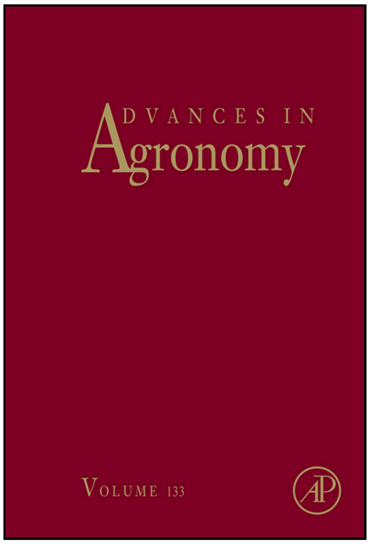

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CHAPTER FOUR

Potential and Challenges of Rainfed Farming in India

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Abstract

India ranks first in rainfed agriculture globally in both area (86 Mha) and the value of produce. Rainfed regions in India contribute substantially toward food grain production including 44% of rice, 87% of coarse cereals (sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), maize (*Zea mays*)), and 85% of food legumes, 72% of oilseeds, 65% of cotton, and 90% of minor millets. Overall, the rainfed areas produce 40% of the food grains, support two-thirds of the livestock population, and are critical to food security, equity, and sustainability.

India is home to 18% of world's population, 15% of the world livestock, 4.2% of fresh water resources, 1% of forests, and 0.5% of pasture land, but only has 2.3% of the geographical area. India is home to 25% of the world's hungry population of ∼1 billion along with an estimated 43% of children malnourished under the age of five. The net sown area in India has remained constant for several years at 141 Mha, but the human and livestock populations have been steadily increasing. Though the Indian population increased from 361 million in 1951 to 1140 million in 2011, tripling over 60 years, the food-grain production has more than quadrupled, but the yield gains are largely from the irrigated agroecosystems. Notwithstanding the increase in average productivity from 0.6 Mg ha^{-1} in the 1980s to 1.1 Mg ha^{-1} at the present time, large yield gaps exist for rainfed crops in the semiarid regions. Even after realizing the full irrigation potential, nearly 40% of the net sown area of 141 Mha will remain totally rainfed. The per capita availability of land has fallen drastically from 2.4 ha in 1951 to about 0.32 ha in 2001; and it is projected to decline further to 0.09 ha by 2050. Increasing productivity of rainfed cropping systems is of critical importance to meet the food demands of an ever-increasing population in India.

The potential productivity of maize (*Z. mays*) in high rainfall regions under rainfed condition is 8.0 Mg ha^{-1} vis-a-vis the national average yield of 2.1 Mg ha^{-1}, indicating an unbridged yield gap of ∼6 Mg ha^{-1}. Large yield gaps exist in other crops as well which are primarily grown under rainfed conditions. Recommended management practices (RMPs) such as improved cultivars, site specific nutrient management (precision agriculture), and water harvesting and recycling can potentially increase the yields in several crops up to 6 Mg ha^{-1}, indicating the large realizable potential under rainfed conditions. There are many districts in India where the actual yields are much lower than the national average, and there is enormous potential for improvement. The objective of this article is to discuss the production potentials and the yield gaps of predominant crops grown under rainfed conditions in India, biotic and abiotic constraints, and RMPs for realizing the potentials.

1. INTRODUCTION

Rainfed agriculture constitutes 80% of global agriculture, and plays a critical role in achieving global food security. However, growing world population, water scarcity, and climate change threaten rainfed farming through increased vulnerability to droughts and other extreme weather events. Out of the total population of 7.3 billion, about 1 billion are food-insecure, and 60% of these live in South Asia (SA) and Sub-Saharan Africa (SSA). The importance of rainfed agriculture varies regionally, but it produces most food for poor communities in developing countries. The proportion of rainfed agriculture is 95% in SSA, 90% in Latin America, 60% in SA, 65% in East Asia, and 75% in Near East and North Africa (FAO, 2003). Most of the food-insecure people are in Asia and the Pacific (578 million), followed by those in SSA, Latin America and the Caribbean, Near East and North Africa, and the lowest in developed countries (19 million). Agriculture in India has been a mainstay for growing population over millennia. It has been a major source of employment in India, with 72.4% in 1952 and 52.1% in 2014. Rapid growth of industrial and service sectors outpaced growth of agricultural sector since the 1990s. Nonetheless, there is no alternative to agriculture to feed and fulfill the needs of growing population. The population of India may reach 1.34, 1.39, and 1.81 billion in 2020, 2025, and 2050, representing 17.5%, 17.3%, and 19.0% of the world population, respectively (Figure 1).

Population of India varies widely among states and districts. In predominantly rainfed regions of the southern plateau, central, western, and eastern parts, population density is as high as 1000 persons km^{-2}. The per capita

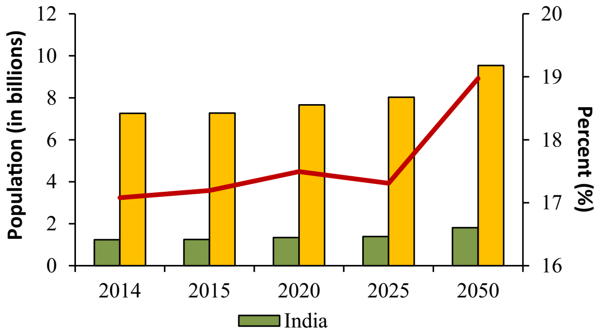

Figure 1 Projected population growth (in billions) of India and the world. *Source:* *Srinivasarao et al. (2014)*.

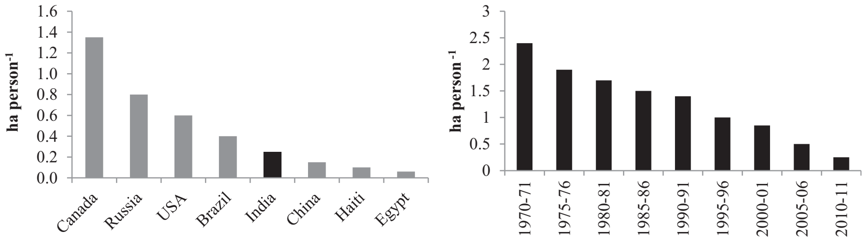

Figure 2 Per capita land availability in different countries (left) and decreasing per capita land availability in India (right) during 1970–1971 and 2010–2011. *Source: Compiled from different sources.*

land availability is low in India as compared to many other countries (e.g., Canada, Russia, USA, and Brazil). The per capita land availability has declined from about 2.4 ha during 1970–1971 to 0.29 ha during 2010–2011 (Figure 2), and will decline further in years to come.

India is also facing the biggest challenge of meeting the food demands by increasing the production (per unit land) simultaneously without degrading the soil and water resources and maintaining a favorable ecological balance. In recent years, there is a general trend of reduction in per capita consumption of food grains and increase in the consumption of livestock products and vegetables. Despite decline in the food grain consumption because of the dietary shift, there is no substitute for cereals and pulses which are the staple foods, and the most economic sources of energy and protein and vital for nutrition of poor people. Hence, greater production of food grains is essential to meet the dietary needs in the near future. The demand for cereals is projected to grow from 185 million metric ton (Mt) in 1944–1995 to 270(Mt) in 2024–2025 (Table 1).

Demand for milk and milk products are projected to increase to 141.5 Mt and those of vegetables to 127.2 Mt by 2020–2021 (Table 2). These demands must be met from the limited land area of only 2.5% of the global geographical area. Domestic production of all these food

Table 1 Projected demand for food products in India for 2024–2025

Year	Cereal production (Mt)	Per capita availability (kg person^{-1} year^{-1})	Demand (Mt)	Deficit (Mt)	Deficit (kg person^{-1} year^{-1})
1995	153	165	185	32	35
2025	227	168	270	43	32

Source: Compiled from different sources.

Table 2 Projections of demand for various food products in India by 2020–2021 (Mt)

Commodity	**Current (2011–2012)**	**Projection (2020–2021)**
Cereals	219.3	262.0
Pulses	16.1	19.1
Food grains	235.4	281.1
Milk and milk products	113.7	141.5
Egg (billion)	60.8	81.4
Meat	8.3	10.9
Fish	8.2	11.2
Edible oilseeds	43.6	53.7
Vegetables	108.0	127.2
Fresh fruits	67.3	86.2
Sugar (in terms of cane)	303.5	345.3

Source: Srinivasarao et al. (2014).

commodities must be increased at the rate of (% year^{-1}) 2 for cereals and pulses, 6 for oilseeds, 0.9 for vegetables, 2.4 for milk, and around 3.5 for fish and egg. Growth rates required for cereals, pulses, and oilseeds exceed those achieved during the last decade. Thus, new and innovative strategies must be identified and implemented for increasing the production of cereals, pulses, oilseeds, and the projected food demand must come from increasing production of the rainfed agriculture, because there is little potential of expansion in irrigated area.

Despite the historic success of increasing production since the Green Revolution of 1960s, even greater challenges lie ahead. India's per capita availability of agricultural land declined to 0.3 ha per farmer compared to over 1.4 ha in the developed world. At the same time, population has more than doubled since 1970s to 1.21 billion, raising concerns about India's ability to feed its growing and increasingly affluent population. Therefore, the rapid growth of agriculture is essential not only for self-reliance but also for advancing the food and nutritional security of the people, to bring about equitable distribution of income and wealth in rural areas, to alleviate poverty and improve the quality of life. Production potential of crops particularly under rainfed conditions depends on the resource endowments of the region and the management practices adopted. Systematic efforts have been made for development of location specific technologies since 1970s with the establishment of All India Coordinated Research Project for Dryland Agriculture (AICRPDA) system and several technologies have been developed which have potential to increase the crop productivity significantly. Comprehensive information about the production potential of predominant rainfed crops in diverse soil orders of India and the yield gaps is lacking. Little efforts were made to quantify the yield gaps and factors contributing across rainfed production systems which are diverse in terms of rainfall, soils, and ecology. The potential for yield enhancement and the constraints for achieving the potential yields in different soil orders of rainfed systems have been discussed which will be useful for enhancing the productivity in similar regions of the world and for scaling up of successful practices through various area-based developmental programs from rainfed regions.

2. NATURAL RESOURCES IN RAINFED ECOREGIONS OF INDIA

2.1 Climate

With diverse climate, India has a high spatial and temporal variability in rainfall and temperature (Rao et al., 2010). Thus, rainfed farming systems are practiced in regions of strong climate contrasts. For example, southern Tamil Nadu experiences typical tropical temperatures with north-east monsoon being the main source of rainfall, whereas Punjab and Haryana in north-western India experience continental climates with extremes of temperatures varying from 45–50 °C in summer and near freezing temperatures in winter. The rainfed farming in north-western India is practiced under south-west monsoon rains. Thus, the climate of rainfed-dryland farming ranges from arid, semiarid to subhumid, with mean annual rainfall varying between 412 and 1378 mm. Length of the growing season ranges from 60–90 days in the arid regions to 180–210 days in the subhumid regions. In terms of the distribution of rainfall, 15 million hectare (Mha) of the land receives an annual rainfall of <500 mm, 15 Mha of 500–750 mm, 42 Mha of 750–1150 mm, and 25 Mha of >1150 mm. The country is divided into 20 homogenous agroecological regions on the basis of topography, climate, soils, and effective growing seasons (Table 3). This classification characterizes the suitability and potential of each subregion for a given land use, and cropping and farming system.

There exists a strong evidence of a noticeable increase in the temperature and more variable rainfall pattern in the country since 1960s. Thus, the district level climatic classification made in 1988 has been revised (CRIDA, 2013). There has been a substantial increase in the area under arid zone in

Table 3 Regrouping of agroecological subregions of the country based on climate types

Type of climate	Annual rainfall (mm)	Moisture index (%)	Growing period (days)	Agro-eco region/ subregion	Physiography	Area (Mha)
Cold arid	<500	>−66.7	60−90	1.1, 1.2	Western Himalayas, parts of Jammu & Kashmir	14.3
Hot arid	<500	>−66.7	<90	2.1, 2.2, 2.3, 2.4, 3.0	Western Plains and Kutch Peninsula, Deccan Plateau	38.1
Semiarid						
Dry	500−700	−66.7 to −55.8	90−120	4.1, 4.2, 5.1, 6.1, 7.1, 8.1, 14.1, 18.1	Northern plains, Central highlands including Aravallis. Deccan plateau, Tamil Nadu uplands, South Tamil Nadu plains	41.6
Moist	750−1000	−55.7 to −33.3	90−50	4.3, 4.4, 5.2, 5.3, 6.2, 6.3, 7.2, 8.2, 8.3, 9.1, 18.2	Indo-Gangetic plains, Bundelkhand uplands, Malwa plateau, eastern Gujarat plain, Vindhyan hills, Central & Western Maharashtra, North Karnataka, Vidarbha, North Telangana, Central Karnataka, Tamil Nadu plains, Punjab & Rohilkhand	72.2
Subhumid						
Dry	1000−1200	−33.3 to 0.0	150−180	6.4, 7.3, 9.2, 10.1, 10.2, 10.3, 11.0, 12.3, 14.2, 18.3	Western Karnataka plateau, Eastern Ghats (south), South Bihar plains, Rohilkhand, Malwa plateau, Vindhyan Scariland, Narmada valley, Bundlekhand plateau, Chattisgarh, Mahanadi basin, Chotanagar plateau, Gujarat hills, South Kashmir, and Andhra plain	58.0

(*Continued*)

Table 3 Regrouping of agroecological subregions of the country based on climate types—cont'd

Type of climate	Annual rainfall (mm)	Moisture index (%)	Growing period (days)	Agro-eco region/ subregion	Physiography	Area (Mha)
Moist	1200–1600	0.0–20.0	150–210	10.4, 12.1, 12.2, 13.1, 13.2, 18.4	Satpura range and Wainganga valley, Gujarat hills, Eastern Ghats, North Bihar, Foot hills of Central Himalayas, Utkal plains, and East Godavari Delta.	35.9
Humid and perhumid						
Humid	1600–2000	20.0–1000.0	180–270	15.2, 18.5, 19.1, 19.2, 19.3, 20.2	Parts of western and eastern Himalayas, Bengal basin and Assam Plains	33.3
Perhumid	>2000	>100	>270	14.3, 14.4, 14.5, 15.3, 15.4, 16.1, 16.2, 16.3, 17.1, 17.2, 20.1	Parts of eastern Himalayas, northeastern hills, Western Ghats and coastal plains.	31.3

Compiled by CRIDA (AICRPAM) using NBSS and LUP data (2004).

Gujarat and a decrease of arid region in Haryana (Figure 3). There is also an increase in semiarid region in Madhya Pradesh, Tamil Nadu, and Uttar Pradesh with a shift of the climate from dry subhumid to semiarid. The moist subhumid regions in Chhattisgarh, Odisha, Jharkhand, Madhya Pradesh, and Maharashtra are now mostly dry subhumid.

2.2 Soils

Soils of India are grouped under eight orders: Entisols (80.1 Mha), Inceptisols (95.8 Mha), Vertisols (26.3 Mha), Aridisols (14.6 Mha), Mollisols

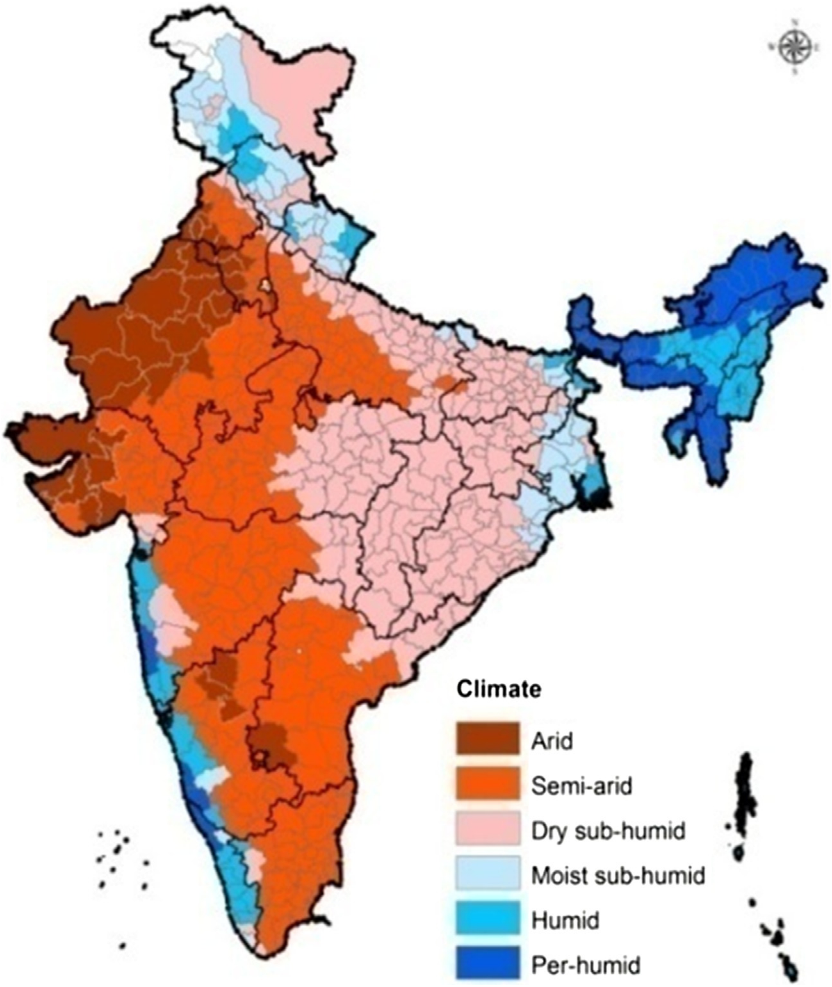

Figure 3 Climatic classification of the country at the district level. *Source:* CRIDA (2013).

(8.0 Mha), Ultisols (0.8 Mha), Alfisols (79.7 Mha), Oxisols (0.3 Mha), and mixed types (23.1 Mha). Alfisols and Vertisols are dominant soils of the peninsular India and Aridisols occur in extremely dry climates along with some Entisols and Inceptisols. In terms of land use and management, alluvial (Inceptisols) soils are the most dominant (93.1 Mha), followed by red (Alfisols, 79.7 Mha), black (Vertisols, 55.1 Mha), desert (Entisols, Aridisols, 26.2 Mha), and lateritic (Plinthic horizon, 17.9 Mha) soils (Table 4). The dominant soil orders in rainfed production systems of India are Inceptisols followed by Entisols, Alfisols, Vertisols, Mixed soils, Aridisols, Mollisols, Ultisols, and Oxisols (Figure 4).

With the exception of Vertisols, most soils in the rainfed areas are generally coarse-textured. Thus, their capacity to retain water and nutrients is low, and crops grown on these soils are prone to drought stress and nutrient deficiencies. With low soil organic matter (SOM) concentration, aggregate stability is low and erosion is a serious problem. Water infiltration rates are low in Vertisols due to clayey texture and in Alfisols due to formation of surface crusts. With the exception of some Vertisols, which are rich in bases, inherent fertility of rainfed soils is generally low.

Table 4 Major soil groups and their moisture storage capacities in rain-dependent areas of India

Broad soil group	Subgroup (based on soil depth)	Moisture storage capacity (mm)
Vertisols and related soils	Shallow to medium (up to 45 cm)	135–145/45 cm
	Medium to deep (45–90 cm)	145–270/90 cm
	Deep (>90 cm)	300/m
Alfisols and related soils	Shallow to medium (up to 45 cm)	40–70/45 cm (sandy loam)
	Deep (>90 cm)	70–100/45 cm (loam) 180–200/90 cm
Aridisols	Medium to deep (up to 90 cm)	80–90/90 cm
Inceptisols	Deep	90–100/m (loamy sand) 110–140/m (sandy loam) 140–180/m (sandy loam)
Entisols	Deep	110–140/m (sandy loam) 140–180/m (loam)

Source: Srinivasarao et al. (2013a).

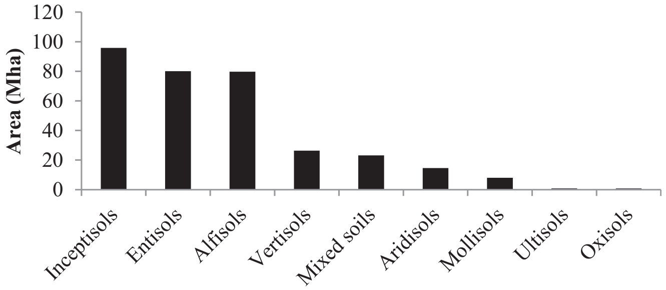

Figure 4 Predominant soil orders in India and their distribution. *Source: Adapted from Srinivasarao et al. (2013a).*

2.3 Water Resources

There has been a paradigm shift in water resources use in India since 1950s from communities (tanks and small water structures) to government (major and medium irrigation projects), and the private domain (groundwater). Groundwater provides about 70% of the irrigation and 80% of the drinking water. The principal source of water is precipitation (rainfall and snowfall), but only a part of the rainfall is stored as groundwater and the remaining is lost as runoff and evaporation. Out of the total annual precipitation (including snowfall) of around 4000 km^3 in the country, the availability from surface water and replenishable groundwater is ~1869 km^3, comprising of 690 km^3 (37%) of surface water, and 432 km^3 of groundwater (GOI, 2002). Total annual national water use may exceed the utilizable water resource by 2050 or 2060, unless significant changes occur through increased water storage and efficient water management. Thus, available water resources must be judiciously used. Nonconventional methods for utilization of water (e.g., through interbasin transfers, artificial recharge of groundwater, and desalination of brackish or sea water) as well as traditional water conservation practices (e.g., rainwater harvesting, including rooftop rainwater harvesting) must be practiced further to increase the utilizable water resources.

2.3.1 Surface Water Resources

India's average annual surface run-off generated by rainfall and snowmelt is estimated at 1869 km^3. However, only 213 km^3 (11.4%) of the surface water resources can be harnessed because: (1) over 90% of the annual flow of the Himalayan rivers occurs over a four-month period and (2) potential to capture such resources is complicated by limited suitable storage reservoir sites. This capacity may nearly double to about 21% by 2050. The utilization in the peninsular basins (e.g., Godavari, Krishna, Cauvery, Mahanadi, Tapti, and Narmada) is more than 70% of the present capacity. The Krishna basin has the highest storage capacity (49 km^3) and can store 64% of the mean annual river flow, or about 220 days of average flow. The number of days of flow which can be stored within the river basins ranges from 2 to 220.

2.3.2 Groundwater Resources

Groundwater plays a key role in meeting the water needs of diverse sectors in India. The annual replenishable groundwater resource is contributed by two major sources, rainfall (290 km^3) and other sources (143 km^3) that include canal seepage return flow from irrigation, seepage from water bodies, and artificial recharge due to water conservation structures. The overall contribution of rainfall to country's annual replenishable groundwater resource is 67%. The current stage of groundwater development at the national level is estimated at 58% of the groundwater potential. Since overexploitation of groundwater through indiscriminate drilling of bore wells and tube wells has reached critical levels in most districts of India, regulation is essential to ensure that groundwater supplies are available in sustainable fashion to meet future requirements. The central groundwater board has drafted a model bill that can be adapted by different states to ensure sustainable and equitable development and use of groundwater resources (NAAS, 2009). The statewise water requirements, estimated by the National Commission for integrated water resource development, are summarized in Table 5; the results indicate a growing water requirement in the years to come.

2.4 Biodiversity

Unlike irrigated areas, which are homogenous for intensive cropping systems, the rainfed areas are more diverse and heterogenous. Despite their relative aridity, drylands/rainfed areas in India harbor a great deal of biodiversity, influenced by both climate and latitude. Variation in topography, geology, soil type, seasonal patterns of rainfall, fires, herbivore pressure, and human management, along with water scarcity, account for a wide diversity of species in the drylands. In the drylands of India, for example, farmers still maintain many of their traditions of nurturing biodiversity of wild and cultivated food crops and medicinal plants, despite the introduction of monocropping during the Green Revolution. In addition, the traditional reverence of Indian farmers for multipurpose trees (e.g., *Prosopis cineraria* in

Table 5 Water requirements of India (State-wise)

	Water requirement (km^3)		
State/Union Territory	**2010**	**2025**	**2050**
Andhra Pradesh	66.4	78.5	109.8
Arunachal Pradesh	1.4	2.1	12.6
Assam	18.8	24.1	50.1
Bihar and Jharkhand	47.7	64.3	106.6
Goa	0.5	0.8	0.9
Gujarat	35.3	46.0	56.8
Haryana	32.1	31.8	31.6
Himachal Pradesh	5.8	6.0	6.7
Jammu and Kashmir	7.1	9.1	15.5
Karnataka	36.4	42.7	58.8
Kerala	11.6	15.6	30.9
Madhya Pradesh and Chhattisgarh	51.2	67.6	113.6
Maharashtra	56.1	74.0	101.5
Manipur	1.5	1.7	5.1
Meghalaya	1.2	1.5	2.2
Mizoram	0.4	0.6	1.2
Nagaland	1.2	1.6	6.1
Orissa	24.0	32.8	49.1
Punjab	51.1	48.8	47.5
Rajasthan	55.3	54.8	59.6
Sikkim	0.4	0.5	0.8
Tamil Nadu	44.1	51.6	61.7
Tripura	1.6	2.0	6.9
Uttar Pradesh and Uttarakhand	118.0	137.0	171.6
West Bengal	37.3	44.5	66.4
Union Territories	1.8	2.5	4.0
Total	**708**	**843**	**1178**

Source: http://www.nih.ernet.in/rbis/india_information/statetotalwaterrequirements.htm.

croplands) enhances agrobiodiversity. Similarly, farmers maintain different varieties of maize, sorghum, pulses, and minor millets. Ancient civilizations in drylands, like everywhere else, cared for medicinal plants because of the experiences of generations of tried and tested curative methods and products. In India, for example, Shankar et al. (1999) reported that 4671 plant species are used in folk medicine. Although not unique to drylands, it is a remarkable fact that the use of medicinal plants is a living tradition of rural people in drylands. However, the loss of biodiversity in Indian drylands is alarmingly high for diverse reasons including degradation and loss of habitats, reliance on high yielding varieties (HYVs) and hybrids, shift from intercropping/mixed-cropping to monocropping, cutting of trees and shrubs, urbanization, mining, and industrialization. For example, the Indira Gandhi Canal in Rajasthan has adversely impacted dryland biodiversity, with wet conditions affecting the habitat of local species. The change in land use, population pressures, and irrigated farms favor species that demand more water, and this transition has led to the loss of several indigenous shrubs and grasses species.

3. FEATURES OF RAINFED ECOSYSTEMS

3.1 Frequent Droughts

Droughts and famines are the general features of rainfed agriculture in India. Conceptually, drought is indicative of situation of limited rainfall that is below the "normal" amount for the area (Pandey and Bhandari, 2007). The perception of drought varies from one region to another depending upon normal climatic conditions, available water resources, agricultural practices, and the specific socioeconomic activities of the region (Prasad, 1998). The risk involved in successful cultivation of crops depends on the nature of drought (chronic vs contingent; meteorological vs hydrologic; pedologic vs agronomic), its probable duration, and periodicity of occurrence within the season. In the arid region, where the mean annual rainfall is less than 500 mm, drought is almost an inevitable phenomenon in all years (Ramakrishna, 1997). In semiarid regions (mean annual rainfall 500–750 mm), droughts occur in 40–60% of the years due to deficit seasonal rainfall or inadequate soil moisture availability between two successive rainfall events. Even in the dry subhumid regions (annual rainfall 750–1200 mm), contingent drought situations occur due to break in monsoon conditions. Very high incidence of drought (>20%) is observed in a few districts in Rajasthan and Gujarat. The incidence is relatively low in the Western Ghats, Eastern and North-Eastern India (Figure 5; Rama Rao et al., 2013).

Long-term data for India indicate that rainfed areas experience 3–4 drought years per decade. Of these, drought in two to three are moderate and in one or two of severe intensity. The occurrence of the drought is frequent in the subdivisions like West Rajasthan, Tamil Nadu, Jammu & Kashmir, and Telangana Region of Andhra Pradesh (Table 6).

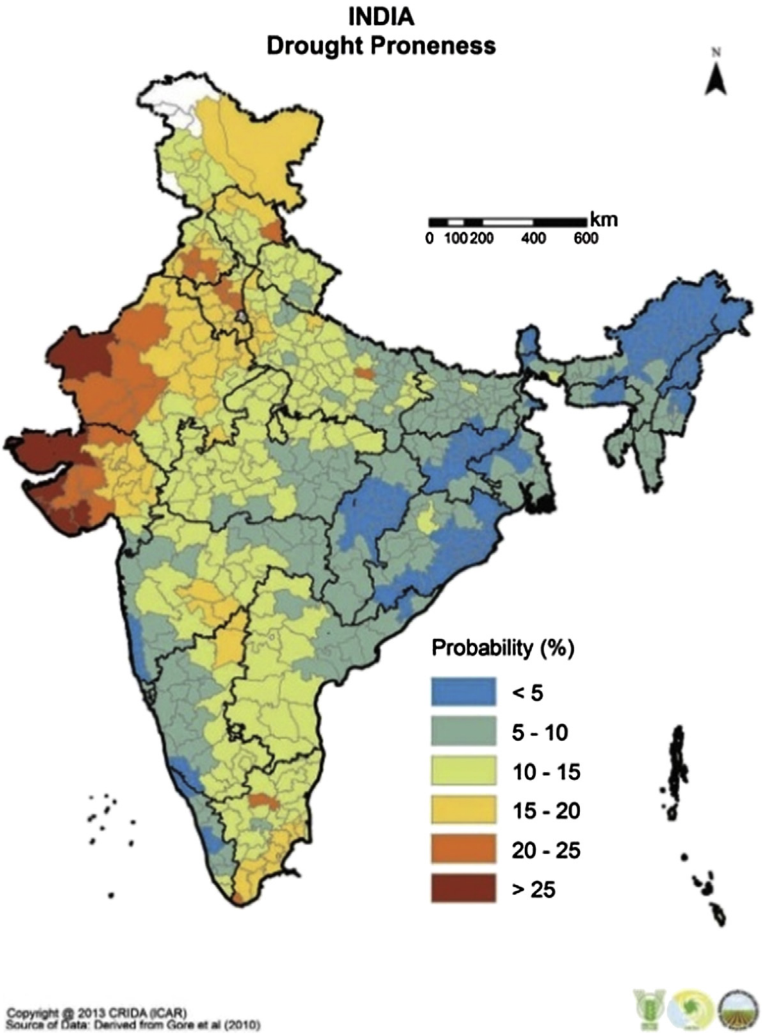

Figure 5 Probability of occurrence of drought in various parts of India. *Source: Rama Rao et al. (2013)*.

A significant decline in food production often occurs with the increase in intensity or extended duration of drought. Drought results in crop losses of different magnitude depending on their geographic incidence, intensity, and duration. Drought not only affects the food production at the farm level, but also affects the overall food security and the national economy. The growth of crops and the food production of the country are strongly influenced by the total rainfall, as is evident from the positive and significant correlation

Table 6 Probability of occurrence of drought in different meteorological subdivisions

Meteorological subdivision	Frequency of deficient rainfall (75% of normal or less)
Assam	Very rare, once in 15 years
West Bengal, Madhya Pradesh, Konkan, Bihar, and Odisha	Once in 5 years
South interior Karnataka, Eastern Uttar Pradesh, and Vidarbha	Once in 4 years
East Rajasthan, Gujarat, and Western Uttar Pradesh	Once in 3 years
West Rajasthan, Tamil Nadu, Jammu & Kashmir, and Telangana Region of Andhra Pradesh	Once in 2.5 years

Source: NRAA (2013).

coefficient of +0.78★★ (1999–2010) (AICRPAM, 2012; Figure 6). During 2002, the deviation in the amount of rainfall received and that in the food production were −100 and −20, respectively, whereas, the corresponding values during 2009 were −150 and −5, respectively, indicating that drought proofing of Indian agriculture has been achieved to some extent because of the adoption of recommended management practices (RMPs), better logistics, and timely interventions from Central and State Governments during the drought years. However, rainfall aberrations during the south-west

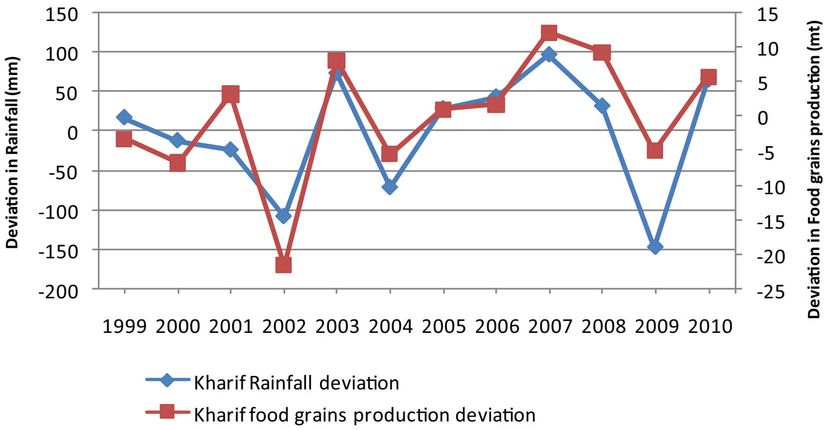

Figure 6 Rainfall versus food production in rainy season (*Kharif*). *Source:* *AICRPAM (2012).*

monsoon continue to be major factor contributing to instability in summer crop production. In 2012, the rainfall during June–September was deficit (−14% to −46%) in many parts of the country (Figure 7).

3.2 Soil Degradation

Since the Green Revolution of the 1960s, the national agricultural policy is driven by the need to maximize crop yield, using irrigation and intensive use of HYVs, chemical fertilizers, and pesticides. The status of natural resources and the rainfed farming have received little attention. As a result, the natural resource base especially in rainfed areas has been severely degraded. Degraded soils with high risks of accelerated erosion resulting in loss of fertile surface soil and soil organic C (SOC), are the major constraints. The magnitude of soil loss ranges from 5 to 150 Mg ha^{-1} $year^{-1}$ depending upon soil type, vegetation, and slope gradient. Soil erosion by wind and water, acidity, alkalinity/salinity, and other complex problems are the principal types of soil degradation.

There have been several estimates of the land area of degraded/waste lands by different organizations. These estimates have been harmonized by adopting spatial data integration with geographical information system for different environments (Maji, 2007). The total degraded area is estimated at 120.7 Mha, of which 104.2 Mha (86.3%) is arable land, and 16.5 Mha (13.7%) is open forest land. Of the total degraded land area, 73.3 Mha (60.7%) is caused by water erosion, 12.4 Mha (10.3%) by wind erosion, 5.4 Mha (4.5%) by salinization, and 5.1 Mha (4.2%) by soil acidification (Figure 9(A–C)). Some areas are affected by more than one degradation processes (Maji, 2007). In many states in India, between 40% and 80% of the land area is classified as degraded by one or the other processes. Soils

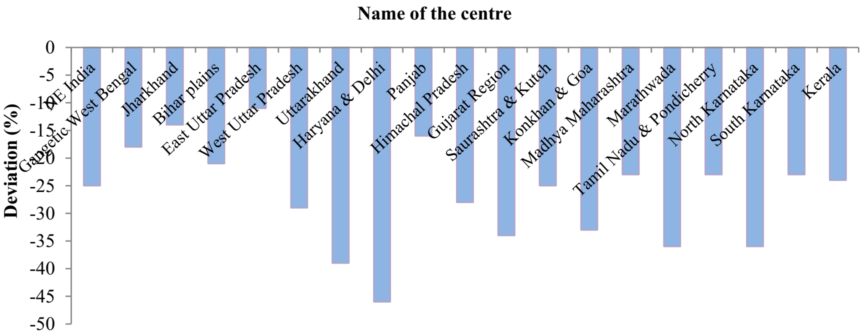

Figure 7 Subdivisional rainfall during rainy season, 2012. *Source:* *AICRPAM (2012)*.

in rainfed areas are subject to a prolonged double exclusion, being unable to gain from chemical fertilizers and receive no support for locally validated fertility enhancing practices like crop residue incorporation, composting, farmyard manure application, etc. Table 7 provides data on land degradation (%) across various states of India, and Figure 8 illustrates the extent of soil erosion in hilly areas causing severe landslides.

Among the major causes of decline in soil productivity is the accelerated erosion of top soil. The extent of degraded soils and the severity of water and wind erosion are presented in Figure 9(A–C). Severe erosion by water is observed in northeast hill ecosystems, and parts of central and northern India (>10 Mg ha^{-1} $year^{-1}$), while wind erosion is severe in soils of the north-west arid regions. Other causes of soil degradation include rapid depletion of SOM because of improper crop management practices, salt accumulation, and contamination of soils with heavy metals. Large areas are affected by toxic levels of Fe, Al, and Mn in eastern and northeastern regions, especially in waterlogged or poorly drained soils such as Vertisols of Madhya Pradesh and Maharashtra during the rainy season (June–September). Figure 10

Table 7 Area under degraded land in states of India that predominantly have rainfed farming

State	Geographical area (Mha)	Degraded land (Mha)	Degraded land (%)
Andhra Pradesh	27.5	10.3	37
Arunachal Pradesh	8.4	3.4	40
Assam	7.8	4.6	59
Bihar	9.4	1.7	18
Chhattisgarh	13.5	4.9	37
Gujarat	19.6	3.4	17
Haryana	4.4	0.6	13
Jammu & Kashmir	22.2	20.9	94
Jharkhand	8.0	4.3	54
Karnataka	19.2	8.7	46
Madhya Pradesh	30.8	15.3	50
Maharashtra	30.8	10.8	35
Odisha	15.6	5.0	32
Punjab	5.0	0.6	11
Rajasthan	34.2	21.0	61
Tamil Nadu	13.0	3.9	30
Uttar Pradesh	24.1	15.3	63
Uttarakhand	5.3	3.2	60

Source: Maji et al. (2010).

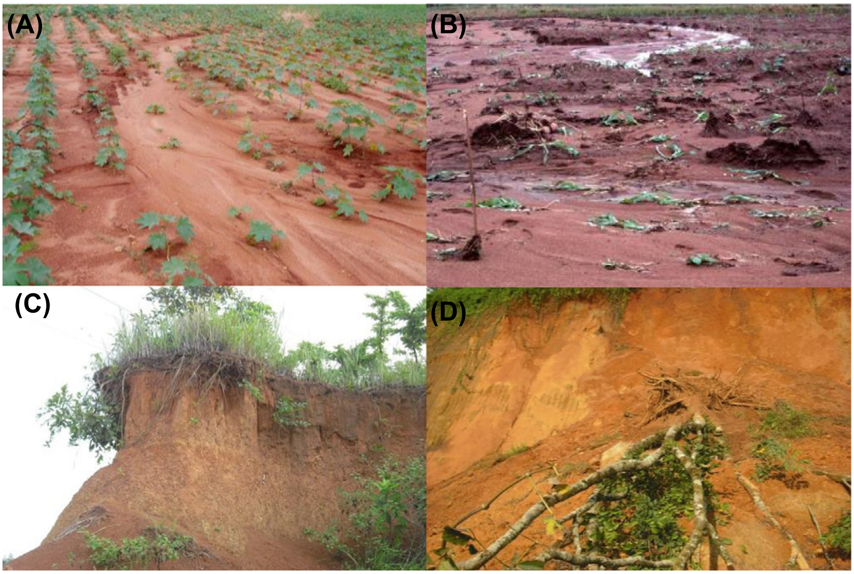

Figure 8 Photos showing the loss of top fertile soil layer through soil erosion in high intensity rains in low rainfall regions (A, B) and high rainfall hill regions (C, D).

illustrates the processes that affect general soil quality. Of these, soil compaction, surface crusting, and decline in soil structure are important soil physical properties contributing to a strong reduction in agronomic productivity.

3.3 Low Soil Organic Carbon Content

Stabilizing or enhancing SOM is critical to minimizing risks of soil degradation and for ensuring sustainability of agriculture in the tropics. A severe depletion of SOM degrades soil physical quality, loss of favorable biology, and leads to the occurrence of multiple nutrient deficiencies. The SOC concentration mostly depends on climate, soil type, and land use (Dalal and Mayer, 1986) and input of biomass. Soils of tropical regions are low in SOC concentration and this is a major factor contributing to low soil fertility and productivity. Soils of drylands are highly degraded and have low SOC concentration because of a high rate of oxidation and accelerated erosion (Figure 9). In addition, low biomass input and accelerated erosion of surface soil under intensive rainfall are other important factors leading to low SOC concentration (Srinivasarao et al., 2011a). The low SOM concentration along with low inputs is among the principal reasons of low production and large yield gap. The severe depletion of SOC in rainfed agroecosystems in India

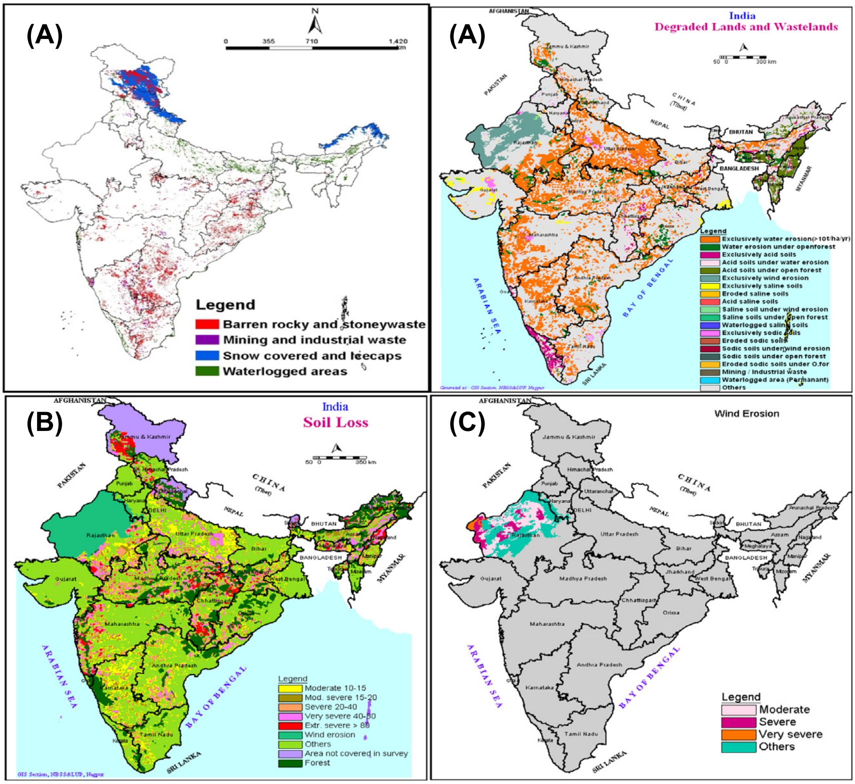

Figure 9 (A) Physical degradation of land in India. (B) Soil loss by water erosion (>10 Mg ha^{-1} year^{-1}). (C) Wind erosion in India (>10 Mg ha^{-1} year^{-1}). *Source:* *Maji et al. (2010)*.

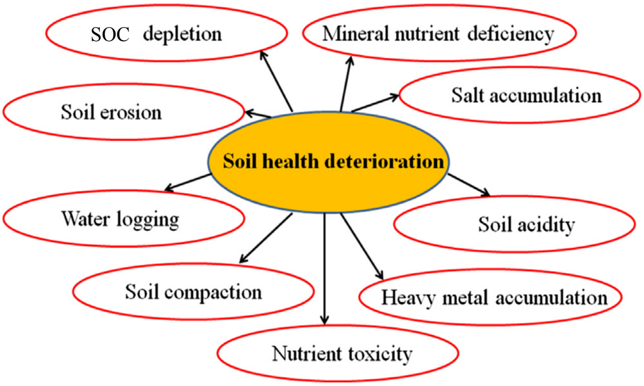

Figure 10 Processes affecting the quality of soils in India.

has adversely impacted soil quality, crop productivity, and sustainability. Vertisols, Inceptisols, and Alfisols comprise a major share of SOC stocks in the top 30-cm-depth. Indeed, SOC stocks in the soil profiles across the country vary widely and follow the order Vertisols > Inceptisols > Alfisols > Aridisols.

3.4 Multinutrient Deficiencies

The increased use of fertilizers alone, often in an unbalanced manner, has degraded soil quality and exacerbated multiple nutrient deficiencies in intensive rainfed production systems. Soils of India are not only deficient in NPK but also in secondary nutrients (S, Ca, Mg) and micronutrients (B, Zn, Cu, Fe, Mn etc.). Besides the three primary nutrients (N, P, K), deficiency of S and micronutrients (Zn and B) in many states, and of Fe, Mn, and Mo in some states, has become a limiting factor in increasing agronomic productivity. The data on soil analysis from farmers' fields in several districts of Andhra Pradesh, Karnataka, Tamil Nadu, Rajasthan, and Madhya Pradesh states and from Junagarh district in Gujarat, showed that almost all farms are low in SOC, low to moderate in available phosphorus (P), but generally adequate in extractable potassium (K). However, there exists a widespread deficiency of sulfur (S), boron (B), and zinc (Zn) (Sahrawat et al., 2010). Crops under rainfed farming systems suffer more from nutrients deficiency than from moisture inadequacy, because of low rates of fertilizer use. Deficiencies of secondary nutrients vary greatly mainly in soils under intensive cropping because of imbalanced fertilization resulting in negative nutrient budget or nutrient mining. Micronutrient deficiencies, particularly of Zn and B, are among the emerging constraints to sustainable crop production in rainfed agriculture (Table 8) (Srinivasarao and Vittal, 2007).

There are widespread deficiencies of macro, micro, and secondary nutrients under rainfed conditions, estimated at 89% for N (63% low and 26% medium); 80% for P (42% low and 38% medium); 50% for K (13% low and 37% medium), 41% for S; 48% for Zn; 33% for B; 12% for Fe; 13% for Mo; 5% for Mn; and 3% for Cu. Large-scale deficiencies of Mg and Ca have been reported recently in red and lateritic sandy soils. Several crops (e.g., groundnut, sunflower, rainfed rice, fruits, and vegetables) are affected by deficiency of Ca and Mg.

3.5 Low External Inputs

Use of production inputs (e.g., fertilizers, supplemental irrigation, good quality seeds, pesticides, and herbicides) are lower in rainfed than in irrigated crops. Thus, yield of rainfed crops is low. Despite documenting that soils in

Table 8 Emerging nutrient deficiencies in dryland soils (0–15 cm) under diverse rainfed production system of India

Location	Rainfall (mm)	Soil type	Production system	Limiting nutrients need to supplied
Varanasi	1080	Inceptisol	Upland rice–lentil	N, Zn, B
Faizabad	1060	Inceptisol	Upland rice	N
Phulbani	1400	Oxisol	Upland rice–horsegram	N, Ca, Mg, Zn, B
Ranchi	1300	Alfisol	Upland rice	Mg, B
Rajkot	615	Vertisol	Groundnut	N, P, S, Zn, Fe, B
Anantapur	590	Alfisols	Groundnut	N, K, Mg, Zn, B
Indore	950	Vertisol	Soybean	–
Rewa	900	Vertic Inceptisol	Soybean	N, Zn
Akola	825	Vertisol	Cotton	N, P, S, Zn, B
Kovilpatti	750	Vertic Inceptisol	Cotton	N, P
Bellari	500	Vertisol	Postrainy Sorghum	N, P, Zn, Fe
Bijapur	680	Vertisol	Postrainy Sorghum	N, Zn, Fe
Jhansi	1020	Inceptisol	Rainy season Sorghum	N
Solapur	720	Vertisol	Postrainy Sorghum	N, P, Zn
Agra	665	Inceptisol	Pearl millet	N, K, Mg, Zn, B
Hisar	412	Inceptisol	Pearl millet	N, Mg, B
SK. Nagar	550	Aridisol	Pearl millet	N, K, S, Ca, Mg, Zn, B
Bangalore	925	Alfisol	Finger millet	N, K, Ca, Mg, Zn, B
Arjia	650	Vertisol	Maize	N, Mg, Zn, B
Ballowal Saunkri	1000	Inceptisol	Maize	N, K, S, Mg, Zn
Rakh-Dhiansar	1200	Inceptisol	Maize	N, K, Ca, Mg, Zn, B

Source: Srinivasarao and Vittal (2007).

rainfed regions are prone to multinutrient deficiency, balanced use of essential inputs in rainfed crops is rarely achieved. There are wide differences in the extent of inputs used for irrigated compared with rainfed regions because of numerous uncertainties in the crop production in rainfed agriculture. The vast majority of rainfed farmers in remote areas still practice low external input or no external input (subsistence) farming which is well integrated with livestock, particularly small ruminants. About 30% of the rainfed farmers in many remote areas of the country do not use any chemical fertilizers or pesticides (Venkateswarlu, 2008). Thus; there is a rapid decline of crop response ratio to applied fertilizer nutrients (NPK). The data in Figure 11compares the fertilizer consumption in rainfed and irrigated areas in high grain producing states of India.

3.6 Low Investment Capacity

Rainfed agriculture in India comprises of small and marginal farmers who accounted for ~81% of operational holdings in 2002–2003 compared with 62% in 1960–1961. Similarly, the land area operated by small and marginal farmers increased from about 19–44% during the same period. However, the monthly income and consumption figures across different land-holding classes show that marginal and small farmers have lower savings compared to the medium and large farmers. The monthly consumption of marginal farmers in 2003 was Rs 2482 (1 US dollar = ~64 Indian rupees) and the monthly income was Rs 1659 with negative savings of Rs 823, and of Rs 655 for small farmers. Thus, small holdings need credit for both

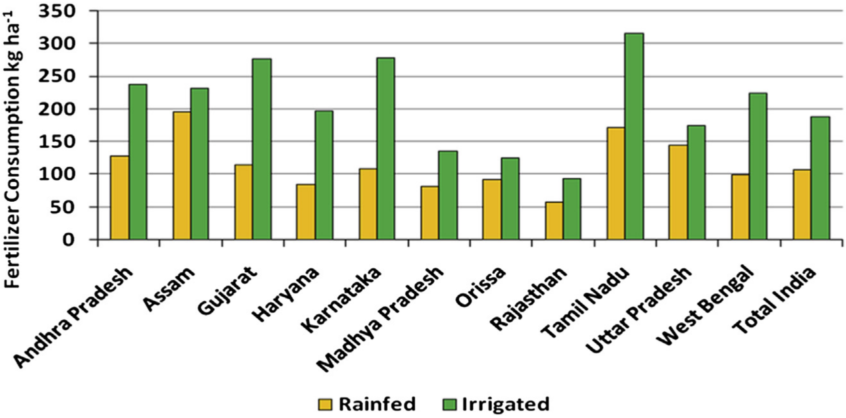

Figure 11 Comparative consumption of fertilizers (NPK) in rainfed and irrigated farming areas. *Source:* Srinivasarao et al. (2014).

consumption and investment. The credit for the small and marginal farmers from formal institutional sources are lower than those of large farmers and the reverse is true in the case of informal sources. The dependence on money lenders remains the highest for submarginal and marginal farmers. Dependence of small and marginal farmers on informal sources (money lenders) is high even in states like Andhra Pradesh, Punjab, and Tamil Nadu. The small farmers need a level playing field with large farms in terms of access to land, water, inputs, credit, technology, and markets.

3.7 Poor Market Linkages

Most of the rural areas are characterized by a subsistence economy. The surplus farm produce is sold only if family requirements are met. Further, individual production units (families) operate independently which makes it difficult to pool the produce for an efficient marketing. The present marketing system in most villages has numerous constraints. Traditional markets are unorganized, unregulated, and nonprofitable. The traditional markets are dominated by middlemen, and are characterized by unreliable marketing channels (Dixit et al., 2013). Facilitating market linkage involves a clear understanding of the demand and supply situation, transient storage opportunities, transport infrastructure, and easy access to markets. The strategy is to intervene at any of these steps in the value chain to enhance farmers' share in the retail market price.

In recent years, there has been some form of contract arrangements in several agricultural crops including tomatoes (*Lycopersicon esculentum*), potatoes (*Solanum tuberosum*), chillies (*Capsicum annuum*), baby corn (*Zea mays*), rose (*Rose* spp.), onions (*Allium cepa*), cotton (*Gossypium* spp.), wheat (*Triticum* spp.), basmati rice (*Oryza sativa*), groundnut (*Arachis hypogaea*), flowers, and medicinal plants. New production–market linkages in the food supply chain are spot or open market transactions, and as agricultural cooperatives and contract farming. One of the most successful producer organizations is the Indian dairy cooperative, which in 2005 had a network of more than 100,000 village level dairy cooperatives with 12.3 million members (Birthal et al., 2008). Another major problem that small farmer's face is that of the price volatility. There also exists a large gap between producer and consumer prices (Mahendra Dev, 2011). There are different models for collective marketing by the small and marginal farmers. These include self-help group model, cooperative model, small producer cooperatives and contract farming, *Apni Mandi* in Punjab, *Rytu Bazars* in Andhra Pradesh, and dairy cooperatives.

4. CROPS AND CROPPING SYSTEMS

4.1 Cropping Patterns

Predominant rainfed crops grown in India include: coarse cereals (85%), pulses (83%), oilseeds (70%), and cotton (65%). In arid regions, single crop system involving a long fallow period (October to June) is a rule rather than an exception. Mixed or intercropping is common as a means of insurance and risk minimization. A large proportion of Vertisols in the semiarid region are left fallow during the rainy season due to water logging and drainage problem. A postrainy season crop is raised on the moisture stored in the soil profile. Sorghum (*Sorghum bicolor*), chickpea (*Cicer arietinum*), and to a lesser extent, safflower (*Carthamus tinctorius*) are commonly grown in Central India. These crops are grown either as sole crops or in intercropping combinations. In the North Central Plains, the main crop wheat is mostly grown as a sole crop, but is occasionally intercropped with chickpea. Common cropping systems in Vertisols are based on cotton. The cotton-based systems are cultivated on soils on the plateau or upper parts of the landscape as these soils are better drained than those at the lower part of the slope. On Alfisols, rainy season cropping is common, except on deeper soils where double cropping is practiced in years with good rainfall.

Cropping patterns in India underwent several changes with the advent of modern agricultural technology, especially during the period of the Green Revolution in the late 1960s and early 1970s. There is a continuous surge for diversified agriculture in terms of crops, primarily because of economic considerations. Changes in cropping patterns are the outcome of the interactive effects of many factors which can be broadly categorized into the following five groups (RBI, 2007):

1. Resource-related factors such as irrigation, rainfall, and soil fertility.
2. Technology-related factors including not only seed, fertilizer, and water technologies, but also those related to marketing, storage, and processing.
3. Household-related factors such as food and fodder self-sufficiency requirement as well as investment capacity.
4. Price-related factors including output and input prices as well as trade policies and other economic policies that affect these prices either directly or indirectly.
5. Institutional and infrastructure-related factors covering farm size and tenancy arrangements, research, extension and marketing systems, and government regulatory policies.

Data in Figure 12 show that sharp increase in the areas under maize, soybean (*Glycine max*), and cotton occurred over a short period at the cost of area under coarse cereals like sorghum, and pearl millet (*Pennisetum glaucum*) primarily because of higher returns. Such changes in crop patterns will have implications to fodder availability for livestock. This trend is likely to increase even further by 2030.

The changes in cropping pattern also have implications on resource use. Continuous monocropping increases vulnerability of farmers to weather risks, degrades soil fertility, depletes groundwater, and increases build up of pests and diseases. These issues have to be addressed through both technological and policy interventions. There is a need to evolve management practices for farmer's preferred crops without degradation of the natural resource base; and also there is need to define agroecological zones where such cropping patterns can be adopted sustainably. Simultaneously, need-based policy incentives are required to encourage farmers to adopt agroecology-compatible cropping patterns so that the farmers' income is enhanced and the resource base is also restored and sustained.

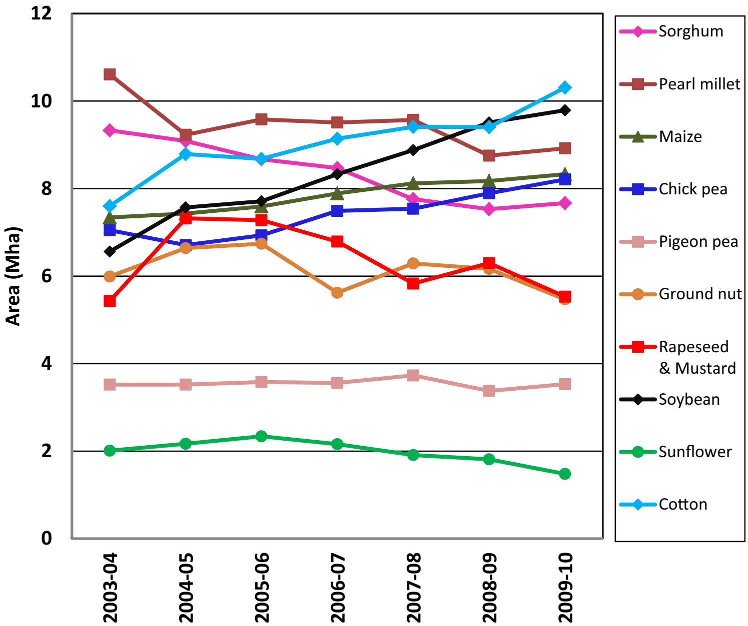

Figure 12 Recent trends showing a shift in the cultivated area under major rainfed crops. *Source:* CRIDA (2011).

4.2 Production and Productivity

India's population is expected to reach 1.45 billion by 2025 from 1.14 billion in 2011 and the demand for food grains is projected to be 308.5 Mt by 2030. However, the production of food grains is projected to be lower, leaving a deficit of 43.1 Mt (Chand, 2007). Thus, productivity enhancement in rainfed areas will play a major role in minimizing the deficit, and must have focused research and development programs and policy support. Food production in India must increase by about 5 Mt annually for the next 25 years to ensure food and nutritional security for the burgeoning population (Kanwar, 2000). The rainfed areas that cover almost 60% of the total land area under agriculture in India need to contribute a greater share to the future food needs of the country (Kanwar, 2000). As rainfed production is spread over different climatic regions, there exists a vast scope for raising diversified crops, while also enhancing agricultural productivity under rainfed conditions. India made significant progress in agricultural production since 1950s in food grain production from 50 Mt in 1950–1951 to 241 Mt in 2010–2011, culminating in self-sufficiency and surplus production; and the food production was mainly achieved through the introduction of HYV, and the implementation of fertilizer technology, popularly called as Green Revolution especially in resource endowed regions. However, the data in Figure 13 show rather a situation of stagnation in

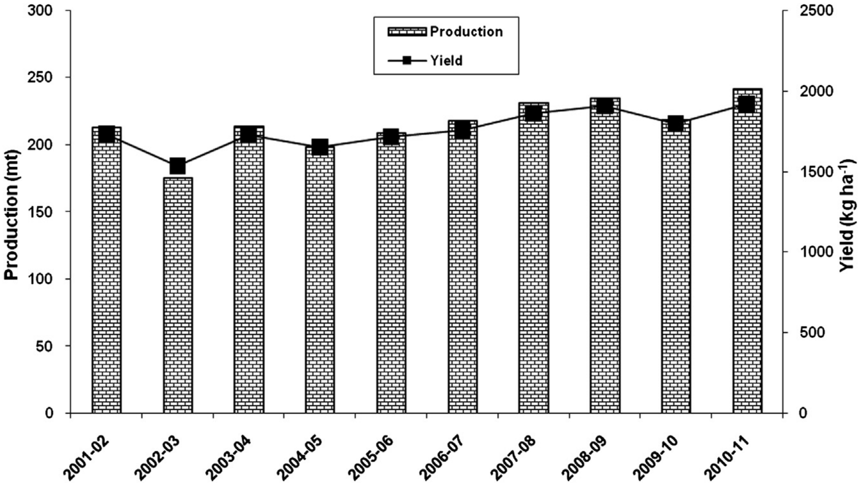

Figure 13 Total food grain production in India versus yield over the last 10 years. *Source: DOAC (2013).*

both food grain production and yield for the decade ending 2010–2011. A large proportion of coarse cereals, pulses, and oilseeds and a significant proportion of rice are grown under rainfed conditions. For the decades during 1998–1999 and 2008–2009, the area sown to coarse cereals decreased by 8% (from 31 to 28 Mha) (Table 9), but the production increased by 20% because yield increased from 1042 to 1357 kg ha^{-1} (Raju et al., 2010).

Within the coarse cereals, the area and yield increases were more conspicuous in the case of maize, but less area was sown to sorghum and pearl millet during TE 2008–2009 than during TE 1998–1999. In the case of pearl millet, the area declined from 9.65 to 9.28 Mha, but the yield increased from 776 to 981 kg ha^{-1} resulting in an increase in production by 21%. Whereas the area did not change between TE 1998–1999 and TE 2008–2009 and it stabilized at ~23 Mha, the production increased by about 0.5 Mt (3%) because of a marginal improvement in yield from 612 to 632 kg ha^{-1}. During the last decade, the area, production, and productivity of oilseeds increased by 2.6%, 16.1%, and 13.1%, respectively. Within oilseeds, the area sown to groundnut decreased from 7.4 Mha during TE 1998–1999 to 6.0 Mha during TE 2008–2009. In case of oilseeds, a slight increase in yield was observed in rapeseed and mustard (*Brassica* spp.) (2.2%) and groundnut (2.3%), and even lower growth in soybean (1.2%). Increase in yields of coarse cereals plus pulses (2.3%) and coarse cereals plus pulses plus oilseeds (2.2%) were only marginally higher than that of rice (1.4%) and much higher than that of wheat (0.5%). All the three crop groups (e.g., coarse cereals, pulses, and oilseeds) grown under rainfed conditions, had strong increase in yield and production for the decade ending in 2010–2011, and also compared favorably with that of rice and wheat (Raju et al., 2010). An analysis of the growth of major rainfed crops showed that there were significant production gains during the decade of 1998–1999 to 2008–2009, and these gains were largely because of increase in yield per unit area. However, in most cases, the rate of increase in production did not exceed that of the population growth, which has strong implications to food security (Venkateswarlu and Prasad, 2012). The production of coarse cereals during 1997–1998 to 2007–2008 increased at the rate of 2.2%, although the area declined by 0.46% (Figure 14). Among the coarse cereals, the rate of yield increase was the highest for pearl millet (3.09%) and the lowest for sorghum (1.62%). The rate of yield increase of sorghum was not high enough to offset the sharper decline in its area. Thus total production declined at a rate of 1.12% year^{-1}. Nonetheless, the rate of yield increase in coarse cereals was more than that of rice and wheat. The low

Table 9 Area, production, and yield of major rainfed crops in India

	Area (Mha)		Production (Mt)		Productivity (kg ha^{-1})	
Crop/crop group	**TE 1998–1999**	**TE 2008–2009**	**TE 1998–1999**	**TE 2008–2009**	**TE 1998–1999**	**TE 2008–2009**
Sorghum	10.67	7.92	8.96	7.44	837	942
Pearl millet	9.65	9.28	7.49	9.09	776	981
Maize	6.26	8.06	10.91	17.93	1743	2220
Coarse cereals	**30.66**	**28.21**	**31.95**	**38.24**	**1042**	**1357**
Chickpea	7.63	7.64	6.17	6.38	809	834
Pigeonpea	3.44	3.56	2.41	2.55	698	716
Pulses	**22.94**	**22.97**	**14.04**	**14.51**	**612**	**632**
Coarse cereals + Pulses	**53.60**	**51.18**	**45.99**	**52.74**	**858**	**1030**
Groundnut	7.36	6.02	8.33	7.07	1131	1163
Castor*	7.24	7.60	8.36	9.36	1165	1233
Sunflower	1.83	1.96	1.03	1.28	570	657
Soybean	5.98	8.91	6.33	9.91	1055	1113
Rapeseed and mustard	6.70	6.31	5.67	6.82	851	1080
Oilseeds	**26.23**	**26.92**	**23.48**	**27.26**	**895**	**1012**
Coarse cereals + Pulses + Oilseeds	**79.83**	**78.10**	**69.47**	**80.00**	**870**	**1024**
Cotton	9.11	9.32	2.12	4.01	232	430
Rice	43.89	44.42	83.45	96.41	1901	2170
Wheat	26.70	27.93	69.00	78.35	2585	2806

TE, Triennium ending.

Values in bold indicate the total for each crop groups.

*Data of castor refer to TE 1997–1998 and TE 2007–2008.

Source: Raju et al. (2010).

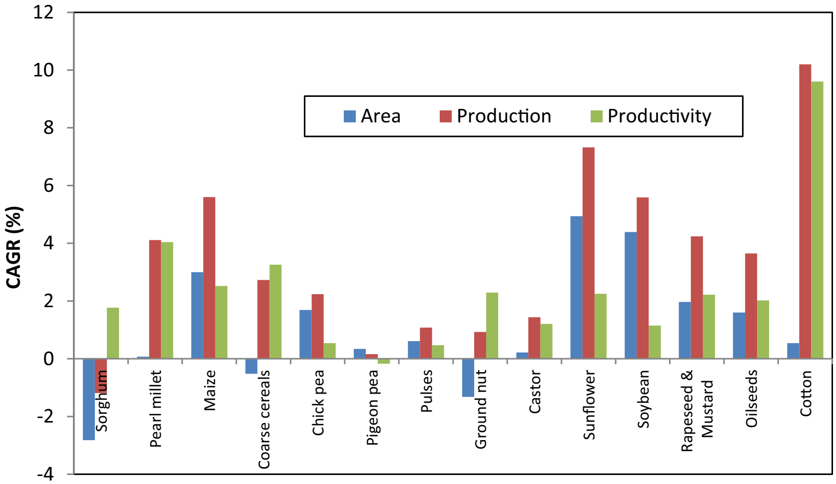

Figure 14 Compound annual growth rate (CAGR) in area, production, and yield of major crops in India, 1998–1999 to 2008–2009. *Source:* *Raju et al. (2010)*.

production of pulses continues to be of concern, because neither the area nor the yields have improved, resulting in a low increase in total production of 0.92% year^{-1}. Consequently, the per capita production of pulses in India has declined. There are mixed results regarding the performance of oilseeds. For example, a faster rate of increase in yield was observed in rapeseed and mustard (3.51%) and groundnut (1.77%), but slower increase in the case of soybean (0.3%). Increase in total production of soybean and sunflower (*Helianthus annuus*) was a result of increase in the area. In contrast, there was a significant decline in the area under groundnut as its profitability was affected by yield and the price risk. Introduction of Bt cotton played an important role and its yield increased strongly at a rate of ~9.60% year^{-1}, leading to a rate of growth of total production of 10% year^{-1}.

4.3 Potential Productivity and Yield Gaps

Potential yield under rainfed conditions is the maximum obtained by a crop cultivar grown under the water limited and nutrient non limiting environment and when other biotic stresses are effectively controlled (Ittersum et al., 2013). Potential yields are generally computed for optimum or recommended sowing dates, planting density, and the suitable cultivars for that region are grown with RMPs. The average/farmers' yield is the yield achieved by farmers in the region under the most widely used management practices. Yield gap is the difference between the potential yield and the actual yields under farmers' conditions. Yield gap analysis provides the foundation for identifying the most important crop, soil, and management factors limiting current farm yields and to identify and develop improved practices for bridging the yield gap.

For assessing the potential yields attained by various crops, the maximum yields obtained at the experimental stations of the AICRPDA and the yields obtained in the demonstrations being conducted under the supervision of scientists were considered. For the farmers' yields, the primary source is the district average yields of the recent years (2011–2013). Crop yields obtained in farmers' fields at a location were compared with the mean potential yield to calculate the yield gap. In addition, the constraints to attain the potential productivity under the soil and climatic condition were identified. The AICRPDA has 25 centers that represent a wide range of soil types and rainfall conditions; and the potential yields obtained at a particular research station were compared with the farmers' yields of that district for quantifying the yield gaps. It is always a matter of concern for the research managers and development administrators to ensure that the real potential of any crop variety is realized at the farmers' field for attaining the potential productivity.

4.3.1 Alfisols/Oxisols

Alfisols cover an area of 42 Mha, and are predominant in the states of Andhra Pradesh (8.3 Mha), Madhya Pradesh (7.3 Mha), Karnataka (5.4 Mha), Tamil Nadu (3.9 Mha), and Uttar Pradesh (1.7 Mha). Oxisols are distributed in an area of 37 Mha, and are concentrated in the states of Odisha (23 Mha), Assam (6.2 Mha), Jharkhand (4.7 ha) etc. (Bhattacharyya et al., 2013). The experimental stations of AICRPDA representing these soil groups are located in Phulbani, Ranchi, Anantapur, and Bengaluru, from Odisha, Jharkhand, Andhra Pradesh, and Karnataka states, respectively. Rainfed rice, groundnut, finger millet (*Eleusine coracana*), pigeonpea (*Cajanus cajan*), sorghum, and castor (*Ricinus communis*) are among the predominant crops grown on Alfisols/Oxisols. Potential yields observed in rice varies from 2.8 to 3.0 Mg ha^{-1} (Mg = megagram = metric ton = t) due to the adoption of in situ moisture conservation practices and timely pest management practices including weed control (Table 10). Rice yields are the highest with integrated nutrient management (INM) practices with 15 kg N through farmyard manure (FYM) plus 20 kg N through urea at Phulbani (Mishra et al., 2012). The highest productivity of groundnut is realized

Table 10 Agronomic yield potential of crops on Alfisols/Oxisols under rainfed farming

		*Potential yield (Mg ha^{-1})			BMPs			
Crop	**Ecoregion**	**Range**	**Mean**	**Variety**	**Land treatment**	**NPK fertilizer**	**Manure**	**References**
Upland rice	Semiarid/subhumid	2.8–3.0	2.9	Pathara/Heera/Vandana	In situ soil moisture conservation/weed management/pest management	40/60/80	FYM/glyricidia	Dixit and Gupta (2000); Vittal et al. (2003); AICRPDA (2011)
Sorghum	Semiarid	3.5–4.3	3.9	NTJ2/SPV422/SSV84	Weed management/deep tillage	60/40/30	FYM/glyricidia	Murthy et al. (2007); Sharma et al. (2005); Reddy et al. (2007)
Finger millet	Semiarid	4.4–5.2	4.8	KM65/HR911/JNR852/L5	Seed priming/weed management	40/50/60	FYM/GLM	Kumara et al. (2007); Ramachandrappa et al. (2013)
Groundnut	Semiarid	2.5–3.1	2.8	TMV2/K6/TPT4/TPT1 Konkan Tapora/Konkan Gaurav	Ploughing-blade harrowing/weed management/primary tillage + two intercultivations	20/40/40	GNS/FYM/INM	Srinivasarao et al. (2012b); Vittal et al. (2004); Patil et al. (2010); AICRPDA (2010)

Sunflower	Semiarid	2.8–3.2	3.0	KBSH1/ MSFH6/ MSFH8	Rotavator tillage	60/80 120	FYM	Rasool et al. (2013); Gopinath et al. (2013)
Maize	Semiarid	6.5–7.5	7.0	DHM111/ DHM117	CA/Balanced fertilization/in situ soil moisture conservation/ INM/deep tillage/SSNM	120/ 150	Gliricidia/ Green leaf manuring/ FYM	Srinivasarao et al. (2011a); Sumanta Kundu et al. (2013); Hadda and Arora (2006)
Castor	Semiarid	1.2–1.3	1.3	DCS9/ DCH32	Minimum tillage	40/20/ 60	Green leaf manuring (Leucaena), glyricidia/ FYM	Sharma et al. (2005) and Ramesh et al. (2013)

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*The maximum yields recorded at the AICRP Dryland centers were considered as the potential yields.

with improved cultivars such as TMV-2, TPT-4, TPT-1, timely sowing and intercultivation practices, gypsum application, and timely pest control measures at Anantapur. In the case of finger millet, the staple food for much of Karnataka, yields of up to 4.8 Mg ha^{-1} have been obtained through adoption of RMPs such as seed priming, weed management, and INM involving the use of groundnut shells and FYM. In case of maize, potential yields up to 7.0 Mg ha^{-1} are obtained at Hyderabad by using single-cross/double-cross hybrids such as DHM-11, DHM-117, and balanced fertilization; and by the adoption of soil and moisture conservation practices. Management practices such as site specific nutrient application, in situ soil moisture conservation, supplemental irrigation, INM, effective weed management, deep and rotavator tillage can contribute toward achieving the potential productivity in Alfisols/Oxisols (Figure 15).

The yields attained at farmers' fields for the commonly grown crops of Alfisols/Oxisols at different locations of the country and the corresponding yield gaps are presented in Table 11. In case of rainfed rice, yields recorded at farmer's fields range from 1.0 Mg ha^{-1} in Palamu, Jharkhand to 1.4 Mg ha^{-1} in Sonitpur district, Assam, resulting in a yield gap of 1.7 Mg ha^{-1}. In case of groundnut, farmer's yields at Anantapur and Bengaluru range from 456 to 510 kg ha^{-1}, resulting in a yield gap of 2.3 Mg ha^{-1}, which offers significant scope for improving the productivity. Crop yields at farmers' fields in case of other major crops grown on Alfisols (i.e., sorghum, maize, sunflower, and castor) are lower, resulting in significant yield gaps. Differences between the potential and farmers yields are relatively higher in maize (5.0 Mg ha^{-1}) among all the crops grown on Alfisols, followed by sorghum (3.3 Mg ha^{-1}) and sunflower (2.4 Mg ha^{-1}).

Constraints for achieving potential productivity on Alfisols can be broadly categorized into soil and moisture related, crop related and those pertaining to socioeconomic aspects (Table 12). Arid conditions with low and highly variable rainfall coupled with shallow depth and low water retention characteristics of Alfisols are some of the major constraints. Crusting and surface sealing are among typical characteristic of Alfisols, which affect seedling emergence resulting in poor stand. Inherently low soil fertility, imbalanced nutrient application, depletion of SOC, and lack of crop residue recycling and micronutrient deficiency are some of the nutrition-related constraints which are widespread in crops grown on Alfisols. Small holdings, low investment capacity, lack of adequate credit facilities, and timely availability affect timeliness of operations in rainfed systems. Access to machinery and information related to improved practices in agriculture, weather

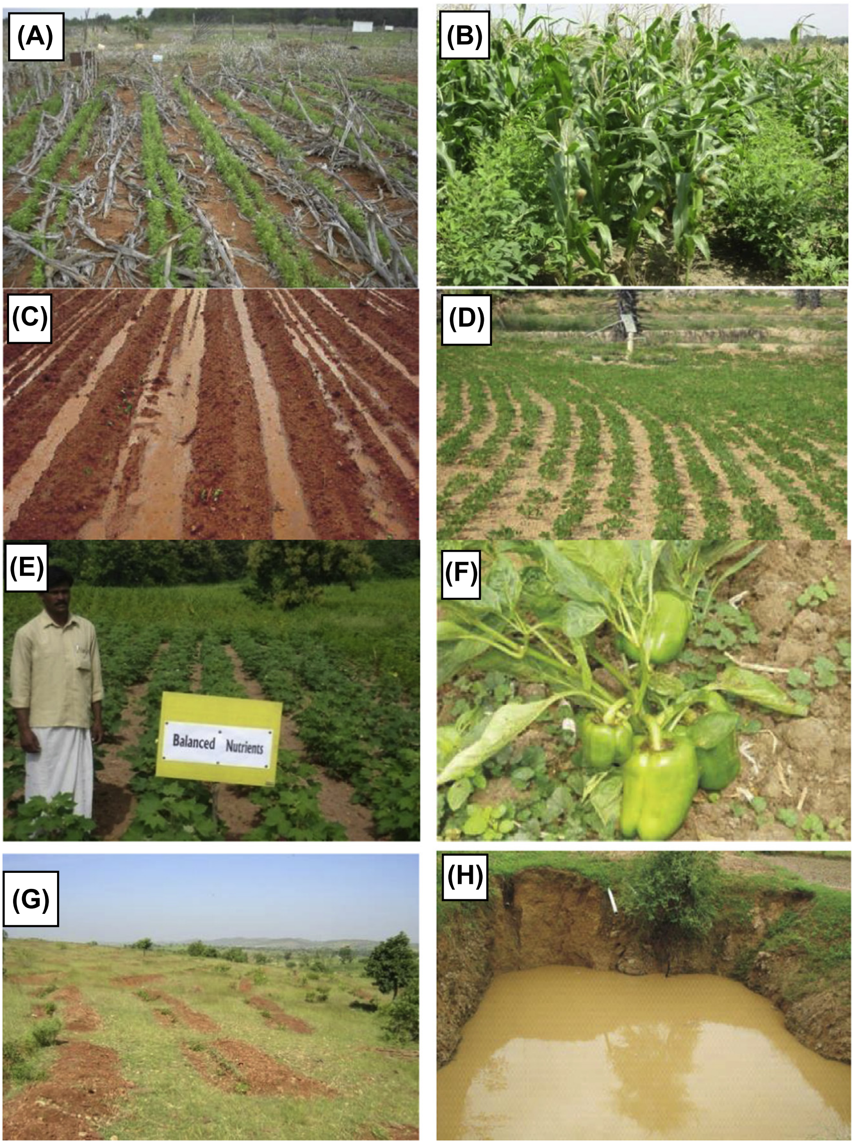

Figure 15 Recommended management practices: (A) Residue incorporation; (B) Legume intercrop; (C) Ridge and furrow; (D) Sowing across the slope; (E) Balanced nutrition; (F) Vermicompost use in vegetables; (G) Contour bunding; (H) Recharging open wells with runoff water from fields.

Table 11 Yield gap of crops on Alfisols/Oxisols under rainfed farming

Crop	Ecoregion	Mean yield (Mg ha^{-1})		Yield gap (Mg ha^{-1})	References
		Potential yield	*Farmers' yield		
Upland rice	Semiarid/subhumid	2.9	1.2	1.7	Behera et al. (2007); Thakur et al. (1999); Mishra et al. (2012)
Sorghum	Semiarid	3.9	0.6	3.3	Keerio and Singh (1985); Laddha and Totawat (1997); Sahrawat et al. (1996); AICRPDA (2012); Sharma et al. (2005)
Finger millet	Semiarid	4.8	2.9	1.9	Adikant and Singh (2009); AICRPDA (2012); Ramachandrappa et al. (2010, 2013)
Groundnut	Semiarid/arid	2.8	0.7	2.1	Chatterjee et al. (2005); Vittal et al. (2004); Bhatia et al. (2006)
Sunflower	Semiarid	3.0	0.6	2.4	Gurumurthy et al. (2008) and Rasool et al. (2013)
Maize	Semiarid	7.0	2.0	5.0	Jat et al. (2013); Kaul et al. (2008); Nanjappa et al. (2001)
Castor	Semiarid	1.3	0.4	0.9	Vani and Bheemaiah (2004) and Murthy and Padmavati (2009)

* The average district yields recorded during the last 2 years (2010–2011) where the AICRPDA centers are located (representing the specific soil, climatic, and rainfed growing environments) were considered as farmers' yields. The source is the published documents of Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India.

Table 12 Constraints to achieving potential yields on Alfisols under rainfed farming

Soil order	Major crops	Soil, water, crop, machinery etc., constraints	Socioeconomic and institutional constraints	References
Alfisols/Oxisols	Upland rice Sorghum Finger millet Groundnut Sunflower Maize Castor Cotton Pigeonpea Blackgram Green gram Chickpea Cowpea Horsegram Minor millets	• Poor crop stand due to surface crusting and poor seed germination • Depletion of soil organic carbon and lack of crop residue recycling • Low soil fertility • Frequent occurrence of weather aberrations (Late onset, midseason droughts, early withdrawal of monsoon, etc.) • Water logging under heavy rains and soil erosion • Soil acidity • Late sowing/planting • Imbalanced nutrient application	• Small farm holdings • Market linkages • Low seed replacement • Accessibility to technology and poor enabling mechanism • Insufficient credit systems and its timely availability • Weak village-level institutions • Low investment capacity of farmers • Labor availability and high cost of labor • Limited farm mechanization • Limited awareness about weather aberrations	Joshi et al. (2005); Maurya and Vaish (1984); Cheralu (2009); Vittal et al. (2004); Srinivasarao et al. (2013a, 2013c); Shalander et al. (2011); Venkateswarlu and Prasad (2012); Kundu et al. (2013); Gopinath et al. (2012); NICRA (2014); Lal (2010)

(*Continued*)

Table 12 Constraints to achieving potential yields on Alfisols under rainfed farming—cont'd

Soil order	Major crops	Soil, water, crop, machinery etc., constraints	Socioeconomic and institutional constraints	References
		• Micronutrient deficiency in particular Zn deficiency. • Emergence of K deficiency in poor mica red soils • Salt affected soils • Lack of multicrop seed drills • Quality seed availability • Timely availability of seed and fertilizers at village levels • Sulfur deficiency in oil seed and pulse crops. • Lack of quality and timely availability of biofertilizers • Poor adoption of water harvesting and efficient utilization	• Limited reach of agro-advisory • Lack of field implementation contingency measures during weather aberrations	

forecast and advisories, and possible contingency measures, are limited. All these factors lead to lower productivity of crops, resulting in significant yield gaps in Alfisols.

4.3.2 Vertisols

Vertisols cover an area of 26 Mha, and are predominant in the states of Madhya Pradesh (10.7 Mha), Maharashtra (5.6 Mha), Karnataka (2.8 Mha), Andhra Pradesh (2.2 Mha), and Gujarat (1.8 Mha) (Bhattacharyya et al., 2013). The AICRPDA centers located on Vertisols are at Rajkot, Indore, Rewa, Akola, Kovilpatti, Bellary, Bijapur, Solapur, and Arjia. Vertisols in India are distributed across varying rainfall regimes ranging from 590 mm in Rajkot to 980 mm in Rewa. The predominant crops grown in these regions are groundnut, soybean, cotton, maize, and pigeonpea during the rainy season and safflower, chickpea, sunflower, and sorghum during the postrainy season.

Sorghum is widely grown on Vertisols during the postrainy season in the states of Maharashtra and Karnataka. Grain yields of up to 7.8 Mg ha^{-1} have been realized with the adoption of improved varieties such as NTJ2, SPV422, SSV84 and by adoption of site-specific soil and moisture conservation practices such as ridge and furrow/broad bed and furrow method of sowing, ensuring timely sowing and optimum crop stand, timely and effective pest control measures (Reddy et al., 2007; Mudalagiriyappa et al., 2012). Soybeans are widely grown in the states of Madhya Pradesh and Maharashtra on Vertisols and potential production of 3.1 Mg ha^{-1} is realized with the adoption of RMPs (Table 13). Maize grain yield of 8 Mg ha^{-1} has been reported at Arjia through the adoption of HYVs such as HM10, PM3, P3501, and by adoption of RMPs. Production potential up to 2.0 Mg ha^{-1} is realized in postrainy season crops, such as chickpea and safflower grown on residual soil moisture (Figure 16).

The actual productivity realized in farmers' fields is less than 1 Mg ha^{-1} in crops such as sorghum, pigeonpea, chickpea, safflower, leaving a yield gap of 7.1, 1.7, 1.3, 1.4 Mg ha^{-1}, respectively (Table 14). Groundnut is grown on Vertisols in Rajkot area of Gujarat and the productivity at farmers' fields is relatively higher compared to that on Alfisols, but the yield gap is similar due to a higher potential productivity of Vertisols. Cotton is one of the important crops grown on Vertisols in central India and the yield gap is large because of no adoption of BMPs.

Some of the major constraints for realizing potential productivity are associated with the inherent properties of Vertisiols such as difficulties associated with the workability under high moisture conditions, deep cracking

Table 13 Agronomic yield potential of crops on Vertisols under rainfed farming

		Potential yield (Mg ha^{-1})			BMPs			
Crop	**Ecoregion**	**Range**	**Mean**	**Variety**	**Land treatment**	**NPK fertilizer**	**Manure**	**References**
Sorghum	Semiarid	7.5–8.1	7.8	NTJ2/M-35-1/SPV422/SSV84	Weed management/compartmental bunding/ridge and furrow/broad bed furrow/sowing across the slope	120/50	FYM	Mudalagiriyappa et al. (2012); Reddy et al. (2007); Tamboli et al. (2011); Upadhya et al. (2010)
Finger millet	Semiarid	3.5–5.0	4.3	MR1/MR2/TRY1	Square planting/tillage blade harrowing/weed management	90	FYM/INM	Srinivasarao et al. (2012a) and Chidda Singh (1983)
Maize	Semiarid	7.5–8.5	8.0	HM10/PM 3 Nithya Shree/Buland/P3501	Nutritional management/weed management	60/80	SBZn/INM/crop residues/FYM	Rajashekhara Rao et al. (2010); Kumpawat (2004); Jat et al. (2005); AICRPDA (2009)
Pigeonpea	Semiarid	2.0–2.8	2.4	LRG30/ICPL87119/ICPL-85012	Weed management/plant spacing's	25	INM/FYM/Leucaena loppings	Sharma et al. (2010, 2012); Tuppad et al. (2012); Gabhane et al. (2006)

Soybean	Semiarid	3.0–3.2	3.1	JS335/NRC 7	Weed management/in situ mulching/conservation tillage	20/30/40	FYM/INM/crop residues	Vittal et al. (2003) and Sharma et al. (2006)
Safflower	Semiarid	1.9–2.1	2.0	DSH129	Weed management	40/60	FYM/INM/vermicompost	Nimbkar (2008) and Srinivasarao et al. (2012a)
Chickpea	Semiarid	1.9–2.5	2.2	JG 16/JG 11/JG 315	Weed management/deep ploughing/sowing time/paired row sowing/ridge sowing	20/40	INM	Abraham et al. (2010); Tomar (2010); Vijaya Sankar Babu et al. (2006)
Groundnut	Semiarid	3.8–4.0	3.9	TG 26/GG 7/TPG 41/Girnar 2&3	Weed management/ridge sowing	40/50	FYM/crop residue/vermicompost SSNM	Akbari et al. (2010); AICRPDA (2010); Srinivasarao et al. (2011b)
Cotton	Semiarid	2.2–2.4	2.3	RCH 530/Tulasi 117/Mallika/Jackpot/NH545/PSS-2 (Arvinda)	Paired row sowing/in situ mulching	100/120	FYM/SSNM	NICRA-AICRPDA (2012); Srinivasarao et al. (2013b)

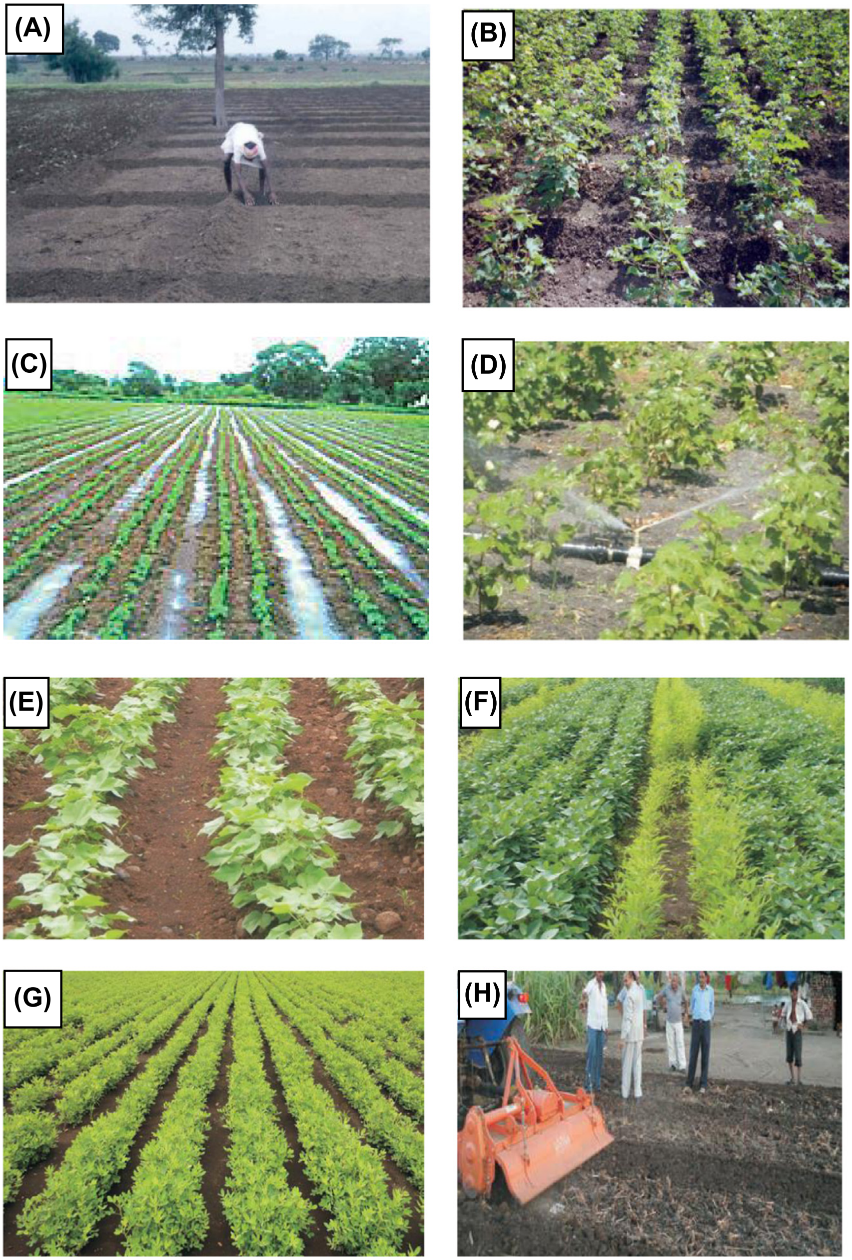

Figure 16 Recommended management practices: (A) Compartmental bunding; (B) Ridge and furrow; (C) Broad bed furrow; (D) Supplemental irrigation; (E) Furrow openings in cotton; (F) Ridge and furrow system in soybean + pigeonpea; (G) Improved variety of groundnut; (H) Incorporation of cotton stalks with rotavator.

Table 14 Yield gap of crops on Vertisols under rainfed farming

Crop	Ecoregion	Mean yield (Mg ha^{-1}) Potential yield	Farmers' yield	Yield gap (Mg ha^{-1})	References
Sorghum	Semiarid	7.8	0.7	7.1	Sahrawat et al. (1996); Patil and Sheelavantar (2004); Marutisankar et al. (2008)
Finger millet	Semiarid	4.3	2.4	1.9	Apoorva et al. (2010)
Maize	Semiarid	8.0	1.7	6.3	Meena et al. (2009); Kanwar and Virmani (1987); Jat et al. (2010)
Pigeonpea	Semiarid	2.4	0.7	1.7	Rathod et al. (2004) and Bhatia et al. (2006)
Soybean	Semiarid	3.1	1.3	1.8	Meghvansi and Mahna (2009); Ghosh et al. (2006); Sharma et al. (2006); Bhatia et al. (2006)
Safflower	Semiarid	2.0	0.6	1.4	Vittal et al. (2003) and Raju et al. (2013)
Chickpea	Semiarid	2.2	0.9	1.3	Reddy (2009); Neenu et al. (2014); Bhatia et al. (2006)
Groundnut	Semiarid	3.9	1.6	2.3	Sutaria et al. (2010) and Sharma et al. (2014)
Cotton	Semiarid	2.3	0.4	1.9	Nagdeve et al. (2008)

under deficit moisture situations, and proneness to erosion among others (Table 15). Excess moisture at some times and moisture stress at others are the twin problems of these soils, and lack of varieties which can tolerate both drought and excess moisture is a serious constraint. Optimum crop stand in postrainy season crops, low fertility, high runoff and associated water and nutrient losses, unbalanced fertilizer use, resource poor farmers and lack of credit availability, nonavailability of quality seed, lack of awareness about RMPs, limited crop/weather insurance coverage, and finally rapid decline of groundwater levels are other important constraints for realizing potential productivity in these soils.

4.3.3 Inceptisols

Inceptisols cover the largest area accounting for 118 Mha, and are predominant in Uttar Pradesh (21 Mha), Madhya Pradesh (17.0 Mha), Maharashtra (12.3 Mha), Gujarat (10.1 Mha), Andhra Pradesh (9.9 Mha), and Odisha (7.4 Mha) (Bhattacharyya et al., 2013). Predominant crops grown are rice, maize, and pearl millet during the rainy season; and wheat, chickpea, mustard, and lentil (*Lens culinaris*) during the postrainy season. The AICRPDA centers located on this soil group are at Varanasi, Faizabad, Agra, Ballowal Saunkri, Rakh-Dhiansar, and Jhansi, and the rainfall ranges from 630 mm at Agra to 1000 mm at Ballowal Saunkri. Pearl millet is one of the important crops grown in rainfed regions of Haryana and Agra region of Uttar Pradesh. The potential productivity attained ranges from 4.1 to 5.3 Mg ha^{-1}. Practices such as high yielding hybrids, off season tillage, soil and water conservation measures (e.g., ridge and furrow sowing, timely and effective pest management practices) have contributed to realizing the potential productivity (Table 16; Figure 17). Upland rice is widely grown in Uttar Pradesh, West Bengal, and Assam and the yield potential is relatively high as compared to that obtained on Oxisols. Among RMPs for rice are appropriate drainage practices, bunding in gently sloping to lowland, integrated pest and weed management, INM, and in situ moisture conservation are critical for achieving the potential yield of 3.0 Mg ha^{-1}. Crops grown in the postrainy season, on residual moisture, and limited irrigation wherever possible, are wheat, chickpea, and mustard, and the potential productivity is $\sim$4 Mg ha^{-1}. Yields recorded under farmer's condition range from 0.6 to 1.0 Mg ha^{-1} in case of soybeans and chickpea, leaving a gap of 4.9 and 3.0 Mg ha^{-1}, respectively (Table 17). Though the productivity of rice is relatively higher compared to that on Oxisols, yet the yield gaps are of the order of 1.2 Mg ha^{-1}, which are substantial. Maize is largely cultivated

Table 15 Constraints to achieving potential yields on Vertisols under rainfed farming

Soil order	Major crops	Soil, water, crop, machinery etc., constraints	Socioeconomic and institutional constraints	References
Vertisols	Rainfed rice Sorghum Finger millet Maize Pigeonpea Soybean Safflower Chickpea Cotton Groundnut Chillies Pearl millet Sunflower	• Lack of optimum crop stand in postrainy season crops • Lack of varieties which can tolerate both drought and excess moisture • Low fertility • Weather aberrations • Frequent occurrence of droughts • Water logging during heavy rains and proneness to erosion • Poor drainage • Limited adoptability of land treatments • High runoff, water and nutrient losses	• Resource poor farmers and lack of credit availability • Non-availability/high cost of labor • Nonavailability of suitable cultivars • Nonavailability of quality seed • Inadequate and irregular power supply and limited options for providing lifesaving irrigation • High cost of inputs • Poor storage facilities • Lack of adequate marketing facilities	Selvaraju et al. (1999); Ramasundaram and Gajbhiye (2001); Srinivasarao et al. (2013a); Venkateswarlu et al. (2011); Chary et al. (2013); CRIDA (2013)

(*Continued*)

Table 15 Constraints to achieving potential yields on Vertisols under rainfed farming—cont'd

Soil order	Major crops	Soil, water, crop, machinery etc., constraints	Socioeconomic and institutional constraints	References
		• Timely availability of quality seed • Inadequate use of fertilizers (low N) • Lack of quality soil testing and timely recommendation • Unbalanced fertilizer use • Deep cracking and loss of stored soil moisture • Moisture stress at critical crop stages • Lack of sowing/ fertilizer machines for intercrops • Increased pest and diseases and nonadoption of timely control measures	• Lack of awareness about improved technology • Inadequate information about market opportunities and exploitation of middlemen • Limited crop/weather insurance coverage • Improper use of pesticides (lack of awareness) particularly in cotton • Huge postharvest losses, limited storage facility of harvested produce • Rapid decline of groundwater levels	

Table 16 Agronomic yield potential of crops on Inceptisols under rainfed farming

Crop	Ecoregion	Potential yield (Mg ha^{-1})		Variety	BMPs			References
		Range	Mean		Land treatment	NPK fertilizer	Manure	
Upland rice	Semiarid/ subhumid	2.0–4.0	3.0	Kayalni-11/ Vanaprabha/ Annada/ Govind/Birsa Dhan/ Basundhar/ NDR 97	Drainage, bunding above medium land, integrated pest, and weed management, in situ conservation	40	FYM	Adhya et al. (2008); Sarma and Sharma (2009); Singh et al. (2012); Mishra et al. (2011)
Maize	Semiarid/ subhumid	3.5–5.5	4.5	Vivek Hybrid 4/ Jawahar/ Composite Makka 12	Nutrient management, mulching practices, weed management	120	INM	Reddy and Ahmed (2000); Sharma et al. (2011); Srinivasarao et al. (2010); Kumar et al. (2014); AICRPDA (2012)
Wheat	Semiarid/ subhumid	3.9–5.1	4.5	PBW 502/PBW 343/Pusa Tripti (HD 2833)	Weed management/ sowing time	120	FYM/Crop residues	Duary and Yaduraju (2005)

(*Continued*)

Table 16 Agronomic yield potential of crops on Inceptisols under rainfed farming—cont'd

		Potential yield (Mg ha^{-1})			**BMPs**			
Crop	**Ecoregion**	**Range**	**Mean**	**Variety**	**Land treatment**	**NPK fertilizer**	**Manure**	**References**
Chickpea	Semiarid/ subhumid	3.8–4.2	4.0	BGD 72/Kabuli/ Kantewala/ Mosambi	BBF	20/50/40	Vermicompost	AICRPDA (2010); Venkatesh and Basu (2011); Ganeshamurthy et al. (2006)
Soybean	Semiarid	5.2–5.8	5.5	MACS124	Flat landform/ graded bunds/ BBF	20	FYM	Singh et al. (2007)
Pearl millet	Semiarid/arid	4.1–5.3	4.7	BJ 104/BK 560/ Nandi-70(MSH 224)	Weed management/ tillage practices/ dhaincha (*Sesbania aculeata*)	60	INM	Kumar et al. (2012) and AICRPDA (2011);
Mustard	Semiarid/arid	2.2–2.8	2.5	Coral-432/ NRCHB 5-6/ NPJ 112 (Pusa Mustard 25)/ NRCDR 601	Seed priming/ ridge and furrow/weed management	40/80	INM/FYM	Shekhawat et al. (2012)

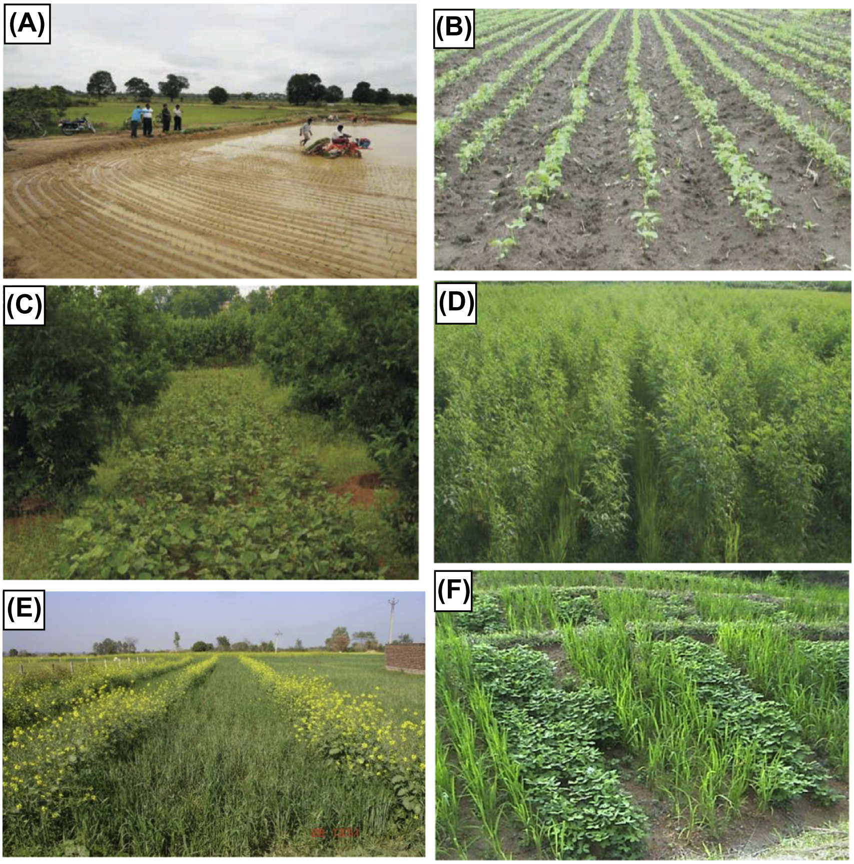

Figure 17 Recommended management practices: (A) Transplanting of rice with Paddy Transplanter; (B) Rainy season crop with ridge furrow system; (C) Custard apple (*Annona reticulata*)-based agri-horti system; (D) Ridge furrow planting of rice—pigeonpea; (E) Improved intercropping systems; (F) Intercropping of cereal—legume.

in hilly regions and the productivity is low because traditional varieties predominate rather than hybrids. Some of the constraints contributing to the low yields on Inceptisols include moisture stress at critical stages particularly for the postrainy season crops and also because of long dry spells in the rainy season; crusting and compaction; acidity; widespread deficiencies of K, S; and micronutrient (Table 18). Non availability of multiple stress tolerant crop varieties, lack of knowledge about RMPs, lack of modern agricultural implements suitable for small holding situations; low investment capacity of farmer, and inadequate access to credit facilities are some of the socioeconomic constraints in these regions.

Table 17 Yield gaps in case of crops grown on Inceptisols under rainfed farming

Crop	Ecoregion	Mean yield (Mg ha^{-1})		Yield gap (Mg ha^{-1})	References
		Potential yield	Farmers' yield		
Upland rice	Semiarid/subhumid	3.0	1.8	1.2	Vittal et al. (2004) and Mandal et al. (2010)
Maize	Semiarid/subhumid	4.5	2.0	2.5	Reddy et al. (2013); Parewa et al. (2010); Sharma et al. (2011); Sankar et al. (2006)
Wheat	Semiarid/subhumid	4.5	2.7	1.8	Tomar (2010); Vittal et al. (2004); AICRPDA (2012); Sharma et al. (2014)
Chickpea	Semiarid/subhumid	4.0	1.0	3.0	Yadav et al. (2007)
Soybean	Semiarid/subhumid	5.5	0.6	4.9	AICRPDA (2009)
Pearl millet	Semiarid/arid	4.7	1.6	3.1	Sharma et al. (2014)
Mustard	Semiarid/arid	2.5	1.5	1.0	Ghosh et al. (2005)

Table 18 Constraints to achieving potential yields on Inceptisols under rainfed farming

Soil order	Major crops	Soil, water, crop, machinery etc., constraints	Socioeconomic and institutional constraints	References
Inceptisols	Upland Rice Maize Wheat Chickpea Soybean Pearl millet Mustard Lentil Pigeonpea Blackgram	• Frequent occurrence of moisture stress at critical stages • Light textured soils and poor water retention • Soil crusting and compaction • Soil acidity • Field burning of crop residues • Lack of cow dung addition to fields (as it is used as firewood) • Emerging K, S and micronutrient deficiencies • Excess N application • Sodic soils • Lack of wider adoptability of in situ moisture conservation • Poor quality seed • Lack of seed treatment • Quality rhizobium culture and timely availability • Lack of multiple stress tolerance crop varieties	• Lack of knowledge about improved cropping system • Dominance of marginal and small farmers and low investment capacity • Lack of modern agricultural implements • Distress sale at nonremunerative prices • Crop damage due to wild animals (lack of mechanism for wild animal control at village level) • Low investment capacity of farmer and inadequate access to credit facilities	Srinivasarao et al. (2003, 2012b, 2013a); NAAS (2013); AICRPDA (2011); Vittal et al. (2004)

4.3.4 Entisols/Aridisols

Entisols/Aridisols cover a significant area of ∼92 Mha, and are predominant in Rajasthan (21 Mha), Maharashtra (9.0 Mha), Madhya Pradesh (8.1 Mha), Uttar Pradesh (4.8 Mha), Bihar (4.7 Mha), and Gujarat (4.0 Mha) (Bhattacharyya et al., 2013). The AICRPDA centers located on these soils are at Hisar and Sardar Krishinagar. The predominant crops in these centers are pearl millet, cluster bean (*Cyamopsis tetragonoloba*), mustard, and castor. The potential yields recorded on Aridisols are relatively low in comparison to that obtained on Inceptisols. The potential yields observed in case of pearl millet are ∼4.0 Mg ha^{-1} in Inceptisols compared with 2.4 Mg ha^{-1} on Aridisols (Table 19). Similarly, potential yields of chickpea and mustard on Vertisols and Inceptisols are relatively higher than those on Aridisols. Adoption of RMPs aimed at harvesting rainwater (e.g., in situ moisture conservation; chiseling and chisel ploughing; deep ploughing; ridge and furrow; and INM) are important to realizing potential yields in pearl millet and castor (Figure 18). However, the farmer's yields are much lower than the potential yields, resulting in yield gaps of 1.2 Mg ha^{-1} for pearl millet; 0.6 Mg ha^{-1} for chickpea; 0.5 Mg ha^{-1} for mustard; and 0.6 Mg ha^{-1} for cluster bean (Table 20). Constraints to realizing potential productivity in Aridisols can be broadly divided in to soil-, crop- and socioeconomic-related (Table 21). Soil-related constraints include low moisture holding capacity coupled with low and high variable rainfall, resulting in severe moisture stress of varying degrees at one or the other stages of crop growth resulting in poor crop yields. Low fertility status of soils and widespread multinutrient deficiencies; secondary salinization; wind erosion; little or no application of manures are some of the fertility-related constraints for realizing the potential productivity on these soils. Subsistence agriculture is widely practiced which has low marketable surplus. Low yields under on-farm conditions are attributed to inadequate credit facilities and low investment in agriculture. Lack of access to irrigation at critical stage of growth, low draft power availability, poor access to technology, and information are other constraints for realizing high returns in these environments.

5. OPPORTUNITIES FOR ENHANCING CROP PRODUCTIVITY

5.1 Soil Management

Soils hold the key for enhancing productivity and improving resilience against harsh climate in rainfed agriculture in India. Loss of fertile soil by

Table 19 Agronomic yield potential of crops on Entisols/Aridisols under rainfed farming

		Potential yield (Mg ha^{-1})			BMPs			
Crop	**Ecoregion**	**Range**	**Mean**	**Variety**	**Land treatment**	**NPK fertilizer**	**Manure**	**References**
Pearl millet	Semiarid/arid	2.0–2.8	2.4	ICMH 356/MPMH 17/MH1663	Weed management/conventional tillage/in situ moisture conservation/chiseling	20/40	FYM/crop residue	Srinivasarao et al. (2011b); Shalander et al. (2011); Aggarwal et al. (1997); AICRPDA (2012)
Chickpea	Semiarid	1.2–1.6	1.4	BGD103/JG11/ICCV10/RG 896	Weed management/deep ploughing/flat furrow/broad bed furrow	20/50/40	Biofertilizer/FYM	Mondal et al. (2005) and Yadav and Verma (2014)
Mustard	Semiarid/arid	1.4–2.2	1.8	Varuna, Sanjukta, RH781, RH7361,RH819	Weed management/ridge and furrow/nutrient management	50/80/100	INM	Kaushik et al. (2006)
Cluster bean	Semiarid/arid	0.8–1.4	1.1	Durgajay/Maru Guar (2470/12)/RGM-112/RGC-936	Shallow tillage/blade harrowing	25/50/50	FYM/biofertilizers	Srinivasarao et al. (2011b) and CAZRI (2013)
Castor	Semiarid	1.1–1.7	1.4	GCH-4, GCH-13, Aruna, CK-970044	Weed management/deep tillage with chisel ploughing	60	Crop residues/FYM	Srinivasarao et al. (2013b) and Shalander et al. (2011)

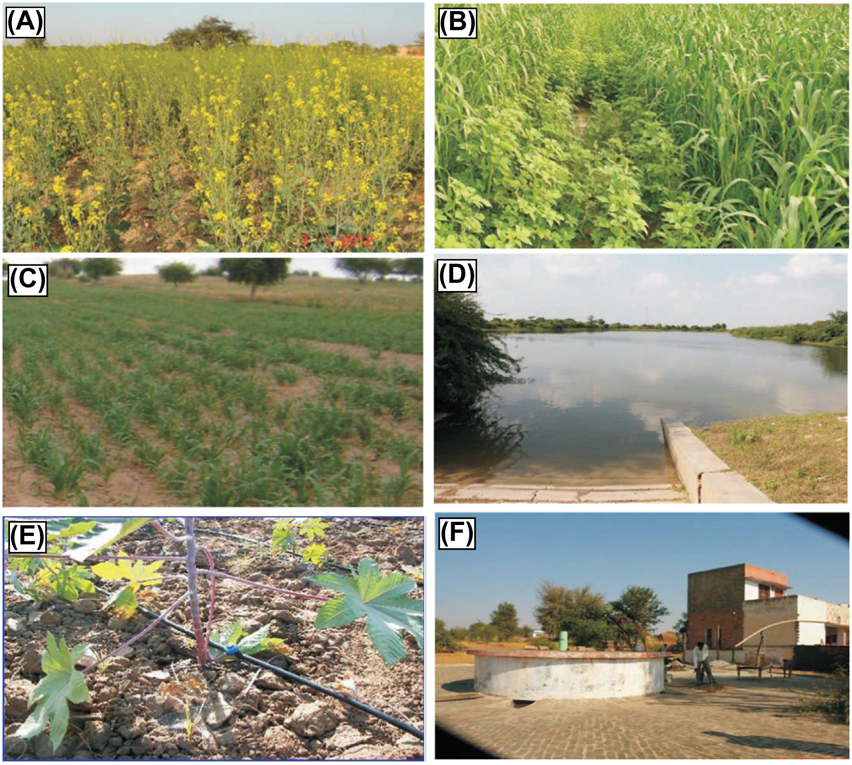

Figure 18 Recommended management practices: (A) Mustard with ridge and furrow system; (B) Pearl millet + legume intercropping; (C) In situ moisture conservation practice with wheel hand hoe; (D) Farm pond for irrigation; (E) Supplemental irrigation in castor; (F) Rainwater harvesting in tanks.

erosion, depletion of SOM, emerging deficiencies of secondary and micronutrients, high soil compaction, surface crusting, loss of soil biodiversity are among strong limiting factors to productivity enhancement of rainfed agriculture in India. Thus, improved soil management systems must take into account not only the constraints associated with the farm and field location and topography, but also consider the production objective, choice of crops, cultivation methods and/or stocking levels.

In rainfed farming systems, soil-related factors are the major constraints to sustainable production, followed by water deficit. Soil-related constraints refer to a situation where the soil environment is suboptimal to produce high yield. The soil-related constraints may be physical, chemical, or biological. Two processes that lead to the loss of soil's capacity to perform its

Table 20 Yield gaps in crops on Entisols/Aridisols under rainfed farming

Crop	Ecoregion	Mean yield ($Mg\ ha^{-1}$) Potential yield	Farmers yield	Yield gap ($Mg\ ha^{-1}$)	References
Pearl millet	Semiarid/arid	2.4	1.2	1.2	Kumar et al. (2012) and Srinivasarao et al. (2011b)
Chickpea	Semiarid	1.4	0.8	0.6	Aziz et al. (2013); Sangwan and Raj (2004); AICRPDA (2011)
Mustard	Semiarid/arid	1.8	1.3	0.5	Mir et al. (2010)
Clusterbean	Semiarid/arid	1.1	0.5	0.6	Srinivasarao et al. (2013c) and Sankar et al. (2012)
Castor	Semiarid	1.4	1.0	0.4	Vittal et al. (2004) and Hegde (2006)

functions: those that change their physical, chemical, and biological properties (intrinsic processes), and those that prevent their use by other causes (extrinsic processes) (Young, 1998). Soil chemical degradation refers to any undesirable change in chemical properties (e.g., pH, magnitude and composition of cation exchange complex, SOM concentration, mineral nutrients, and soluble salts). Change in one or more of these properties often have direct or indirect adverse effects on the chemical quality of soils, which can decrease productivity (Suraj Bhan et al., 2001).

5.2 Soil Quality Restoration

Regressive decline in soil quality is the principal cause of stagnation or even decline in agricultural productivity under both irrigated and rainfed agriculture in India. Soil quality can be restored through the adoption of RMPs. Important among the RMPs for rainfed agriculture include: (1) timely tillage at optimum moisture content to minimize formation of large clods and to improve soil tilth, (2) reduce secondary tillage and adopt no-till, or ridge tillage systems and leave crop residue mulch on the soil surface, (3) adopt

Table 21 Constraints to achieving potential yields on Entisols/Aridisols under rainfed farming

Soil order	Major crops	Soil, water, crop, machinery etc constraints	Socioeconomic and Institutional constraints	References
Entisols/Aridisols	Upland Rice Pearl millet Chickpea Mustard Clusterbean Castor	• Frequent occurrence of moisture stress and droughts of various degrees • Drinking water problem for livestock • Scarcity of fodder (dry and green) • Poor fertility status of soils and widespread multinutrient deficiencies • Unabated land degradation • Secondary salinization • Sodicity • Wind erosion • Little or no application of manures • Timely seed and fertilizer availability	• Low level of input use and technology adoption • Low draft power availability • Inadequate fodder availability • Institution support for fodder banks • Lack of access to critical/lifesaving irrigation facilities • Resource poor and inadequate credit facilities	Srinivasarao et al. (2011b); AICRPDA (2013); Sahrawat et al. (2010); Chander et al. (2014); CAZRI (2013)

crop rotations which include cereals and legumes, (4) include cover crops in the rotation cycle, (5) use manure to enhance SOM concentration, and (6) use a strong hoe to break any surface crust for improving seedling emergence and increasing crop stand. Choice of RMPs differs among soil type and other site-specific factors. Recognizing the importance of soil quality in dryland Alfisols, Sharma et al. (2005) assessed the effects of appropriate land management treatments to develop an overall soil quality index (SQI) that is meaningful to dryland agricultural systems. Among the various treatments, CTGLN90 (CT: conventional tillage; GL: gliricidia loppings; N90: 90 kg N ha^{-1}) had the highest SQI. This treatment was the most promising for sustainability, maintaining higher average yield levels, and better SQI in dryland Alfisols under sorghum–castor rotation. Among BMPs, the conjunctive use of 25 kg P_2O_5 ha^{-1} plus 50 kg N ha^{-1} through leuceana (*Leucaena leucocephala)* green biomass maintained significantly higher SQI with a value of 2.10 followed by use of 25 kg N + 25 kg P_2O_5 + 25 kg N ha^{-1} through FYM with SQI of 2.01. Experiments conducted to assess the effects of 10 fertilizer and FYM treatments applied for 31 years included maize, pearl millet, wheat, and cowpea (*Vigna unguiculata*) on an Inceptisol at the Indian Agricultural Research Institute in New Delhi, India (Masto et al., 2007). The data showed that SQI increased by INM (NPK + manure) treatment including the following: N (7.1% increase), P (7.8%), K (14.4%), Zn (4.8%), and manure (15%). A study conducted on Aridisols at Hisar under a pearl millet-based system showed that the three best conjunctive nutrient-use treatments in terms of SQI were, 25 kg N (compost) (1.52) > 15 kg N (compost) + 10 kg N (inorganic) + biofertilizer (1.49) > 15 kg N (compost) + 10 kg N (green leaf manure) (1.47). And the three best tillage + nutrient treatments identified for SQI were CT + two intercultures (IC) + 100% N (organic source/compost) (1.74) > CT + two IC + 100% N (inorganic source) (1.74) > low tillage + two IC + 100% N (organic source/compost) (1.70). All studies conducted on Alfisols, Vertisols, Inceptisols, and Aridisols indicate that SQI can be enhanced and restored by adoption of INM.

Principal strategy of improving SQI under rainfed conditions is to restore SOM concentration. The goal is to strategically combine a number of practices that enhance soil's biological, chemical, and physical properties and processes relevant to crop production. Some important RMPs of restoring SQI include controlling erosion, alleviating nutrient deficiencies, reclaiming problematic soils, reducing compaction by decreasing heavy equipment traffic, and using INM (Figure 19). Food production in the tropics and

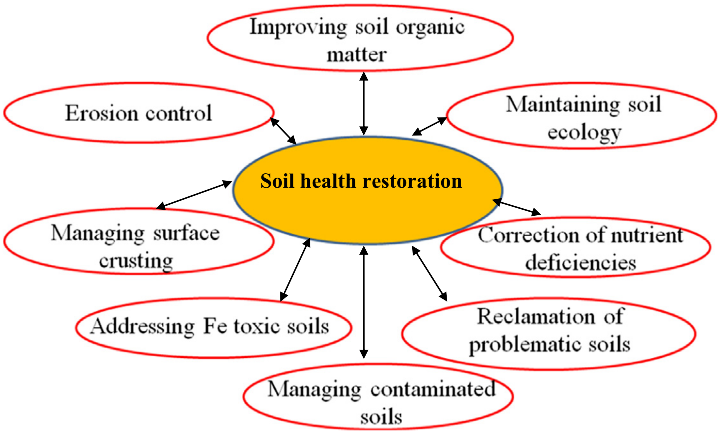

Figure 19 Components of RMPs for soil-quality restoration.

subtropics can be increased through improvement in soil quality by adopting RMPs. Crop yields can be increased by 20–70 kg ha^{-1} for wheat, 10–50 kg ha^{-1} for rice, and 30–300 kg ha^{-1} for maize with every 1 Mg ha^{-1} increase in SOC pool in the root zone through enhanced soil quality (Lal, 2006).

5.3 Water Harvesting and Management

In rainfed regions, due to the temporal and spatial variability and due to skewed distribution of rainfall, crops invariably suffer from moisture stress at one or the other stages of crop growth. Besides, the demand for water is growing continuously at an accelerated pace for meeting the requirements of various other sectors such as drinking, domestic, energy and industry, resulting in strain on water resource availability for agriculture sector. As the rainfall is the single largest source of water and water being the critical input for rainfed agriculture, effective rainwater management is critical for successful rainfed agriculture. The strategy for rainwater management in arid and semiarid regions mainly consists of selection of short duration and low water-requiring crops and conserving as much rainwater as possible so that crops can escape moisture stress during the growing period. In addition to in situ conservation, efforts need to be made to divert the surplus water into storage structures, which can be used either as stand alone resource or in conjunction with groundwater for meeting the critical irrigation requirements. In relatively high rainfall regions, the strategy is to conserve as much rainwater as possible and to harvest the surplus water for lifesaving irrigation and also for enhancing the cropping intensity, and to maximize returns from the harvested water. Apart from enhancing the availability of water by various methods, the approach is to increase the water-use efficiency by arresting losses associated with utilization of water and to maximize returns from every drop of harvested water. Watershed management is the flagship program of the country to enhance the water resource availability, which aims at reducing the severity of erosion, drought, and floods; optimize the use of land, water, and vegetation; and improve agricultural production and enhance the availability of fuel and fodder on a sustained basis.

6. CONCLUSIONS

The importance of rainfed agriculture varies regionally, but rainfed areas produce most food for poor communities in developing countries. Although irrigated production has made a higher contribution to Indian food production (especially during the Green Revolution), rainfed agriculture still produces about 60% of total cereals and plays an important role. In India, rainfed regions contribute substantially toward food grain production and 58% of total net sown area is rainfed spread over 177 districts of the country. In these regions, rainfed agriculture produces 40% of the food grains and supports two-thirds of the livestock population. 90% of coarse cereals, food legumes and about 70% of oilseeds and cotton are cultivated in rainfed regions, besides there is substantial area under rainfed horticulture crops. Uncertainty of rainfall, increasing frequency of droughts, midseason droughts, decrease in number of rainy days, extreme and untimely rainfall, and natural calamities such as hail storms are making rainfed farmers more vulnerable, and their frequency is increasing in recent years.

AICRPDA with its 25 centers in different agroecological regions covering diverse rainfed production systems has developed several location-specific technologies during the past 40 years. These technologies have potential to enhance the yields significantly and some of them are designed for meeting to various weather-related contingencies effectively. The actual yields under farmers' situation are low-leaving large-yield gaps. Though the crop productivity levels on farmers' fields in some of the soil orders such as Vertisols and Inceptisols are high in comparison to Aridisols; the yield gaps are also high for these crops due to the higher production potentials in Vertisols and Inceptisols. The constraints for achieving the potential productivity can be broadly grouped in to technology/resource related, knowledge and institutional and related to socioeconomic aspects. Of these, the constraints related to technology and resource related can be effectively addressed with the available technologies which can contribute to improvement of the productivity significantly under rainfed conditions.

Soil and water management holds the key for enhancing the productivity and bridging the yield gaps. The main emphasis is to build the SOM for soil health restoration. Water is a critical natural resource and managing rainwater in situ or harvesting runoff water and recycling is the key to sustain rainfed farming. To make rainfed farming more economical and sustainable, efficient use of water, soil, and farm management practices in an integrated approach is both essential and a prerequisite. There is a need to scale these technologies through farm science centers and Agricultural Technology Management Agencies which are located at every district of the country and several national/state programs of the Governments for realizing the productivity enhancements and large-scale impacts. We hope that the publication of this chapter would further stimulate and strengthen efforts on bridging the yield gaps and to unlock the potential of rainfed agriculture as these areas are of critical importance for India's food security.

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