thar has increased significantly, from 32% in the 1960s to 52% in the 1990s, to sustain population growth. This explains the cultivation of marginal lands that accelerates desertification. Animal husbandry, the erstwhile mainstay of the desert populations, has gone into oblivion. To arrest and possibly reverse this trend, improved livestock husbandry needs to be restored. Livestock management should therefore form the central strategy of farming systems in the Thar and in other arid and semi-arid regions. Restoring the quality of cattle breeds by introducing pure males and meeting forage needs by planting grasses and fodder trees can significantly shift the scenario toward sustainability.

Another important issue for FSR in arid regions is the integration of various components of the system: dryland crop production, animal husbandry, management of common property resources, rehabilitation of degraded lands, and efficient utilization of limited irrigation resources. Some suggestions for such integration follow:

1. Focusing on animal husbandry, with increased area under grasses, trees, and horticultural crops, will encourage farmers to reduce the area under arable crops. Smaller cropped areas can be managed more efficiently. This may upgrade livestock husbandry and eventually more than compensate for the reduced cropped area in terms of economic returns. Similarly, maximizing production on irrigated lands can reduce the pressure on dryland farming.
2. More manure from livestock and organic wastes applied to the reduced area under arable crops can help boost productivity.
3. Rotating pastures and croplands every fourth or fifth year can help improve the quality of the soil for crop production.
4. Planting on field boundaries, besides conserving soil and generating forage and firewood, can also upgrade the microclimate for better performance of arable crops in the long run.
5. Planting of fuel trees, such as *Prosopis juliflora,* on degraded lands and use of solar-driven appliances may help discourage the practice of using cattle dung as fuel. More FYM made available in this way can help maintain soil fertility.

Conclusions

On-farm research with a farming systems perspective has been a missing link in technology transfer programs in dryland agroecological regions of India. Farming systems prototype models that focus on forage production and livestock rearing thus need to be developed through a systematic program of on-farm research involving scientists, extension personnel, and farmers. Wherever possible, the watershed should be taken as a unit to integrate technology components and conserve natural resources, as water is the main factor limiting plant production in these regions. Once developed, these prototype technology models, coupled with participatory training of farmers and extension personnel, could then be successfully and extensively replicated by extension and development agencies through programs such as the DPAP and DDP.

References

GOI (Government of India). 1990. Report of the Technical Committee on Drought Prone Areas Programme and Desert Development Programme. New Delhi, India: Government of India Ministry of Rural Development. 22 pp.

GOI (Government of India). 1994. Report of the Technical Committee on Drought Prone Areas Programme and Desert Development Programme. New Delhi, India: Government of India Ministry of Rural Development 16 pp.

Chambers, R. 1991. In search of extension strategy for minimising risk in rainfed agriculture. Pages 47-51 *in* Extension strategies for rainfed agriculture (Prasad, C., and Das, P., eds.). New Delhi, India: Indian Society of Extension Education.

Singh, H.P. 1995. Forage production: the sustainability issues and the farming systems perspective. Pages 559-573 *in* The Manual of Regional Training Cum Workshop on Silvipastoral Systems in Arid and Semi-arid Eco-systems, 15 Nov-Dec 1995, Central Arid Zone Research Institute (CAZRI), Jodhpur, India. Jodhpur 342 003, Rajasthan, India: CAZRI.

Singh, H.P. 1996. Watershed as a unit for development of land resources and their management for sustainability in Arid Region. Pages 105-116 *in* Land resources and their management for sustainability in arid regions (Kolarkar, A.S., Joshi, D.C., and Kar, A., eds.). Jodhpur, Rajasthan, India: Scientific Publishers.

von der Osten, A., Ewell, P., and Merrill-Sands, D. 1989. Organisation and management of research for resource poor farmers. Pages 69-92 *in* Technology systems for small farmers: issues and options. Boulder CO, USA: Westview Press.

Water and Nutrient Management: Farmers' Practices, Perceptions, and Researchable Issues

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Abstract

In the arid regions of Rajasthan, farmers' traditional strategies for managing their limited soil, water, and nutrient resources include moisture-conservation structures; fallowing; and the use of legumes, animal and crop wastes, and deep tillage. As agriculture intensifies, traditional practices are disappearing and the sustainability of these systems is at risk. A diagnostic study of three villages concludes that there is some potential for improving nutrient management by the limited use of inorganic fertilizers. There appear to be additional opportunities for conservation structures that create more assured moisture conditions, under which high-yielding strategies could be adopted. There is a need to understand better the traditional institutions for managing soil and water conservation, existing practices for maintaining soil fertility, and farmers' continuing use of traditional practices in the face of more intensive cultivation.

The Background

A clear understanding of farmers' perceptions and practices is the key to developing a longterm research agenda driven by farmers' needs. Recognizing this, a group of scientists from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the Central Arid Zone Research Institute (CAZRI) made an exploratory study of how farmers currently manage their water and nutrient resources. Using participatory communication techniques, the researchers interacted with farmers across a transect of the target region to understand current practices and to identify priority research issues.

The team began with a hypothesis, based on prior observations and discussions with farmers, that due to the pressure of rapidly increasing population in western and central Rajasthan, soils are being more intensively cultivated, exhausting soil nutrients and reducing crop yields. Secondary data on land use, cropping patterns and production, and input use were analyzed by district; these indicated that

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- the amount and reliability of rainfall increases from western to central Rajasthan;
- pearl millet is the dominant crop, with a wider range of crops grown in the central districts;
- crop yields are closely related to amount and distribution of rainfall;
- cropping intensity has increased only marginally over the years;
- land-use intensity in the western districts has increased, as more fallow area has been brought under cultivation;
- fertilizer use is negligible, except on irrigated crops;
- adoption of high-yielding varieties has occurred only in the central districts; and
- crop yields seem to be declining in the western districts but increasing in the central districts.

Although the secondary data did not provide conclusive evidence that the nutrient status of soils was declining over time, there was circumstantial evidence of this. In the drier western districts, land-use intensity has increased, fertilizer applications have remained low, and yields have declined. There are clear differences in cropping patterns, adoption of high-yielding varieties, and fertilizer use between the drier western districts and the wetter central districts. Barmer, Jodhpur, and Nagaur—three districts spanning the range of rainfall conditions—were selected for further field work to test the hypothesis that land use is intensifying, leading to nutrient mining and declining crop productivity. In March 1996, an interdisciplinary team of ISP1 researchers from ICRISAT and CAZRI spent a week working with farmers in three villages in the selected districts to (1) improve researchers' understanding of the problems of agriculture in western and central Rajasthan, with particular focus on how farmers manage their soil, water, and nutrient resources; and (2) identify priority research issues.

The villages studied offer diverse conditions within the arid environment in western,and central Rajasthan. Average annual rainfall is 278 mm in Barmer, 360 mm in Jodhpur, and 440 mm in Nagaur. The farming practices that have evolved over the years have been carefully adapted to make the best use of resources and the environment, particularly to minimize the risk inherent in arid land agriculture.

The differences in soil conditions and topography within and across villages have influenced prevailing practices. Soils range from sandy soils that consist primarily of fine sand to heavier soils with higher proportions of silt and clay. In general, the sandier soils are characterized by deeper wetting, lower water retention within the plant root profile, and lower yields. The heavier soils have better water-retention capacity and produce higher yields, but are more prone to crusting.

The soil type and the location of fields relative to the movement of surface water determine soil moisture and nutrient conditions. Where slopes are slight or soils are sandy, there is little or no movement of water between fields. Water movement is greater where slopes are greater and the soils are heavier. Fields located at the base of such catchments receive water and accompanying silt and nutrients. If this silt is captured within the field, the silt content in the soil builds up over time, leading to higher moisture-holding capacity and nutrient status. Where there is considerable movement of surface water and soil that can be effectively trapped, farmers do conserve soil and water. Tanks have been built on public land to capture water for drinking and for livestock. *Khadins* (bunding on three sides of a field to retain rainwater) and boundary and contour bunds capture flows within fields for cropping. In Agolai (Jodhpur), a variety of moisture-conservation structures harvest surface water from catchment areas created by eroded hills and sloping areas. In contrast, in Arbi ki gaffan (Barmer) and Khari (Nagaur), the sandier soils and lack of sloping catchment areas limit the possibilities for water-conservation structures. There seems to be considerable scope for building more khadins where physical conditions are suitable, but hydrological dependence between structures demands coordination in their operation and maintenance.

Farmers' Perceptions and Current Practices

Farmers are fully aware that the consequences of what they do now will affect the capacity of the soils to produce in the future. Even practices that lead to shortterm gains appear to be taken up with a full understanding of the consequences, but often there are few alternative courses of action, particularly on small farms producing to meet family food requirements. For example, many small farmers must crop fields continuously, even though they are aware that this leads to declining "soil strength"—farmers terminology, interpreted by researchers as relating to soil fertility—and crop yields. At a broad level, most farming decisions—tillage, manuring, crop choice, rotations, and fallowing—seem to be directed at maintaining soil fertility while minimizing production risks and maximizing yields.

Only a few crop species are grown in the region. But crop choice does vary in terms of crop mixtures, extent of sole cropping, and proportion of different crops in mixtures. Farmers plant sole crops where moisture and fertility conditions are most favorable. At the high rainfall end (Khari), when rains are early, farmers expect enough moisture in most fields to plant sole crops. In lower rainfall areas, such as Agolai, farmers expect enough moisture for sole crops only in the heavier soils, which contain relatively more silt and clay and consequently store more moisture.

Similarly, only under the most assured moisture conditions do farmers grow hybrid pearl millet or postrainy-season crops. For example, only hybrid pearl millet is grown in Khari, and wheat and mustard are grown in heavier soils and in khadins in Agolai.

As moisture availability becomes less certain, crop mixtures become the norm. In soils with lower water-holding capacity in Agolai and in all soils in Arbi ki gaffan, mixtures of pearl millet and short-season legumes are grown; the millet is rarely cultivated as a sole crop. When rains are delayed and farmers expect a poor season, they substitute more drought-tolerant short-season legumes for pearl millet.

Managing soil fertility is important to all farmers. Soil fertility is maintained or enhanced through the use of legumes in crop mixtures and of fallow periods in crop rotations, the application of farmyard manure (FYM) and tankbed soil to fields, the penning of animals in fields, the capture of silt along with surface water flows, and the use of chemical fertilizers.

Of the legumes, cluster bean is considered the most effective in improving soil fertility, followed by moth bean and mung bean. On poorer soils, pearl millet alone or in mixtures is always rotated with legumes to maintain fertility. In fields of declining fertility, crop mixtures are dominated by legumes.

Fallowing is an important practice to maintain soil fertility, especially on sandy soils. Continuous cropping is more likely to be practiced on heavier soils and on soils around *dhanis* (farm homesteads located on farmland outside the village). Fallow land provides an important source of fodder for grazing and stall feeding. When fallowed fields are grazed, there is an added benefit from penning. However, the frequency and duration of fallowing have declined due to pressure on land.

Farmers consider addition of manure important to maintaining the nutrient status of soils. Manure applications depend on the location of fields in relation to where animals are kept and on the quality and fertility status of the land. Most manure is applied to fields near dhanis, where transport costs are lowest, while distant fields receive little or no manure. Farmers give priority to adding manure to sandy soils, which are usually deficient in nutrients, except in the driest village, Arbi ki gaffan, where farmers felt that sandy soils located far from the village are so unproductive that it is not worth adding manure to them.

Most farmers would like to use more manure, but not all can afford to purchase it or are willing to do so. Within each village, there are considerable differences in manure availability, because of differences in animal holdings in relation to land holdings. Families that have relatively more animals and less land may sell manure. Even in villages with a manure deficit, manure may be sold outside in irrigated areas, where its value is much higher. Sometimes manure surpluses may occur due to high transport costs and low returns from adding manure to sandy soils. Some farmers feel that applying manure increases crop moisture requirements and that crops only benefit from it in unusually good moisture conditions.

Farmers believe that chemical fertilizers increase the risk of crop loss and hence seldom apply them to rainfed crops. Thus few farmers have experience with the use of fertilizers. Although they realize that fertilizers are in some sense a substitute for manure, they believe that manure has positive effects on the soil beyond those conferred by chemical fertilizers. Furthermore, some farmers believe that frequent use of fertilizers has a damaging effect on soil structure, and that once they are used, repeat applications are necessary to maintain productivity

Only some farmers in Khari, the village with the highest and most reliable rainfall, have experimented with fertilizer applications on rainfed crops. They have applied nitrogen fertilizers late in the season to severely stunted crops; i.e., only in situations when the expected consequence of doing nothing was nearly total crop loss. While some fortunate farmers' crops responded well, others' crops burned in the absence of rainfall. Few will again take chances with fertilizer application. However, there is scope for developing less risky alternatives to the methods that these farmers have tried.

Deep plowing is done periodically, most typically once every 3 or 4 years. The perceived benefits from deep tillage are that it increases water-holding capacity, facilitates crop establishment by loosening the soil, and acts as a substitute for manure. Perceived disadvantages are that it brings up poorer soil from the deeper layers, makes the topsoil more vulnerable to erosion, and leaves deep furrows that are unproductive and enhance gully formation.

As farmers reduce the frequency of fallowing, they deep-plow, often in conjunction with a cluster bean crop, as they believe it substitutes for the effect of fallowing. Thus the frequency of deep tillage is increasing. For example, in Khari, farmers who do not have sufficient manure deep-plow their fields annually if there is adequate moisture.

Scope for Enhancing Production

Our interpretation of this strategy is that deep plowing mines the soil of nutrients as it produces a shortterm increase in available soil fertility; however, in the absence of added nutrients, this increase is at the cost of longterm fertility. Soil fertility status may decline due to increased crop uptake of nutrients. Organic matter may also decompose faster as more moisture is retained in the soil profile. Thus farmers minimize the frequency of deep plowing if they can.

Given their resource endowments and environment, farmers have limited opportunities to enhance production from agriculture. Where rainfall, topography, and soil conditions are suitable, there is some potential to conserve moisture in soils to reduce risk and increase productivity. Where moisture conservation is feasible, there are more options for enhancing productivity by improving soil fertility or adopting alternative crops or new varieties. Recent efforts by the state government and nongovernmental organizations to construct khadins suggest that there is still scope for moisture conservation structures under appropriate physical conditions, such as those observed in Agolai. Farmers are also keen on building khadins and field bunds. The construction and management of common khadins or a series of smaller interdependent ones require considerable coordination, and appropriate construction design, techniques, and institutions are critical to their functioning.

Options are far more limited where moisture is particularly low and uncertain. Farmers' current strategies for maintaining and enhancing yields, such as the use of manure and fallowing, are under threat, because of limited supplies of manure and increasing pressure on land. In the absence of opportunities to conserve soil moisture, strategies such as the adoption of high-yielding varieties or application of inorganic fertilizers may increase production risk and are hence unacceptable to most farmers. Despite the existence of fertilizer recommendations for western and central Rajasthan, farmers are reluctant to use fertilizers, and few have experience with their use. It is not clear whether the recommendations that exist and the information currently available to scientists and extension workers are appropriate to these farming environments.

There may be some potential for improving farmers' current nutrient management strategies by introducing the use of inorganic fertilizers where moisture is relatively assured or in tandem with strategies to conserve moisture, so that risk is not increased substantially.

Future Research

Further research may be useful on the following issues: moisture conservation, nutrient management, decision criteria, crop establishment, crop options, and alternative land-use strategies.

Moisture conservation

It would be useful to examine how khadins have been managed traditionally, the nature of interdependence among them, and the potential for improving cropping systems and fertilization strategies where khadins offer more secure soil moisture regimes. The effectiveness of current utilization of rainfall and the potential for improving rainfall-use efficiency by manipulating plant spacing and density should also be examined.

Nutrient management

The role that FYM plays in existing farming systems needs to be understood and the potential examined for improving nutrient management, whether by improving the-efficiency of FYM use or by developing methods for managing use of FYM with other nutrient sources.

Scientists do not clearly understand the role legumes play in fertility management in this region, in terms of the effects of different legumes on soil fertility. This information is a prerequisite to improving existing nutrient strategies.

We need to examine the potential for strategies that minimize risk in fertilizer use; for new options, such as slow-release fertilizers; and for strategies that integrate low levels of fertilizer with other traditional fertility amendments. There is scope for combining these techniques with moisture-conservation strategies.

These possibilities will be studied through experimentation combined with simulation modeling.

There is also a need to examine the status of phosphorus in soils of this region. Here again, modeling can supplement experimentation.

Decision criteria

We want to understand how farmers acquire and use information in making cropping decisions; i.e., what indicators they monitor and rules of thumb or decision criteria they use to make management decisions. The purpose is to identify simple techniques to help farmers collect and process information more easily and accurately and, possibly, to improve upon their decision rules. In conjunction with modeling, we need to develop indicators to improve farmers' predictive capability.

Crop establishment

There is scope for improving crop establishment. Possibilities include presoaking seeds; improving seed vigor by seed production under high-nutrition conditions; improving stability in planting depth by seed placement; and soil compacting.

Crop options

Short-duration pearl millet varieties are needed to provide farmers with additional options for late sowing. This is already being addressed in the breeding work at ICRISAT and the national research system in Rajasthan.

There may be a need for other improved cultivars, such as a more farmer-friendly cluster bean to reduce skin irritation from harvesting.

Alternative land-use strategies

In the highly risky crop production environments of western Rajasthan, it would be useful to examine the potential for alternative land-use strategies that place greater emphasis on pasture and tree cultivation as a means of enhancing and stabilizing farm income, and hence the sustainability of farm enterprises.

Note: For further details of the work described in this paper, see Kolavalli, S., Whitaker, M.L., Myers, R.J.K., van Oosterom, E.J., Anders, M.M., Joshi, N.L., Laryea, K.B., Seeling, B., Vyas, K.L., Kshirsagar, K.G., and Potdar, N. 1996. Management of soil, water, and nutrient resources in western and central Rajasthan: problem diagnosis and identification of research issues. Integrated Systems Project 1 Progress Report 1. Patancheru 502 324, Andhra Pradesh, India; International Crops Research Institute for the Semi-Arid Tropics. 42 pp. (Semiformal publication.)

Applications for Cropping Systems Simulation Models in On-farm Nutrient Management Research

E J van Oosterom[1]

Abstract

Cropping systems simulation modeling can be a powerful tool to complement field experimentation, particularly in areas where highly variable environmental conditions are combined with complex cropping patterns, and field experimentation cannot capture the wide range of environments found in farmers' fields. An example is western Rajasthan, where seasonal climatic variations are extreme, soils variable, and numerous crop mixtures grown. Therefore, the Integrated Systems Project 1 (ISP1) of ICRISAT—working in close collaboration with the Central Arid Zone Research Institute (CAZRI) in Jodhpur and the Agricultural Production Systems Research Unit (APSRU) in Australia—has embarked on a cropping systems modeling initiative in which the Agricultural Production Systems Simulator (APSIM) software package takes a central place. APSIM is structured around a central "engine," via which modules (for crop growth, soil water, soil nutrients, etc.) communicate. By linking multiple modules to this engine, it is possible to simulate crop rotations and crop mixtures. However, several of the modules that are relevant to the pearl millet-based cropping systems of western Rajasthan are not yet available in APSIM and need to be developed and validated. APSIM can then be used for applications of three types: (1) environmental characterization, (2) matching crop growth and development with resource availability, and (3) farm management options. On-farm nutrient management research can play an important role in obtaining the necessary data sets for validating modules of a cropping systems model. At a later stage, simulation modeling can help to set the agenda for future on-station and on-farm nutrient management research.

Introduction

In research projects targeting low-input, subsistence agricultural production systems, the research focus is shifting from on-station experimentation to both on-station and on-farm work. Because on-station experiments are performed under

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better-endowed conditions than those found in farmers' fields (especially with respect to soil fertility), they are not representative of on-farm conditions. This difference between station and farm poses a problem if significant genotype x environment interactions occur; crossover types of interaction, where genotype A outyields genotype B on-station but yields less on-farm, limit the usefulness of on-station experiments.

Although data that compare on-farm and on-station results are scarce, crossover interactions between high- and low-yielding environments are common, both on-farm (e.g., rice, Simmonds and Talbot 1992) and on-station (e.g., barley, Ceccarelli et al. 1992). Pearl millet is no exception. Grain yields of local Rajasthani pearl millet varieties and improved varieties were compared across a set of on-station experiments with a wide range of yields (Table 1). At yield levels of 1 t ha^{-1}, local pearl millet yield was only about 60% of the yield of improved varieties, but at yield levels <0.5 t ha^{-1}, local pearl millet yields were higher than those of the improved varieties. The crossover point occurred around 0.6 t ha^{-1}. At research stations, grain yields are typically above this crossover point, but in western Rajasthan, the average grain yields are <0.45 t ha^{-1} (GOR 1994). These results suggest that, for pearl millet in Rajasthan, varieties or plant types that are superior in on-station experiments are not necessarily so under farmers' field conditions. On-farm research is therefore necessary if we want to understand the farming systems in Rajasthan and be able to simulate them accurately.

Table 1. Grain yields of improved and local Rajasthani pearl millet varieties and their yield ratios in on-station experiments.[1]

	Grain yield (t ha^{-1})		
Station	Improved (12)	Local (17)	Yield ratio
Patancheru summer control 1989	2.51	1.47	0.59
Hissar 1988	2.48	1.31	0.53
Patancheru summer stress 1991	2.45	1.40	0.57
Patancheru summer control 1990	2.43	1.19	0.49
Fatehpur 1988	2.18	1.77	0.81
Patancheru 1988	2.03	1.27	0.63
Hissar 1989	2.01	1.32	0.66
Patancheru 1989	1.98	1.06	0.54
Patancheru summer stress 1990	1.15	0.70	0.61
Jodhpur 1988	0.41	0.81	1.98
Fatehpur 1989	0.10	0.17	1.70

1. Experiments have been grouped according to grain yield of improved varieties.

Need for Cropping Systems Simulation Models

Once we have established the need for on-farm work, it becomes relevant to ask whether simulation modeling is necessary to enhance our understanding of the cropping systems. In general, simulation modeling can address a broader range of questions and interactions than field experimentation. It has a comparative advantage, especially where field experimentation is time-consuming, difficult to conduct, and expensive; for instance, in complex cropping systems or ones that are highly variable in space and/or time.

Environmental conditions in Rajasthan are highly variable in time and space (Sharma and Pareek 1993). Not only is there a steep gradient in rainfall from the central to the western part of the state, but the yearly fluctuations are also huge: the coefficient of variation (CV) for seasonal rainfall at individual locations is about 50% (Table 2). These variations result in huge differences in planting opportunities and associated differences in water availability (van Oosterom et al., in press). In general, drought stress is likely to occur in western Rajasthan, but its timing and intensity are highly variable. The effects of drought stress on crop development depend on the crop growth stage at the time of stress (Gupta et al. 1994). As a consequence, scientists must deal with a wide range of stress environments. Capturing a representative sample of these conditions in field experiments would require many years of experimentation.

Table 2. Seasonal rainfall (calculated from 5 days before until 80 days after estimated sowing date), minimum and maximum rainfall, and coefficient of variation (CV) for four locations in Rajasthan, India.

		Seasonal rainfall (mm)			
Location	Years	Mean	Minimum	Maximum	CV(%)
Ajmer	87	431.6	87.2	1114.9	45.3
Jodhpur	84	303.9	25.9	827.1	52.3
Bikaner	83	229.4	38.5	608.0	53.2
Banner	56	239.0	48.5	878.4	56.9

Not only are the meteorological conditions in Rajasthan highly variable, the cropping systems are also complex. Most farmers sow crop mixtures—of up to ten different crops—rather than sole crops. This causes competition, compensation, and interactions between crops, and the comparative advantage of each individual crop depends largely upon seasonal conditions. This complexity is further increased because (1) fields are often partially resown to fill gaps that have poor plant stands, resulting in a staggered sowing within fields, and (2) the composition of the crop mixture depends on the timing of the onset of the rains (van Oosterom et al., in press) and on the condition of the field (e.g., water storage, fertility level). Within fields, complexity is increased by field heterogeneity, which is often associated with differences in fertility that can result from the presence of trees, an old threshing floor, previous penning of animals, etc. Thus, in practice/each field or part of it can be a different environment.

Scientific experimentation requires a reasonable level of field homogeneity; otherwise errors are so large that differences between treatments become nonsignificant. Scientists would have to conduct a large number of experiments for many years to get a full understanding of the complex cropping systems in the variable environmental conditions of Rajasthan. This task can be made easier if some of the experimentation could be replaced by cropping systems simulation modeling.

Cropping Systems Simulation Modeling in Integrated Systems Project 1

The ISP1 of ICRISAT has initiated its modeling efforts within the framework of the Collaboration on Agricultural and Resource Modeling in the Semi-Arid Tropics (CARMASAT), a collaboration between ICRISAT, the Agricultural Production Systems Research Unit (APSRU) in Australia, and National Agricultural Research Systems (NARS); the Central Arid Zone Research Institute (CAZRI) at Jodhpur is the main collaborator in ISP1. Within the CARMASAT framework, the Agricultural Production Systems Simulator (APSIM) software package takes a central place.

APSIM is structured around a central "engine" (Fig. 1), via which modules (crop growth, soil water, soil N, erosion) communicate with each other (McCown et al. 1996). Any module can, in principle, be incorporated in a simulation run, provided it uses the same variables as APSIM and the formats are recognized by APSIM. This flexibility allows, for example, simulation of crop rotations or mixtures by linking two or more crop growth modules to the engine. An innovation in APSIM, as compared with many other models, is that it considers the soil, rather than the crop, as the central entity (McCown et al. 1996).

At the moment, most of the modules that are essential for the pearl millet-based cropping systems of Rajasthan are not yet operational within APSIM (Table 3). However, experiments for developing several of these modules are currently being conducted as part of a CAZRI-ICRISAT-APSRU collaboration. A first version of the pearl millet module should be available by late 1996 or early 1997, although validation for farmers' field conditions will take longer. We have also begun development of a cluster bean module. As new crop modules are developed, the focus on module development should shift to other crops. For the soil modules, those for nitrogen and water are available within APSIM, but need to be validated for Rajasthan. A phosphorus module is under development in the western African part of ISP1, whereas work on a farmyard manure (FYM) module was started in Rajasthan in the 1996 rainy season. The development of livestock

APSIM

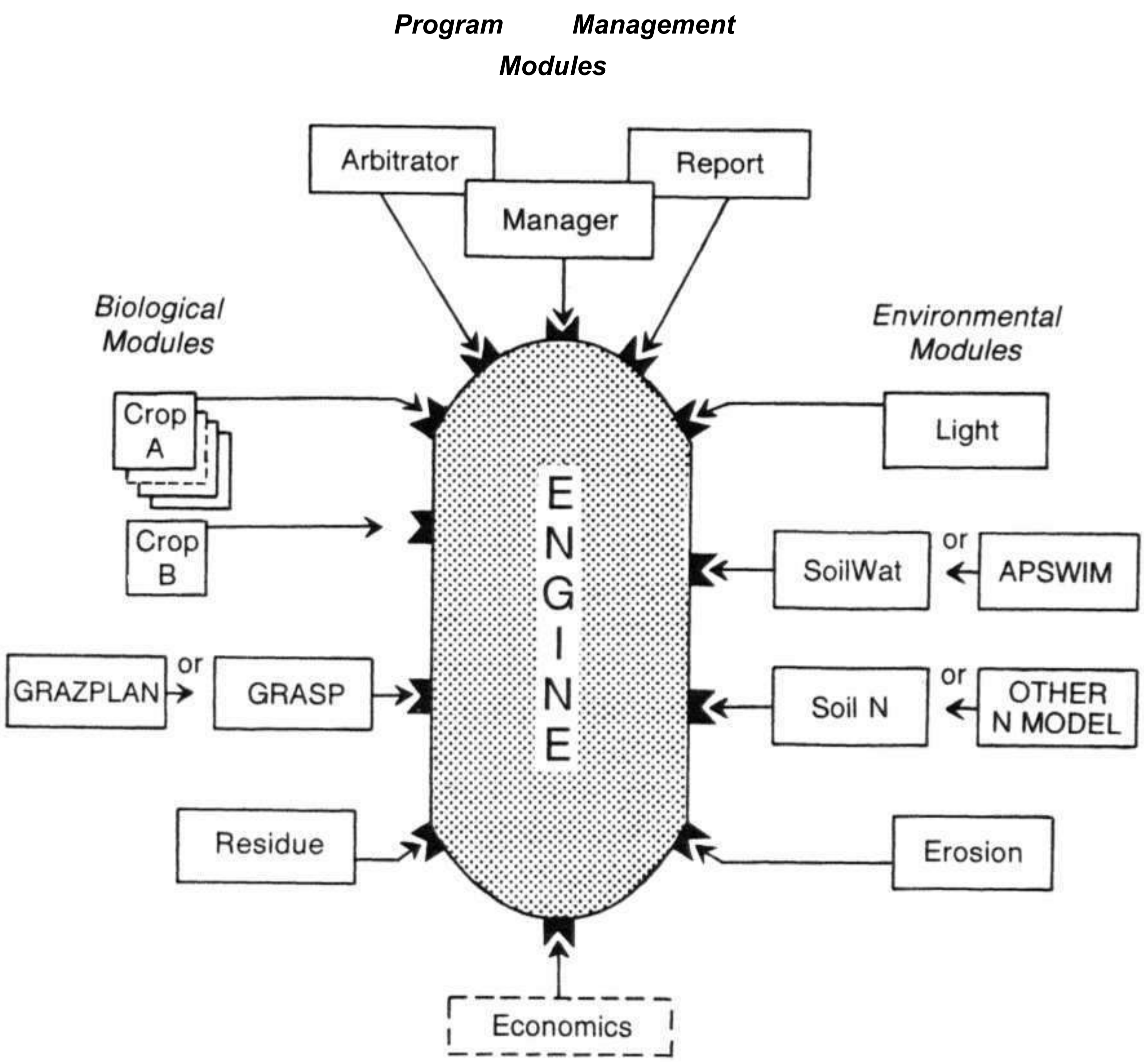

Figure 1. The structure of the APSIM program. (Source: McCown et al., 1996.)

and economic/decision support modules has not yet begun, due to a lack of resources. It is anticipated that a cropping systems model for Rajasthan can be operational within a few years.

The modeling effort in ISP1 can be divided into three stages: (1) model development, (2) validation, and (3) application.

Model development

Development of a module requires a sound knowledge of its component processes. Such knowledge can only be acquired through detailed measurements of the specific parameters involved in these processes. Because of the level of

Table 3. Simulation of cropping systems in Rajasthan: modules needed and their current availability within APSIM.[1]

Crop	Soil	Other
Pearl millet (na)[2]	FYM(na)	Livestock (na)
Cluster bean (na)	Nitrogen (a)[2]	Economic/decision support (na)
Moth bean (na)	Phosphorus (na)	
Mung bean (a)	Water (a)	
Sesame (na)		

1. APSIM = Agricultural Production Systems Simulator.
2. na = not available; a=available.

detail required, it is impossible to collect data on all the parameters required for a particular module in one experiment, and experiments have therefore to be targeted at specific subroutines of a module.

For several reasons, model development is preferably carried out on-station. First, the measurements are often intensive (up to twice a week) and the logistics involved make it difficult to do them on-farm. Secondly, field heterogeneity can be better controlled on-station, resulting in more accurate parameter estimates. Thirdly, experiments may require environmental control (irrigation, rain-out shelter, high fertility), which is not available on-farm: crop modules, for example, require that many growth and development parameters are estimated for nonlimiting conditions.

A drawback of on-station experiments, however, is the risk that the growing conditions are irrelevant to farmers' fields. This can be a problem, particularly where we want to develop relationships for the effects of nutrient deficiency on crop growth and development. One useful solution would be to have low-fertility fields on-station, but on-farm data will still be an essential supplement to the on-station experiments at the model development stage.

Model validation

The data required for model validation are less detailed, but more comprehensive; therefore, experiments at this stage need to be multidisciplinary. Results will only be useful for validating models if data on soil water, soil nutrients, and crop growth and development are collected from the same part of a field, especially where fields are heterogeneous. Because available evidence (Table 1) suggests that results obtained on-station may not adequately represent farmers' fields, at least part of the data for model validation should be collected on-farm.

The problems that on-farm experiments pose at the model development stage are less relevant at the model validation stage. As validation requires less detail, the logistics are easier. In addition, a multidisciplinary approach will reduce logistical problems, as everybody will have the same experimental sites (farmers' fields). Field heterogeneity is not a problem at this stage and can even be exploited if we consider different patches in a field (under trees, near fences) as different environments. Thus, even an individual field can provide a wide range of environments for model validation. Environmental control is not required, with the exception of rainfall data, which need to be recorded within a reasonable distance from the field. Temperature and radiation, parameters that are less variable than rainfall, can easily be extrapolated from the nearest meteorological station, using Geographic Information Systems (GIS) facilities if necessary.

The on-farm nutrient management work can be an important source of input data for model validation, as the data requirements are not greater than those needed for integrated nutrient management research per se.

Model application

Once the necessary modules are available, APSIM can be used to test a range of hypotheses that are part of the research agenda of ISP1. Although many of the potential applications of systems modeling are related, they can be divided into three broad categories: (1) environmental analysis; (2) matching crops to resource availability; (3) evaluating farm management options. Examples of possible applications within each category are listed below.

Environmental analysis. The environmental analysis application characterizes the variability in environmental constraints Longterm weather data can be used to estimate the frequency of occurrence of specific patterns of drought stress during the growing season in a particular region. In a preliminary analysis of rainfall patterns in Rajasthan, van Oosterom et al. (in press) suggested that, although differences exist between locations in the frequency of occurrence of drought patterns, these differences were partly related to differences in the onset of the monsoon. Relatively simple parameters can be effective in characterizing variable semi-arid environments in terms of the incidence of water deficits (Muchow et al., in press). By combining meteorological data with soil and crop parameters, it is thus possible to explain a much larger proportion of the variation in crop yields than is possible by using only meteorological data (Muchow et al., in press). Combined with GIS, models can improve our understanding of the effects of variability in available resources on crop production.

Matching crops and resource availability. This type of application is important in identifying targeted varieties of a crop, adapted to specific environments. It can especially help breeders assess the value of certain plant traits for their target environments. Among the issues that can be addressed are (1) the effects of plant type on stress tolerance and adaptation, and (2) the effects of earliness on stress escape.

The plant traits that farmers in Rajasthan perceive as most important to achieving high grain and fodder yields in pearl millet vary widely across the state In the wetter central part, large panicles are considered the main yield component contributing to high yields; in the dry areas of western Rajasthan, however, profuse tillering is considered more important (van Oosterom et al., in press). Preliminary results of detailed studies on yield components suggest that tillering is a useful characteristic in environments where midseason drought is temporarily relieved, because genotypes with profuse tillering have the developmental plasticity to respond to this rainfall by producing additional panicle-bearing tillers (van Oosterom, unpublished data), A preliminary analysis of rainfall data suggested that this type of drought pattern is indeed more likely to occur in western than in central Rajasthan (van Oosterom et al., in press). By combining longterm meteorological data with crop and soil modules, regions can be identified where tillering of pearl millet is expected to be a desirable trait.

In Rajasthan, if sowing is delayed until the end of July, farmers replace pearl millet with legumes in their crop mixes, because by this time, the expected duration of the rainy season is too short for pearl millet, resulting in severe end-of-season drought stress. However, in village surveys, farmers indicated that if shorter-duration pearl millet was available, they would wait until later in the season before replacing pearl millet. Simulation modeling can be used to quantify the niche for early-flowering pearl millet, by identifying the window during which sowing of short-duration pearl millet will be more advantageous than normal-duration pearl millet or legumes.

Farm management options. Applications to evaluate different management options are especially important under the uncertain environmental conditions of Rajasthan. For both farmers and scientists, the appeal of these applications is that the potential of different management options can be tested by modeling, after which the most promising options can be tested on-farm to verify their usefulness. In this context, so-called "what-if" questions are important and should be developed by scientists in collaboration with farmers.

Within individual seasons, what-if questions can be used in situations such as response farming (Stewart 1988), where farmers adjust their management decisions as the season unfolds, based upon the expected occurrence of stress. Examples of response farming in Rajasthan are the strategy of changing the composition of the crop mixture that is sown if the monsoon is late (van Oosterom et al., in press) and the application of chemical fertilizer if rainfall is good.

Applications of this type can also address longterm issues related to the sustainability of the cropping system. For example, soil fertility in Rajasthan has declined over the last few decades, due to reduced fallowing, which, in turn, is a result of population pressure. Simulation modeling can be used to study the effects of reduced fallowing on soil fertility and the role of different legumes, trees, and FYM in maintaining soil fertility. Similarly, models can identify the circumstances where investment in water conservation strategies is economically worthwhile.

Conclusion

Initially, on-farm nutrient management research can play an important role in obtaining the necessary data sets for validating the different modules of a cropping systems model. The data requirements are minimal, as most of the data are already collected within the framework of the nutrient management research itself. After this initial stage, simulation modeling can be a useful tool to assist in setting the agenda for future on-farm research, in which nutrient management should play a central role. Development of a cropping systems simulation model for the complex and variable cropping systems of Rajasthan is a challenging task. To achieve this goal, a close collaboration between ICRISAT, CAZRI, and APSRU is required.

References

Ceccarelli, S., Grando, S. and Hamblin, J. 1992. Relationship between barley grain yield measured in low- and high-yielding environments. Euphytica 64:49-58.

GOR (Government of Rajasthan). 1994. Resource atlas of Rajasthan. Jaipur, Rajasthan, India: Department of Science and Technology, Government of Rajasthan. 231 pp.

Gupta, B.S., Mathur, B.K., and Dave, B.K. 1994. Effects of weather on yield of pearl millet *(Pennisetum glaucum)* in Jodhpur district. Indian Journal of Agricultural Sciences 64:53-55.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., and Freebairn, D.M. 1996. APSIM: A novel software system for model development, model testing, and simulation in agricultural systems research. Agricultural Systems 50:255-271.

Muchow, R.C., Cooper, M., and Hammer, G.L. (In press.) Characterising environmental challenges using models. *In:* Plant adaptation and crop improvement (Cooper, M., and Hammer, G.L., eds.). Wallingford, UK: CAB International.

Sharma, P.C., and Pareek, R.S. 1993. Variability of southwest monsoon in west Rajasthan during last two decades. Mausam 44:389-391.

Simmonds, N.W., and Talbot, M. 1992. Analysis of on-farm rice yield data from India. Experimental Agriculture 28:325-329.

Stewart, J.I. 1988. Development of management strategies for minimizing the impact of seasonal rainfall variation. Pages 131-150 *in* Drought research priorities for the dryland tropics (Bidinger, F.R., and Johansen, C., eds.). Patancheru A.P., 502 324, India: International Crops Research Institute for the Semi-Arid Tropics.

van Oosterom, E.J., Whitaker, M.L., and Weltzien, E.R. (In press.) Integrating genotype by environment interaction analysis, characterization of drought patterns, and farmer preferences to identify adaptive plant traits for pearl millet. Pages 383-402 *in* Plant adaptation and crop improvement (Cooper, M., and Hammer, G.L., eds.). Wallingford, UK: CAB International

Discussions and Workshop Recommendations

Two discussion sessions were held, the first to identify research needs and promising technologies; the second to develop experimental plans and select research sites. Summaries of the discussions follow.

Research Needs and Promising Technologies

Introduction

Nitrogen deficiencies are widespread in western Rajasthan and frequently limit the productivity of pearl millet-based cropping systems, particularly in years with favorable rainfall. To a lesser extent, this is also true of phosphorus. Potassium and micronutrient deficiencies are not common. Integrated nutrient management would be an appropriate approach to alleviating nutrient deficiencies in the complex farming systems of this region.

Today, yield levels in farmers' fields are only a fraction of those obtained on-station. However, constraints to crop growth might be quite different in the two situations. In this context, on-farm nutrient management research could provide a better understanding of the realities farmers face and help make research more relevant to their needs. This is particularly important for development and validation of cropping system models. In addition, on-farm research can serve as a catalyst for change, leading farmers to do their own experimentation.

Cropping systems modeling will help reduce the need for experimentation. The Agricultural Production Systems Simulator (APSIM) is one model currently being adapted and validated for the pearl millet-based cropping systems in western Rajasthan. The pearl millet crop module in APSIM will be ready for validation in 1997. Development of a farmyard manure (FYM) and phosphorus module is in progress. However, development of a cluster bean module has not begun, and some time will be needed to develop model components and validate them on-farm. Therefore, we do not expect that cropping systems models will be adequate to replace nutrient management experimentation in the near future. While the systems model is being developed, on-farm nutrient management experimentation will provide valuable data for model validation, provided data collection is structured to meet these needs.

Nutrient supply from farmyard manure

The large numbers of animals in the complex farming systems of arid western Rajasthan make FYM a major nutrient source for crops. However, quantitative information on the nutrients supplied from this source is lacking. A survey on the quantity and quality of FYM was considered necessary. The availability of FYM depends on fodder production, which in turn supports livestock numbers;

therefore, FYM cannot be increased without increasing crop production. And production can only be enhanced through the use of external nutrient inputs.

Nitrogen fixation by legumes

One traditional way of adding N to the system is to include legumes, either sole-cropped in rotation or intercropped with pearl millet. However, the effectiveness of legume N_2 fixation in arid environments is in question. A survey of the soil rhizobial population and nodulation density on legume roots at intervals during the season is necessary.

Fertilizer nitrogen management

Response of pearl millet to fertilizer N has been observed in many on-station trials. This response depends on the amount and distribution of rainfall. The optimum N rate reported in these trials ranged from 23 to 84 kg ha^{-1} N. Yield increases in the reviewed experiments were, on average, 800 kg grain ha^{-1} (or 500 kg grain ha^{-1} if we take into account years in which drought sharply reduced grain yields). Yield responses ranged from 300 to 2100 kg ha^{-1} grain at yield levels of 300 to 2300 kg grain ha^{-1}. These substantial yield increases demonstrate that fertilizer application may considerably improve productivity in pearl millet-based cropping systems, even in drought-prone western Rajasthan. Increased productivity would improve food security and provide a better livelihood for the large human population in these rural areas. However, farmers' adoption of fertilizer recommendations is low. Farmers observe that applying N fertilizer increases the crop water requirement and can lead to terminal drought stress in years with below-normal rainfall. Recommendations based on the immediate rainfall (response application of fertilizer) may help reduce this risk.

Recommendations

Based on these discussions, three research activities were recommended:

- A survey to evaluate the nutrient (N, P, K) contribution of FYM in pearl millet based cropping systems.
- A survey to evaluate the effectiveness of legume atmospheric N_2 fixation in formers' fields.
- On-farm experimentation to develop response-application schemes for nitrogenous fertilizer.

Experimental Plans and Research Sites

Survey of nutrient contribution from farmyard manure in pearl millet-based cropping systems

The objective of the survey is to collect quantitative information on the availability and quality of the FYM at the village, community, and farm level.

Previously conducted Rapid Rural Appraisal surveys had indicated that there are considerable differences in FYM availability within and between communities and a significant flow of nutrients in the form of FYM within and between villages. However, these surveys are not suitable for the collection of quantitative data. Therefore, a formal quantitative survey including measurements of FYM quantity and quality is required. Quality parameters will include C:N ratio; total N, P, and K; mineral N; and available P. These parameters should be measured for dung and for FYM as it reaches the field. Combined with information on animal numbers and their estimated dung production, this will provide a basis for estimating nutrients potentially available from dung and nutrient losses during dung collection and storage and through alternative uses. This survey would help assess potential improvements that could result from more efficient recycling of nutrients through better FYM management. It would also provide the information needed to relate nutrient availability to animal numbers. This relationship could be used to predict nutrient availability from FYM if animal density changes.

Survey to evaluate legume N_2 fixation in farmers' fields

Nodulation densities of legumes in pearl millet-based cropping systems have been measured earlier in farmers' fields of western Rajasthan. However, these data are not sufficient to relate differences in nodulation to management or environmental conditions. Additional information needed in conjunction with these observations is on (1) soil characteristics: soil type, farmers' soil classification, official classification, soil texture, soil moisture conditions (at the time of sampling and during the season), and salinity status; and (2) management: cropping history, FYM or fertilizer application, cropping system (i.e., sole cropping, mixed or intercropping), and rooting pattern.

Nodulation density should be rated rather than quantified through actual counting, because of problems with realistic root length estimates. For the evaluation of nodule activity, a nodule color rating should be used. Simple greenhouse nodulation tests will be used to determine the presence of *Rhizobium* strains in the soil.

On-farm experimentation to develop response-application schemes for fertilizer

Some promising results from nutrient management studies in pearl millet were presented at this workshop:

- Nitrogen requirement depends on expected yield and is approximately 40 kg ha^{-1} N.
- Nitrogen fertilizer applied in two or three split doses is more beneficial than a single basal application.
- If the previous crop in the rotation is a legume, the basal application of N can be withheld with no yield loss.

- Plant stand and development, soil depth, and the current rainfall situation can be used to determine if additional topdressings are needed.

These results form the basis of a proposed scheme for fertilizer application in response to current rainfall and plant development, which potentially will reduce the risk associated with fertilizer application.

A simple nonreplicated experiment was designed for farmers to carry out in sole-cropped or mixed-cropped pearl millet fields. The objective of such an experiment is to determine yield increments resulting from N fertilizer applications to pearl millet over several seasons, to evaluate farmers' perceptions of the performance and acceptability of low-risk N application strategies, and to generate data sets for pearl millet model validation. The experiment would consist of a control with traditional fertility management and two treatments of 40 kg ha^{-1} N applied in split doses, one treatment with a basal dose of N, and one without The fertilizer applications are conditional on rainfall and plant development.

The following observations are to be taken during the season and used for analysis and crop model validation:

- daily rainfall
- soil moisture during the season
- initial soil mineral N and available P
- sowing date
- emergence date
- plant density after emergence
- date of flowering
- flag leaf sample for determining nutrient deficiencies
- date of physiological maturity
- dry matter and nutrient uptake at harvest.

Research sites

Two contrasting locations were identified for the surveys and on-farm experimentation, based on the probability of farmers' adoption of fertilizer application in rainfed pearl millet. Seasonal rainfall, use of pearl millet hybrids, and farmers' experience with fertilizer application were used as indicators of the probability of adoption. Additional criteria used for selection were information available on the village (previous research), established contacts (village worker), and logistics (distance to Jodhpur).

Agolai in Jodhpur district was selected as the low-adoption village, because rainfall is comparatively low for pearl millet, farmers have little or no experience with fertilizer, and adoption of improved pearl millet genotypes is low. Rupawas in Pali district was selected as the high-adoption village, because it has relatively high rainfall, farmers have some experience in using fertilizer, and adoption of improved pearl millet genotypes is significant.

Conclusions

The main conclusions of the workshop follow:

- Indigenous nutrient sources are irreplaceable components of nutrient management in the pearl millet-based cropping systems of western Rajasthan.
- More accurate quantitative information is needed on the contribution of FYM and legume N_2 fixation in farmers' fields.
- Improving cropping system productivity requires external inputs, namely mineral fertilizers, since complete recycling of nutrients is not possible.
- The main constraint to the use of mineral fertilizers is risk due to rainfall variability between and within seasons.
- Schemes for applying fertilizer in response to rainfall, plant stand, and crop development could reduce this risk. However, this technology has not been developed or tested under the conditions of arid western Rajasthan.
- Such schemes for response application of fertilizer should be developed in cooperation with farmers, to identify and remove constraints to adoption; this should be done at an early stage of technology development.
- Cropping systems modeling could eventually play an important role in fine-tuning nutrient application recommendations. However, more time and research effort are needed to develop the crop and soil modules necessary to accurately simulate the pearl millet based cropping systems of western Rajasthan.

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Acronyms and Abbreviations

ARS	Agricultural Research Station
C	carbon
CAZRI	Central Arid Zone Research Institute
DAS	days after sowing
DDP	Desert Development Programme
DPAP	Drought Prone Areas Programme
Fe	iron
FYM	farmyard manure
GOI	Government of India
GOR	Government of Rajasthan
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ISP1	Integrated Systems Project 1
K	potassium
N	nitrogen
P	phosphorus
RAU	Rajasthan Agricultural University
S	sulfur
Zn	zinc

About ICRISAT

The semi-arid tropics (SAT) encompasses parts of 48 developing countries including most of India, parts of southeast Asia, a swathe across sub-Saharan Africa, much of southern and eastern Africa, and parts of Latin America. Many of these countries are among the poorest in the world. Approximately one-sixth of the world's population lives in the SAT, which is typified by unpredictable weather, limited and erratic rainfall, and nutrient-poor soils.

ICRISAT's mandate crops are sorghum, pearl millet, finger millet, chickpea, pigeonpea, and groundnut; these six crops are vital to life for the ever-increasing populations of the semi-arid tropics. ICRISAT's mission is to conduct research which can lead to enhanced sustainable production of these crops and to improved management of the limited natural resources of the SAT. ICRISAT communicates information on technologies as they are developed through workshops, networks, training, library services, and publishing.

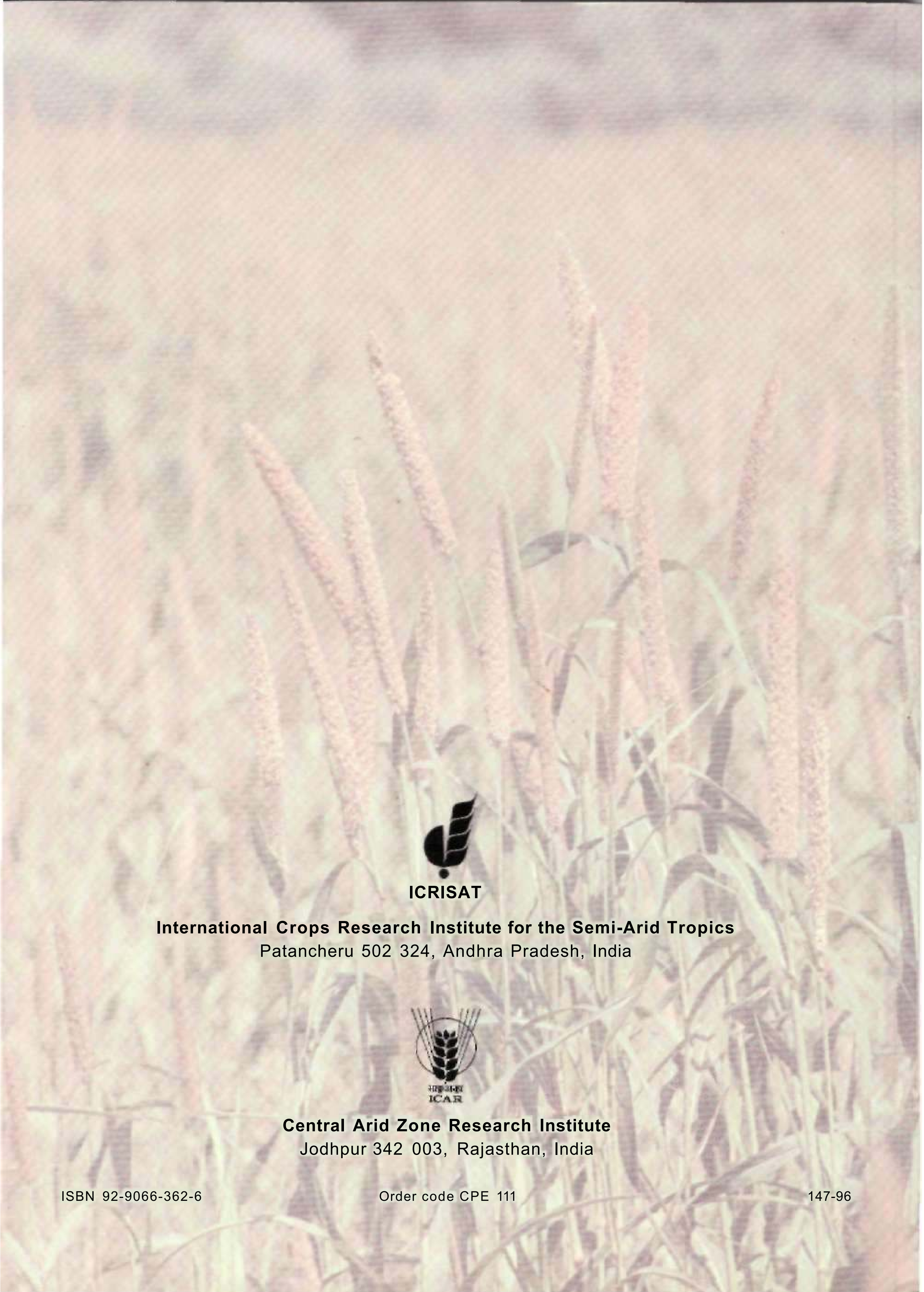
ICRISAT was established in 1972. It is one of 16 nonprofit research and training centers funded through the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is an informal association of approximately 50 public and private sector donors; it is co-sponsored by the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP), and the World Bank.

About CAZRI

The Indian arid zone is one of the world's most heavily populated arid tracts. The land-use and management systems of farming, pastoralism, and animal husbandry, evolved over the years by the local inhabitants, have become inadequate for present needs. Overexploitation of resources has caused rapid and widespread land degradation and desertification.

The Central Arid Zone Research Institute (CAZRI) was established in 1959 to help reverse this trend. Its mandate is to conduct research and—in collaboration with state agricultural universities—develop location-specific technology for improved and sustainable farming systems in arid ecosystems; act as a repository for information on natural resources and desertification processes; and serve as a center for training in research methodologies.

In the last four decades, CAZRI has developed viable and cost-effective technologies, many of which have been transferred to the field through various agencies concerned with the sustainable development of the region.



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