Assessment of Agricultural Technologies for Dryland Systems in South Asia: A Case Study of Western Rajasthan, India

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Acronyms and abbreviations

ACU	Adult Cattle Unit
AES	Agro-Ecological Situation
ARI	Arid Forest Research Institute
ALUS	Alternate Land Use System
ARS	Agricultural Research Station
CV	Coefficient of Variation
CAZRI	Central Arid Zone Research Institute
CFB	Complete Feed Block
CIAE	Central Institute of Agricultural Engineering
CPR	Common Property Resources
CRIDA	Central Research Institute for Dryland Agriculture
CRP-DS	CGIAR Research Program on Dryland Systems
CVB	Contour Vegetative Barrier
DAS	Days After Sowing
DCP	Digestible Crude Protein
EC	Electrical Conductivity
ET	Evapotranspiration
FMD	Foot and Mouth Disease
FYM	Farm Yard Manure
GRAVIS	Gramin Vikas Vigyan Samiti
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFS	Integrated Farming Systems
IGNP	Indira Gandhi Nahar Pariyojna
INM	Integrated Nutrient Management
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Pest Management
IWMP	Integrated Watershed Management Programme
LER	Land Equivalent Ratio
MGNREGS	Mahatma Gandhi National Rural Employment Guarantee Scheme
MIS	Market Intervention Scheme
MNB	Multi-Nutrient Block
MPTS	Multi-Purpose Tree Species
MSP	Minimum Support Price
NGO	Non-Governmental Organization
PET	Potential Evapotranspiration
PoP	Package of Practices
PPR	Peste des Petits Ruminants
PRA	Participatory Rural Appraisal
PRI	Panchayati Raj Institution
PSB	Phosphate Solubilizing Bacteria
RSC	Residual Sodium Carbonate
RWC	Relative Water Content
SAR	Sodium Adsorption Ratio

SAU	State Agricultural University
SC	Scheduled Caste
SRR	Seed Replacement Rate
ST	Scheduled Tribe
TDN	Total Digestible Nutrient
TIPIP	Technology, Institutional and Policy Innovation Platform
TMR	Total Mixed Ration
TSC	Tumba Seed Cake
VAM	Vesicular Arbuscular Mycorrhiza
WUE	Water Use Efficiency

1. Introduction

Western Rajasthan accounts for 61% of the total hot arid zone in India (31.7 m ha). The rest of the arid area is spread over Gujarat (20%), Punjab and Haryana (9%), as well as small parts of Andhra Pradesh and Karnataka (10%). The arid region receives <450 mm annual rainfall with 40-80% coefficient of variation. With evapotranspiration (ET) four to five-fold higher than rainfall, aridity, deficit water balance, and scarcity of water for drinking and other purposes are often severe. Natural resources such as water, land and vegetation are very fragile and partly non-resilient, and hence the area is prone to irreversible land degradation and desertification under excessive pressure from human and livestock populations. Arable cropping alone is not a dependable proposition in these drylands. Animal wealth provides sustainable support to livelihoods, but the sector is not yet well organized. Only one crop can be grown during a good rainfall year, and on average, a year of good harvest is normal during a cycle of five years, while two are expected to yield moderate crops and at least two failures are usual. The arid region offers limited scope for water harvesting and recycling, particularly at a watershed scale. There is better scope for integrated land resource development on the basis of village clusters, index catchments and dune-interdune complex.

1.1 Problems and opportunities in arid zones

The average annual rainfall in western Rajasthan (also known as the Thar desert) varies from less than 100 mm to the west of Jaisalmer to 450 mm to the east of Jalore, but the major part receives between 185 and 472 mm rainfall (Table 1), which decreases as we go from the southeast to the northwest. Over 90% of the rainfall occurs in a short span from the end of June to the first week of September. High solar radiation (500-600 cal/sq cm/day), strong turbulent summer winds (20-40 km/h) and high temperatures (45-48°C) cause 1800 to 2200 mm/yr potential evapotranspiration (PET) resulting in negative water balance for 9 to 11 months in a year. Frequent droughts (1 in 2.5 years) call for drought proofing, mitigation and relief strategies involving traditional drought-coping mechanisms, water harvesting and its utilization, and diversification. The dominant soils are light sandy with low organic matter (0.03-0.30%), alkaline reaction (pH 8.2-8.8), poor fertility, low water-retention capacity (70-100 mm/m), weak to moderate profile development, crust formation and susceptibility to wind and water erosion.

Surface and groundwater resources are very scarce due to scanty rainfall, poor water yielding efficiency of the sandy terrain and high potential for evaporation. The maximum surface water potential in the drainage basin of Luni river is $858 \times 10^6 m^3$, of which $700 \times 10^6 m^3$ is utilizable. The Indira Gandhi Nahar Pariyojna (IGNP) has brought in $1727 \times 10^6 m^3$ to $2961 \times 10^6 m^3$ water into the western sandy terrain. The utilizable groundwater is $2435.43 \times 10^6 m^3$ to $2957 \times 10^6 m^3$, which is largely overexploited, and has quality problems

Table 1. Status of rainfall, growing season and drought in arid districts of Rajasthan (1980-2010).

Districts	Average rainfall (mm)	Rainfall range (mm)	Coefficient of variation (%)	Crop growing season (weeks)	Drought years (%)
Jodhpur	340	244-424	35-55	9-12	58
Bikaner	259	237-289	50-65	9-10	54
Jaisalmer	185	144-211	49-91	4-7	53
Barmer	268	207-343	57-70	8-11	54
Churu	325	260-374	40-60	11-13	54
Jhunjhunu	445	402-548	36-40	14-15	52
Sikar	460	426-504	35-40	12-15	52
Nagaur	383	315-460	33-50	11-14	47
Pali	472	369-619	41-55	14-16	54
Jalore	421	371-460	51-60	11-12	52
Ganganagar	253	240-270	50-55	9-10	50

Source: ICRISAT-ILRI 2013. Report on Groundwork for CRP on Dryland Systems: South Asia.

in many areas. For example, 33% of groundwater in the districts of Barmer, Jaisalmer and Bikaner have a sodium adsorption ratio (SAR) of >18, whereas high residual sodium carbonate (RSC) (av. 3.1 meq/l) in groundwater occurs in the districts of Jhunjhunu, Nagaur and Sikar.

Nature has bestowed the arid zone with valuable vegetation which is overexploited, leading to the near-extinction of rare species including *Commiphora wightii, Tecomella undulata, Asparagus recemosus,* etc. Moreover, about 10 m ha is available as vast open grazing land for livestock, but this too is shrinking and deteriorating. Valuable fodder plant species such as *Eleusine compressa, Lasiurus sindicus, Cenchrus ciliaris, Cenchrus setigerus* and *Dactyloctenium sindicum* are getting replaced by less palatable plant species such as *Aristida spp.*, *Cenchrus biflorus, Tephrosia purpurea, Cymbopogon jawarancusa,* and *Indigofera spp*. The forage productivity of these lands has dwindled to 0.4 - 0.5 t/ha, adversely affecting grazing animals (Bhati 1997). Likewise, most of the rocky terrain is devoid of vegetation and thus leads to high runoff, degrading community and private lands. There is an urgent need to rehabilitate and manage these crucial Common Property Resources (CPRs) through active community participation, which in turn will help sustain livestock husbandry and the rural economy.

The region supports a population of 28 m humans and 28.6 m livestock, which have trebled and doubled respectively in the last 40 years, placing great stress on a fragile ecosystem. In terms of adult cattle units (ACU), livestock has increased by 51%. Human population density during 1961 was 37/sq km, while livestock density was 66/sq km. By 2001, the respective densities increased to 108/sq km and 113/sq km. Sheep and goat now constitute about 70% of the livestock population, and cattle and buffalo about 27.4% (Table 2). Buffalo population in Rajasthan has registered a three-fold increase during the last decade. Since livestock husbandry is the backbone of this region's rural economy, pasture grasses, fodder trees and shrubs and cultivated fodder crops should find appropriate place in alternate farming systems.

Development indicators such as literacy, employment, sex ratio, fertility rates, nutrition and age at marriage point to the very low status of women in Rajasthan. The female literacy status of the state stood 35th in the country. It has the 5th highest maternal mortality ratio, the 3rd highest total fertility rate and 6th highest infant mortality rate among the major states in India (Census 2011 & NITI Aayog 2013). The development indicators are much lower in these districts. Conscious and sustained efforts are required to enhance women's participation and position in the community by ensuring their effective integration into village institutions and in the decision-making process. The thrust on women empowerment is pivotal to improve livelihood opportunities in the targeted villages of the action sites.

1.2 Objectives

The objective of this report is to identify technologies that can enhance the productivity and resilience of dryland production and livelihood systems in South Asia, especially in the arid western Rajasthan region in India. Clustering of technologies as system components related to biophysical, institutional and policy

Table 2. Livestock populations in action villages.

Livestock	Dhirasar	Dhok	Dedha	Damodra	Govindpura	Mansagar	Didhu	Sankaria
Cattle	939	1760	650	1775	702	1442	900	1350
Buffalo	73	12	23	10	50	372	21	14
Goat	4035	5650	2520	2050	700	2100	2900	4160
Sheep	5240	2275	4565	1655	400	1310	3950	1840
Camel	38	110	-	52	04	19	160	336
Horse	3	6	13	13	-	-	-	-
Poultry	-	-	100	-	-	-	-	-
Total	10328	9813	7871	5555	1856	5243	7931	6800

Source: Panchayat records of respective villages.

interventions for better implementation, convergence, coordination, and community participation are also discussed. Further, the report suggests targeting of technologies at selected action sites in western Rajasthan in line with the strategies of the CGIAR Research Program on Dryland Systems (CRP-DS), a global research partnership to improve agricultural productivity and incomes in the world's dry areas.

2. Methods and approaches

2.1. The study areas

The action sites of CRP 1.1 in India were located in three states -- Karnataka, Andhra Pradesh and Rajasthan. This report focuses on action sites (districts) and villages in arid western Rajasthan. An overview of the dryland systems in western Rajasthan, specifically in selected districts of Jodhpur, Barmer and Jaisalmer, follows in this section.

2.1.1. Prevalent dryland production systems

The systems in western Rajasthan fall under pastoral and agro-pastoral arid farming systems as classified by Dixon et al. (2001), which across south Asia cover 112 m ha. Systems in Rajasthan are contiguous with, and representative of, large areas in Gujarat and Pakistan's Punjab. The cultivated land (including current fallow) in arid western Rajasthan during 2001 was 12.2 m ha (58.7%; includes 5.3% current fallow) with an average productivity of 0.61 t/ha for pearl millet, 0.28 t/ha for cluster bean, and 0.24 t/ha for moth bean (dew bean). The agro-pastoral system is predominantly a rainfed crop-tree- livestock-based production system with millets and legumes being the major crops providing food and fodder. Common pastures, rangelands and fallow lands are the main sources of fodder. The tree component together with livestock provide stability to the system. Off/non-farm income is one of the important sources of livelihood. Inter-region and intra-region mobility of people is common due to resource scarcity, frequent droughts and fewer employment and income opportunities. With good management practices, even a minor increase of 10-12% in the achievable potential of these crops will make a large difference on total factor productivity. Similarly, a slight gain in productivity of the vast livestock population would ensure better incomes. There is also good scope for furthering medicinal and aromatic plants, cash crops, condiments and spices that are endemic to the region.

Broadly, the current production of cereals in western arid Rajasthan, which houses the Thar desert, is 2.52 million tons against a demand of 2.84 million tons. In the case of kharif (rainy season) pulses, the region has presently an estimated demand of 0.25 million tons, while production stands at 0.3 million tons. Oilseeds production in the region stands at 0.8 million tons, against an estimated demand of 0.36 million tons. While pearl millet (*Pennisetum glaucum*), sorghum (*sorghum bicolor*) and wheat (*Triticum aestivum*) are the major cereals, moth bean (*Vigna aconitifolia*) and mung bean (*Vigna radiata*) are the major kharif pulses. Groundnut (*Arachis hypogaea*), sesame (*Sesamum indicum*), castor *(Ricinus communis*), rapeseed (*Brassica napus*) and mustard are the major oilseed crops. The region's demand for fruits and vegetables is currently not very high. The demand for fruits is about 1 million tons, and for vegetables 1.26 million tons. Yet, the present production of fruits is estimated to be 0.01 million tons (CAZRI 2007).

Livestock is one of the most important sources of rural livelihoods. Small ruminants and cattle dominate in rainfed areas and buffaloes in irrigated tracts. Horticulture, with limited presence, is generally practised on sub-marginal rainfed lands. Together with the ovine and household industries, it contributes to the strength of the low-income generating rainfed croplands, which is organic by default. The three sub-systems together need a holistic farming systems approach for development, with improved rainwater use efficiency, stress-tolerant crop varieties and land management practices (CAZRI 2007). The scenario in prevailing farming systems in the drylands of western Rajasthan is depicted in Figure 1.

The irrigated croplands that make a significant contribution to agricultural production and income are largely a result of groundwater exploitation that is nearing exhaustion in many districts. Declining groundwater reserves, uncertain canal irrigation in lower command areas, higher input costs and

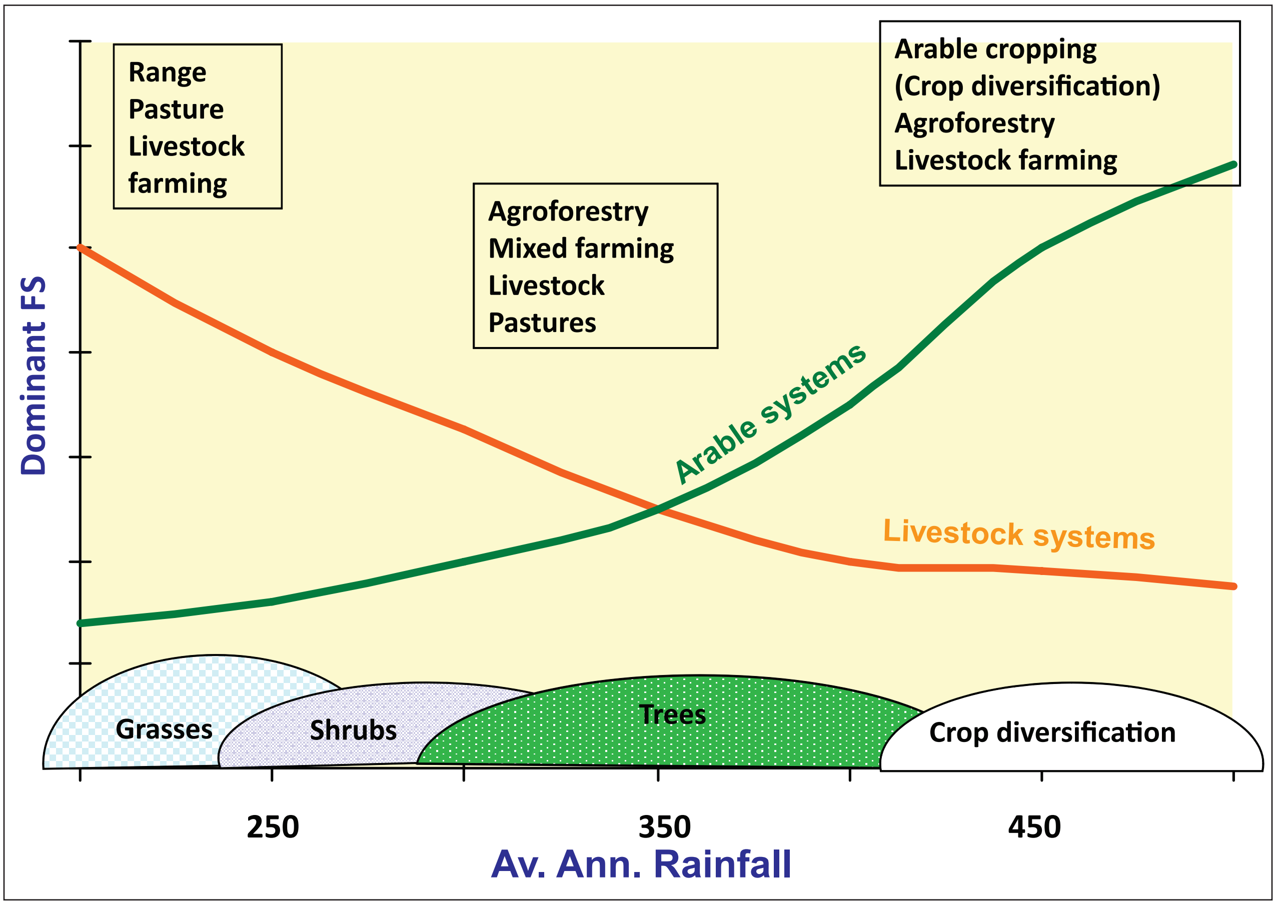


Figure 1. Traditional farming systems in the arid region of Rajasthan.

salinity threaten to upset the income advantage of the irrigated tracts in the near future. The foremost requirement in this system is irrigation, water-use efficiency, integration of livestock economy with that of the cropping system, and a close soil monitoring and amendment program due to the depleting soil nutrient balance.

The main socio-economic problems of the region are illiteracy, uncontrolled animal grazing, subsistence farming, poor economic base and nomadism. Mining, tourism, handicrafts and outsourcing are becoming major sources of employment. Negative impacts of some of these factors on the fragile arid ecosystem get magnified due to very high population pressure. Consequently, the natural resource base is fast degrading and if continued unchecked, may accentuate desertification. Thus the major challenges in the chronically drought-affected arid western Rajasthan involve sustainable land and rainwater management that ensures adequacy of food, fodder, energy and drinking water and livelihood support through both on-farm and off-farm employment.

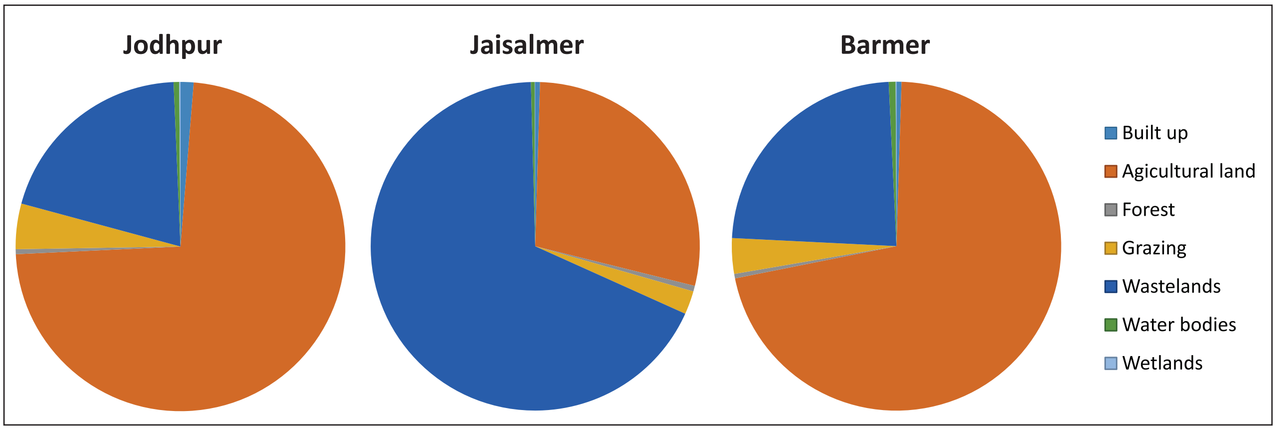
The three districts that were chosen as action sites for the CRP-DS-funded project cover about 80,000 sq km or 8 m ha, and have a population of 6.9 million. In terms of both livelihood and natural resource indices, they rank the lowest of all districts in India (CRIDA/NRAA 2012). Within the action sites, three tehsils or administrative units were selected: Osien in Jodhpur district, Chohtan in Barmer district and Jaisalmer in Jaisalmer district (Fig. 2).

In the west (Jaisalmer), pastoral and small ruminant systems dominate, with some transhumance to Gujarat and Central India depending on the season. These are rangeland systems with extensive and degraded natural pastures and some wadis or *khadins* (depressions) where trees and some crops can be grown. Moving east, as rainfall increases, systems change from pastoral to agro-pastoral and then to mixed crop–livestock–tree systems. In Jodhpur district, these are essentially parkland systems with

Figure 2. Location of target villages in action sites in western Rajasthan.

Prosopis cineraria as the main tree. In all tehsils there are pockets of irrigation, mostly from wells but also from surface water. In Jodhpur and Barmer, about 75% of land is under some form of agriculture while in Jaisalmer only 30% is agricultural land and the rest are defined as wasteland (Figure. 3).

The major crops are pearl millet and legumes (moth bean, mung bean, cluster bean and groundnut) in kharif (rainy season) and wheat, chickpea, mustard, cumin (*Cuminum cyminum*), isabgol (*Plantago ovata*) in rabi (postrainy) season. Yields increase across the rainfall transect (Table 3) but are still very low with high year-to-year variability (for instance, pearl millet's average yield during 1966-2009 was 0.24 t/ha;



Source: ICRISAT-ILRI 2013. Report on Groundwork for CRP on Dryland Systems: South Asia

Figure 3. Land use (%) in Jodhpur, Jaisalmer and Barmer districts.

Table 3. Production and yield of major crops in Jaisalmer, Barmer and Jodhpur districts in 2007-2009.

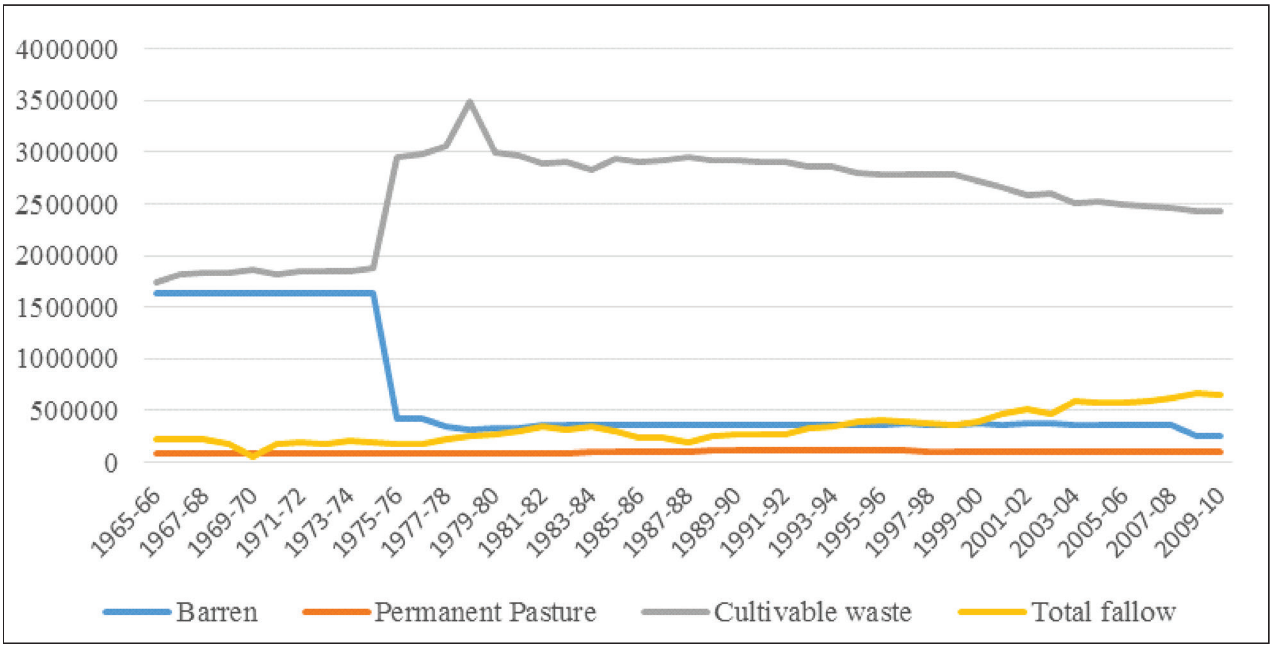
	Jaisalmer			Barmer			Jodhpur		
Crop	Area ('000 ha)	Production ('000 t)	Yield (kg/ha)	Area ('000 ha)	Production ('000 t)	Yield (kg/ha)	Area ('000 ha)	Production ('000 t)	Yield (kg/ha)
Pearl millet	147.0	10.8	0.08	976	105.3	0.11	591.5	214.7	0.36
Chickpea	63.5	28.7	0.45	0	0	0	0.5	0.3	0.62
Mustard	58.5	29.7	0.50	20.7	13.8	0.70	83.8	90.9	1.09
Wheat	10.0	9.9	0.98	13.8	18.4	1.33	45.5	100.3	2.18
Groundnut	8.6	10.4	1.24	0.6	0.8	1.49	36.8	55.8	1.54

Source: ICRISAT-ILRI 2013. Report on Groundwork for CRP on Dryland Systems: South Asia.

standard deviation 0.239 t/ha). All farms have ruminants and total livestock numbers per district in 2009 were 2.8 million in Jaisalmer, 3.3 million in Jodhpur and 4.3 million in Barmer.

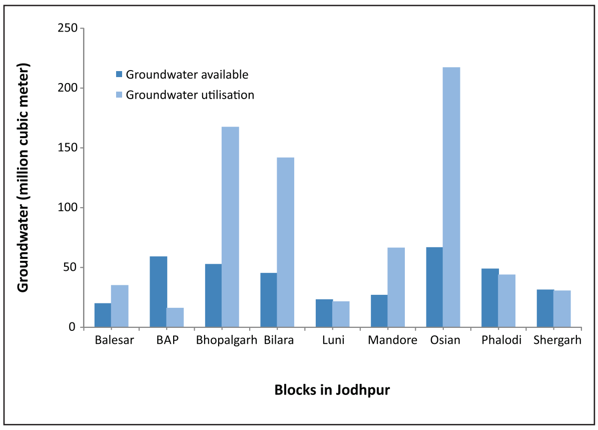
Drivers and intensification/diversification trends in selected action sites:

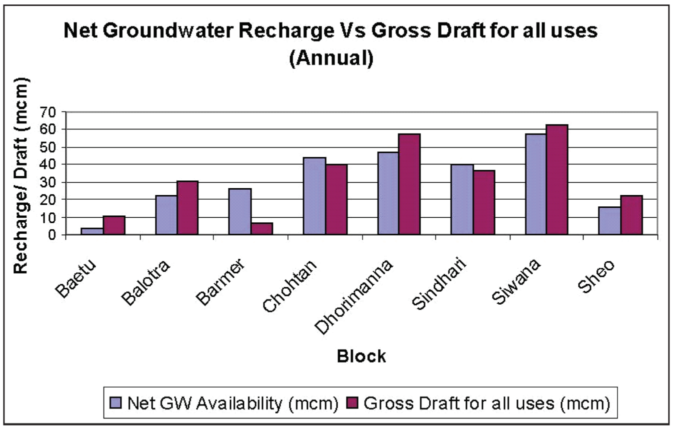
- *Rainfall variability*: Average rainfall is a low 350 mm in Jodhpur to 196 mm in Jaisalmer, with coefficient of *variation* between 42 and 57%. Climate change is expected to exacerbate this variability with Intergovernmental Panel on Climate Change (IPCC) 2070, A2 scenarios suggesting a 30% reduction in seasonal rainfall and a 4-5°C increase in mean temperature in the region.
- *Degradation*: This is a major driver of land use change in Rajasthan, with 83% of the total mapped area of 210,399 sq km affected (Kar et al. 2009). Wind erosion is the major cause of degradation with 92,000 sq km of rainfed and irrigated croplands being slightly-to-moderately affected.
- *Land use change*: The biggest change has occurred in Jaisalmer where barren wastelands have turned into cultivated wastelands (Fig. 4). In Jodhpur district, about 103,000 ha of rangelands have changed to rainfed or irrigated cropping and about 136,000 ha converted from rainfed to irrigated single or double cropping in the last 10 years.



Source: ICRISAT-ILRI 2013. Report on Groundwork for CRP on Dryland Systems: South Asia

Figure 4. Land use changes in Jaisalmer district between 1966 and 2010.

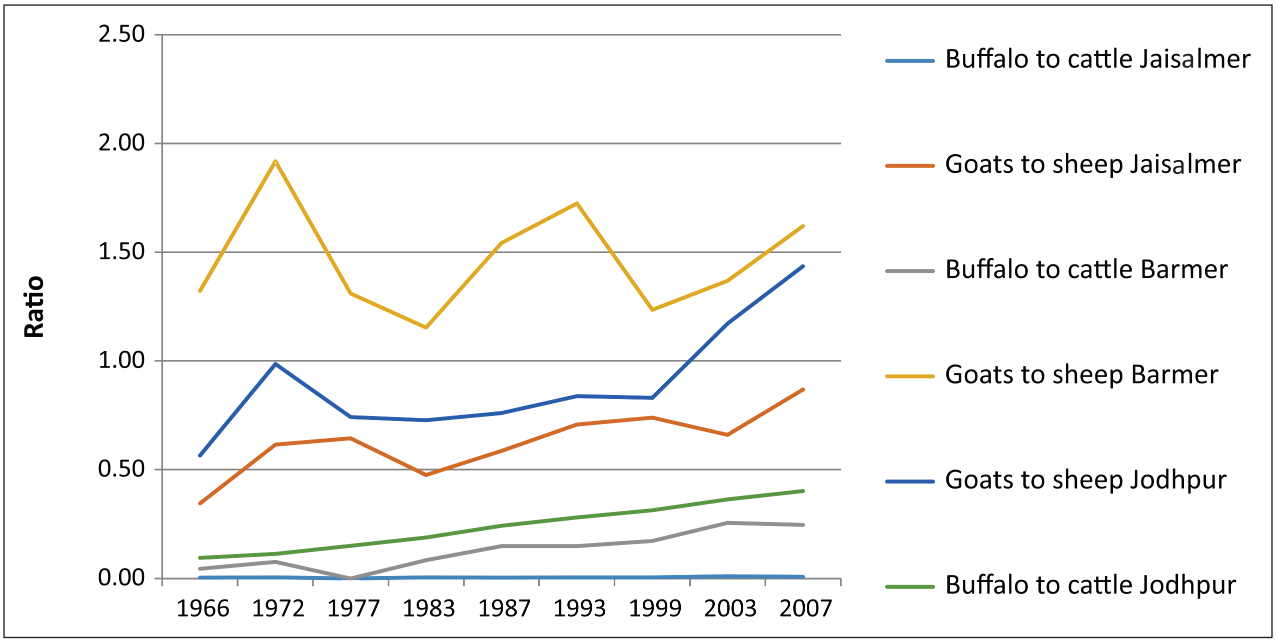




Source: ICRISAT-ILRI 2013. Report on Groundwork for CRP on Dryland Systems: South Asia

Figure 5. Net groundwater availability and extraction in million cubic meter (mcm) in different tehsils in Jodhpur (left) and Barmer (right).

- *Irrigation and groundwater*: The net irrigated area in Jodhpur and Barmer are 1.45 m ha and 0.96 m ha respectively, mostly from open wells or bore wells. There are major surface water canal systems in Rajasthan, and the expansion of these into Barmer and Jaisalmer will drive intensification in command areas. Groundwater is being overexploited (Figure. 5).
- *Agro-biodiversity*: There has been a loss of agro-biodiversity on farm lands as well as CPRs, driven by land degradation and associated with aolian processes (caused by wind erosion), increasing livestock and human pressure and mechanization.
- *Landholding*: The number of landholdings has increased throughout the action sites, with the biggest changes occurring in Jaisalmer where holdings in the range 4-10 ha have increased while larger holdings have decreased. In Jaisalmer, land area has increased as barren/wastelands have come under cultivation. Landholding sizes are therefore declining throughout the action sites. Land tenure, encroachment of CPRs and other land issues are disincentives to invest in agriculture.
- *Livestock dynamics*: In Jaisalmer, where small ruminants dominate, there is a shift from sheep to goats and a small increase in buffaloes. Elsewhere, large ruminant numbers have increased – buffaloes more so than cattle (Figure. 6). This reflects the increasing demand for dairy products. In general, buffaloes are preferred where there is adequate water. However, this change in trend will increase green fodder demand in the region, also enhancing the need of water for animal production.
- *Labor shortage and alternative livelihoods*: Labor shortage and the high cost of labor are problems throughout the action sites. This is partly driven by the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS) – a nationwide scheme that guarantees work for rural people, and partly by better education and access/availability of alternative sources of livelihood. Among the farmers there is a high demand for mechanization and low labor intensive technologies.
- *Cropping systems change*: While pearl millet has remained the dominant rainfed crop, and wheat the dominant irrigated crop, there have been some changes in other crops. For example, cluster bean pearl millet and mustard and cumin against wheat are the changing cropping patterns instead of because of low water requirement, less vulnerability and better economic gains. Similarly, the area under fruit trees has increased in recent years due to high economic returns.



Source: ICRISAT-ILRI 2013. Report on Groundwork for CRP on Dryland Systems: South Asia

Figure 6. Ratio of buffalo to cattle and goats to sheep in Jodhpur, Barmer and Jaisalmer districts.

Possible gradients across the action sites

Jaisalmer is largely pastoral or silvo-pastoral with small ruminants and small pockets of intensification around *wadis* and *khadins* where runoff water is available. Jodhpur has more intensive mixed crop-tree-livestock (parkland) systems. Barmer is in transition from pastoral to agro-pastoral. Population density varies from 161 per sq km in Jodhpur to 17 per sq km in Jaisalmer. From west to east, the landscape also changes from those dominated by sand dunes to rocky-gravelly pediments to alluvial plains. Also, within taluks across the action sites, there is a variation in potential for and access to groundwater, market access and demand, livestock dynamics, industrialization and alternate livelihoods, and land degradation.

In an innovation platform workshop at Jodhpur (29-30 May, 2012), four major production systems were identified in the action sites:

I. *Small ruminant-based production system*. This system is mainly in low rainfall (<250 mm) areas and is a traditional system in the western parts (eg, Jaisalmer). A distinct feature of this system is that the management of the herd involves seasonal or permanent mobility within and between districts/taluks in search of feed and markets. Recently, this system has been marked by a shift in herd composition from sheep to goats as a result of increase in milk and meat demand. As more land was converted from barren or rangeland to cropland and livestock numbers increased, there has been increased land degradation, shortage of feed, degradation of biodiversity, lack of equitable access and continued degradation of CPRs.

II. *Large ruminant-based production system.* The large ruminant-based production system can be found in pockets across the action sites and the major defining factor here is availability of water to grow enough feed. This system is evolving towards an intensive dairy system. Shortage of feed and spread of diseases are some of the major constraints.

III. *Rainfed crop production system*. This is found throughout the action sites but its intensity, productivity, diversity and system components are shaped by the amount and frequency of rainfall (which ranges between 150 mm and 350 mm). With increasing exploitation of groundwater and access to canal irrigation, this system overlaps with irrigated systems. Rainfall variability, soil erosion, land degradation, nutrient depletion, poor access to improved inputs, shortage of labor, decreasing landholding size and increased costs of production are the major problems here.

IV. *Partly irrigated crop production systems.* Certain areas (10-18%) have access to water and irrigated agriculture is practiced here. In addition to the problems mentioned for the rainfed system, poor recharge and continual depletion at alarming rates (0.50-1.0 m/year), poor quality of groundwater, (Residual Sodium Carbonate (RSC) > 3.1 meq/l, Electrical Conductivity (EC) > 6.0 dSm^{-1}, and increasing soil salinity are major constraints in this system.

On a limited scale, another production system in this sub-region is the runoff-based farming system called *khadin*. Here the major livelihood activity stems from intensive crop cultivation, especially of high value crops such as chickpea, mustard and wheat. Another small area under canal irrigation grows cotton, cluster bean, groundnut, wheat, cumin, castor, etc.

The major source of livelihood in areas receiving rainfall of 200-250 mm interspersed with privately owned dunes and interdunal landscape (Barmer district), the production systems are mainly agri-pasture and rainfed farming which can be developed taking index catchments as units. Some potential sites in Barmer can be treated as watersheds for integrated agriculture development livelihood systems. Some pockets in this district have good groundwater potential, where farmers grow cash crops like cumin and isabgol. Mining and furniture industries (*Tecomella undulata* based) are also the mainstay of communities here.

The villages selected in Jodhpur district, namely Govindpura and Mansagar, receive about 300-350 mm of rainfall with sandy soils interspersed with rocky low hills/outcrop. Govindpura is a typical watershed where farmers live in hamlets. Mixed crop (rainfed pearl millet and kharif pulses) and livestock (mostly cattle) production system are the most prevalent. On the other hand, Mansagar represents both dryland and irrigated farming systems. Livestock is mostly bovine with an increasing buffalo population. Irrigation is mostly from tube wells. The crops mainly grown in kharif are pearl millet, moth bean, mung bean and cluster bean and in rabi wheat, mustard, cumin and plantago. Cultivation of green fodder crops such as forage sorghum/pearl millet in kharif and lucerne in rabi are common.

2.2 Data collection

2.2.1 Village appraisal

Village appraisal and participatory rural appraisal (PRA), outcome of field visits, observations from local advisory group meetings and literature review were the major sources of data (Tables 4, 5 and 6). Field visits and farmer consultations were conducted during May and June 2013 in all the eight action villages to understand constraints and farmer perspectives on technologies.

Table 4. Area (ha) and human population (no.) in selected villages of Jodhpur district.

	Villages (average rainfall = 280 mm)	
Particulars	**Mansagar**	**Govindpura**
Area	2443	1280
Nonirrigated	1758	783
Irrigated	566	130
Cultivable waste (including gauchar and groves)	50	444
Area not available for cultivation	69	24
No. of households	341	150
Total population	2412	1143
Scheduled Caste (SC) population	69	2*
Scheduled Tribe (ST) population	Nil	4*

* Number of households
Source: Records of village panchayat for Govindpura and Mansagar.

Table 5. Area (ha) and human population (no.) in selected villages of Barmer district.

Particulars	Village (average rainfall = 235 mm)	
	Dhok	Dhirasar
Area	5063	1536
Nonirrigated	1739	1521
Cultivable waste land (including gauchar and groves)	329	-
Area not available for cultivation	2994	15
Irrigated area	Nil	-
No. of households	355	157
Total population	2174	1037
Scheduled Caste population	-	120
Scheduled Tribe population	1044	51

Source: Records of village panchayat for Dhok and Dhirasar.

Table 6. Area (ha) and human population (no.) in selected villages of Jaisalmer district.

Particulars	Village (Tehsil Sum average rainfall = 170 mm)		Village (Tehsil Nachna average rainfall = 150 mm)	
	Dedha	Damodara	Sankaria	Didhu
Area (ha)	4031	4625	5093	13020
Nonirrigated	2030	516	215	359
Cultivable waste (including gauchar and groves)	1871	2452	3112	1878
Area not available for cultivation	130	1657	354	5168
Irrigated area	-	-	917	Nil
No. of households	130	76	275	189
Total population	823	516	1688	1216
Scheduled Caste population	116	31	56	361
Scheduled Tribe population	91	163	133	38

Source: Records of village panchayats of respective villages.

3. Traditional and improved technologies for enhancing resilience and productivity of agriculture in dryland systems

Over the centuries, desert dwellers have developed survival strategies, but in the last 5-6 decades many of those strategies have either become obsolete or disappeared. This has resulted in the degradation of the natural resource base of this fragile ecosystem. This section makes an inventory and discusses improved agricultural technologies, best indigenous practices vis-à-vis institutional and policy issues.

3.1. Technologies related to biophysical system components

3.1.1 Crop planning and husbandry

The principal source of water for dryland crops in western Rajasthan is the southwest monsoon, which is highly unreliable in terms of volume, distribution, onset and withdrawal. The general cropping patterns in the drylands of western Rajasthan are rain-dependent. For instance, in years when the monsoon is on time, sowing of pearl millet and sesame is attempted; if the monsoon is delayed by 2-3 weeks, a large part of drylands is diverted to pulses (moth bean and mung bean). A further delay by one or two weeks (by the first week of August) leaves no option but to grow short-duration varieties of cluster bean and dew gram.

A delay beyond the first week of August leaves no scope except to grow kharif crops either as sole or mixed for fodder. Technologies related to the bio-physical system components such as crop varieties, land preparation and sowing techniques, major cropping systems, crop husbandry, and harvesting and storage of agricultural produce are discussed here. Technologies related to optimization of water and nutrient use efficiency are discussed in section 3.1.4 in greater detail but are also referred to in this section.

Existing crop varieties and their drawbacks

Farmers in the study area still cultivate traditional landraces on a large scale, mainly in mixed cropping systems to minimize the risk of crop failure due to severe drought. The non-adoption of pearl millet hybrids currently available is largely due to the non-availability of seed and lack of awareness as well as their inadequate adaptation to the marginal environment. As a result, increasing the productivity of pearl millet in the arid zone remains a challenge. In this region, legumes farmers mainly grow their own seed material of longer duration varieties with low yield potential. These landraces are more suited to mixed cropping, and there is a need to popularize short duration varieties of these crops with higher harvest indices.

Alternative crop varieties and their merits

The suitability of a crop in the region depends on edaphoclimatic and socio-economic factors. The major part of rainfall is received during July and August and generally recedes by the first fortnight of September. Thus, the rainy season remains for only 50-60 days (Rao and Singh 1998) revealing the limitation of the cropping period. Hence, it is imperative for a variety to mature within this limited period of moisture availability. As rainfall is very low and erratic, the high interannual variability of rainfall is a major single factor influencing crop yield (Rao and Singh 1998). Presently, the landraces/varieties in vogue are of long duration, susceptible to insects and pests and diseases besides having low yield potential.

Typical features of important varieties of major crops

The three study districts selected in western Rajasthan (Jodhpur, Barmer and Jaisalmer) belong to a zone called Agroclimatic Zone 1(a). The villages selected in these districts represent different agro-ecological situations (AES):

- AES-I: Low rainfall areas (< 300 mm) with sandunes interspersed with undulated cultivated land; for example, Dhirasar, Govindpura and Didhu
- AES-II: Low rainfall areas (< 300 mm) representing plain land with coarse sand to sandy loam soils; for example Mansagar, Dhok and Sankaria
- AES-III: Low rainfall areas (< 200 mm) with heavy soils deposited as runoff from large rocky gravelly catchments (*khadins*); for example Damodara and Dedha.

The selection of crop and variety depends on the AES concerned and prevailing monsoon conditions. Information available on the merits, impacts, rate of adoption, suitability of commonly recommended varieties of important kharif and rabi crops in relation to specific villages is listed here.

The improved varieties of major crops recommended for various situations of the arid region are listed below:

Kharif crops

Pearl millet: HHB 67 (I), GHB 538, RHB 121, ICMH 356, MH 169, Raj 171, CZP 9802, MBC 2
Dew gram (moth bean): RMO 40, RMO 225, RMO 257, RMO 435, CZM 2

Mung bean: K 851, RMG 62, RMG 268, RMG 344, SML 668, GM 4

Cluster bean: RGC 936, RGM 112, RGC 1002, RGC 1003, RGC 1017

Sesame: RT 46, RT 125, RT 127, RT 346

Castor: RHC 1, RHC 4, GCH 5, GCH 7, DCS 9

Groundnut: M13, HNG 10, GG 20, TG39, TH 37A

Cotton: RG 8, Bikaneri Narma, Ganganagar Ageti, RST 9, MRCH 6304, MRCH 314, MRCH 6025, JKCH 1947, NECH 6, MRC 7017

Fodder pearl millet: Raj Bajra Chari 2, Gaint Bajra, Raj 171, JBV 2, JBV 3

Fodder sorghum: SSG 59-3, MP Chari, CSH 24, Raj Chari 1, Raj Chari 2, SU 1080

Pearl millet: Variety HHB 67 (I) is of the shortest duration (65-78 days) and is most suitable in areas where the monsoon retreats early, for instance in Barmer and Jaisalmer. Varieties that mature in 70-78 days (RHB 121, CZP 9802, MBC 2 and GHB 719) are more suitable to areas where the monsoon continues for a longer period, as in Jodhpur district. Varieties MH 169 and Raj 171 are of longer duration (80-85 days) but are dual-purpose and so should be kept for purposes of varietal diversification. Varieties RHB 121, GHB 538, HHB 67 (I), GHB 719, MBC 2, MH 169, and ICMH 356 are tolerant to green-ear disease and downy mildew, whereas variety RHB 121 is less prone to bird attacks due to the presence of hairs on its head. Further, the varieties in the GHB series are tolerant to attacks by the stem fly and stem borer.

Dew gram (moth bean): Local landraces prevalent with farmers are of longer duration (75-85 days), produce less fodder and are susceptible to insects, pests and diseases. The maturity period of most of the improved varieties is 60-70 days. Both grain and fodder production are higher by 100-125% and 30-40% respectively in these varieties. There is acute shortage of seed of improved varieties. In dew gram, the seed replacement rate (SRR) is less than 2%. However, farmers are showing great interest in growing improved varieties of this crop.

All the improved varieties of dew gram are tolerant to yellow mosaic virus. Variety RMO 257 besides being disease resistant, is tolerant to thrips and other sucking insects. Variety CZM 2 developed by CAZRI is a very high yielder (800-1000 kg/ha) and is also tolerant to virus and (xanthomonas) infestations.

However, the main problems with the improved varieties of moth bean are that their anthesis (2^{nd} week of August) and podding often coincide with the heavy rain period (second to third week of August) which adversely affects seed setting and seed quality. Further, due to continual rains in the last week of August and the first week of September, seeds tend to germinate within the pods, almost completely damaging the crop. Also, there is a severe problem of bird damage to the moth bean crop both before and after harvest. On the other hand, under extended monsoon situations, local cultivars of the crop tend to be in the vegetative phase and thereby escape pod damage.

Mung bean: Mung bean is sown as a sole crop as well as mixed with pearl millet. The crop grows well in deep sandy loam soils with good drainage and pH ranging from 7.5-8.5. The SRR of mung bean is better than that of moth bean (3-5%). The crop is grown both as a summer and kharif crop. The main problems with the indigenous seed material of this crop are that they are of longer duration (90-110 days) with indeterminate growth habit. Due to these physiological characteristics the crop is prone to heavy losses at anthesis, pod development and seed maturity stages particularly due to enhanced insect pest and disease problems. In years with shortened monsoons, forced maturity of the crop occurs resulting in poor yield and seed quality. The improved varieties listed mature in 60-75 days depending on rainfall duration, with an average seed yield of 800-1000 kg/ha. The recently released variety GM 4 matures earlier (by 5-10 days) than other improved varieties with a high yield range of 1300-1400 kg/ha. Varieties RMG 268 and RMG 62 are suitable for cultivation both in summer and rainy seasons, besides being tolerant to bacterial blight and leaf spot diseases.

Cluster bean: Cluster bean is a very important crop of the arid region. It is very drought hardy and is useful both for animal and human consumption. It is used as a vegetable. Besides, the crop is industrially very important for gum production and thus has export value. The traditional varieties of the crop are of longer duration (130-135 days), indeterminate in growth habit, have low productive potential, staggered pod maturity and are prone to insectpest and disease infestation. On the other hand, they have better potential for fodder production and aid better build up of soil fertility. The improved varieties are distinctly of shorter duration (80-110 days), partially resistant to diseases such as bacterial blight (RGM 112, RGC 936) and angmari (RGC 936). They are suitable for cultivation both in summer and rainy seasons (RGC 936, RGM 112), and in both arid and semi-arid ecosystems (RGC 1003, RGC 1017).

Sesame: Farmers mostly use their own seed which tend to yield less (0.10-0.20 t/ha). The local seed material has many other problems: it is infested with seedborne diseases, has longer periods of maturity (110-120 days), poor harvest index and low oil content (35-40%). The improved varieties mentioned earlier are of shorter duration (80-90 days), are partially resistant to diseases and insects-pests; the seeds have higher oil content (48-50%), higher test weight (2.5 to 3.15 g) and good texture (shiny white).

Groundnut: The recommended varieties are of short duration (115-130 days) whose podding is either in clusters (TG 37A, TG 39) or semi-spreading (HNG 10, GG 10). Their yields vary from 2-3 t/ha with 45-50% oil content. Variety TG 39 is comparatively less sensitive to stem rot and yellowing diseases.

Rabi crops

Wheat: Raj 3077, Kharchia 65, Raj 1482, Lok 1, WH 147, Raj 3765, Raj 3777, Raj 4083

Barley: RD 2052, RD 2035, RD 57, RD 31, RD 103, Bilara 2, RD 2552

Chickpea: C235, RSG 44, RSG 888, GNG 663

Mustard: T 59, RH 30, Bio 902, GM 2, RH 619, GM 2, JM 1, Ashirwad

Cumin: RZ 19, RZ 209, GG 4, RZ 223

Plantago (Isabgol): RI 1, RI 89, GI 2

Oats: Javi 8, OL 9, OL 529, Kent, DFO 57

Lucerne: Anand 2, LLC 3, LLC 5, Type 9, Type 8, Sirsa 8, Sirsa 9

Cowpea: Bundel Lobia 1, UPC 9202, IC 42116

Rabi crops

Wheat: Raj 3077 and Kharchia 65 are varieties specially recommended for AES-III and for use in *khadins*. On the other hand, varieties 1482, 3077, 3765, 3777 and 4083 of the Raj series and WH 147 and Lok 1 are better suited for AES-IV. For late sowing, Raj 3765, Raj 3777 and Raj 3077 are a good choice, and for timely sowing varieties Raj 1482, WH 147, Raj 3777 and Raj 4037 are recommended. Varieties Kharchia 65 and Raj 3077 are better suited to alkaline soils. Varieties such as Raj 4037 and Raj 3777 are tolerant to high temperatures as well. Wheat has a very high SRR of about 70-75%.

Barley: Barley is not popular among farmers of this region and only a few grow it for its use as animal concentrate. However, it can be an excellent choice in unusual and adverse situations such as late sowing, cultivation on conserved moisture (*khadins*), in poor fertility soils, saline and alkaline soils and when irrigation water is of high RSC (2.5 to 4.5 meq/l). Farmers' local seed is not of good quality and is mostly infested with seedborne diseases. The varieties mentioned in the previous section need to be introduced in the area. The high-yielding varieties (4.5-6 t/ha) are responsive to nutrient application, mature in 110-120 days and are mostly of dual purpose.

Mustard: The area under this crop has increased substantially in the last two decades. Mustard has a high seed replacement ratio (SRR) but farmers tend to use the same seed year after year, which reduces varietal purity and seed quality, thereby resulting in poor yields (1.5-2 t/ha). Instead, improved varieties offered have these features:

- Varieties T 59, RH 30 and RH 819 are suitable even under nonirrigated conditions (*khadin* system)
- RH 30 is suitable for mixed cropping with wheat, barley and chickpea
- RH 30 is semi-tolerant to aphid attacks
- Bio 902 and JM 1 are resistant to white rust
- CS 52 is more tolerant to saline and alkali soils.

Despite higher yield potential (2.5-3 t/ha), the improved varieties are not tolerant to frost, and heavy damage (80-90%) to crops has been observed in areas susceptible to cold waves.

Chickpea: Chickpea is an important rabi pulse and is grown in western Rajasthan mostly on conserved moisture (in *khadins* and in medium to heavy soil areas). Farmers here mostly use their own seed, which has low yield potential (8-10 q/ha) and is prone to insect-pest and disease infestations. Improved varieties such as RSG 44, RSG 888 and GNG 663 have high yield potential (20-25 q/ha) and mature in 125-130 days. They are also semi-tolerant to dry root rot and nematode infestation. However, the adoption rate of these varieties is very low (< 2%).

Cumin: Cumin is a very important cash crop of west Rajasthan; about 70% of cumin in India is produced in this state. Many farmers still grow local seed year after year on the same piece of land which causes heavy infestation of soilborne diseases (such as wilt), resulting in almost total crop failure. The improved varieties (GC 4, RJ 19, RZ 209, and RZ 223) are comparatively tolerant to wilt, powdery mildew and downy mildew and have higher yield potential (0.6-0.7 t/ha). The crop is also very sensitive to weather aberrations, particularly at flowering and seed development stages.

Isabgol: Isabgol is an important medicinal crop of arid Rajasthan. Since it requires less water than wheat and mustard and fetches a better price in the market, the area under this crop has increased tremendously (5-8 times) in the last two decades. It is very sensitive to rains at maturity stage and total damage to yield has often been reported. The varieties recommended for this region, GI 2, RI 89 and RI 1, mature in 110-125 days with a yield range of 1.2-1.6 t/ha. The crop is sensitive to downy mildew and powdery mildew and insects such as aphids, jassids and thrips.

Recommended land preparation methods

Besides clearing the field of unwanted bushes, one deep tillage (10-15 cm) in two years with a disc plough is beneficial to conserve soil moisture and aid proper decomposition of crop residues. For a proper plant stand, farmers should go for cross harrowing prior to sowing. This operation may be dovetailed with the application of farmyard manure (FYM) @ 5-15 t/ha. In medium to heavy soils, one or two rounds of harrowing may be needed for proper seedbed preparation. This may be followed by sowing with a seed-cum-fertilizer drill. Further, for deep tillage in these soils, a disc plough may be replaced by a mold board plough.

It has been observed that in soils where crust is formed, application of FYM over the seed funnel helps control crust formation (Joshi 1987); however, this operation needs low-cost innovations and methods to be evolved. Another technique recommended for crop planting (Singh and Bhati 1988) is the ridge furrow system. In this method, seed furrows of 30 cm width, 20-25 cm depth and 60 cm spacing between two furrows are created with the help of tractor-drawn ridgers. The sowing is done in paired rows at 30 cm spacing either at the base of the furrow or in the middle of the slanting edge of the ridge with 60 cm as fixed space. The method is useful in controlling crusting of soil surface, maintains high soil moisture, and reduces soil temperature thereby leading to higher yield of cluster bean (51.9%) and pearl millet (74.4%) in drought years. However, the ridge seeder has limitations; it is not effective in soil on undulating topography. Sometimes poor seed germination as a result of rainfall aberrations has been observed in ridge furrow system of planting. Overall, the recommendations for various intercropping systems are pearl millet + arid legumes (1:1 or 2:4) and pearl millet + sesame (1:1).

In the Thar desert, about 65% of the area is affected by dunal activities, and privately owned sand dunes are also under crop cultivation. So finding sowing implements suited to cultivation on these lands without causing natural resource degradation is a challenge. There is also a need to promote guided contour cultivation on sloping lands (2-3% slope) for improved soil and water conservation. Access to proper seeding devices for this purpose is important.

Major cropping systems and crop husbandry practices in Thar desert

The major cropping systems prevalent in the arid regions of Rajasthan are discussed below:

I. **Mixed cropping system**: To cushion the adverse effect of weather aberrations and drought and meet the food needs of the family, mixed sowing of dryland crops is common in western Rajasthan. Bhati and Singh (2002) observed that the common crop mixtures are pearl millet + mung bean + cluster bean + sesame (48%), followed by a mixture of the same crops without sesame (24%). Irrespective of the categories of farmers (small, marginal and medium), the mixing of seed of dryland crops was common and it was largely because of wider risk coverage and higher economic gains (₹ 4638 to ₹ 5200/ha) as compared to a pulse and oilseed mixture (₹ 3085/ha) and sole cropping of cluster bean (₹ 3793/ha), particularly in years where there is a break in monsoon during the vegetative phase of crops but an extension into the reproductive phase (Vittal and Bhati 2009). Seed of pulses like moth bean and mung bean are mixed with pearl millet in low rainfall areas of Barmer and Jodhpur districts. In index catchment areas, with the possibility of more water availability, pulses are preferred over pearl millet, and sesame is included, for instance in Barmer district. In Barmer, Jodhpur, Jalore and Jaisalmer, watermelon is mixed, forming a sub-system of the pearl millet-based mixed cropping system. The sub-system largely covers low rainfall areas (200-300 mm) of these districts. Cluster bean is a very important crop of the Thar desert and districts of Barmer and Bikaner are dominated by this crop. It is grown either as a mixed crop with pearl millet or as a sole crop. There is another significant sesame-based cropping system, in which sesame dominates and it is largely adopted in the central alluvial plains where soils are of medium texture with good water holding capacity. Kharif pulses and cowpea are grown mixed with sesame in areas such as Nagaur and Pali.

II. **Intensive crop production system**: These are the areas where rainfall is above 350 mm with high groundwater potential, and can be found in the irrigated belts of arid districts -- Jalore, Sikar, Churu, Jhunjhunu, parts of Jodhpur, Nagaur, Hanumangarh, Sriganganagar, Bikaner and Jaisalmer. Farmers grow kharif and rabi crops mostly as sole crops in rotation. Among kharif crops, the emphasis is on pearl millet and mung bean whereas in rabi, season diversified crops including cereals, oilseeds, fodder, fruit and vegetable crops are grown.

III. **Runoff-based farming system (*khadins*):** This system is practiced at specific suitable sites. A *khadin* is an earthen embankment built across a slope to conserve the maximum possible rainwater runoff within the agricultural field. The embankment helps increase moisture in the submerged land, and depending on the rainfall available, kharif and rabi crops are cultivated. *Khadins* are found mostly in the three districts of Jaisalmer, Barmer and Jodhpur. These semi-natural oases in the drylands of the Thar have great potential for improvement and extension.

In general, the crop husbandry followed in mixed cropping systems is subsistence oriented. Mixing of seed of different kharif crops followed by broadcast sowing hampers the adoption of improved technologies/practices. The intensive crop production system in irrigated areas of western Rajasthan has become an environmental threat due to excessive use of chemical fertilizers and pesticides, inefficient use of irrigation water (both surface and ground water) and faulty crop choices.

IV. **Alternative cropping systems and crop husbandry:** The choice of efficient crops and cropping systems depends on agro-climate, depth and water holding capacity of soils and profitability. For a crop to grow under specific agro-climatic conditions, the crop's lifecycle must fall within the time of the year which provides favorable conditions. In irrigated agriculture, the length of growing season may be decided by temperature, day length, etc. But in rainfed areas, the length of growing season is determined mainly by moisture availability, which in turn depends on rainfall amount and distribution, the soil's moisture retaining properties and ET and PET. The rainfall status, growing season and drought prevalence in arid districts of Rajasthan are given in Table 1.

The depth and water-holding capacity of arid zone soils are highly variable ie, soil depth varying from 10-15 cm in sodic/gypsiferus soils to very deep (10-15 m) in duny, inter duny and sandy plains. Water-holding capacity of the soils also varies from 50-60 mm/m soil depth on duny and coarse sandy soils to as high as 160-200 mm/m in medium textured soils in low lying areas and *khadins*.

It has been observed that the duration of traditional crops/varieties grown in dryland areas is often longer than the length of the growing season. These crops/varieties usually experience moisture stress, mostly during the grain filling period. The traditional varieties of pearl millet with about 110 days duration usually suffer from drought stress at later stages of crop growth. Introduction of a relatively short-duration cultivar, HHB 67 (70 days) or short-duration varieties of arid legumes such as mung bean, cluster bean and moth bean, found favour with the environment in this pearl millet growing area (Bhati and Joshi 2007). Crop intensification, diversification and cultivar options are the building blocks of the ideal cropping system. Considering the specific needs of the arid region, suitable cropping systems are designed based on these three main approaches.

Cropping intensification

The cropping intensity in the drylands of the arid region is less than 100% since fallows are an indispensable component of the cropping sequence. However, cropping intensity can be increased by sequence cropping and intercropping. The cropping sequences recommended in arid Rajasthan are:

- Pearl millet – fallow – arid legume – fallow – pearl millet – arid legume (suitable for drylands of Jodhpur and Barmer districts)
- Pearl millet – chickpea – pearl millet – mustard (for *khadins* in Jaisalmer district)
- Ley farming: *C. ciliaris* for four years followed by pearl millet – fallow – arid legume/sesame (for dry areas of Jodhpur district).

Cultivation of medicinal crops like shankhpushpi (*Convolvulus pluricaulis*), jeevanti (*Leptadenia reticulate*) and Erna (*Clerodendrum phlomidis*) as assessed under CRP 1.1 are other promising options for crop intensification.

Intercropping/strip cropping/triplet planting systems for different situations

Growing one or two legumes with pearl millet as a mixed crop has been a traditional practice in arid areas primarily to reduce the risk of complete crop failure. In the traditional practice, specific row arrangements were not followed, which led to low yields of both the mixed crop components. Studies on cereal/legume intercropping have indicated that it offers considerable yield advantage over sole and mixed cropping because of more efficient utilization of plant growth resource.

In arid conditions, paired planting has produced comparatively good yields. For the cereal-legume intercropping system, paired planting of pearl millet is done keeping two rows of pearl millet 30 cm apart and two such pairs 70 cm apart. One or two rows of grain legume intercrops are planted in the space between the pair rows of pearl millet. In a two-year study, double rows of moth bean, cluster bean and mung bean planted in the interspaces of paired rows of pearl millet (30/70 cm) yielded 381 kg/ha, 381 kg/ha and 458 kg/ha additional grain without adversely affecting the yield of pearl millet (Singh and Joshi 1980). Assessment of land equivalent ratio (LER) indicated that a maximum advantage of 54% could be achieved by growing double rows of moth bean in the interspaces followed by the double rows of sesame (31%), single rows of moth bean (30%), and double rows of cluster bean (21%) and mung bean (19%). Growing two rows of mung bean though resulted in comparatively lower LER (1.19) or only 19% better land utilization but gave better economic returns.

Strip cropping

It has been observed that in sub-normal rainfall years with erratic distribution, intercropping of legumes in the inter-pair spaces of pearl millet (30/70 cm) performed lower than strip cropping mainly because of the higher plant population. In strip cropping, the replacement series works well and does not lead to higher populations (Singh and Joshi 1997). Four rows of pearl millet could be alternated with four rows of legume (mung bean or cluster bean). The following year, the rows could be shifted in such a way that legume rows occupy the space that was occupied previously by pearl millet. This kind of rotation of rows could be followed year after year.

Triplet planting system

Pearl millet is relatively less susceptible to drought, yet its yields are reduced by 69-81% under moderate-to-severe drought conditions. Reduction of population and change in planting systems has been found to achieve sustained production through the better use of radiant and commercial energy, thereby saving inputs. The innovation of triplet planting typically skips every fourth row in normal planting. Without any population adjustment (125 x 10^3 plants/ha), the triplet planting system produced as good a yield as uniform planting (Joshi 1990) in normal rainfall (409 mm) and moderate drought years (260 and 193 mm) while giving significantly higher yields in a severe drought year (152 mm). This indicated that yield losses, which would have occurred owing to 25% less sown area in the triplet system, were compensated by higher yields of border rows. The triplet system with adjusted population (retaining the recommended population of 1.6 x 10^5 plants/ha) gave 7.7-36.6% higher yields besides resulting in a 25% saving in fertilizer input over uniform rows in different years. The beneficial effect was more prominent in a severe drought year (Rao and Joshi 1986). Such a system can be invaluable in the low rainfall areas of Barmer and Jaisalmer districts.

Response of field crops to tillage: In the arid region, zero tillage was found to be significantly inferior to conventional tillage with arable crops. Pearl millet yield was higher under conventional tillage over no tillage across four years continuously. In the fourth year, the crop failed completely in the ‘no-till’ plot. Root growth was poor and considerable reduction in biomass was noticed due to reduction in initial plant population (Aggarwal et al. 1998). Studies on preparatory tillage showed that one sub-surface cultivation with a sweep at the onset of the monsoon and again once prior to sowing were conducive to a good crop stand and higher yield of pearl millet (Mann and Singh 1978). Yadav and Singh (1978) recorded the highest yield of pearl millet (3.6 t/ha) with one deep ploughing followed by one cross harrowing of the field. Singh et al. (1973) and Singh and Singh (1988) advocated that one tillage was enough for sandy soils and that it improved yield by 43%. In another study at Jodhpur, deep tillage resulted in increased yield of pearl millet over conventional and minimum tillage due to improved moisture storage in the soil providing relatively better moisture conditions (Saxena et al. 1997). Gupta (1987) and Bhati (1996) also reported reduction in crop yield due to no tillage. Seeding after field preparation through harrowing was better than plough planting (CAZRI 1978a). The plough plant method led to higher weed population (344%) and more weed dry matter (243%) compared to shallow preparatory tillage. The weeds caused intense competition for water and nutrients to the pearl millet crop and consequently resulted in low yield. Almost complete control of java grass (*Cyperus rotundus)* was achieved using the MB plough for seedbed preparation. If weeds could be controlled through chemical means, the practice of plough seeding could be advocated; but for the most part, a preparatory tillage would be a minimum requirement for a satisfactory harvest from pearl millet in light arid soils (Kathju et al. 1998). In the case of cowpea, deep tillage along with soil mulching increased soil moisture content significantly over shallow and no tillage treatment thereby affecting grain yield favourably (Gupta and Gupta 1986). One discing with harrow significantly increased grain yield of cowpea (Gupta 1987) and mung bean (Bhati 1996) compared with no tillage. At Bikaner, deep ploughing brought significant improvement in grain yield of crops such as cluster bean, mung bean and pearl millet (CAZRI 2006a). Pitting with deep ploughing was the best soil working practice for successful plantation of *Azadirachta indica*, *P. cineraria* and *T. undulata* (Gupta and Meena 1993).

Residue management

Pearl millet residue (leaving pearl millet stubble of 45 cm height in the field at harvest) and stable mulch decrease wind erosion, and increase organic matter and yield of pearl millet (Misra 1956), but mulching is not adopted by farmers due to stover's high utility as animal feed. Praveen Kumar et al. (2009) also observed that one of the reasons for lower productivity under reduced tillage is low availability of crop residue. Residue production and availability in the arid region is very low, and pearl millet residue (being the predominant crop) is a very important source of fodder. Moreover, pearl millet residues if left as mulch by farmers, are easily destroyed by termites. Thus, residue application with minimum tillage has limited scope under hot arid conditions.

Crop stand and crust management

Crust formation on the soil surface is common in arid soils. Crusts are formed as a result of the beating effect of raindrops and subsequent drying of oriented particles in the compacted layer. The impact of rain on exposed soil causes structural breakdown. The dispersed finer fractions of soil deposit on the soil surface move downwards with percolating water and impregnate the soil pores. The consequent rapid drying of soil, owing to high radiation, results in the formation of surface crust. These crusts impede seedling emergence and often result in very poor crop stands or total crop failure. Application of FYM on the seeded rows after sowing reduces crust strength from 73 KPa to 32 KPa (CAZRI 1976). Application of FYM over seed furrows reduced crust strength to 49 KPa on the 3rd day and 69-74 KPa on the 7th day after sowing as compared to 108-128 KPa on the 3rd day and 162-172 KPa on the 7th day under drill sowing (Joshi 1987). The lower crust strength obtained with FYM allowed higher seedling emergence rate resulting in a low mean period of emergence. The application of FYM over seed furrows firstly reduced the beating effect of raindrops and thus avoided breaking of aggregates. Secondly, FYM being amorphous in nature, absorbed more rain water; besides its mulching effect, it retained 2.26% higher moisture content in the surface layer. Other methods such as the use of pearl millet husk as mulch (CAZRI 1976) and mixing of legume (mung bean) seeds with millet seeds (Joshi 1987) have also been found satisfactory for securing better plant populations and final yields in crusted soils. The furrow system laid out in the North-South direction or with 25° diversion either towards the west or the east (NW-SE or NE-SW) was also effective in combating crust as it reduced wind action and lowered soil temperature, which resulted in reducing soil surface drying rate by 25-35% (Singh 1984).

Sowing time

More than 85% of the total rainfall in the arid region is received during the south-west monsoon between July and mid-September. The crop growing period in arid Rajasthan varies from 7 to 14 weeks depending upon the location and type of soil (Rao et al. 1994). Pearl millet, cluster bean, moth bean, mung bean and sesame have been in cultivation since ages in these regions owing to their short growing period and the fact that their growth phases match well with the rainfall pattern of the region. Though, the normal period for sowing here is between 1st and 15th July, rainfall records show that the rains can be delayed by as late as the 1st week of August in western parts and the 3rd week of July in the eastern parts of western Rajasthan (Rao and Singh 1998). With the early onset of monsoon, pearl millet and sesame get preference while in the case of delayed onset, cluster bean, mung bean and moth bean get preference. However, the performance of cluster bean under late-sown conditions was invariably the best over other legumes in the arid regions (Henry 2003).

The suggested optimum seeding time for rainfed castor in different parts of the country is the second fortnight of June in Andhra Pradesh and the first fortnight of July in Gujarat and Rajasthan. Yield decreases progressively with delay in planting from this point onwards. Though the total yield is the summation of primary, secondary and tertiary spikes during the life cycle of the plant, primaries contributed 59% to the total yield. Early planting results in higher yield of primaries and lower yield of tertiaries compared to delayed planting and vice versa. Sowing after 20th July gives poor yields in the kharif season. Late sowing is not desirable as the incidence of a serious pest, castor semi-looper, tends to be high. With the introduction of new, early and high-yielding varieties and hybrids, cultivation has extended to rabi and summer seasons. The optimum planting time of rabi and summer castor for the arid region is September and March, respectively. In Rajasthan and Gujarat, the first fortnight of July is considered the optimum sowing time.

The optimum sowing time for cluster bean is from the onset of monsoon to the third week of July (Henry 2003). Taneja et al. (1982) reported that 10th July is the optimum time to sow cluster bean and that further delay in sowing up to 30th July caused more than 70% reduction in seed yield. Similarly, Bhati (1989) found that the optimum sowing time for moth bean was the second week of July. Sowing of moth bean beyond the second rain after the onset of monsoon significantly reduced seed yield (Shekhawat 1992). Sowing of rainfed cowpea is also done with the onset of monsoon. In the case of cowpea, cultivar Charodi 1 performed better under normal sowing while K 11 showed promise under late-sown conditions (Henry and Daulay 1988). The optimum sowing time of horse gram was the 2nd fortnight of July (Singh and Singh 1993).

Seed rate and crop geometry

A proper plant stand is prerequisite for successful crop production, and depth and seed rate play a vital role in maintaining adequate plant populations. Placing seed at a depth of 3-5 cm is optimum for seedling emergence and grain yield of pearl millet (Misra and Vijay 1963). However, for arid legumes, the seed placement should be at about 5-7.5 cm depth depending on the type of soil and the depth of soil moisture. Seed rate depends on method of sowing, soil moisture, seed size and the purpose for which the crop is grown. The use of seed in adequate amounts would be helpful in maintaining optimum plant stand and yield. The optimum seed rate of pearl millet was found to be 3.36 kg/ha.

Crop geometry determines the area available to each plant and the competition for inputs: mainly moisture, nutrients, light and space. In the arid region, particularly under rainfed conditions, a larger canopy may be disadvantageous as it may exhaust available soil moisture from the root zone in drought conditions (Singh 1977). Therefore, in drought-prone areas, a lot of consideration needs to be given to maintaining optimal plant stand and row spacing. It was observed that thinning or removing some plants to make room for the growth of others is a beneficial practice at the three-week stage, by keeping 15-20 cm intra-row spacing, at a recommended row spacing of 45 cm (ARS 1990a). Row spacing of 45-60 cm was found optimum in pearl millet whereas 30 cm, 75 cm and 90 cm row spacing reduced yield significantly (ARS 1991a). Results from a five-year observation revealed that sowing of pearl millet at 50 rows x 15 cm plant spacing (ie, 133 thousand plant/ha) recorded the highest yield of 1228 kg/ha while reducing plant stand to 66 thousand plants/ha (50 x 30 cm, 75 x 20 cm, 100 x 15 cm) suppressed seed yield significantly (ARS 1991b). Rao and Joshi (1986) observed that skipping every 4th row in the uniform planting system (border row system with adjusted population on hectare basis) gave 14% higher yields over the uniform row system despite 25% lower population.

In cluster bean, at Mandore, the highest grain yield was recorded at 30 x 15 cm (222 thousand plants/ha) which was at par with 45 x 10 cm but was significantly superior to 45 x 15 cm (148 thousand plants/ha) and 30 x 10 cm (333 thousand plants/ha) (ARS 1994). At Hissar, Yadav et al. (1992) and Rana et al. (1991) reported that 30 cm row spacing under late sown condition and 45 cm spacing under early sown condition for cluster bean gave better results.

Moth bean variety RMO 40, which is erect in growth, recorded the highest mean seed yield of 755 kg/ha when sown at 30 cm row spacing, indicating the need for a higher seed rate (15 kg/ha), while Jwala and IPCMO-880 which are creeping/spreading in nature gave better performance at a seed rate of 10 kg/ha (ARS 1991c). Dauley and Singh (1982) observed that sesame yields were highest with the lowest plant density (250 thousand plants/ha) in subnormal years whereas in good rainfall years, plant densities did not influence seed yield significantly. Trials conducted to study the effect of intra-row spacing in sesame at 30 cm row-to-row spacing revealed that 15 cm intra-row spacing produced maximum seed yield of 563 kg/ha which was at par with 10 cm intra-row spacing (554 kg/ha). However, 15 and 10 cm intra-row spacing remained significantly superior over 8 cm intra-row spacing indicating that a plant stand of 200,000-300,000/ha in sesame is sufficient to achieve good yield under arid environmental conditions (ARS 1991c).

A study conducted to test the seed performance of newly released sesame varieties (RT 127, RT 46 and RT 274) at varying crop geometries revealed that these varieties recorded significantly higher seed yield at 30 × 15 cm (632 kg/ha) than 30 × 10 cm (596 kg/ha) and 30 × 8 cm (531 kg/ha) spacing (ARS 1996).

At Mandore, it was concluded that planting senna at 45 cm row spacing gave the highest mean leaf yield of 1253 kg/ha followed by 30 cm (1180 kg/ha). However, the highest net return (₹ 6392/ha) and Benefit:Cost ratio (1.73) was observed in 60 cm row spacing. Plant-to-plant spacing of 10 cm gave maximum seed yield of 1257 kg/ha (ARS 1997).

In arid areas, competition for moisture is more severe than usual. Row spacing that gave highest yields were: 45 cm in pearl millet (Garag et al. 1993); 30 cm in late-sown and 45 cm spacing in early-sown cluster bean (Yadav et al. 1989; Rana et al. 1991); 30-40 cm in cowpea (Mali 1991; Anitha et al. 2004) and 45 cm in moth bean (Shekhawat 1992; Yadav and Beniwal 2006). A row spacing of 30 cm for unbranched and 45 cm for branched genotypes of cluster bean (Taneja et al. 1982) under normal season and 40 cm row spacing in drought years gave the highest seed yield (Garg et al. 2003), whereas Patel et al. (2004) found 45 cm row spacing as optimum. Castor plants which are prolific in growth produced a maximum seed yield of 3732 kg/ha at 90 x 60 cm spacing closely followed by 60 x 60 cm (3616 kg/ha) geometry. At 60 x 30 cm spacing, castor produced its lowest seed yield of 3320 kg/ha (ARS 1992a).

3.1.2 Technologies related to optimization of water and nutrient use efficiencies

Fertilizer use in the arid zones is very low and irrational. The average production level is 320 kg/ha and fertilizer use is about 2.0 kg/ha and 27 kg/ha in kharif and rabi respectively. The nutrient balance with respect to N, P and K show a deficit of about 90.4 thousand t, 14.3 thousand t and 95.4 thousand t respectively and the gap is expected to widen in the near future. In these areas, the application of nutrients or follow-up of integrated nutrient management (INM) is very important to increase production as well as to maintain soil fertility (Venkateswarlu and Aggarwal 1991). There is a direct relationship between nutrients applied and yield obtained. It has been estimated that for every ton of grain yield of cereals, approximately 50-60 kg/ha nutrients must be applied. Besides, the applied fertilizers N, P and K must be in the desired proportion.

Rainfall in the arid region is low and scanty. Annual average rainfall varies from 150-400 mm and its annual coefficient of variation is 37->50% (Rao and Singh 1998). The annual estimated PET values range from 1600 mm in the eastern part to >1800 mm in the western part. The soils of the region are generally coarse textured with sand content varying from 90% in dunes to 60% in comparatively heavy soils, and they are deficient in organic matter as well (Joshi 1993). The availability of surface water is very limited. Underground water is very deep, limited and mostly brackish. Under such situations, the only option available is to harness precipitation to its fullest.

Current practices for optimizing water and nutrient uses

In all the selected study villages of Jaisalmer, Barmer and Jodhpur districts, there is limited awareness about the optimization of water and nutrient use efficiency. Except in pearl millet where top dressing of urea (10-15 kg/ha) is practiced by few farmers depending on the season, other kharif crops are hardly treated with any chemical fertilizer. The crops are mostly grown with very limited application of organic manure. Although rabi crops are treated with chemical fertilizers, even this is not as per recommendations because of lack of awareness, uncertain electricity and water availability. In the action sites, the scientific management of rainwater through *in situ* and inter-plot water harvesting systems is almost non-existent except for the limited efforts made under various government schemes. In tube well-irrigated villages, only a few innovative farmers are practicing sprinkler irrigation. In other villages, dryland farming is the mainstay of farmers. To reduce soil and nutrient losses caused due to flow of rain water, some farmers resort to field bunding, safe removal of excess water through spillways backed by locally available vegetation such as *Leptidenia pyrotechnica, Crotalaria burhia,* and *Panicum turgidum*. Villages Damodara and Dedha have very old *khadins;* scientific management of water is needed to enhance water and nutrient use efficiencies in these potential areas. Most of the sites are affected by wind erosion that leads to major soil loss every year. No measures have been taken to address this issue.

There is a need to rebuild the soil-plant-animal continuum in highly degraded lands to sustain valuable land resources, restore the environment and ensure higher farmer incomes. Large tracts come under sacred lands (Oran) in villages Dhok and Didhu, these sites have potential to be developed as silvo-pastures, biodiversity sites and for ecosystem services. Similarly, water loss in *agours* (water catchment sites adjoining common grazing lands), *gauchar* (pasture lands) and village ponds are urgently required to be checked. Their potential can be augmented and efficiently used.

Improved nutrient management practices

The improved nutrient management practices relevant in Thar desert of India are briefly discussed here.

Nitrogen: Rainfed arid lands are deficient in nitrogen. Good responses have been shown to applied nitrogen in a majority of crops. Increased nitrogen-use efficiency in crops has been reported by many workers in different crops. Singh et al. (1973) working on the interaction between tillage and N application on pearl millet reported that application of FYM to supply 11.2 and 22.4 kg N/ha increased grain yield over the control by 60% and 100% respectively. Application of 20 kg N/ha was an economical dose for anjan grass (*Cenchrus ciliaris*) according to Faroda (1974). Singh and Singh (1977) working on intercropping of annual legumes with sunflower reported that application of 60 kg N/ha to sunflower grown as a sole crop led to a significant yield increase of over 30 kg N/ha than the farmer practice. However, in the case of an intercropping system involving mung bean and cowpea, the application of 30 kg N/ha in the second year gave as good a yield as with 60 kg N/ha.

Deep placement of N (10 cm deep) and broadcast at the rate of 40 kg N/ha increased the grain yield of pearl millet from 44-96% over the control. The response of N application at 40 kg N/ha, 80 kg N/ha and 120 kg N/ha was 10, 5.3 and 3.4 kg grain/kg N respectively. Applying half of N (20 kg N/ha) as deep placement (10 cm deep) at sowing and applying the remaining half (20 kg N/ha) as a top dressing 35-40 days after sowing was found to be more economical (Singh et al. 1978). In rainfed conditions, the water use efficiency of pearl millet in terms of kg grain produced per mm of evapo-transpiration was highest with 60 kg N/ha, which was 3.54 kg/mm, 5.38 kg/mm and 4.83 kg/mm under N_0, N_{60} and N_{120} kg N/ha, respectively (Krishnan et al. 1981). Daulay and Singh (1982) reported that seed yield increased with increase in N dose in sesame. The response was 9.3 kg seed at 30 kg N/ha and 8 kg seed at 60 kg N/ha. Bhati and Singh (1982) working on fertilizer management in perennial grasses reported that dry matter and crude protein yields along with the growth parameters and N and P uptake increased with the application of 60 kg N/ha in *Cenchrus setigerus*.

Joshi and Singh (1985) reported that nitrogen as an independent input increased grain yield of pearl millet linearly up to 40 kg/ha. Under partial irrigated condition, application of 80 kg N/ha was as good as 120 kg N/ha but proved superior to 40 kg N/ha and resulted in 72% increase in grain yield of pearl millet (Parihar et al. 1998; Aggarwal and Kumar 1996). The application of crop residues along with 20 kg N/ha provided pearl millet grain yield equivalent to that of 40 kg N/ha with no residue. Yadav and Beniwal (2000) reported highest dry matter yield of 4.70 t/ha and 4.53 t/ha of *C. ciliaris* and *Lasiurus sindicus* respectively, at 40 kg N/ha, which was significantly higher over the control, under rainfed conditions at Bikaner.

At Hissar, the application of 20 kg N/ha recorded the highest cluster bean yield of 790 kg/ha, which declined to 640 kg/ha at 40 kg N/ha. Green and dry matter yields were not affected due to increase in N doses while crude protein was affected significantly. Singh and Khan (2003) reported that application of 20 kg N/ha + 40 kg P/ha significantly increased the grain yield of cluster bean by 25.1% while water use efficiency was 21.7% higher over the control. Yadava et al. (2008) reported that among different varieties of cluster bean, variant RGC 936 gave highest grain and straw yields at 10 N/ha + 20 P kg/ha under rainfed conditions.

Phosphorus: Phosphorus is a major nutrient and plays an important role in plant metabolism. Deficiency of phosphorus in soil leads to severe disorders in the plant and hence adversely affects productivity. Phosphorus deficiency affects nitrogen fixation and other metabolic activity of legumes. Experiments conducted at Mandore (Jodhpur) on the method of application of different fertilizers on pearl millet revealed that the method of application ie, whether broadcast or placement, has no effect on yield. Basal application of 30 kg N/ha with 15 kg P/ha gave the highest yield of pearl millet (Mehta et al. 1970). Tomer et al. (1973) reported that application of 40 kg P/ha significantly increased the forage yield of cluster bean over the control but observed no substantial increase in yield beyond 40 kg P/ha. A study on the response of moth bean revealed that application of phosphorus did not affect seed yield (Singh and Singh 1980). However, the application of 30 kg P/ha and inoculating the moth bean seed with 'Nitragin' resulted in significant increase in yield in 1978 (Singh and Singh 1981). The placement of fertilizer was better than broadcast application, with response varying from 1.3-2.7 kg/kg P in normal sown and 0.9-2.0 kg/kg P in the case of late-sown moth bean.

A 16-year-study on pearl millet revealed that when grown with cluster bean, it gave 11% higher yield over pearl millet-pearl millet rotation. Application of 26 kg P/ha once in two years to the legume instead of to pearl millet in rotation gave 36% higher yield. Application of 60 kg N/ha + 26 kg P/ha to the legume in alternate years resulted in high yields and maintained soil productivity (Singh et al. 1985). Joshi and Mali (2004) reported that gum content in cluster bean increased with the application of 10 kg P/ha over the control. The weight of nodules increased with the increase of P level from 40-60 kg/ha, which was more in cluster bean followed by mung bean and moth bean (Kathju et al. 1987).

It was found that the response of rainfed crops to phosphorus will not increase without increasing the soil moisture content (Katyal et al. 1987). In cowpea, dry weight and nitrogen accumulation in nodules improved with phosphorus application. Further, the graded dose of phosphorus significantly affected grain yield; however, phosphorus at 17.2 kg/ha registered the highest yield.

Application of 40 kg P/ha in fenugreek significantly increased the height, branches/plant, pods/ plant, pod length, seeds/pod and test weight compared with 20 kg P/ha, according to Bhati (1993). Application of 30 kg P/ha increased the seed yield of cluster bean significantly by 16% over the control; however, there was no additional benefit from 60 kg P/ha over 30 kg P/ha. Application of 25 kg P/ha resulted in 9.13% higher crude protein and gum content in cluster bean besides significantly increasing seed yield over the control (Joshi and Mali 2004).

A study showed that application of phosphorus beyond 20 kg/ha does not increase yield of cluster bean (Kumar et al. 2005). Kandpal et al. (2006) at Jaisalmer under rainfed conditions reported that highest growth and yield of moth bean were recorded at 20 N + 40 P kg/ha -- 21.1% in plant height, 15.3% in biomass/plant, 9.6% in seed yield and 24.4% in straw yield over 10 N + 20 P kg/ha. Highest P use efficiency has been recorded at 20 kg P/ha; a further increase in P decreased P use efficiency (Bhunia et al. 2006).

However, it is recommended that decisions on fertilizer doses for different crops and locations should be based on the soil tests.

Micronutrients: Although arid legumes do not show symptoms of micronutrients' deficiency in most rainfed areas, under intensive cultivation tracts, there are some pockets where deficiency has been observed. Nandwal et al. (1990) reported that application of zinc to cluster bean increased nitrogenase activity, carbohydrate and protein content, which was higher at 60 days over 80 days of the crop. Seed yield and dry matter production were higher with the application of zinc as $ZnSO_4$. At Gwalior, application of 40 kg sulphur (S)/ha increased growth and yield of cluster bean up to 10.7% and 28.3% over 20 kg S/ha over the farmer practice. It also enhanced sulphur, phosphorus, protein and gum content in the seed. Under rainfed conditions, S application at 20 kg/ha increased the yield of cluster bean at SK Nagar. It did not affect the status of N and P in the soil. In the case of supplements through different sources, studies at Bikaner showed that S application through gypsum was better than through pyrite, and yield increased with 30 kg S/ha.

At Jobner, sulphur increased growth, yield attributes, seed yield and harvest index up to a dose of 60 kg S/ha under rainfed conditions. The increase in seed yield was 19.5% and 33% applying 30 kg S/ha and 60 kg S/ha respectively (Shivran et al. 1996).

In Jodhpur, the effect of sulphur application on pearl millet was found non-significant. Studies showed that a foliar spray of 1 kg $ZnSO_4$/ha (0.2%) on cluster bean at 45 days after sowing was better than soil application of 5-10 kg Zn/ha. At Bawal, the application of 0.5% $ZnSO_4$ either at 25 or 45 days after sowing or at both the stages and 25 kg $ZnSO_4$/ha as a basal dose at sowing significantly increased the yield of cluster bean over the control.

The combined application of 40 kg S/ha and 5 kg Zn/ha significantly increased pod yield in groundnut (2251 kg/ha) whereas the maximum cost:benefit ratio was recorded at 40 kg S/ha + 2.5 kg Zn/ha (Singh and Mann 2007). Kumawat et al. (2009) reported that application of 40 kg S/ha significantly increased the grain and biological yield of mung bean by 65.9% and 37.7%, respectively over the control. Soil-applied $FeSO_4$ (25 kg/ha) significantly improved the accumulation of dry matter, grain and biological yield of mung bean by 66.6% and 41.9% respectively over the control (Kumawat et al. 2009). However, application of micronutrients should be based on soil tests.

Microbial inoculants: Different microbial inoculants such as *Rhizobium, Azotobacter*, and Phosphate Solubilizing Bacteria (PSB*)* help in savings in fertilizer and increasing crop yield with very little investment. Many blue green algae growing in arid zones help in controlling soil erosion as well as improving soil fertility. Nitrogen-fixing bacteria in Indian arid soils vary with soil organic matter content.

Rhizobium inoculation alone in mung bean obviates the needs of N and P under natural conditions in arid agriculture (Singh 1977). Microbial properties of arid soils vary widely with land use pattern, soil moisture status and soil organic matter content (Rao and Venkateswarlu 1983). Joshi and Rao (1989) reported that *Azospirillum brasilense* inoculation on pearl millet increased tillers by 37.9%, heads by 44.3% and test weight by 32.1%. The inoculation effect was reduced with increase in N application.

Biofertilizers can fertilize the crop by augmenting nutrient supply. Most nitrogen-fixing bacteria relevant to the rainfed cropping system belong to the legume–*Rhizobium* symbiosis, which relates to a number of pulse crops, groundnut and soybean.

The strains of *Azospirillum* isolated from arid zone plants were found to be tolerant to chlorides and suplhate but sensitive to carbonate. A 8-15% increase in seed yields in moth bean and cluster bean has been observed with inoculation of *Azospirillum* (Tarafdar and Rao 1990). The very encouraging response of PSB to effective utilization of native P in arid soils in pearl millet has also been recorded (Tarafdar et al. 1991).

In mobilizing soil phosphorus, some phosphatase-producing fungi were identified and their application was found to significantly enhance dry matter production and grain yields of cluster bean and mung bean (Tarafdar et al. 1995). Tarafdar and Rao (1997) reported that phosphatase activity was enhanced significantly due to Vesicular Arbuscular Mycorrhiza (VAM) inoculation. An improvement in dry matter production (20-38%) and grain yield (15-22%) due to inoculation was obtained in legumes.

The application of 10 kg N/ha + 20 kg P_2O_5/ha + biofertilizer inoculation (*Rhizobium* + PSB) gave highest seed yield (28% higher over the control); net returns were on par with application of 20 kg N/ha + 40 kg P_2O_5/ha (Singh et al. 2004). Singh and Singh (2008) reported that the highest yield attributes and seed yield of cluster bean were recorded with the application of 2.6 t FYM/ha + (10 kg N/ha + 20 P_2O_5/ha) + biofertilizer (*Rhizobium* + PSB). Seed yield increased by 30%, 14.3% and 8.3% over the control with the application of 5 t FYM/ha and 20 kg N/ha + 40 kg P_2O_5/ha respectively.

Integrated nutrient management (INM)

In rainfed arid regions where soils are very poor in nutrients and loss of applied nutrients are more due to adverse climatic situations, INM can be a rewarding strategy. Leaving crop residues in soil has shown positive effects on grain yield of crops (Hadmani et al. 1982).

Green manuring with *Leucaena* improved the efficiency of fertilizer N and helped overcome N immobilization (Katyal and Das 1993). Substituting 50% of fertilizer with organic manure (FYM) resulted in higher yields nearly similar to those obtained with full fertilization (Rao and Singh 1993). Rao and Singh (1993) reported crop residues to be as efficient a source of nutrients as FYM and compost. It also increased the organic matter content of soil.

High yield stability was observed when recommended NPK was used with 10 t FYM/ha (Hegde and Gajanan 1996). The application of 5 t/ha FYM on pearl millet-cluster bean rotation and monoculture of pearl millet gave 17.2% and 6.1% higher yields than pearl millet monoculture without FYM, respectively (Saxena et al. 1997).

The integration of chemical fertilizers with organic manure and biofertilizers can maintain soil fertility and sustain crop productivity (Jeyabal et al. 2000). The increase in water-use efficiency under treatments involving the combined application of FYM and inorganic fertilizer is due to relatively rapid root and shoot growth (Ghosh et al. 2003). The combined application of 10 kg N /ha+ 9 kg P/ha + (*Rhizobium* + PSB) gave at par seed yield in cluster bean but higher net returns compared to the application of 20 kg N/ha + 18 kg P/ha (Singh et al. 2004). Kumar et al. (2005) reported that application of 5t FYM + 50% of recommended dose of fertilizer (40 kg N/ha + 8.75 kg P/ha) gave significantly higher dry matter in forage sorghum over the control.

In cluster bean, inoculation with *Rhizobium* and PSB individually increased yields by 17.06% and 19.69% respectively, whereas their combined application increased yield by 22.35% (Anonymous 2006a). At SK Nagar, the inoculation of moth bean seed with PSB alone or in combination with *Rhizobium* resulted in significant increase in seed yield over the control (Anonymous 2008). A barley-moth bean rotation study at Bikaner revealed that application of 10 t compost/ha + 50% recommended dose of fertilizer in barley recorded the highest grain and straw yields over the control and its residual effect on moth bean crop gave 235 and 345 kg higher grain and straw yield over the control (Anonymous 2007). Rao et al. (2007) working in Pali district of Rajasthan reported that the application of 5 t FYM + 50% of recommended dose of 30 kg N/ha and 8.75 kg P/ha significantly increased green and dry fodder yields of sorghum by 35.1% and 35.7%, respectively over the control. The water use efficiency in FYM-treated plots was also higher over that of the control.

These studies clearly show a large variation in crop responses to fertilizer and manure application across locations. This could be because arid soils vary with land use pattern, soil moisture status and soil organic matter content. Therefore, soil test-based application of fertilizers and manure is of utmost importance and developing soil test-based health cards for each farmer should be a priority intervention.

Improved water management practices

The arid zone is showing a permanent negative water balance; groundwater is deep and often brackish as well. Evaporation losses account for 20-25% water loss. About 1169 mcm water comes from reservoirs and tanks, 1.723 x 10^6 m^3 to 2.961 x 10^6 m^3 flow from canals and 2435.4 x 10^6 m^3 from groundwater. Together these sources irrigate 1.82 m ha at present and it is expected that about 2.69 m ha would come under irrigation upon the full development of the canal command area. But indiscriminate use of water on undulating, highly permeable sandy soils through conventional irrigation practices resulted in a 3-7 m fall in the groundwater table and waterlogging in the canal command area of IGNP.

1. Increasing water storage in soil

The options for increasing water stored in the soil are follows:

a) Bunding and vegetative barriers

Bunding has been an age-old practice to reduce runoff and improve moisture storage in the soil. At Pali, bunding prevented runoff, increased infiltration and improved the availability of moisture to rabi crops, ie, mustard, taramira (*Eruca sativa*) and chickpea by 11.4 mm in a soil core of 100 cm (CAZRI 1998; Regar et al. 2007). Contour bunding is extensively recommended for controlling soil erosion and moisture conservation in arable areas on slopes ranging from 1% to 6%. Wasi Ulah et al. (1972) observed that contour furrows alone stored more soil moisture (39%) than the contour bunds alone (27%) and a combination of both (26-32%). Singh (1984) recommended contour bunding of 75 cm height and 80 cm vertical spacing combined with contour furrowing at 10-15 cm depth and 100-125 cm vertical spacing. This option recorded higher forage yield than the control. The moisture pattern of the system was studied and higher soil moisture was recorded at the centre of the furrow and middle of the ridges throughout the season (Verma et al. 1977; Sharma et al. 1980; Sharma 1983). Hence, the middle of the ridge recorded the highest plant population, dry matter production and precipitation use efficiency (Sharma 1983).

In partial modification to contour bunds, Sharma et al. (1983) designed contour vegetative barriers (CVB) wherein local grasses with extensive root system, such as *Cymbopogon jwarancusa, C. ciliaris* and *C. setigerus* were transplanted 0.3 m apart on contours at 0.6-1.0 m vertical intervals forming a dense hedge. In a four-year study of this system, it was found that the runoff volume reduced by 28-97%, the soil stored about 2.5 times more moisture and cluster bean and pearl millet yields improved by 37-51% and 19-40% over the control, respectively. In another study, vegetative barriers of different grasses were established at a horizontal interval of 30 m and pearl millet was sown in between. For a cumulative rainfall of 105 mm, about 36.5%, 72.1% and 54.2% higher moisture storage were observed under the alleys of *Cassia anguistifolia, Lasirus sindicus* and *Saccharum munja,* respectively compared to the control (36.9 mm every 60 cm). The average yield of pearl millet improved by 39.1% over the control (CAZRI 1998). The combination of bunding and vegetative barriers of *C. ciliaris* improved soil profile moisture in a field with 1-2% slope and resulted in a 40% increase in yields of mung bean and moth bean (CAZRI 2000). These barriers being easy to raise, are less expensive and provide fodder during lean periods, and can be readily adopted by farmers.

b) *In- situ* moisture conservation

Two *in-situ* water harvesting systems were devised at CAZRI, Jodhpur, during the '70s and '80s (Singh 1988b). In inter-plot water harvesting, a micro-catchment is prepared on one or both sides of the cropped area and 2/3 of the area is cropped, leaving 1/3 as catchment (1.5 m or 0.75 m area is used as catchment on both sides respectively) with a slope of 5% towards the cultivated area. The experiment increased soil moisture and the yield of many crops (Singh et al. 1973, Singh 1988a). It also resulted in saving of 1/3 of inputs. In semi-arid part of catchments in Pali, a 4-8% slope provided 50-80% runoff to the cultivated area and enhanced the yield of crops such as castor, sunflower and mung bean (Jain and Singh 1982).

The ridge and furrow system (inter-row water harvesting system) was designed by modifying inter-plot water harvesting (Singh 1988a). No land is wasted for catchment purposes. Furrows of about 30-40 cm width and 15-20 cm depth are made. A distance of 60-90 cm is maintained between two ridges. This system is particularly suitable for medium to heavy textured and deep to moderately deep soils (Faroda et al. 2007). In light soils, the crops are sown in furrows whereas in heavy soils, planting may be done on ridges to eliminate waterlogging. Under this system, pearl millet yield improved by 210% over regular flat planting, whereas the comparative yield for micro-catchment was 120% (Singh and Saxena 1998). Laying out the ridge and furrow configuration against the prevailing wind direction of south-west to north-west was found more effective in increasing moisture availability (15-20%) in the arid region.

Another approach to conserve rain water is to adjust row spacing and make conservation furrows at the time of intercultivation. Planting pearl millet at 60 cm and making ridge-furrows after interculture (30 DAS) with wider row spacing (60 cm) with 50% N through FYM recorded significantly higher grain (49.7% and 53.41%) and fodder yields (40.36% and 43.14%) respectively in Jodhpur and Barmer districts over farmers' practice of 30 cm planting. Plants maintained higher relative water content (RWC) and stomatal conductance at grain formation stage (Lal et al. 2007). In sorghum, the inter-pair row conservation furrow improved grain yield by 63% over the control (Regar et al. 2006). In henna, inter-row and inter-pair row water harvesting (conservation furrow) provided 8.6% and 7% higher yields respectively over inter-triplet row water harvesting and the control (Regar et al. 2005).

c) Sub-surface moisture barriers

High percolation rates in sandy soils in the arid region not only affect moisture retention but also cause nutrient leaching. Such soils can be made productive by the use of sub-surface barriers. At CAZRI, in 1971, pits of 50 cm diameter were dug by tractor augur and bentonite was placed at a depth of 75 cm and pit walls were also thoroughly dusted with bentonite. It resulted in 49% higher yields of round gourd (*Citrullus vulgaris*) than the conventional system (Singh et al. 1975; Singh 1980). Other materials like pond sediments, asphalt and vermiculite were also tried. Bentonite clay and pond sediments at 60 cm depth at 5 mm thickness were 60-70% and 50-60% effective respectively in retaining total rainfall in the root zone (Singh et al. 1979). Use of asphalt as a sub-surface barrier (2 mm thick at 60 cm depth) restricted deep percolation loss to 24 mm compared to 120 mm from unbarriered soil profile and increased pearl millet yield by 40-50% (Gupta and Aggarwal 1978, 1980). Large scale use of these barriers is limited due to their cost and non-availability of machinery to incorporate them.

d) Soil amendments

In arid regions with very low soil organic matter and weak soil structure, soil amendments like pond/ tank sediments, vermiculite, FYM, etc. were found very promising in improving the moisture retention capacity of, soil. The mixing of pond silt up to 30-40 cm of the soil depth at 76 t/ha increased available water storage capacity from 6.5-6.9%, reduced infiltration rate from 15-13.2 cm/ha and hence increased yields of pearl millet by 40-50% and of mung bean by 35-40% over the control. Use of vermiculite at 20 t/ ha increased 0.1 bar moisture retention from 10.03% to 12.4%, reduced saturated hydraulic conductivity from 8.6 to 6.5 cm/h and bulk density from 1.62% to 1.57 g/cu cm (Gupta et al. 1979). Surface application of FYM (5 t/ha) and *Calotropis procera* residue (2t/ha) increased the yield of pearl millet by 30% (Agarwal and Sharma 1980, CAZRI 2007a). Therefore, the desilting of village ponds and tanks as done under various governmental schemes such as MGNREGS, integrated watershed management program (IWMP) should be properly dovetailed with agriculture development programmes in dry areas of western Rajasthan and be utilized for improvement of soil quality and water availability on cultivated lands. Further, the use of FYM, compost and vermicompost would improve soil productivity and moisture conservation.

e) Use of mulches

The use of mulches has been reported to favorably modify the hydrothermal regime of soil and suppress weeds (Parihar et al. 1977; Gupta 1978, 1980; Gupta and Gupta 1985). In normal years, the effect of mulches may not be visible because the top surface of sandy soil acts as a self-mulch after drying up a few centimeters. However, during drought years, covering of soil surface with mulch, such as grass waste, pearl millet husk and organic matter waste immediately after sowing delays surface drying, promotes better establishment of crop and results in higher yields. Singh (1977) has reported that mulches effectively conserve soil moisture until 50% of the ground area is covered with crop canopy.

Application of grass mulch at the rate of 6 t/ha depending on weather aberrations decreased the maximum temperature of soil by 1-9°C, reduced losses through evaporation and increased seedling emergence in pearl millet. Polyethylene mulch, on the contrary, raised soil temperature by 1-3°C. These mulches also suppressed weed growth and improved soil moisture status. Mulching increased the yield of mung bean, moth bean and cluster bean by 178%, 90% and 71% over the control respectively. Chickpea seed yield increased by 12.6% and 18.1% due to grass and polythene mulch respectively. Mulching (straw and polyethelyne) improved the yield of pearl millet in farmers' fields. Plastic mulch increased crop yield by 23.7%, which was at par with straw mulch. The use of polythene and straw mulch conserved 28% and 24% more soil moisture than the control (CAZRI 2000). Non-edible plant materials available on the farm can be used as mulch for general field crops and the polyethylene mulch can be used for high value crops.

2. Water harvesting at surface

Runoff water harvested through surface bodies like *khadins*, ponds and tanks has traditionally been an important part of farming systems in the arid zones. Some of the major surface water storage structures on farmlands are:

a) Khadin

In larger catchments, runoff trickles to distant places in small streams and collects wherever it meets a depression or a natural topographic barrier, which limits its further movement. Runoff water is harvested from shallow, gravelly and rocky upland catchments in the low lying valley plains that are converted into bunded farmland structures (*khadin*) where either kharif or rabi crops are raised, depending upon the amount of rainfall and consequent runoff received during the monsoon. Any excess water in *khadins* is passed out through a spillway provided in the bund. Soils in the *khadins* are fertile because of the frequent deposition of fine sediment, while the water that seeps away removes salts (Kolarkar et al. 1983). Crops such as wheat, mustard, taramira (*Eruca sativa*) and chickpea are successfully grown on receding moisture during the postrainy season. Average pearl millet yield ranges from 300-500 kg/ha during poor rainfall (60-70 mm) years. Similarly, during better and high intensity rainfall seasons, wheat yield ranges from 1200-2000 kg/ha and chickpea from 1000-1500 kg/ha (Kolarkar and Singh 1984). Khan and Singh (2005) recorded a grain yield of 1803 kg/ha of chickpea (cv. RSG-44) grown under the *khadin* system, besides the benefit of improved physico-chemical properties of the soil.

b) Farm ponds

Farm ponds are water bodies made either by constructing an embankment across a water course or by excavating a pit. They provide life saving irrigation to rainfed crops in low and erratic rainfall areas and also for the development of agroforestry systems. Runoff water is collected from a treated or untreated catchment and stored in a reservoir or farm pond. The stored water is utilized for supplemental irrigation during long dry spells at critical stages of plant growth. Experience has shown that a supplemental irrigation of 5-7 cm to rainfed pearl millet or legumes at the reproductive stage can make all the difference between the success and failure of a crop.

3. Minimizing evaporation relative to yield

Evaporation from the soil surface causes considerable reduction in the water available to crops. In kharif pearl millet, cowpea, mung bean, sorghum and cluster bean, the evaporation rates were 20%, 23%, 34%, 38% and 40% respectively of total ET. Evaporation losses can be minimized by reducing the availability of energy to the soil and limiting heat or vapor exchange between the soil and the atmosphere. Evaporation can be reduced by the elimination of weeds, use of mulches, planting geometry including deciding the direction of sowing and population, use of organic manure/ fertilizers, biofertilizers, wind breaks and intercropping.

Weed control is an age old mechanism to increase water availability to crops. In pearl millet, weeding resulted in substantial increase in yield under suboptimal and optimal rainfall conditions at Jodhpur. It improved water use efficiency (WUE) from 3.1-3.4 kg/mm/ha under normal rainfall (450-550 mm) and from 4.2-6 kg/mm/ha under suboptimal rainfall (252 mm) years. The use of improved weeding tools such as peg tooth weeders, tractor-drawn sweeps, slotted hand hoes cover more area and facilitate soil mulching (Rao et al. 2007). Chemical weed control followed by mechanical weeding at appropriate stages can eliminate weeds and make water available to crops.

4. Integrating agro-techniques for higher water periodicity

Relying on water alone for higher production is not logical unless it is combined with other factors of production. Evapotranspiration (ET) is dependent on climate, while improved management practices either don't or negligibly increase crop ET. For example, the application of 40 kg N/ha in inter-plot or inter-row water harvesting enhanced pearl millet production by 72-75% and improved water use efficiency over the control (Singh and Singh 1993). The characteristic value of crop water productivity at crop/field levels in the Indian arid zone is given in Table 7.

5. Irrigation water management

About 10.8% of the area in arid western Rajasthan is irrrigated. The IGNP has led to a boom in agricultural production and remarkably improved the socio-economic condition of the local population. However, overexploitation and injudicious use of water has resulted in a sharp decline in groundwater table, waterlogging and soil salinization, calling for urgent measures. The emphasis should be on extensive rather than intensive irrigation. It is estimated that as much as 70% of water is lost in conveyance, application and distribution. Thus, efforts should be made to reduce water losses and consequently increase irrigation efficiency. Adopting sprinkler and drip systems of irrigation, which also increase crop yield, can save sufficient amounts of water. Kushal and Pathak (1977) obtained 38 cu m, 18 cu m and 33 cu m saving in water in wheat, groundnut and cotton respectively and the highest water use efficiency as well. Irrigation through sprinklers increased wheat and potato yields by 8.7% and 29% respectively, over surface irrigation (Aggarwal 1985). At Jodhpur, the yield of cucumber under drip system was 1 to 1.5 times higher over furrow irrigation (Singh and Singh 1978). The grain yield of wheat was 33% and 37% higher with sprinkler irrigation over check basin and border strip irrigation respectively in the arid region (CAZRI 1979). However, this method has limitations under wind velocity and saline water conditions. Saline water can, however, be used with drip irrigation system. Besides higher production, 30-50% water

Table 7. Crop water productivity at field level in the Indian arid zone.

Crops	Location	Treatment	Water productivity/WUE	Reference
Pearl millet	Arid, Jodhpur	N-Application Intercropping with cluster bean	3.2-8.2 kg/mm/ha	Krishnan et al. 1981; CAZRI 2007
Sorghum	Semi-arid, Pali	Moisture conservation	2.76-4.10 kg/mm/ha	CAZRI 2005
Sorghum (fodder)	Semi-arid, Pali	Fertility levels; weed control	16.5-27.1 kg/mm/ha	Rao et al. 2007
Cowpea	Arid, Hisar	Recommended package of practices (PoP)	1-2 kg/cu m	Phogat et al. 1984
Cotton	Semi-arid, Pali	N application	0.339-0.458 kg/cu m	CAZRI 2007b
Wheat	Arid, Jodhpur	Optimum irrigation	7.7 kg/mm/ha	Singh and Singh 1993
	Arid, Hisar	Recommended PoP	0.7-1.4 kg/cu m	Choudhury and Kumar 1980
	Semi-arid, Pali	FYM + Deep tillage	1.25-1.26 kg/cu m	CAZRI, 2008
Mustard	Arid, Jodhpur	N application	1.22-4.43 kg/mm/ha	Garag et al. 2001
	Semi-arid, Pali	Sprinkler irrigation	6.40 kg/mm/ha	CAZRI 2006b
Cumin	Arid, Jodhpur	N application	4.1 kg/mm/ha	Singh and Rao 1994
	Semi-arid, Pali	FYM + N application	0.319-0.328 kg/cu m	CAZRI 2007b
Tomato	Arid, Jodhpur	Drip irrigation	101-125 kg kg/mm/ha	Singh et al. 1989
Chillies	Arid, Jodhpur	Drip irrigation	2.05-5.17 kg/mm/ha	Singh et al. 1999

in most of the high-value vegetable crops can be saved with drip irrigation (Singh et al. 1978). A study conducted at Jodhpur revealed that potato and tomato crops were successfully raised with 3-10 dSm^{-1} saline waters using drip irrigation method. The detrimental effects of salinity were minimized because the soil maintained higher moisture content due to daily drip irrigation; thereby salts were drained beyond the active root zone (Gupta and Singh 1983). Water use efficiency increased further by adequately fertilizing the crops through drip irrigation. Drip system provided gainful use of nutrient management with water and provided maximum yield of tomatoes and chillies in arid conditions (Singh et al. 1989). Thus, the adoption of efficient irrigation methods such as sprinkler and drip can be effective for increasing water use efficiency in the arid zone.

3.1.3 Harvesting and storage

With changing times, agricultural labor is becoming scarce and timely harvest becomes a challenge for farmers, leading to heavy losses of produce during harvesting. Overdrying of arable crops, specially pulses, results in splitting of pods and shedding of leaves that cause heavy losses in valuable fodder resource. Also, delayed harvesting invites birds and insect pests to damage seed in the field. Even after harvesting, the nonavailability of a proper threshing floor makes farmers keep the harvest in the field for a longer time, subjecting it to heavy damage by birds, rodent and insects. The losses are maximum in kharif pulses and minimum in cluster bean. Heavy damage to a standing crop of pearl millet by birds has been observed. Similarly, overdrying of the sesame crop may result in total loss of seed due to splitting of capsules. In rabi crops too, unscientific management during harvesting and postharvest has been observed to lead to heavy losses due to insectpests, diseases, rodents, birds and untimely rains.

Proper facilities to store grain are almost nonexistent with small and marginal farmers of this arid tract. However, medium to large farmers store the grain in their houses for two to three months. In the absence of proper storage facilities, the dryland farmers sell the surplus produce at the earliest, mostly at a lower price. However, traditional storage bins called '*obries*' where grain is stored for year round consumption are still prevalent. Other traditional storage structures are '*kothis'*, or wooden boxes, straw bins, iron boxes, etc. It is estimated that about 20-30% of produce gets damaged due to harvest and postharvest losses in arid Rajasthan.

3.1.3.1 Alternative harvesting and storage practices

Proper harvesting practices, both manual or with tractor-drawn implements, need to be popularized among farmers of the arid zone. The traditional sickle in use is not very efficienct and needs to be replaced by serrated sickles developed by various research institutes [Central Research Institute for Dryland Agriculture (CRIDA), Central Institute of Agricultural Engineering (CIAE), and State Agriculture Universities (SAUs)]. Studies conducted on farmers' fields revealed that serrated sickles are 25-30% more efficient than the traditional implement. Similarly, tractor-drawn threshers need to be made popular among the farmers to save time and reduce drudgery, especially for women who mainly carry out this operation.

Removing potential pests and their food before filling grain bins will greatly prevent postharvest losses. New grain should never be stored on top of existing grain. Treating empty bins is most effective when insect activity is likely (in temperatures over 30°C). The inner walls and floors should be treated with residual insecticides such as Malathion after thorough cleaning. The external walls (up to 15 feet) and outer base of the bins may also be treated.

The kernels must be cleaned prior to storage. Dirty grain can prevent adequate air flow and uniform aeration. Any grain protectant (neem products, etc.), top dressing or fumigation will be more effective with clean grain. It is crucial that the grains mass temperature be reduced to 20°C and the moisture is below 9-11% soon after storage. Whenever the grain mass is above 32°C, it should be inspected for insects every two weeks. Samples should be taken from several depths and locations, paying particular attention to the grain mass surface, central core and development of any hot spots.

If grain is expected to remain in storage bins for over 12 months, use of protectants may be considered. These are generally applied to whole grains as they are being augered, loaded, or turned into storage facilities. Application is avoidable before high temperature drying. Sometimes, top dressing with insecticides is recommended instead of treating the entire grain mass. Application should be made as soon as the grain bin is filled and the surface is levelled.

Fumigation is done for stored grain infested with internal feeders (eg, weevils and lesser grain borer). Fumigants are extremely hazardous and should be applied by a professional. Fumigants have no residual activity and grain will become susceptible to reinfestation.

The following precautionary measures minimize crop loss during storage:

Cereals, oilseed and pulses

- Before harvesting, rough out diseased and insect infested plants and weeds
- Properly air dry the harvested crop in a clean and hardy floor before threshing
- Properly sieve the seed and dry it in the sun for about a week
- Put the seed in clean bags to take to the market; if not, store in a clean storage room. Before storing, the walls and floor of the room should be sprayed with Malathion 50 EC (50 ml/l).

Seed

- Dry the harvested crop either on a cement floor or on polythene sheets before threshing
- After threshing, the seed should be further dried for 2-3 days in a shed followed by complete drying in the sun
- Store seed in bags, keep away from the walls of the storage; also keep the bags on sheets of wood
- To disinfect the storage structure, treat it with Malathion 50 EC 2-3 days in advance; after that avoid the use of insecticides. If needed, use bio-control agents such as neem leaves or neem products.
- Keep the area adjoining storage and the house rodent-free by frequent treatment of active burrows nearby with suitable rodenticides such as bromadilion, zinc phosphide, etc.

3.1.4. Technologies related to agroforestry/trees

3.1.4.1 Existing agroforestry systems and their drawbacks

In order to avoid the risk of frequent drought, farmers in western Rajasthan traditionally grow arable crops in conjunction with perennial trees and shrubs. Besides ensuring production even during the worst drought, the traditional agroforestry components provide most of the family's requirement for food, fodder, fuel, timber, etc. The common tree, shrub, crop and grass combinations in the traditional agroforestry systems in different rainfall zones of western Rajasthan are given in Table 8. *Prosopis cineraria* (khejri) and *Ziziphus nummularia* (bordi) are the two most important multipurpose woody components in traditional agroforestry systems of the region (Kar et al. 2009).

However, due to overexploitation and faulty management of perennial components, the existence of these traditional agroforestry systems is threatened. For example, uprooting *Calligonum polygonoides* for firewood, removal of *Z. nummularia* due to tractorization of cultivated lands, almost complete removal of *Tecomella undulata* for furniture and heavy mortality in fully grown trees of *P. cineraria* are the major causes of reduction in the density of these multi-purpose tree species (MPTS) in croplands resulting in reduced productivity and unsustainable livelihoods. Due to mechanization, new seedlings of many of these agroforestry plants are not coming up. Most of these tree species are very slow growing and even after replanting, take a long time to come to production stage; for example, *P. cineraria* requires at least 10 to 15 years to produce leaf twigs (*loong*) and *T. undulata* takes at least 20-30 years to be used in the furniture industry. Trees have been the backbone of the rural economy in Barmer district. Most of the traditional fodder tree and shrub species of the Thar desert are not only slow growing but are of low

Table 8. Common tree, shrub, crop and grass combinations in western Rajasthan.

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

productivity in the early years of growth. Better alternatives which yield faster results (*Hardwickia binata, Ailanthus excels,* etc.) are available on cultivated lands depending on the sub-agroclimatic situation in the Thar desert.

3.1.4.2 Alternative agroforestry systems for sustainability and higher production

Crops alone cannot meet the formidable task of sustaining dryland farming in the arid ecosystem. Therefore, Alternate Land Use System (ALUS) synergistic with arable farming and livestock management has been sought as a farming system mode not only for sustained agricultural productivity but also to rebuild and conserve the natural resource base of the ecosystem. A sustainable farming system must meet the requirements of food, fiber, fodder, fuel and provide income for livelihood, while conserving the natural resource base. The farming system perspective of arid zone agriculture depicted in Figure 7 takes into account various steps required to attain the major goals – poverty alleviation, livelihood security, sustainable natural resource management, economic viability and ecological sustainability – essential for sustainable and holistic development of this fragile ecosystem (Bhati and Joshi 2007).

Agri-silviculture

Trees by virtue of their perennial nature provide stability in production as well as a microclimate and soil fertility. *P. cineraria*, *Holoptelia integrifolia, H. binata, C. mopane, Z. nummularia,* and *T. undulata* are some of the tree species suitable for the agri-silviculture system in this dry region (Muthana and Arora 1977; Shankarnarayan et al. 1987). Harsh (1995) outlined suitable tree and shrub combinations for different rainfall regions of the arid zone (Table 9).

Harsh and Tewari (1993) found that growing trees with crops increases the system's productivity as compared to sole arable cropping of *T. undulata* as the woody component together with various dryland

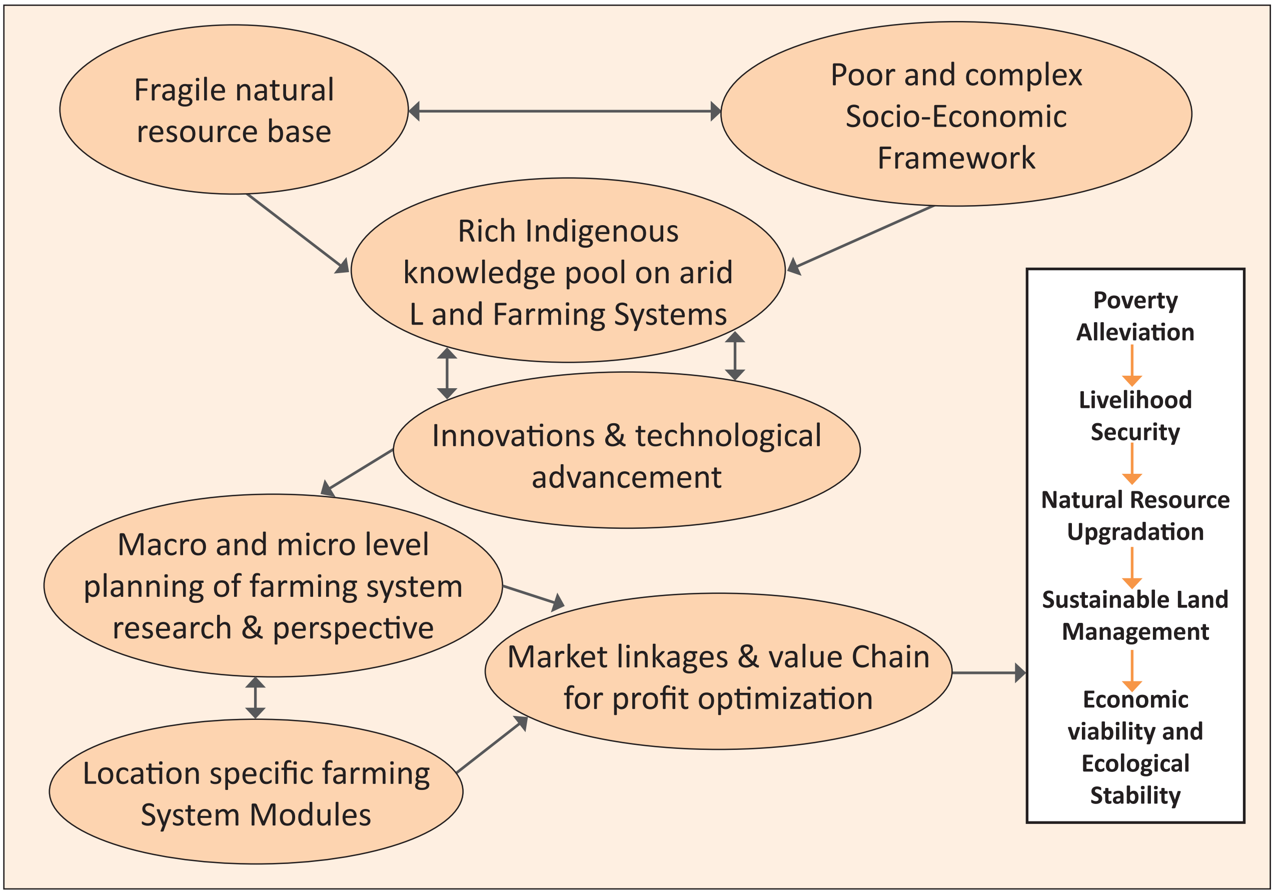


Figure 7. Farming system perspective of arid zone agriculture.

Table 9. Trees species ideal for different rainfall regions.

Rainfall (mm)	Tree/shrub species
< 250	*Ziziphus nummularia, Acacia tortilis, A. senegal, Prosopis cineraria, Calligonum polygonoides, P. juliflora, Tecomella undulata*
250-400	*P. cineraria, Hardwickia binata, Colophospermum mopane, Dichrostachys nutans, Ailanthus excelsa, Acacia catechu, Grewia tenax, Acacia nilotica, Ziziphus* spp.
400-600	*Albizzia amara, A. lebbek, Cassia siamea, Emblica officinials, Hardwickia binata, A. excelsa, Moringa oleifera, Ziziphus* spp.

crops was found promising due to improved soil fertility, microclimate and moisture availability. A tree density of 100-200 plants/ha was found optimum for minimum interference combined with a dryland crop like cluster bean under *P. cineraria* canopy. Cowpea and pearl millet showed better performance with tree species than mung bean and moth bean. Besides a good yield of dryland crops, a bonus yield of leaves and twigs (650-1050 kg/ha) and fuel wood (1.8-2.5 t/ha) could be obtained from *P. cineraria* (Table 10) through annual lopping (Bhati et al. 2008).

Table 10. Yield of various dryland crops grown in combination with *Prosopis cineraria*.						
	Radial distance from tree pole (m)				Produce from *P. cineraria* (kg/ha)	
Crop	**2**	**3**	**4**	**5**	**Dry leaves and twigs**	**Fuel wood**
Mung bean	75	112	125	125	800	2000
Moth bean	16	42	84	113	1050	2500
Cowpea	106	175	156	173	850	2200
Pearl millet	780	1037	1354	1388	650	1800

Table 11. Improvement in microbial population and biomass under different agri-silvi systems.				
	Increase over sole crop (%)			
Silvi component	**Fungi**	**Bacteria**	**Actinomycetes**	**Microbial biomass**
P. cineraria	13-24	21-37	9-18	18-23
T. undulata	18-27	27-39	10-16	19-25
Z. mauritiana	19-39	23-53	23-53	20-77

In the arid region of Gujarat, *Azadirachta indica* and *Ailanthus excelsa*-based agri-silviculture system involving cowpea, green gram, cluster bean and sesame, on an average fetched 59.3% and 25.7% more income respectively than sole cropping. In addition, The adoption of agroforestry system improved soil organic carbon and catered to diverse needs of farmers, such as fodder, fuel wood and timber (Patel et al. 2008). In four years of experiments (2003-2007) in Bikaner, arable crops failed to attain harvest maturity due to paucity of rainfall. Under these conditions, perennial woody components such as *Calligonum polygonoides* and *Acacia jacquemontii* provided fodder and fuelwood. Further, the growth of *Calligonum* is influenced by an associated component, and it attained maximum growth in association with legumes (cluster bean and moth bean) and the least growth in association with grasses (*L. sindicus* and *C. ciliaris*). At Pali, strip cropping of *Lawsonia intermis* consisting of four rows of henna alternated with four rows of cluster bean at 60 cm spacing provided higher returns than their sole planting (Singh et al. 2005).

Proper management of tree and crops is vital for optimizing productivity in the agri-silviculture production system. Harsh (1995) reported that the yield of mung bean was 25% higher under lopped trees compared to unlopped trees. Tarafdar (2008) reported substantial improvement in soil biological activities under agri-silviculture system compared to a sole crop (Table 11).

Agri-pasture

Studies conducted at Jodhpur and Bikaner on agri-pastoral systems, ie, cropping between grass strips laid out against prevalent wind direction revealed that the average yield of cluster bean at Jodhpur was 418 kg/ha under an unprotected plot, which increased up to 503 kg/ha in a protected plot. Thus with strip cropping at least some biomass is produced in low rainfall years besides reducing soil erosion. In good rainfall years, production of arable crops increased along with an increase in forage yield of grasses. At Bikaner, the average yields of cluster bean during normal and low rainfall were 589 kg/ha and 181 kg/ha respectively. Dry forage yield from *Lasirus sindicus* with strip cropping obtained during normal and low rainfall years were 6400 kg/ha and 2650 kg/ha respectively. The practice of strip cropping of legumes and grasses holds promise, increasing grain yields significantly over the control (Singh and Gupta 1997). However, farmers are generally not inclined to adopt the agri-pasture system.

Agri-horticulture

Horticulture-based production systems are an effective strategy for improving productivity, employment opportunities, economic condition and nutritional security in dry regions (Chundawat 1993; Pareek 1999; Chadha 2002, Kumar et al. 2014). Several drought-hardy fruit crops like *Capparis decidua, Salvadora oleoides, Cordia dichotoma, Cordia gharaf, Ziziphus nummularia* var. *rotundifolia, Z. mauritiana,* and *Cordia myxa* are suitable for areas receiving rainfall <300 mm. Besides providing fruit, these plants produce moisture-laden nutritious leaves for animals. Several other fruits such as *Emblica officinialis, Punica granatum, Aegle marmelos*, *Phoenix dactylifera* and *Tamarindus indica* can be grown in areas with irrigation facilities. Among the vegetable crops, *Solanum melongena, Lagnaeria siceraria, Luffa acutangula, Luffa cylindrica, Citrullus lanatus, C. lanatus* var. *fistulosus, Cucumis melo* var*. utillismus, C. melo* var*. momardica, C. callosus, Moringa oleifera, Cymopsis tetragnoloba* and *Vigna* unguiculata are suitable for horticulture-based farming systems (Pareek and Awasthi 2008).CRP

The management practices for horticultural crops have been standardized to optimize productivity. Suitable rootstocks of improved cultivar of ber have been identified. Biofertilizer inoculation of ber (*Ziziphus mauritiana*) seedlings recorded improved growth and nutrient uptake (Meghwal 2006). Seed treatment of *Cordia myxa* seed with gibberellic acid (GA) 250 or 500 ppm was found to improve germination (Meghwal 2007). Seed treatment of karonda (*Carissa carandas*) with GA_3 (Anonymous 2007) and of *Emblica officinialis* with 1% KNO_3 improved germination. In some of indigenous fruit plants, vegetative propagation techniques have been standardized. In Kair (*Capparis decidua*), hardwood cutting helped in better rooting (30-40%) in July-August (Meghwal and Vashishtha 1998). In *Cordia myxa*, budding during July-September gave highest success (Meghwal 2007). Pruning of fruit is very important to attain sustainable yield. With regard to severity of pruning in ber, pruning at 17-23 nodes on the main axis produces vigorous shoot with maximum fruit production. The main axis of the branches should be pruned keeping 15-25 nodes depending on climatic conditions ie, 20-25 nodes in arid areas and 15 nodes in semi-arid areas along with the complete removal of secondary branches (Pareek 2001). In case of Phalsa (*Grewia asiatica*), pruning in the last week of December at 120 cm from ground level was found optimum (Meghwal 2006).

Water harvesting techniques have been developed to augment water availability to fruit plants. Higher runoff yield was obtained from catchments having 5% slopes (Sharma et al. 1983). Circular catchments around each tree (1.5 m radius) with 5% slope towards the tree trunk and covering the catchment with black polyethylene sheet have been found effective to conserve moisture. The application of irrigation water at 1.0 IW: CPE (Irrigation Water: Cumulative Pan Evaporation) ratio at 10 cm depth with 11 to 12 irrigations from June to February was found to be best for pomegranate for higher fruit yield. Drip irrigation resulted in early commercial fruit production in *Ziziphus*, *Punica granatum* and *Emblica* and application of water equal to 60% of pan evaporation registered significantly higher fruit yield compared to 40% pan evaporation (Anon 2007). Beniwal et al. (2006) attempted to schedule irrigation in Kagzi lime under drip irrigation. They found irrigation at 0.7 ETc was better over 1.0 and 0.40 ETc in terms of plant growth and conserving water.

At Pali, the highest yield of mung bean (2700 kg/ha) was observed when grown with lemon plants and of cluster bean (3800 kg/ha) with karonda (*Carissa carandas*). Maximum increment in height was found in pomegranate and the best collar diameter was found in ber. Intercropping of bottlegourd during kharif and pea (arkel) and fenugreek (kasuri methi) with ber did not have any adverse effect on three-year-old ber; it led to the production of 40,900 kg/ha bottlegourd, 8100 kg/ha green leaves of fenugreek and 880 kg seed/ha of gourd peas (Singh and Kumar 1993).

In the arid region, the agri-horticulture system involving *Z. rotundifolia + V. radiata/V. aconitifolia/C. tetragonoloba* and *Z. mauritiana + V. radiata/C. tetragonoloba* have been found to be environmentally friendly and economically viable even during drought years. In a combination involving *Ziziphus* and mung bean during a subnormal year when rainfall was 51% less than the long-term average of 360 mm, the yield of mung bean fell by 44% whereas as a sole crop its yield was reduced by 51%. An inventory of the system showed that it can provide a year-round supply of fodder for five goat/sheep/ha and fuelwood for a family of four, besides being efficient at nutrient cycling and economically more stable (Faroda 1998). Gupta et al. (2000) reported that a three-year-old plantation of *Z. mauritiana* @ 400 plants/ha in association with green gram performed well with seasonal rainfall of 210 mm; fruit yield from intercropping increased net profit to ₹ 288.6/ha. This shows that the agri-horticulture system minimizes risk in arid regions and aids economic stability, and is recommended for regions with <250-300 mm rainfall. Saroj et al. (2003) recommended *C. tetragonoloba – B. juncea* and Indian aloe as the ground storey component in ber to optimize productivity and profitability in the arid ecosystem. Integration of *C. tetragonoloba*, *V. radiata* and sesamum with *Z. mauritiana* (cv. Seb) increased fruit yield three-fold (14.8 kg/tree) compared to a pure orchard (5.2 kg/tree) (Singh 1997). Intercropping in a newly planted ber orchard had no adverse effect on plant growth up to five years. The intercrop exhibited higher yield when planted with ber compared to monoculture under rainfed conditions. A combination of *Ziziphus* + mung bean provided fruit, fue wood and year-round employment even during below average rainfall years (Sharma and Gupta 2001). Intercropping of mung bean in a ber orchard was recommended by Gupta (1992). According to Singh et al. (2003), intercropping of legumes with ber produced higher grain yield of intercrops by 5-20% over their sole cropping, and intercropping is promising particularly during the juvenile period of fruit plantation. Table 12 shows the promising results of an experimental agri-horticulture system conducted at Bikaner (Yadava et al. 2006).

A study on a kinnow-based agri-horticulture system under irrigated arid conditions at Sriganganagar showed that the intercrop had no significant negative effect on fruit yield. The yield was highest under mung bean and lowest under cotton intercropping; fruit yield was at par with intercropping of mung bean, cotton–barley and cotton–chickpea (Bhatnagar et al. 2007). Lal (2008) reported that integration of arable crops (cluster bean, horse gram, mung bean and henna) with pomegranate improved profitability over sole pomegranate on medium soils of Pali. Pomegranate has been found compatible with pearl millet, mung bean, isabgol, sorghum and cumin in Jalore district of Rajasthan (Gupta 2000).

An Indian gooseberry (aonla)-based multi-storey production system initiated at the Central Institute of Arid Horticulture (CIAH), Bikaner, comprising gooseberry–ber–brinjal–moth bean–fenugreek and aonla–bael–karonda–moth bean showed that ground crops did not affect the growth of the over storey crop and vice-versa and these systems have been promising under arid conditions of Rajasthan (Awasthi et al. 2005). The net returns obtained from the ground crop during the first year was ₹ 23,614/ha and ₹ 25,662/ha respectively, which increased by 20% and 15% respectively in the 2nd and 3rd years. This indicates that during the juvenile phase of the fruit tree, there are ample opportunities to raise annual, biennial and perennial crops that can meet diversified needs of farmers. Samadia et al. (2004) proposed suitable horticultural crops for agricultural production systems of the arid region (Table 13).

Table 12. The economics of different agri-horticulture systems at Pugal, Bikaner district.

Agri-horticulture system	Net profit (₹ /ha)	Benefit:Cost Ratio
Ber (*Ziziphus mauritiana*) + moth bean	10,852	2.06
Ber (*Ziziphus mauritiana*) + cluster bean	12,970	2.33
Ber (*Ziziphus mauritiana*) + groundnut	20,379	2.45
Bael (*Aegle marmelos*) + moth bean	14,310	2.86
Bael (*Aegle marmelos*) + cluster bean	16,054	3.02
Bael (*Aegle marmelos*) + groundnut	21,799	2.75
Kinnow (*Citrus nobilis*) + moth bean	11,015	2.20
Kinnow (*Citrus nobilis*) + cluster bean	11,122	2.10
Kinnow (*Citrus nobilis*) + groundnut	19,830	2.50

Table 13. Vegetable crop components for cropping systems in the hot arid region.

Rainfall (mm)	High storey crop	Medium storey crop	Ground storey crop			Micro wind break, bio fence
			Vegetable	Agronomic crop	Grass	
Rainfed (150-300)	Khejri, ber (*Ziziphus mauritiana*)	Ber (*Ziziphus mauritiana*), kair (*Capparis decidua*)	Materra, kachari (*Cucumis melo* var. *agrestis*), snape melon, tumba (*Citrullus colocynthis*)	Guar (*Cyamopsis tetragonoloba*), moth, bajra (*Pennisetum glaucum*), til (*Sesamum indicum*)	*Cenchrus spp., L.sindicus*	Ker (*Capparis decidua*), phog (*Calligonum polygonoides*), khimp (*Leptadenia pyrotechnica*), jharber (*Ziziphus nummularia*)
Rainfed (300-500)	Ber (*Ziziphus mauritiana*), lasora (*Cordia dichotoma*), khejari (*Prosopis cineraria*)	Sehjana (*Moringa oleifera*), Lasora (*Cordia dichotoma*)	Materra, kachari (*Cucumis melo* var. *agrestis*), snape melon, tinda, brinjal, Indian bean, cluster bean, cowpea	Guar (*Cyamopsis tetragonoloba*), moth, bajra (*Pennisetum glaucum*), til (*Sesamum indicum*)	*C. ciliaris, P. antedetala, D.assmulatur*	Ker (*Capparis decidua*), khimp (*Leptadenia pyrotechnica*), jharber (*Ziziphus nummularia*)
Irrigated	Date palm (*Phoenix dactylifera*), ber (*Ziziphus mauritiana*), aonla (*Phyllanthus emblica*)	Lime, guava (*Psidium guajava*), pomegranate	Cucurbits, chilli, tomato, brinjal, cole crops, peas, beans, onion, okra (*Abelmoschus esculentus*) and leafy vegetables	Cumin, isabgol, groundnut, mustard		Lasora (*Cordia dichotoma*), karonda (*Carissa carandas*)

Silvi-pastoral system

Silvi-pasture refers to the combination of pasture grasses/legumes and trees to optimize land productivity, conserve plants, soil and nutrients to produce forage, fuel wood, timber, etc. on a sustainable basis. About 75% of the area in the hot arid region of the country is degraded (Dhurvanarayan 1993). The silvi-pasture system has been found to be a suitable alternative to develop such degraded lands (Rai 2008). Keeping 10-15% of the landholding fallow for 2-3 years is a normal practice among farmers in arid areas. To a certain extent, such areas may be developed as silvi-pasture and then as agroforestry and agri-horti systems. For silvi-pasture development, *A. lebbeck, T. undulata, C. mopane, A. senegal, Z. numularia* and *Z. rotundifolia* are some woody species that are compatible with grass components. Among pasture legumes, *Clitoria ternatia* and *Lablab purpureus* showed good compatibility with *L. sindicus* and *C. ciliaris* in areas receiving >300 mm rainfall (Bhati et al. 1986). Shankar (1980) opined that silvi-pasture provides forage/grazing availability and quality for longer periods of the year and 5-7 times more forage yield compared to natural grazing lands. Shankarnarayan et al. (1987) reported that *Acacia tortilis*-based silvi-pastoral system in arid Rajasthan fetched more returns than sole tree or grass planting.

Integration of *Z. nummularia* with *Cenchrus ciliaris* strips in 1:2 ratio gave higher live weight (33 kg/ha/yr) and wood production (5.65 kg/ha/yr) over sole pasture, thereby giving high returns of ₹ 1326/ha/year from grazing of a mixed flock of sheep and goat (Bhati et al. 1986). Further, silvi-pasture of *Z. rotundifolia* and *C. ciliaris* could sustain 554 Tharparkar cattle days/ha with 60% pasture utilization (Pratap Narain and Bhati 2004).

Silvi-pastoral studies conducted at Bhuj with combinations of trees such as *A. Indica* (neem), *A. nilotica* (Desi babool) and *Leucaena lucocephola* (subabul) and grasses (*C. ciliaris* and *C. setigerus)* showed that the neem + grass combination was the most productive for the Kutch region in term of both grass yield and tree growth. Among the grasses, *C. ciliaris* was found to be superior to *C. setigerus* in terms of fodder production. The total number of tillers per grass plant and dry fodder yield of grass did not differ significantly due to the association of trees with grasses in a silvi-pasture system (Devi Dayal et al. 2008).

Horti-pastoral system

This involves growing fruit crops and grasses together as per species' suitability and is recommended in shallow to medium deep soils (Singh and Osman 1995). Horti-pastoral studies on sandy rangelands of Rajasthan revealed that *C. ciliaris – Z. mauritiana* system produced 1.2 t/ha forage yields and did not affect fruit yield (Sharma and Diwakar 1989). A long-term study conducted on sandy rangelands at Samadari (in Pali) revealed that planting *Z. rotundifolia* @280 plants/ha, 140 plants/ha and 170 plants/ha with *C. ciliaris* produced 624-824 kg/ha forage yield and that it is safe to maintain a plant density of 280 plants/ha (Sharma and Vashishta 1985). Under semi-arid conditions of Jhansi, introduction of pasture did not show adverse effect on growth parameters of orchards during the establishment phase up to five years and produced 3-7 t dry matter/ha forage in the initial three years (Sunil Kumar et al. 2002). Under arid ecosystems in Rajasthan, the horti-pastoral system was more profitable than arable cropping. The horti-pasture comprising ber and *C. ciliaris* was highly economically viable on the basis of B:C ratio, net present worth and annuity value at 10% rate of interest (Gajja et al. 1999).

3.1.4.3 Major constraints to adoption of agroforestry systems

Several constraints impede the implementation of agroforestry systems in arid regions. Apart from climatic constraints, uncontrolled and free grazing after harvest of kharif is a major handicap. Further, the considerable time lag between investment and return is also a reason for farmer apathy towards these systems. Lack of coordination among agricultural and rural development agencies coupled with lack of orientation of research and development professionals about integrated farming systems (IFS) is another limitation.

3.1.5. Technologies related to livestock husbandry

The hot arid zone of Rajasthan has a livestock population of more than 28 million, which is about 50% of the state's total population. Of the total, the arid region lays claim to 40% cattle, 30% buffaloes, 70% sheep, 54% goats and 82% camel. The breeds of cows, buffaloes and goats in this region have better adaptability, which reflects in their better average milk yield per head of 4.13, 5.60 and 0.87 liter/day respectively, compared to the overall average productivity of 3.53, 5.25 and 0.68 liter/day respectively in the state. Wool productivity from sheep in the arid region was found to be better (1.79 kg/head/year) than the overall state average of 1.6 kg/head/year (Livestock Census 2003).

Though livestock has great potential in arid areas, some of the major contraints to improving livestock productivity in this region are limited fodder resources, traditional subsistence-oriented rearing systems, difficulty in implementation of a breeding policy, poor breed health and pest management.

3.1.5.1 Major livestock type and their management practices

(a) Large ruminants-based production system

The arid region is the home tract of Tharparkar, Kankrej and Rathi breed of cattle recognized for their milk production and efficiency. The Nagauri bullocks are well known draught animals. Murrah, Mehsana, Jaffarabadi and Surti breeds of buffalo are reared in the arid areas. Marwari and Kathiawari horses of the region are among the best race horses of the country. Bikaneri and Jaisalmeri camel breeds are known the world over for their resilience under drought situations. Sirohi is one of the best dual-purpose goat breeds available.

The Tharparkar breed of cattle once common in Jaisalmer, Jodhpur and Barmer is a good milker (2500 litres per lactation) and is adapted to harsh climatic conditions. However, the Tharparkar pure breed is now rare, even in its native districts (Mathur et al. 1991). The heat tolerance co-efficient value (88.88±1.92) of free grazing animals of this breed was equal to those of the Rathi breed (89.87±2.51).

Rathi cattle are a milch breed native to Bikaner district. Brown in color and large, these animals are traditionally reared in Bikaner, Ganganagar and Hanumangarh districts by the Rathis, a local tribe in the region. The cows are good milkers and have a standard lactation yield of 2500 liters. The heifers mature on average at three years and attain a weight between 208 kg and 302 kg (Kaushish et al. 1998). The lactating cows have pendulous udders which make them prone to physical injuries. The animals have also been observed to suffer from the pre- and postpartum uterine prolapse and resultant secondary uterine infections. Rearing these animals on the ranges is a concern for farmers of Bikaner district as most ranges are severely degraded in edible biomass and feeding in intensive systems is not cost effective.

The Kankrej breed of cattle native to Banaskantha district of Gujarat is widely prevalent in Barmer and Jalore districts of western Rajasthan. Cows of this breed have a milk production capacity of 1500-2500 litres per lactation and bullocks are excellent draught animals. The well managed heifers can mature at an average age of two years with first calving at about three years. The reproductive performance in terms of calving interval and service period were an optimum 12-12.5 months and 65-68 days, respectively. The cows have a standard lactation yield of 2200 litres (Gujar 1989).

The buffalo breeds common in western Rajasthan are Murrah and Mehsana, which are preferred in the northern and southern parts of the desert, respectively. These animals yield on average 3000 litres of milk in a lactation period of 305 days. The buffaloes like to wallow in water, but have adapted to the hot arid climate very well. The Banni breed of buffalo in Gujarat produces about 2500 litres of milk with high fat content.

The camel population in India is mainly confined to the north-western states of Rajasthan, Gujarat, Haryana and Punjab, which account for 93.12% of the total population, with the highest density (70.13%) being in the arid districts of Rajasthan. The camel breeds in these regions are Bikaneri and Jaisalmeri which are particularly hardy breeds. For instance, camels in the central desert of Australia with a daily temperature of 40°C are reported to have died without water in four days while camels survive for more than 15 days in the same environment in Rajasthan. Camels are able to sustain up to 20-22% of body weight loss during severe famine conditions whereas other livestock like cattle and buffalo cannot sustain beyond 10-12% loss in body weight. The camel population in India has declined from 1.03 million to 0.63 million within a decade due to swift mechanization, increased irrigation and shrinking grazing/browsing land. However in future the camels will remain very important for farming and livehood systems in certain areas of western Rajasthan and Kachh region of Gujarat.

(b) Small ruminant-based production system

Sheep: The arid regions have a sizeable population of sheep. The important breeds in the desert region are Chokla, Magra, Marwari, Nali, Pugal and Jaisalmeri, with yearly wool production potential of 1.54 kg, 1.80 kg, 1.38 kg, 2.12 kg, 1.67 kg and 1.65 kg, respectively. Marwari is one of the most popular breeds in the arid region. Unorganized markets for the sale of wool and meat coupled with poor quality pastures are the major constraints in the sheep industry in the region.

Goats: The important goat breeds of arid Rajasthan are Marwari, Jhakrana and Sirohi. Mehsana and Kachchhi breeds are found in the arid regions of Gujarat. The goats are primarily raised for meat. The Sirohi and Jhakrana breeds are known for good milk and meat production. The Marwari doe on an average yields 84 litres of milk in 180 days lactation, whereas the Sirohi doe may yield up to 132 litres in 170 days lactation. The Marwari goat is extremely well adapted to the arid environment. However, due to lack of proper nutrition, its genetic potential is not expressed to the maximum (Mathur et al. 1999a). It grows and breeds faster, can tolerate higher salt loads, needs less water and survives on a wider variety of feeds including many weeds, as compared to sheep. Studies on productivity and adaptability of various breeds such as Marwari, Sirohi, Jhakrana, Kutchhi, Barbari and Jamunapari under desert conditions showed that they were non-seasonal in their reproductive behavior (Mathur and Mittal 1990). A deep-rooted bias against the goat may not be wholly justified on scientific grounds and its proper place in the agro-system of the desert needs to be redefined, particularly in view of its potential to meet the protein gap in the country.

3.1.5.2 Technologies related to improved livestock husbandry

(a) Feed resources for arid livestock

Arid regions have many feed resources in the form of agricultural produce, weeds, by-products from agro-processing methods, etc. Tumba (*Citrullus colocynthis*) seed cake, a by-product of the oil extraction industry, is nutritionally rich as it contains 16-22% crude protein. Inclusion of 25% tumba seed cake (TSC) in concentrate feed lowers the cost of animal feeding by 18-35% without any adverse effect on production, general health and reproductive performance (Mathur et al. 1989; Mathur 1996). Salty shrub lani (*Salsola baryosma*) at vegetative stage can be a good source of fodder for animals. The acceptability and palatability of fresh cut shoots showed that lani is palatable (Mathur et al. 2007). Lana (*Haloxylon salicornicum*) seeds having 18.60% crude protein could replace about 25% of the conventional oilseed cakes in concentrates for lactating cows (Anonymous 2007). Up to 35% of the powder of *P. juliflora* pods can be used in the concentrate of lactating goats without any detrimental effect on their health (Mathur et al. 2003). Similarly, up to 50% *P. juliflora* pod husk can be used in the concentrate along with *C. colocynthis* seed cake as low-cost ration for sheep without any adverse effect on animal health (Mathur et al. 2002).

Fresh leaves of *Hardwickia binata* are palatable to goats and sole feeding supports body weight growth in growing kids (Patil et al. 2009). Feeding fresh leaves of *Colophospermum mopane* is not possible for goats but it can comprise 35-40% of the whole ration (Patil et al. 2009). The palatability of dry *C. mopane* leaves was low and decreased from 15% to 5% with progressive feeding from the 1^{st} to the 5^{th} week. Traditional local *P. cineraria* leaves were a better source of supplement even in the dry form, supporting the milk yield of goats.

The weeds in the rocky and sandy habitat of arid regions have a distinct relative preference index for grazing sheep and goats. Studying their preference for weeds, Patil et al. (2005) found it to be in this order: kanti (*Tribulus terristris*), kagio (*Tetrapogon tenellus*), santo (*Trianthema protulacastrum*), lolaru (*Digeria muricata*), bekar (*Indigofera cordifolia*) and gangan (*Grewia tanax*).

Top feeds contribute about 60% of the total feed requirement of small ruminants in dry areas. Traditionally in dry arid areas, these are heavily lopped, and mostly used to feed grazing small ruminants. *P. cineraria* is extensively lopped in winter. A moderate-sized mature tree of the species yields about 15 kg of leaf forage locally known as loong. *Z. numularia* locally known as *bordi* is also heavily lopped in winter for its leaf fodder known as *pala*. Studies at Pali and Jodhpur have shown that the species growing at a medium density of 14% is optimum in natural grazing lands for maximum fodder production, which may yield about 125 kg of *pala*/ha. Some suitable top feed species need to be introduced in common grazing lands of this tract to enhance fodder availability, especially for goats and camels. Trees can be planted along boundaries, inspection paths and approach roads to serve the dual role of windbreaks and source of fodder. A good pasture may have 30-35 such trees per hectare. The important top-feed-cum-shade trees for pasture and rangelands are *A. nilotica*, *P. cineraria*, *S. oleoides*, *A. senegal*, *A. lebbeck*, *A. rotundifolia*, *A. pendula*, *A. indica*, *G. tenax*, *G. spinosa*, *T. undulata* and *H. binata*. Shrubs such as *Z. nummularia*, *C. polygonoides*, *H. salicornicum*, *C. decidua* and *A. jacquemontii* are also relished by goats, camels and other livestocks.

Although desert top feeds *P. cineraria* and *Z. nummularia* leaves have appreciable quantities of crude protein, their DCP value is very low because of tannins and lignin (Bohra et al. 1999), which reduces palatability and hinders absorption of dietary proteins by the animals. This is indicated by an *in situ* degradability study of *P. cineraria* leaves in sheep rumen (Mathur et al. 1998). Attempts have been made to improve the nutritive value of *Z. nummularia* leaves by treating them with diluted formaldehyde (Ghosh et al. 1971) and *P. cineraria* leaves with ferric chloride. Soaking leaves overnight in a 0.5N aqueous sodium carbonate solution, followed by washing with water proved to be the best method for detanning *P. cineraria* leaves. The process removes about 94% tannins in these leaves (Bohra and Goyal 1986). *A. tortilis* pods contain 5.7% DCP and 62% TDN and *P. juliflora* pods contain 7% DCP and 75% TDN (Mathur and Bohra 1993). These pods contain appreciable quantities of micro-minerals too.

(b) Supplementary feed blocks

Livestock in arid regions are mostly range managed except during monsoons when dry grasses are available in the ranges and pastureland, and crop residues are available in the fallow lands. In general, therefore, the animals suffer from deficiency of essential nutrients including fermentable energy, protein, minerals as well as carotene. Several nutritional deficiencies have been identified in animals of the arid zone. Deficiency of vitamins A, D, B1, calcium, phosphorus, zinc and iron are registering an upward trend, with increasing reproductive disorders, particularly anoestrus (Mathur et al. 2001). There are different means to supplement essential nutrients in livestock. Appropriate formulations of multi-nutrient feed blocks (MNB) using locally available feed resources, wheat bran, guar korma, bajra husk, ardu leaves, *P. juliflora* ground pods, sugarcane molasses, urea, vitaminized mineral mixture, dolomite, common salt, and deoiled soyabean meal have been developed and locally available guar gum powder is used as binder.

During a 16-week feeding trial, sheep that were given MNB supplements recorded 3.6% gain over sheep maintained on roughage diets. In a digestibility trial study on Rathi cows, the digestibility coefficient for dry matter (DM) and crude protein were found better (Mondal and Bohra 2001). Supplementary feed blocks were found to improve the production performance of lactating animals, especially cows, buffaloes and goats. Farmers also reported improvement in the condition of Pica in animals suffering from mineral deficiency along with an increase in feed and water intake. In the case of cattle and buffaloes, a 2-kg block offered as a lick lasted for about seven and five days, respectively (Patel et al. 1998).

Supplementary multi-nutrient mixture

For small grazing ruminants that do not lick these blocks, supplementary multi-nutrient mixture formulations were developed using the same ingredients. Feeding these mixtures to goats and sheep after grazing hours was found to improve body weight and milk yield appreciably (Rohilla et al. 2009).

Complete feeds and/or fodder banks for arid livestock

To improve livestock productivity, Total Mixed Ration (TMR) or Complete Feed Block (CFB) has been developed. In an evaluation trial, lactating Tharparkar cows that were fed TMR prepared out of local fodder *C. ciliaris* and concentrates available in the area were found to produce milk more economically compared to cows fed on local grasses and supplemented with pelleted cattle feed (Mathur et al. 2006). In another study, lambs fed intensively on 50:50 RC (a feed brand) based complete feed attained 33.5 kg finishing weight with 11% feed efficiency at six months of age (Shinde et al. 1995). In a study conducted on Marwari kids, Patil et al. (2006) observed that the kids weaned at two months had comparatively better growth rate than the kids weaned at three and four months when they were fed on complete feed diets with a roughage to concentrate ratio of 30:70. The feed contained khejri leaves and masoor straw in equal proportion as a roughage source and local material in the concentrate mix. The cost of feeding was economical for kids reared on CFB after weaning at two months (₹ 65.37/kg) as compared to those weaned at three months (₹ 70.40/kg) and at four months (₹ 71.27/kg).

Complete feeds are appropriate for livestock in arid regions which see frequent droughts. In such situations, planning in advance to ensure sufficient stock of complete feeds as feed banks, which can be mobilized to places of deficiency, is essential.

Stress management in arid livestock

High air temperatures of up to 45-47°C during summer, low relative humidity of 12-18%, high wind velocity of 13-14 km/h, scanty and erratic precipitation and a high rate of evaporation and soil salinity lead to high stress conditions that result in poor productivity of livestock. Such extremes in environmental conditions have enormous effects on the physiology and productivity of farm animals (Singh and Upadhyay 2009). Studies indicate that providing proper shelter improved livestock performance through moderation of environmental factors (Singh et al. 2003 and Patel et al. 2007). The animals need to be protected from direct solar radiation during the hottest hours of the day to ameliorate the effect of heat stress (Shinde et al. 2002).

Health disorders in arid livestock and preventive measures

Epidemiological studies indicate the prevalence of diseases like foot and mouth disease (FMD), peste des petits ruminants (PPR), ephemeral fever, sheep and goat pox, tuberculosis, Johne's disease, botulism, enterotoxaemia, mycoplasmal infections, blood protozoa, coccidiosis, brucellosis, haemorrhagic septicaemia, black quarter and anthrax among livestock in arid regions. High incidence of subclinical mastitis has also been reported from this area (Singh et al. 1999). With increased availability of water for irrigation and the prevalent animal husbandry practice being either migratory or of intensive type, it leads to unreported types of parasitism in animals. There is need for effective prophylactic coverage of livestock through ongoing government programmes and developing the capacity of rural youth as livestock service providers. Cyanide, sodium chloride and nitrite poisoning have been reported in this zone since long (Sharma and Gahlot 1997). Newer toxicities include those from pesticides/farm chemicals, feed additives, drugs, environmental pollutants, etc. (Radostits et al. 1994); hence the need to create awareness in farmers of the treatment required for these.

4. Summary

It is envisaged that this report will not only help enhance the productivity and resilience of dryland production and livelihood systems of western Rajasthan, but will be also be useful in other parts of the world with similar agro-climatic and socio-economic conditions.

The summary of the report is as follows:

- Western Rajasthan covers 61% of the total hot arid zone of India (31.7 m ha). Increasing biotic and abiotic stresses are threatening this fragile arid ecosystem leading to desertification and degradation of the natural resource base.
- The action sites cover about 8 m ha with a population of 6.9 m humans and 10.4 m livestock. The districts represent the lowest states of natural resource base and livelihood opportunities in India.
- The major production systems prevalent in the action sites vary as per the rainfall gradient: range management/community grazing land-based livestock farming (ie, Jaisalmer with rainfall <200 mm); agri-silvi-pastoral-based livestock farming (eg, Barmer with 200-300 mm rainfall) and crop–livestock–tree-based farming (eg, Jodhpur with 300-400 mm rainfall). Runoff farming (*khadins*) in depressions and irrigated agriculture through surface (IGNP) and groundwater resources also exist in the area.
- The major crops grown in the action sites are pearl millet and arid legumes (moth bean, mung bean and cluster bean) in kharif and wheat, chickpea, mustard, cumin and isabgol in rabi. However, under irrigated conditions, the area under groundnut, castor, cotton, green fodder, lucerne, sorghum and pearl millet and vegetables is increasing. The drivers of intensification/diversification of cropping system are rainfall, land use changes, surface and groundwater irrigation, landholding, livestock dynamics, labor availability, market demand, etc.
- While human and livestock population have increased by about three and two times respectively, in the last 40 years, the productivity of grazing lands has remained almost static at 0.4-0.5 t/ha. The small ruminant population comprises about 70% of the total livestock population and largely depends on these lands. Similarly, the contribution of cattle and buffalo in livestock population is about 27.4%, with buffalo population having trebled in the last decade. However, there is an acute scarcity of feed and fodder, which can be vastly overcome with the spread of improved crop and livestock management technologies.

- Participatory Rural Appraisal (PRA) analysis revealed that the villages selected as action villages for CRP on Dryland Systems were truly representative of prevalent dryland production and livelihood systems of western Rajasthan. Govindpura and Dhok represent arid-micro watersheds, Dhirasar is an index catchment, and Damodara and Dedha represent runoff farming systems (*khadins*). Irrigated agriculture through groundwater use is largely represented by Mansagar and Didhu, while agricultural land in Sankaria is irrigated through canals (IGNP). The livestock with agro/agro-pastoral/pasture and range management was an integral part of the farming systems across all the action villages. However the mix of livestock species were influenced by rainfall levels, land use pattern and farmer/community preferences. Hence there is a need to undertake research in farmers'/community participatory mode by taking the watershed/ index catchments/*khadin*/village as a unit of development.
- Arid Rajasthan is beset with scarcity of fodder, animal losses due to pest and diseases and breed degeneration, shortage of drinking water and human malnutrition. The lack of knowledge on improved agriculture and animal husbandry technologies leading to low productivity, lack of education, and shortage of agricultural labor are other characteristics. Considering these problems, priority technologies that were identified in the targeted villages are given in Annexure I.
- Majority of the farmers still grow local landraces/old varieties of dryland crops which are of long-duration, susceptible to insect-pests and diseases and of low yield potential compared to available improved varieties. However, the old landraces/old varieties have higher fodder production potential than improved cultivars, which may be one of the reasons for their continued used.
- Prevailing land preparation and sowing techniques of dryland crops are highly inadequate due to lack of knowledge and nonavailability of proper preparatory tillage and sowing devices. There is an urgent need to improve this situation by opening farm machinery custom hiring centers at the village level. Traditional mixed cropping systems must be replaced by/modified with improved cropping systems such as intercropping, strip cropping, crops and varietal diversification, cropping system intensification and ALUS chosen on the basis of agro-ecological situations (AES I, II, III) and farmers' preferences.
- Preparatory tillage as single/cross harrowing and planking is important in this tract to achieve proper crop stand and weed management. Deep tillage with disc plough/MB plough once in two/four years (as per AES) is conducive to soil moisture conservation, nutrient availability and control of weeds, specially perennial weeds like nutsedge, bermuda grass, *Areva* spp., and *Haloxylon* spp.
- Crust formation on soil surface is a serious problem in the arid zone. Applying FYM @ 5 to 10 t/ha on seed furrow, ridge-furrow system of planting laid out in the north-south direction or 25° diversion either to the west or east, mechanical breaking of crust, mixed sowing of pearl millet and arid legumes, mulching and light irrigation are some of the measures to control crust formation.
- The positive impact of wider spacing between plants is perceptible. Therefore, for most of the arable crops a row x row spacing of 45 to 60 cm is recommended. The plant-to-plant spacing may be decided as per the morphophysiological behavior of the individual crop and variety.
- Thinning of extra plants is a labor intensive and costly proposition and should be avoided. Therefore, use of proper seed rate and sowing devices (seed-cum-fertilizer drill for pearl millet and planter for arid legumes) are of paramount importance. Seed rate varying from 3-to 4.00 kg/ha for pearl millet and 12-15 kg/ha for arid legumes is recommended depending on the agro-ecological situation, quantum and time of onset of monsoon, varietal character, etc.
- Despite very poor soil fertility, fertilizer use is very low and irrational. To obtain optimum agricultural productivity levels without soil degradation, adopting integrated nutrient management approaches using both inorganic and organic sources of nutrients is imperative.
- To obtain a good harvest of pearl millet and arid legumes in their kharif-to-kharif cropping sequence, application of 40 kg N/ha to pearl millet in two doses (half as basal and half as top dressing 30-40 DAS) and 30-40 kg P_2O_5/ha in arid legumes as basal application (placement at 7-10 cm soil depth) supplemented with 10-20 kg N/ha as starter dose has been recommended for drylands of this tract.

Further, half the dose of nitrogen to pearl millet should be given through organic manure, ie, FYM/ compost at the time of sowing. The efficiency of applied fertilizers can be further enhanced by inoculation of seeds with suitable microbial inoculants like *Rhizobium*, PSB, Azotobacter, VAM, etc.

- In certain pockets, particularly in Jodhpur district (Osian and Mandore tehsils), kharif legumes have responded to sulphur and zinc. Application of 20-40 kg S/ha and 5 kg Zn as $ZnSO_4$/ha (foliar spray) have enhanced yield (by 20-30%) and seed quality (test weight, texture etc.). However, soil test-based application of fertilizers is recommended.
- In a runoff farming system *(khadin)*, response to applied N and P is more conspicuous due to the high moisture content. Rabi crops such as wheat and mustard grown on conserved moisture responded up to 60 kg N/ha and 40 kg P_2O_5/ha while chickpea's response to P application was up to 40 kg P_2O_5/ha. However, the application of nitrogen should be partially met from organic manure like FYM or small ruminant manure (5 to 10 t/ha) for better moisture conservation and to maintain the soil's physico-chemical composition.
- In irrigated crops such as cotton, groundnut, castor, vegetables and fruit trees, forages like lucerne and oats and rabi crops like wheat, mustard, cumin, and isabgol, and integrated nutrient management (INM) schedule should essentially be used with proper irrigation management and agro-techniques.
- For soil and moisture conservation, improving the effectiveness of contour bunds (1 to 6% slopes) of 0.30-0.60 m height placed in a series from ridge to valley are recommended. Contour bunding of 75 cm height at 80 cm vertical interval (VI) combined with contour furrows of 10-15 cm depth at 100-125 cm VI were effective to conserve soil and runoff water in pasture lands representing medium soils.
- In partial modification of contour bunds, contour vegetative barriers (CVB) erected from local grasses such as *C. jwarancura* and *C. ciliaris* planted on contours at 30 cm spacing in alternate row of each grass either at 0.6 to 1.0 m VI or 30 m apart depending on land topography, are useful in controlling soil and water erosion in cultivated fields, resulting in markedly higher crop yields. The barriers are easy to raise, less expensive and provide fodder during lean periods, and are therefore adopted better.
- The soil's physico-chemical composition and moisture availability can be improved by application of pond sediment (70-80 t/ha). Similarly, depending on the need, amendments like gypsum, bentonite, compost, and non-edible seed cakes (neem cakes, castor cake) can also be utilized to ameliorate soil physico-chemical composition and moisture availability.
- Rainwater harvesting and its effective use are crucial for humans, agriculture and animal husbandry in the region. Both existing water bodies and other potential untreated sites need the immediate attention of government and community. On farmlands, surface water storage can be improved by constructing/improving farm ponds, *tankas*, *diggi* (water harvesting structures made in canal irrigated areas for irrigation purpose), *khadins,* etc. However, judicious use of water should be made through its scientific management for higher water productivity.
- Proper harvesting and threshing implements specifically for small and marginal farmers are lacking; tools developed by various research institutes still need to be fine-tuned in farmers' participatory research mode for acceptability in this region. Further, the farmers do not have concrete floors for threshing, which causes heavy losses of produce. It is estimated that 20-30% of the produce gets damaged due to harvest and postharvest losses in arid Rajasthan. To prevent postharvest losses of grain, besides proper storage structures, Integrated Pest Management (IPM) practices like sanitation, empty bin treatment, grain cleaning and storage, use of grain protectants and top dressing, grain monitoring and fumigation should also be adopted.
- Traditional agroforestry systems are now threatened due to mechanization of agriculture, faulty management of system components, population pressure, indiscriminate and overgrazing of animals, etc. To achieve system sustainability, various ALUS such as agri-silviculture, agri-pasture, agri-horticulture, silvi-pasture, horti-pasture etc. have been developed and recommended for different agro-climatic zones of western Rajasthan. Agroforestry systems have very poor adoption by farmers

and there is a need to fine-tune them from the farmers' perspective. Important perennial plant species identified suitable for ALUS under varying agro-climatic and micro-farming situations of this tract are *P. cineraria, H. integrifolia, H. binata,* and *T. undulata* for agri-silviculture; *P. cineraria, C. mopane, Z. nummularia, Z. rotundifolia, A. tortilis, A. lebbeck, C. ciliaris, C. setigerus, L. sindicus,* and *C. ternatia* for silvi-pasture; *Z. mauritiana, C. decidua, C. dichotoma, C. gharaf,* and *S. oleoides* under drylands; and *E. officinialis, P. granatum, Aegle marmelos,* and *P. dactylifera* for irrigated agro-horticulture. However, to get higher returns they need to be managed scientifically.

- Livestock husbandry is the backbone of arid Rajasthan's economy. Except in Hanumangarh and Sriganganagar, in all the other ten districts, the small ruminant production system accounts for 55-77.5% of total livestock population. But due to constraints like acute fodder scarcity, traditional subsistence-oriented rearing, breed degeneration and poor health and parasite management, production levels are far below the optimum.
- This region is home to many unique cattle breeds such as Tharparkar, Kankrej, Nagauri, and Rathi; sheep breeds like Marwari, Pugal, Jaisalmeri; goat breeds like Marwari and Sirohi; and camel breeds like Bikaner and Jaisalmeri which are not only potential producers but are also well adapted to the fragility of the arid ecosystem. Maintaining their breed purity is crucial for the future of livestock husbandry in India and other countries.
- Deficiency of essential nutrients is very common in livestock in this region. Multi nutrient blocks and multi-nutrient mixtures developed from indigenous feed resources need to be popularized.
- Complete feed block developed by research institutes from indigenous material are of immense importance for livestock growers of this region, particularly for feeding in the lean period (April to June) and also in drought years.
- Traditional shelters for livestock are not very efficient; therefore the improved structures need to be assessed and refined through farmers' participatory research for scaling up in the region.
- The burning issues that call for urgent attention through policy interventions are the alarming depletion in groundwater, very poor storage of rain water and its faulty management, poor drinking water and sanitation facilities, unplanned industrialization leading to pollution of streams, groundwater and agricultural land and poor drought management strategies.
- To improve marketing facilities in arid Rajasthan, there is need to improve private investments in infrastructure development, for which the Smallholder Agricultural Productivity and Market Access Program (SAPMA) needs amendments. Also required are the timely declaration of Minimum Support Price (MSP) for commodities specific to west Rajasthan such as guar, cumin, moth bean etc.; the effective implementation of price support policy, formulation of Market Intervention Scheme (MIS) for arid areas, strengthening research on agriculture marketing system, special commodity parks/zones pertaining to endemic high value products like *sangria, kair, nagauri methi* etc; capacity building of arid zone communities/farmers in PHT, group marketing, packaging, quality control, emphasis on technology dissemination and institutional arrangements for their proper marketing, improved communication network and the development of online marketing facilities for agricultural and livestock producers.
- Although, the extension delivery system to farmers is reasonably strong in Rajasthan, bottlenecks like inadequate staff, lack of funds, improper capacity building, poor linkages and unsatisfactory dissemination of technology to farmers are prevalent. Further, the role of Non-Governmental Organizations (NGOs) and pachayati raj institutions needs to be improved for better community participation.
- In western Rajasthan, policy related issues such as the management of common property resources, harnessing of sources of renewable and non-renewable energy, land degradation and wasteland management, wind and water erosion hazards, small ruminant production systems and biodiversity conservation have to be addressed more prudently and systematically to ensure the very existence of dryland production systems and livelihoods which are already under stress.

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6. Annexure I

Priority technologies by village in the CGIAR Research Program on Dryland Systems project*

Village with characteristic features	Village-specific technological interventions
Jodhpur district **Govindpura** Of the total geographical area (1280 ha), about 60% area is cultivated. Dryland agriculture is the mainstay of farmers in this village. Cattle are the main livestock (35%) and the area available as pastureland is about 400 ha. The buffalo population is fast increasing and presently 50 buffaloes are reared by farmers. The farmers live in hamlets and there is scope to introduce integrated farming systems in the village. Further, the village is geographically a watershed, which after treatment has high potential to enhance productivity and employment opportunities.	• Improved varieties of kharif crops in cropping system perspective. • Rainwater harvesting by constructing improved farm ponds/tanka with IFS. • Improved hand-operated weeding and hoeing tools and harvesting sickles. • Production of gum arabic from *A. senegal* (there are about 1500 fully grown trees in the village). • Alternate land use systems viz. agroforestry with *H. binata*, agri-horticulture with ber, agri-pasture with *C. cilaris* and *L. sindicus*. • Integrated watershed development in community participatory mode: stabilization of banks of *nala*, WHS to reduce the flow rate of rainwater, gully control measures, silvi-pasture development, field bunding, farm pond. • Integrated Nutrient Management introduced into the farming system. • Livestock: Fodder augmentation through CPRs, breed upgrading and prophylaxis. • Value addition to kair, sangri, *A. senegal* etc, as there is a market for these in Osian.
Mansagar Mansagar is adjacent to Govindpura and is separated by a stream (*nala*) originating from the hilly dune area in Govindpura. The village has flat lands with very good groundwater potential. The livestock population is very high (5243) with large parts comprising cattle (1442) and buffalo (372), depending solely on farmlands. However, there is acute shortage of fodder, especially green fodder. Also, water erosion in the fields adjacent to the nala is a big problem.	• Fruit and vegetable cultivation through micro-irrigation systems like drip and sprinkler irrigation. • Production of cultivated fodder crops like oat, lucerne, napier, sorghum chari, etc., coupled with dairy farming. • Integrated nutrient and pest management in irrigated and nonirrigated crop production systems. • Establishment of compost and vermicompost units at selected sites. • Use of solar energy-based appliances like animal feed cooker, solar dryer, and cool chambers (for vegetable preservation), etc.

Continued

Annexure 1. Continued

Village with characteristic features	Village-specific technological interventions
Barmer district **Dhirasar** This is a typical index catchment with the whole area under dryland agriculture. Most farmers practice agriculture and live in hamlets. The village has a very high population of sheep and goats (90%) largely owned by small and marginal farmers who represent 70% of the total households. Female dominated households are high in number. Dune complexes interspersed with interdunal lowlands in saucer shape is the topography of the land. The dunes are partially stabilized with *A. Senegal, T. unduluta* and other desert plant species.	• Sand dune stabilization and pasture development. • Farm forestry to control wind erosion on farmlands. • Improved roof water harvesting coupled with improved drinking water ponds/ tanka. • Renovation of farm ponds (207) and constructions of new ones coupled with agro-horticulture system with ber. • Agroforestry systems like agri-pasture, agri-silviculture, etc. • Strengthening deadwood and live hedge fencing, vegetative barriers, etc., to check wind and water erosion from cultivated lands. • Revival of agri-based industries like leather shoes, rope and carpet making, etc., and new industries from *Salvadora oleoides* and *A. senegal* products. • Proper crops and cropping system diversification with focus on high value crops like cluster bean and watermelon. • Introduction of animal-drawn improved farm machinery as the cultivation on dunes in the village is still done with donkeys. • Interventions related to livestock feed, fodder and health management are essential to meet the cash and nutritional need of the farmers.
Dhok The village is mostly nonirrigated except for 10 households with irrigation facilities. Most of households (386) live in the village, and cultivate land only in the kharif season. The main crops in kharif are pearl millet, mung bean, moth bean, sesame and watermelon; and in rabi cumin, castor, isabgol, and mustard. More than 60% of the total land area (5063 ha) is uncultivated and is mostly under woodlands devoted to a local deity. The main problems farmers are encountering are water erosion, damage to crops due to insect-pests, diseases and frost. There is a mixed population of livestock (9813) with cattle (1760) and camel (110) being substantial.	• Control of water erosion through watershed development approach. • Introduction of efficient irrigation systems such as drip and sprinklers backed by the cultivation of vegetables and fruit trees like ber, gonda, pomegranate, cucurbits, cauliflower, etc. • Development of scarred lands as a bio-diversity conservation site for development of eco-tourism. • Interventions related to improved crop production and livestock husbandry, especially with respect to camel and cattle. • Revival of old livelihood opportunities like carpet, bedsheet and blanket making, sale of dairy products, etc.

Continued

Annexure 1. Continued

Village with characteristic features	Village-specific technological interventions
Jaisalmer District **Dedha** The village is totally rainfed with 107 farm families. *Navoda khadin* in Dedha is 15-20 years old and is adjacent to *Bujju khadin,* one of the oldest (700-800 years old) *khadins* of Jaisalmer district. This is a good site for runoff farming. There is a very high population of livestock (7900), out of which 90% are small ruminants. Backyard poultry is in vogue. Besides the problem of low yield of crop the condition of livestock is miserable due to fodder scarcity and lack of veterinary facilities. The village is located on a hilltop and there is good scope of water harvesting from about 1000 ha of rocky area. Besides, about 2000 ha is under animal grazing. Initiation of silvi-pasture development and management programmes can help address fodder scarcity.	• Introduction of improved production technology in kharif and rabi crops in the *khadin*. • Repair of *khadin* to enhance water availability and safe disposal of excess water in underlying area/ *khadin*. • Soil and water conservation measures such as field bunding, vegetable barriers, counter furrows and bunds, wind breaks, shelter belts, circular catchments, etc., in donor area as well as within the *khadin*. • Facilitate formation of farmers' cooperative society in the *khadin* to ensure proper distribution of rainwater among the beneficiaries and its effective utilization. • Livestock-related interventions like deworming, vitamin-mineral mixtures, vaccination, water facilities for animals in grazing lands, etc. • Promotion of backyard poultry on a scientific basis. • Policy intervention on proper pricing of wool, employment generation through livestock based agro-industries, and the avoidance of crop damage from wild antelopes and pigs.
Damodara Micro-farming is prevalent and problems encountered by the farmers are almost similar to those at Dedha. A chain of 10 *khadins* is located near villages Dedha and Damodara: *Navoda, Bujju, Raniyat, Mandret, Temrasar, Chandat, Masurdi*, *Babrala, Adapar* and *Bhatad.* Of these, *Navoda and Bujju* have been suitable for R&D in village Dedha and *Raniyat and Masurdi* in Damodara. An R&D approach that could be followed is to adopt all the contiguous *khadins* as a unit for the integrated development of runoff farming.	• Introduction of improved production technology in kharif and rabi crops in the *khadin*. • Repair of *khadin* to enhance water availability and safe disposal of excess water in the underlying area/*khadin*. • Soil and water conservation measures such as field bunding, vegetable barriers, counter furrows and bunds, wind breaks and shelter belts, circular catchments, etc., in the dune area and also within the *khadin*. • Facilitate the formation of farmers' cooperative society in the *khadin* to ensure the proper distribution of rainwater and its effective utilization by all the beneficiaries. • Livestock-related interventions like deworming, vitamin-mineral mixtures, vaccination, drinking facilities for animals in grazing lands, on-the-spot treatment for diseases and parasites, etc. • Policy intervention on proper pricing of wool, employment generation through livestock-based agro-industries, and the avoidance of crop damage from wild antelope and pigs.

Continued

Annexure 1. Continued

Village with characteristic features	Village-specific technological interventions
Didhu Of the 13,020 ha area of the village, more than 50% is uncultivated. About 2000 ha of scarred woodland devoted to a goddess provides good scope to be developed into a grove for fodder production and partly as a biodiversity conservation unit. The cultivated land (360 ha) has rolling topography with severe wind erosion and losses in summer months. Recently, about 120 ha of cultivated land was converted into irrigated agriculture with the help of 100 newly dug tube wells. The village has a high population of livestock (7931), out of which 85% are small ruminants. The population of buffaloes is fast increasing and farmers are showing interest in dairy farming. However, the main problems here are fodder scarcity, livestock diseases (especially FMD), nonavailability of improved seed of kharif and rabi crops, soilborne insect-pest damage, particularly white grub and termite, and poor marketing facilities.	• Development of silvi-pasture system in community grazing land and R&D on various systems of grazing. • Promotion of micro-irrigation systems like drips and sprinklers. • Shelterbelts and wind breaks to arrest soil and water losses due to wind action. • Integrated pest management in crops & livestock. • Promotion of low water requiring high value crops like cumin, isabgol, chickpea and mustard. • Besides traditional kharif crops prevalent in the region, the introduction of *Citrullus colosynthis* in suitable proportion to arrest wind erosion. • ALUS, specially agri-pasture and silvi-agriculture systems in drylands. • Livestock-related interactions like animal prophylaxis, hygiene and breed improvement. • Facilitate easy availability of quality seed. • Use of solar appliances in agriculture and livestock management. • Developing the village as a seed production village.
Sankaria Sankaria village is irrigated by canal systems (IGNP). Out of the total geographical area (5093 ha), about 65% is uncultivated. The irrigated area comprises about 74% of the total cultivated land (1232 ha). Despite the prevalence of irrigated agriculture, the population of small ruminants is quite high (73%); so there is scope to develop pastures in community grazing lands. The population of cattle (1350) and camels (336) is also high and interventions are needed for their improvement. All the households are either marginal (190) or small (85) farmers and interventions to ensure their livelihood security need consideration. The main kharif crop is cluster bean while chickpea, mustard and wheat are grown in rabi. The major problems farmers face in crop production are irregular and uneven water supply from the canal, waterlogging in part of the area due to the presence of hard pan in the subsoil and sometimes one-time heavy discharge from canal, frost damage in winter, and damage to kharif and rabi crops due to hot winds. Crop damage occurs due to insect-pests (termite, white grub, caterpillar) and obnoxious weeds like orobenchi, nutsedge, and bermuda grass.	• Construction of *diggis* in some farm sites and lifting of water from solar pumps connected to drips to grow fruits or vegetables. • Adoption of wind erosion control measures like wind breaks and shelterbelts. • Development of a few sites as seed multiplication blocks. • Introduction of low water requiring crops like cumin, isabgol, barley and cultivated fodder crops like lucerne, oats, and napier. • Development and management of pasture blocks in community participatory mode for small ruminant grazing. • Popularization of micro-irrigation systems with precision farming. • Integrated nutrient and pest management in kharif and rabi crops. • Interventions in livestock husbandry with focus on enhancement of livestock-based livelihood opportunities. • Interventions to control cold and hot wind damage in crops. • Intervention for the scientific management of camels can be sought from NRC, Bikaner.

*Note: Besides the village-specific technological interventions mentioned, those addressing common problems faced by the farmers/ community in all the villages, such as the shortage of drinking water for humans and livestock, fodder scarcity, lack of awareness about new technologies, lack of benefit from Government schemes in the area, overall low production and income from agriculture and animal husbandry are also included. However, the proposed interventions were later prioritized for each farm type through participatory methods.

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