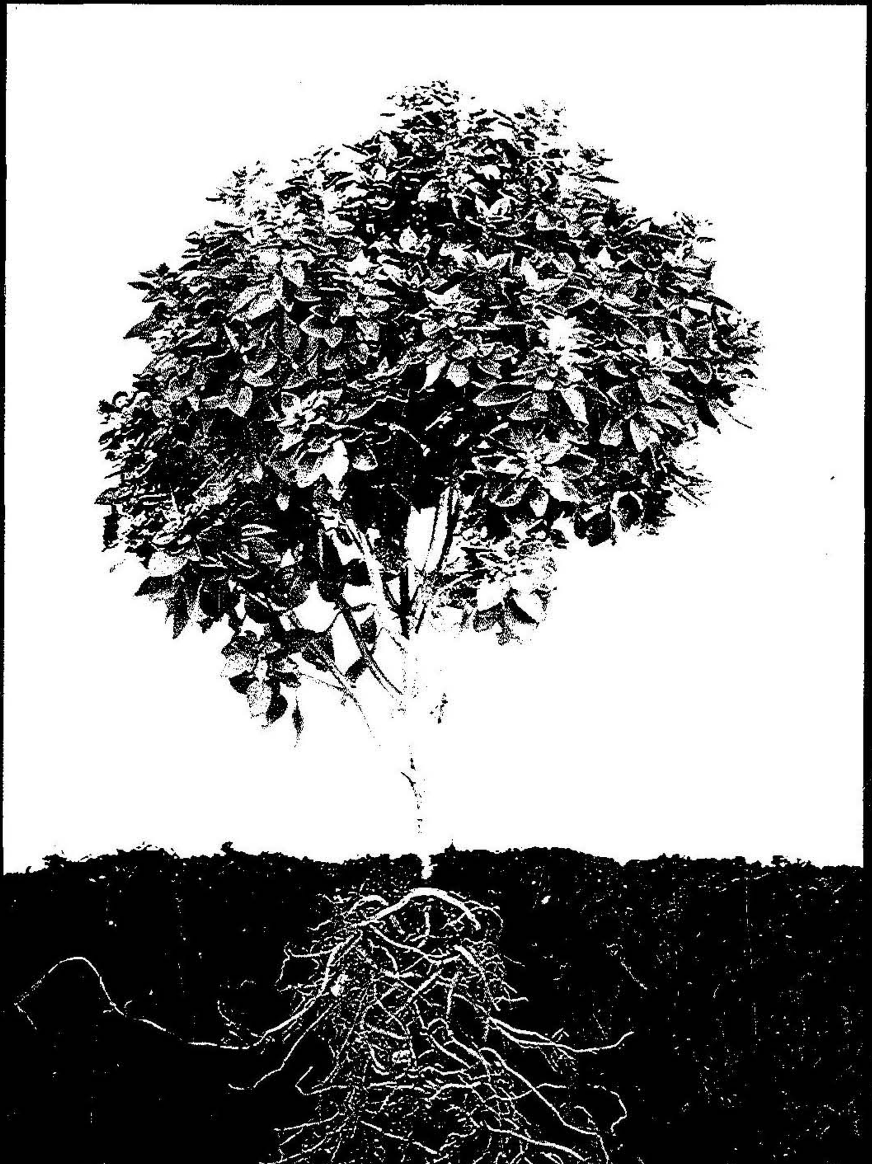
Advances in Soil Science

WORLD SOIL RESOURCES AND FOOD SECURITY



Edited by

Rattan Lal and B. A. Stewart

CRC Press
Taylor & Francis Group

9 New Paradigm to Unlock the Potential of Rainfed Agriculture in the Semiarid Tropics

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9.1 CHALLENGES FOR HUMANKIND IN THE TWENTY-FIRST CENTURY

The twenty-first century has presented complex and multiple challenges for humankind and the main challenge is to achieve food security for all with scarce water resources and increasing land degradation. The world is facing a severe water scarcity that is already complicating national and global efforts to achieve food security in several parts of the world. Agriculture is the world's second largest consumer of water after forestry. The second important factor controlling world food production is soil health, which is severely affected due to land degradation. The growing human population is reducing the per capita availability of land as well as water differently in different parts of the world. Growing water scarcity and land degradation are emerging as the major biophysical factors affecting food security in the world.

9.1.1 HIGH AND INCREASING RISK WITH CLIMATE CHANGE

Rainfed agriculture in the semiarid tropics is a fragile and risk-prone ecosystem due to high spatial and temporal variability of rainfall. Rainfall is concentrated in a short rainy season (approximately 3 to 5 months), with few intensive rainfall events that are unreliable in temporal distribution that is manifested by high deviations from the mean rainfall (coefficients of variation of rainfall are as high as 40% in semiarid regions) [Wani et al. 2004]. In fact, even if water is not always the key limiting factor for yield increase, rainfall is the only truly random production factor in the agricultural system. This is manifested through high rainfall variability causing recurrent flooding, droughts, and dry spells.

Established but incomplete evidence suggests that the high risk for water-related yield loss makes farmers risk averse, which in turn determines farmers' perceptions on investments in other production factors (such as labor and improved seed and fertilizers). Smallholder farmers are usually aware of the effects of shortage and/or variability of soil moisture on the variety, quantity, and quality of produce, leading to a very narrow range of options for commercialization. This, together with the fluctuations in yields, makes it hard for resource-poor men and women in semiarid areas to respond effectively to opportunities made possible by emerging markets, trade, and globalization. Therefore, temporal and spatial variability of climate, especially rainfall, is a major constraint to yield improvements, competitiveness, and commercialization of rainfed crops, tree crops, and livestock systems in most of the tropics. Management options should therefore start by focusing on reducing rainfall-induced risks.

Evidence is emerging that climate change is making the variability more intense with increased frequency of extreme events such as drought, floods, and hurricanes [IPCC 2007]. A recent study assessing rainfed cereal potential under different climate change scenarios, with varying total rainfall amounts, concluded that it is difficult to estimate the exact degree of regional impact. But most scenarios resulted in losses of rainfed production potential in the most vulnerable developing countries. In these countries, the loss of production area was estimated at 10%–20%, with an approximate potential of 1–3 billion people affected by 2080 [IIASA 2002]. In particular, sub-Saharan Africa is estimated to lose 12% of the cultivation potential. This loss is mostly projected in the Sudan–Sahelian zone, which is already subject to high climatic variability and adverse crop conditions. Because of the risk associated with climate variability, smallholder farmers are generally and rationally keen to start reducing risk of crop failure due to dry spells and drought before they consider investments in soil fertility, improved crop varieties, and other yield-enhancing inputs [Hilhost and Muchena 2000].

Global warming and associated impacts of climate change will have adverse impacts on water availability and food production and, here again, the developing tropical region countries are likely to be affected more by impacts of climate change [IPCC 2007]. Poverty and food security are very closely related and are affected by the growing water scarcity and land degradation, which are also affected by growing population pressure on the limited land and water resources essential for food production.

An adequate human diet requires about 4000 liters of water per day to produce, which is over 90% of the daily human water requirement. The increasing [illegible] ing from population growth, rising incomes, and climate change limits the amount of water available for food production and threatens food security in many countries. To meet the food demand of the world's growing population and rising incomes with the current production options, we will need an additional 1600 km^3 water per year just to achieve the UN Millennium Development Goal of halving hunger by 2015 [SEI 2005], and another 4500 km^3/yr with current water productivity levels in agriculture to feed the world in 2050 (Figure 9.1) [Falkenmark et al. 2009; Rockström et al. 2009].

This is more than twice the current consumptive water use in irrigation, which is already contributing to depleting several large rivers before they reach the ocean. It is becoming increasingly difficult on social, economic, and environmental grounds to supply more water to farmers. There is a correlation between poverty, hunger, and water stress [Falkenmark 1986]. The UN Millennium Development Project has identified the "hot spot" countries in the world suffering from the largest prevalence of malnourishment. These countries coincide closely with the countries in the world hosted in semiarid and dry subhumid hydroclimates in the world (Figure 9.2),

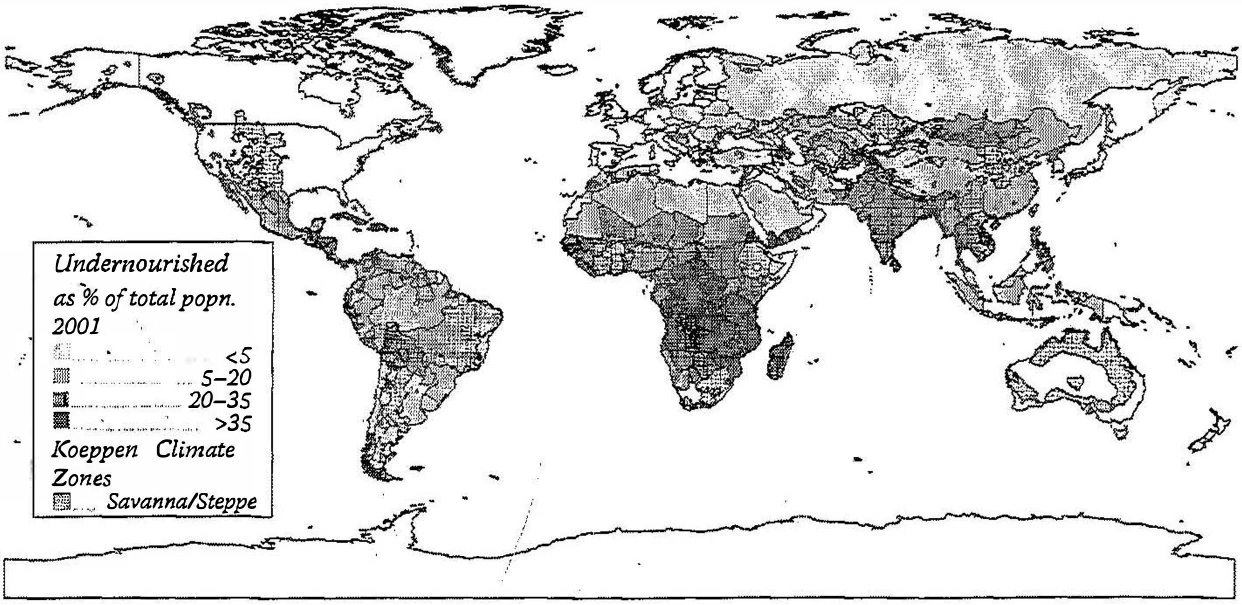


FIGURE 9.1 The prevalence of undernourished in developing countries (as percentage of population 2001/2002), together with the distribution of semiarid and dry subhumid hydroclimates in the world, i.e., savannah and steppe agroecosystems. These regions are dominated by sedentary farming subject to the world's highest rainfall variability and occurrence of dry spells and droughts. (From SEI, Sustainable Pathways to Attain the Millennium Development Goals—Assessing the Role of Water, Energy and Sanitation. Document prepared for the UN World Summit, Sept. 14, 2005, New York, SEI, Stockholm, Sweden, http://sei-international.org/mediamanager/documents/Publications/Water-sanitation/sustainable_pathways_mdg.pdf, 2005. With permission.)

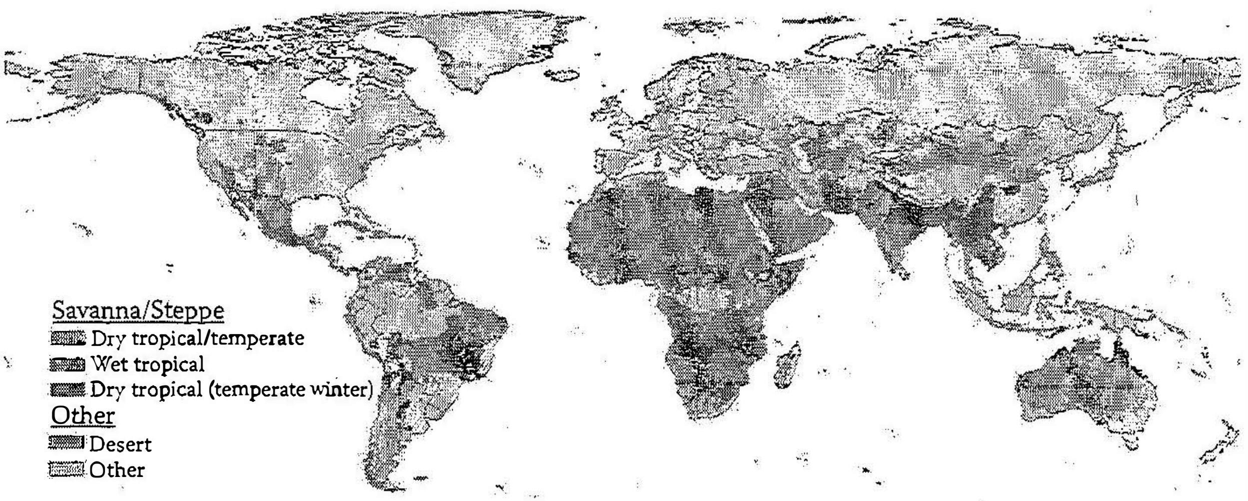


FIGURE 9.2 The zone with savanna type hydroclimate – the zone with large hunger eradication challenges but also huge potential for additional food production. (From SEI, Sustainable Pathways to Attain the Millennium Development Goals—Assessing the Role of Water, Energy and Sanitation. Document prepared for the UN World Summit, Sept. 14, 2005, New York, SEI, Stockholm, Sweden, http://sei-international.org/mediamanager/documents/Publications/Water-sanitation/sustainable_pathways_mdg.pdf, 2005. With permission.)

i.e., savannahs and steppe ecosystems, where rainfed agriculture is the dominating source of food, and where water constitutes a key limiting factor to crop growth [SEI 2005]. Of the 850 million undernourished people in the world, essentially all live in poor developing countries, which are predominantly located in tropical regions [UNStat 2005]. Drought (water scarcity) and land degradation are interlinked in a cause-and-effect relationship, and the two combined are the main causes of poverty in farm households. This unholy nexus between drought (water scarcity), poverty, and land degradation has to be broken to meet the Millennium Development Goal of halving the number of food insecure poor by 2015 [Wani et al. 2006].

9.2 CURRENT STATUS OF RAINFED AGRICULTURE

The importance of rainfed agriculture varies regionally, but it produces most food for poor communities in developing countries. In sub-Saharan Africa, more than 95% of the farmed land is rainfed, while the corresponding figure for Latin America is almost 90% and is about 60% for South Asia, 65% for East Asia, and 75% for Near East and North Africa [FAOStat 2010] (Table 9.1). Most countries in the world

TABLE 9.1
Global and Continent-Wide Rainfed Area and Percentage of Total Arable Land

Continent Regions	Total Arable Land (million ha)	Rainfed Area (million ha)	% of Rainfed Area
World	1551.0	1250.0	80.6
Africa	**247.0**	**234.0**	**94.5**
Northern Africa	28.0	21.5	77.1
Sub-Saharan Africa	218.0	211.0	96.7
Americas	**391.0**	**342.0**	**87.5**
Northern America	253.5	218.0	86
Central America and Caribbean	15.0	13.5	87.7
Southern America	126.0	114.0	90.8
Asia	**574.0**	**362.0**	**63.1**
Middle East	64.0	41.0	63.4
Central Asia	40.0	25.5	63.5
Southern and Eastern Asia	502.0	328.0	65.4
Europe	**295.0**	**272.0**	**92.3**
Western and Central Europe	125.0	107.5	85.8
Eastern Europe	169.0	164.0	97.1
Oceania	**46.5**	**42.5**	**91.4**
Australia and New Zealand	**46.0**	**42.0**	**91.3**
Other Pacific Islands	**0.57**	**0.56**	**99.3**

Source: FAO, AQUASTAT: FAO's Information System on Water and Agriculture, http://www.fao.org/nr/aquastat, 2010; FAO, FAOStat, http://faostat.fao.org/site/567/DesktopDefauly.aspx?pageID=567#ancor, 2010.

depend primarily on rainfed agriculture for their grain food. Despite large strides made in improving productivity and environmental conditions in many developing countries, a great number of poor families in Africa and Asia—where rainfed agriculture is the main agricultural activity—still face poverty, hunger, food insecurity, and malnutrition. These problems are exacerbated by adverse biophysical growing conditions and the poor socioeconomic infrastructure in many areas in the arid and semiarid tropics (SAT) and the subhumid regions.

Even with growing urbanization, globalization, and better governance in Africa and Asia, hunger, poverty, and vulnerability of livelihoods to natural and other disasters will continue to be greatest in the rural tropical areas. These challenges are complicated by climatic variability, the risk of climate change, population growth, health pandemics (AIDS, malaria), a degrading natural resource base, poor infrastructure, and changing patterns of demand and production [Ryan and Spencer 2001; Walker 2010]. The majority of poor in developing countries live in rural areas; their livelihoods depend on agriculture and overexploitation of the natural resource base, pushing them downward into a spiral of poverty. The importance of rainfed sources of food weighs disproportionately on women, given that approximately 70% of the world's poor are women [WHO 2000]. Agriculture plays a key role in economic development [World Bank 2005] and poverty reduction [Irz and Roe 2000], with evidence indicating that every 1% increase in agricultural yields translates to a 0.6% to 1.2% decrease in the percentage of absolute poor [Thirtle et al. 2002]. On an average for sub-Saharan Africa, agriculture accounts for 35% of the gross domestic product (GDP) and employs 70% of the population [World Bank 2000], while more than 95% of the agricultural area is rainfed [FAOStat 2010]. Agriculture will continue to be the backbone of economies in Africa and South Asia for the foreseeable future. As most of the poor are farmers and landless laborers [Sanchez et al. 2005], strategies for reducing poverty, hunger, and malnutrition should be driven primarily by the needs of the rural poor, and should aim to build and diversify their livelihood sources. Substantial gains in land, water, and labor productivity, as well as better management of natural resources, are essential to reverse the downward spiral of poverty and environmental degradation, apart from the problems of equity, poverty, and sustainability and, hence, the need for greater investment in SAT areas [World Bank 2005; Rockström et al. 2007; Wani et al. 2008a, 2009].

9.2.1 CROP YIELDS IN RAINFED AREAS

Over the past 40 years, agricultural land use has expanded by 20%–25%, which has contributed approximately 30% to the overall grain production growth during the period [FAO 2002]. The remaining yield outputs originated from intensification through yield increases per unit land area. However, the regional variation is large, as is the difference between irrigated and rainfed agriculture. In developing countries, rainfed grain yields are on an average 1.5 t/ha, compared to 3.1 t/ha for irrigated yields [Rosegrant et al. 2002], and the increase in production from rainfed agriculture has mainly originated from land expansion.

Trends are clearly different for different regions. With 99% rainfed production of main cereals such as maize, millet, and sorghum, the cultivated cereal area in sub-

Saharan Africa has doubled since 1960, while the yield per unit land has nearly been stagnant for these staple crops [FAOStat 2010]. In South Asia, there has been a major shift away from more drought-tolerant, low-yielding crops such as sorghum and millet, while wheat and maize has approximately doubled in area since 1961 [FAOStat 2010]. During the same period, the yield per unit land for maize and wheat has more than doubled (Figure 9.3). For predominantly rainfed systems, maize crops per unit land have nearly tripled and wheat more than doubled during the same time period.

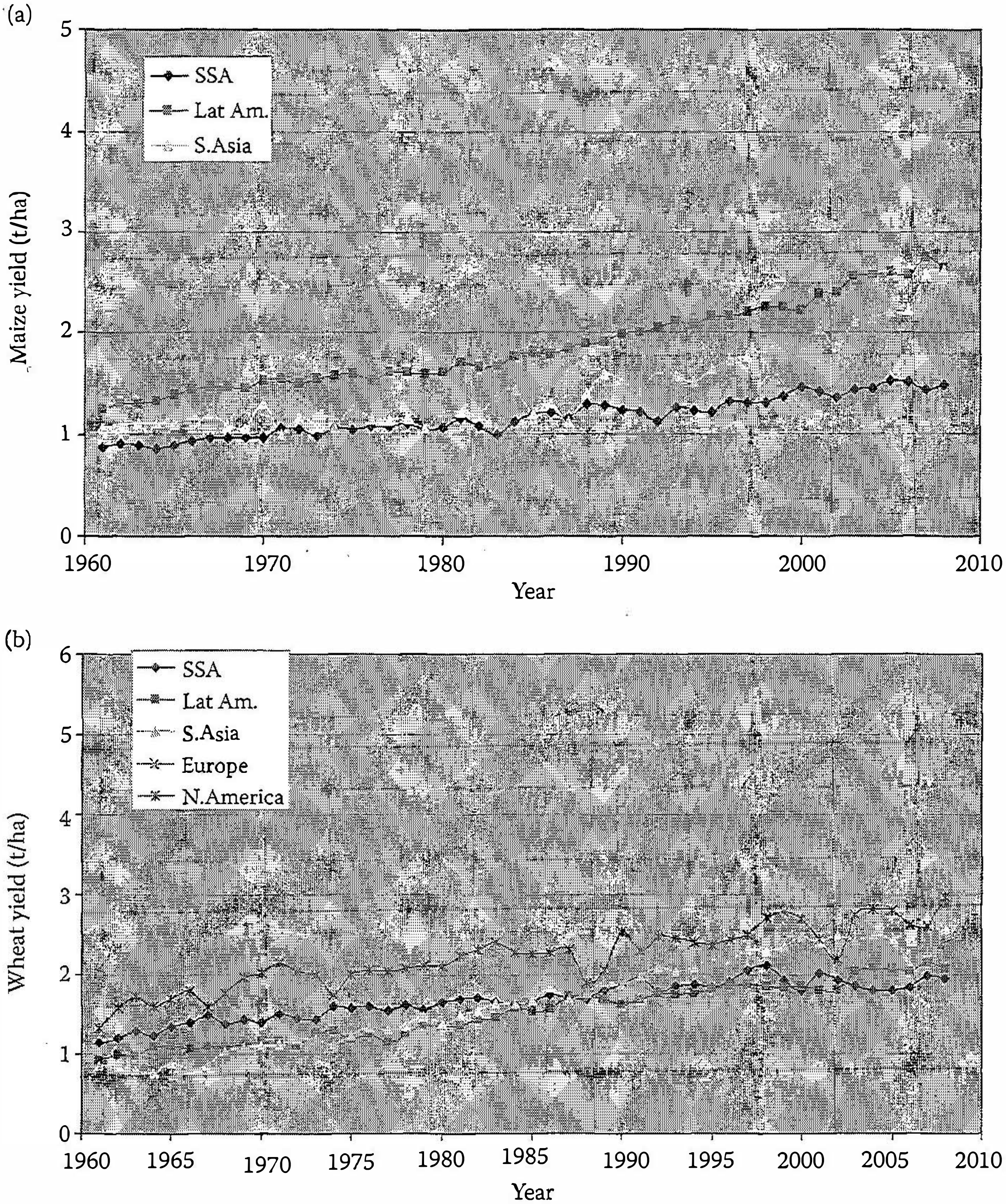


FIGURE 9.3 Grain yield of predominantly rainfed maize and wheat for different regions during 1961–2010. (From FAO, FAOStat, http://faostat.fao.org/site/567/DesktopDefauly.aspx?pageID=567#ancor, 2010. With permission.)

Rainfed maize yield differs substantially between regions (Figure 9.3a). In Latin America (including the Caribbean) it exceeds 3 t/ha, while in South Asia it is around 2 t/ha, and in sub-Saharan Africa it only just exceeds 1 t/ha. This can be compared with maize yields in the United States or Southern Europe, which normally amount to approximately 7–10 t/ha (most maize in these regions is irrigated). The average regional yield per unit land for wheat in Latin America (including the Caribbean) and South Asia is similar to the average yield output of 2.5–2.7 t/ha in North America (Figure 9.3b). In comparison, wheat yield in Western Europe is approximately twice as large (5 t/ha), while in sub-Saharan Africa it remains below 2 t/ha. In view of the historic regional difference in development of yields, a significant potential appears to exist for raised yields in rainfed agriculture, particularly in sub-Saharan Africa and South Asia.

9.2.2 RAINFED AGRICULTURE—A LARGE UNTAPPED POTENTIAL

In several regions of the world, rainfed agriculture generates yields among the world's highest. These are predominantly temperate regions, with relatively reliable rainfall and inherently productive soils. Even in tropical regions, particularly in the subhumid and humid zones, agricultural yields in commercial rainfed agriculture exceed 5–6 t/ha [Rockström and Falkenmark 2000; Wani et al. 2003a, 2003b] (Figure 9.4). At the same time, the dry subhumid and semiarid regions have experienced the lowest yields and the weakest yield improvements per unit land. Here, yields oscillate between 0.5 to 2 t/ha, with an average of 1 t/ha in sub-Saharan Africa and 1–1.5 t/ha in South Asia, Central Asia, and West Asia and North Africa (CWANA) for rainfed agriculture [Rockström and Falkenmark 2000; Wani et al. 2003a, 2003b].

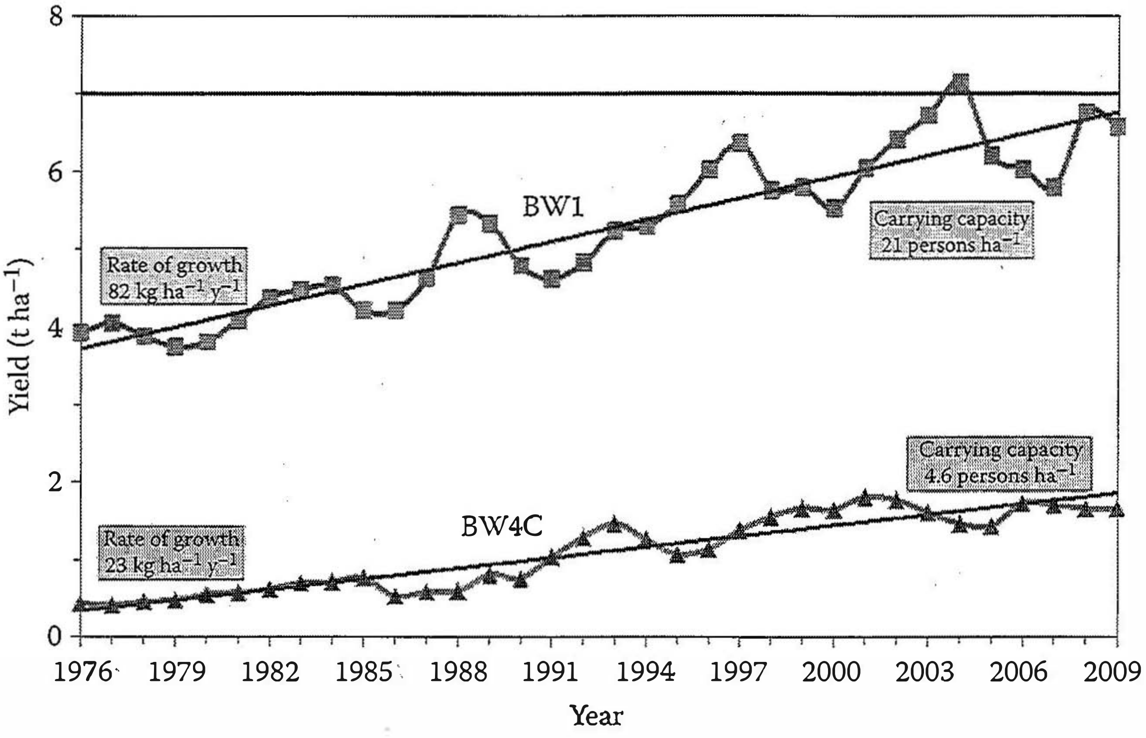


FIGURE 9.4 Three-year moving average of crop yields in improved and traditional management systems during 1976–2009 at ICRISAT, India.

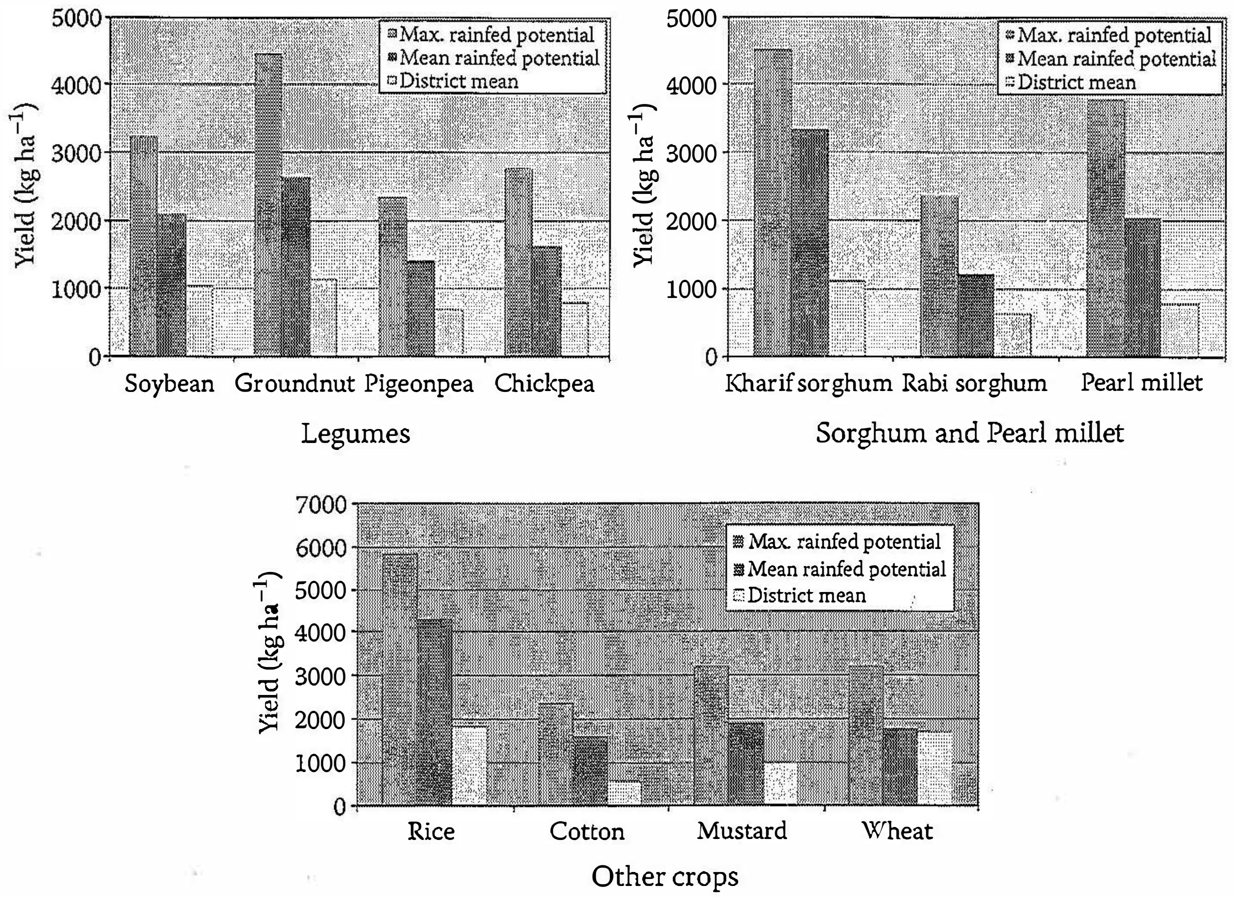


FIGURE 9.5 Rainfed potential yields and yield gaps of crops in India. (From Singh, P., et al., *Yield Gap Analysis: Modeling of Achievable Yields at Farm Level in Rain-Fed Agriculture: Unlocking the Potential*, CAB International, Wallingford, UK, 81–123, 2009. With permission.)

Yield gap analyses carried out for comprehensive assessment (CA) for major rainfed crops in semiarid regions in Asia and Africa and rainfed wheat in West Africa and North Africa (WANA), revealed large yield gaps, with farmers' yields being a factor 2 to 4 times lower than achievable yields for major rainfed crops (Figures 9.5 and 9.6). Detailed yield gap analysis for major rainfed crops in different parts of the world are discussed [Singh et al. 2009; Fisher et al. 2009]. In countries in Eastern and Southern Africa, the yield gap is very large (Figure 9.6). Similarly, in many countries in West Asia, farmers' yields are less than 30% of achievable yields, while in some Asian countries, the figure is closer to 50%. Historic trends present a growing yield gap between farmers' practices and farming systems that benefit from management advances [Wani et al. 2003b, 2009a].

9.2.3 CONSTRAINTS IN RAINFED AGRICULTURE AREAS

An insight into the inventories of natural resources in rainfed regions shows a grim picture of water scarcity, fragile ecosystems, drought, and land degradation due to soil erosion by wind and water, low rainwater use efficiency (35%–45%), high population pressure, poverty, low investments in water use efficiency (WUE) measures, poor infrastructure, and inappropriate policies [Wani et al. 2003b, 2003c, 2009; Rockström et al. 2007]. These rainfed areas are also prone to severe land degradation.

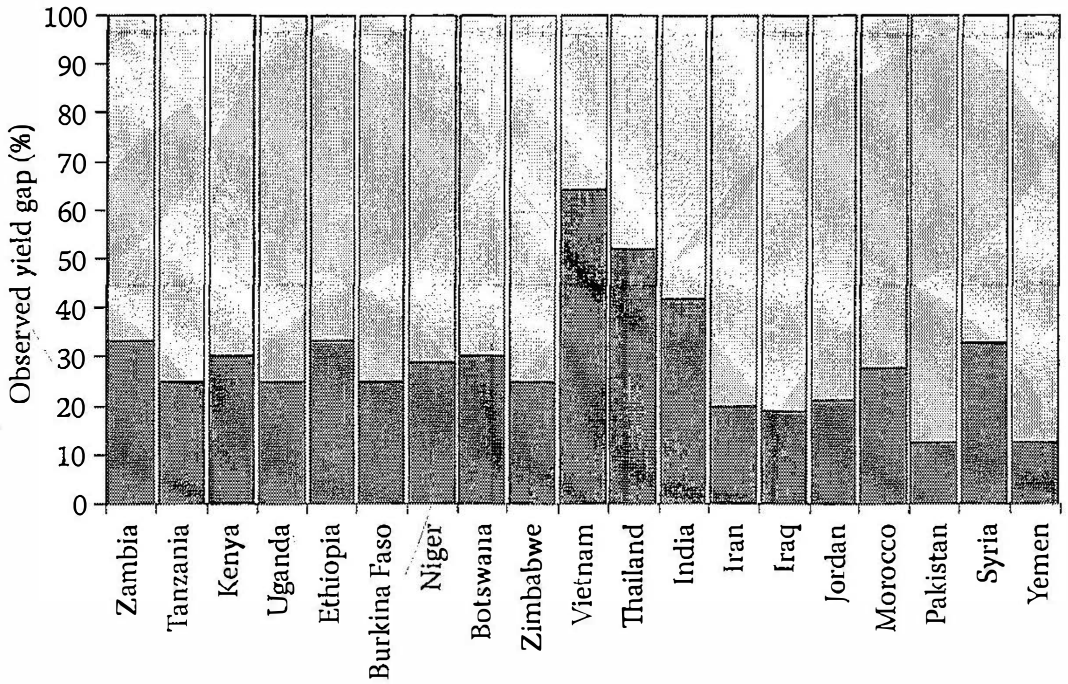


FIGURE 9.6 Examples of observed yield gap (for major grains) between farmers' yields and achievable yields (100% denotes achievable yield level and columns contain the actual observed yield levels). (From Rockström, J., et al., In *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*, Earthscan and IWMI, London and Colombo, Sri Lanka, 315–348, 2007. With permission.)

Reduction in the producing capacity of land due to wind and water erosion of soil, loss of soil humus, depletion of soil nutrients, secondary salinization, diminution and deterioration of vegetation cover, as well as loss of biodiversity, is referred to as land degradation. The root cause of land degradation is inappropriate land use and management practices. Land degradation represents a diminished ability of ecosystems or landscapes to support the functions or services required for sustaining livelihoods. A global assessment of the extent and form of land degradation showed that 57% of the total area of drylands occurring in two major Asian countries, namely China (178.9 million ha) and India (108.6 million ha), are degraded [UNEP 1997].

9.3 STRATEGIES FOR HARNESSING THE POTENTIAL OF RAINFED AGRICULTURE

9.3.1 Understand the Issue of Water Scarcity

Water scarcity is a relative concept. Using the conventional approach and assessing the amount of renewable surface and groundwater per capita (i.e., so-called blue water), suggests that water stress is increasing in a number of countries and that regions are moving into increasing water-stressed conditions. Although the global amount of fresh water has not changed, the amount available per person is much less than it was in 1950, with a significant difference between countries and regions. Water is not equally scarce in all parts of the world. As Figure 9.7a illustrates, Southeast Asia and the Middle East North Africa (MENA) regions are the worst affected in terms of blue water scarcity. However, this picture may be misleading

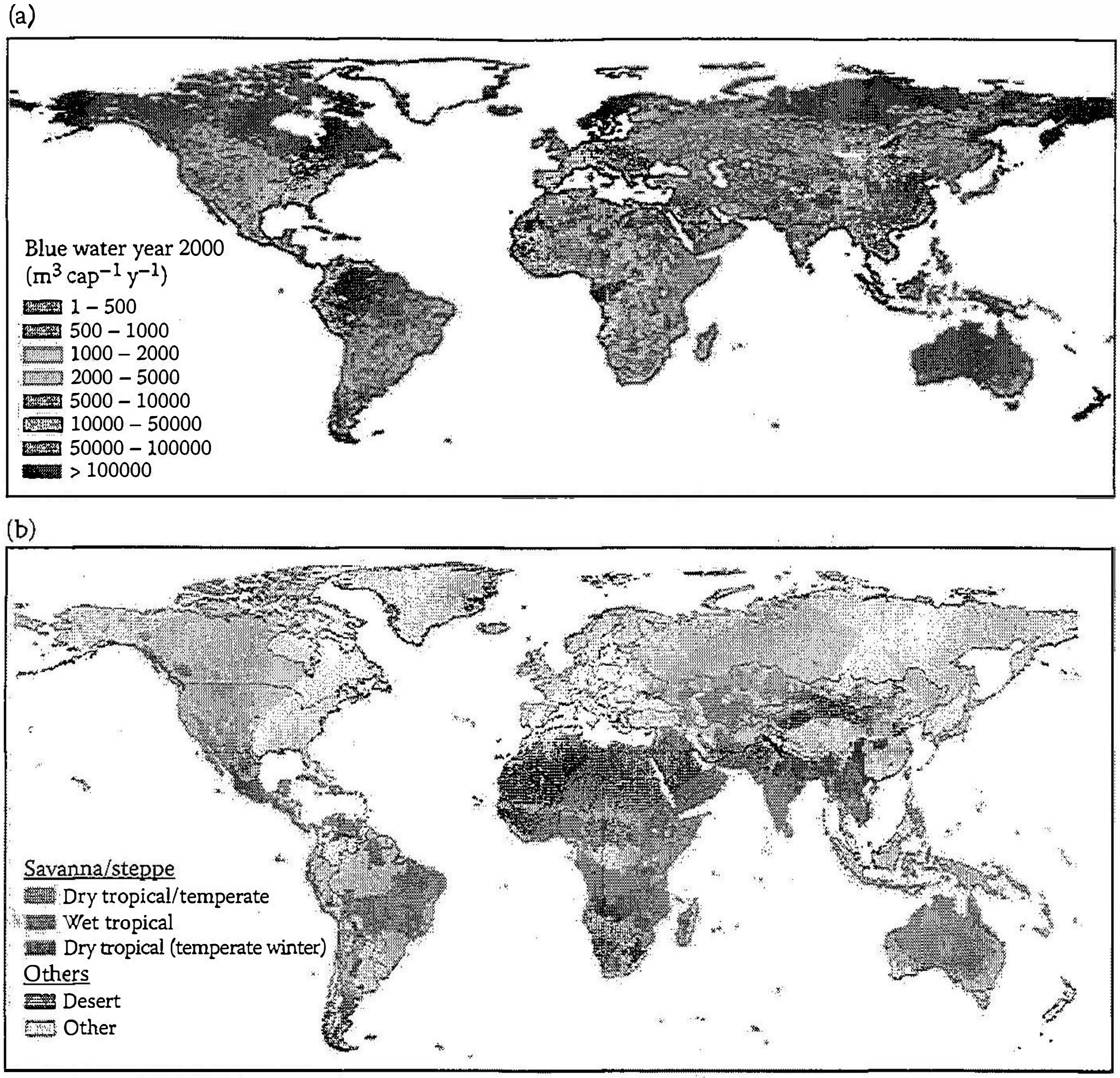


FIGURE 9.7 (a) Renewable liquid freshwater (blue water – hatched in dark) stress per capita using LPJ dynamic modeling year 2000. (From Rockström, J., et al., *Water Resources Research,* 45, W00A12, 2009.) (b) Renewable rainfall (green and blue water – hatched in semi dark and dark) stress per capita using LPJ dynamic modeling year 2000. (From Rockström, J., et al., *Water Resources Research,* 45, W00A12, 2009.)

because the average amount of water per capita in each pixel could obscure large differences in actual access to a reliable water source. In addition, these water quantities only include blue water. The full resource of rainfall, and notably green water, i.e., soil moisture used in rainfed cropping and natural vegetation, is not included. In a recent assessment that included both green and blue water resources, the level of water scarcity changed significantly for many countries (Figure 9.7b).

Among the regions that are conventionally (blue) water scarce, but still have sufficient green and blue water to meet the water demand for food production, are large parts of sub-Saharan Africa, India, and China. If green water (on current agricultural land) for food production is included, per capita water availability in countries such as Uganda, Ethiopia, Eritrea, Morocco, and Algeria more than doubles or triples. Moreover, low ratios of transpiration to evapotranspiration (T/ET) in countries such as Bangladesh, Pakistan, India, and China indicate high potential for increasing water productivity through vapor shift [Rockström et al. 2009].

Absolute water stress is found most notably in arid and semiarid regions with high population densities such as parts of India, China, and the MENA region. The MENA region is increasingly unable to produce the food required locally due to increasing water stress from a combination of population increase, economic development, and climate change, and will have to rely more and more on food (and virtual water) imports.

For the greater part of the world, the global assessment of green and blue water suggests that water stress is primarily a blue water issue and large opportunities are still possible in the management of rainfed areas, i.e., the green water resources in the landscape [Rockström et al. 2009]. The current global population that has blue water stress is estimated to be 3.17 billion, expected to reach 6.5 billion in 2050. If both green and blue water are considered, the number currently experiencing absolute water stress is a fraction of this (0.27 billion), and will only marginally exceed today's blue water stressed in 2050.

Given the increasing pressures on water resources and the increasing demands for food and fiber, the world must succeed in producing more food with less water. Hence, it is essential to increase water productivity in both humid and arid regions. Some describe the goal as increasing the "crop per drop" or the "dollars per drop" produced in agriculture. Regardless of the metric, it is essential to increase the productivity of water and other inputs in agriculture. Success will generate greater agricultural output, while also enabling greater use of water in other sectors and in efforts to enhance the environment.

Water productivity can vary with household income, as farmers' yields vary as a result of local input and management styles. In a household level study of 300 farmers in eight sub-Saharan countries, the more wealthy farmers had generally higher yield levels [Holmen 2004], and subsequently better water productivity (Figure 9.8). The differences were significant between the wealthier classes and poorest classes.

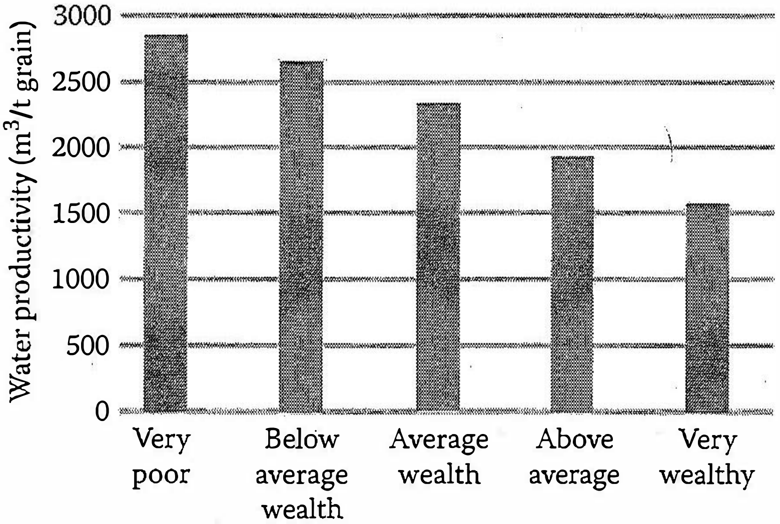


FIGURE 9.8 Water productivity for maize yields and income levels for smallholder farming systems in sub-Sahara Africa. (Based on Holmen, H., *Currents*, 34, 12–16, 2004.)

More than 1000 m^3 additional water was required per ton of maize grain produced by the poorest farmers compared to the wealthiest farmers. Data suggest that yield improvements for the purpose of poverty alleviation can also significantly improve water productivity, especially in current low-yielding rainfed (green water) agriculture in sub-Saharan Africa and parts of South Asia. Improved water use efficiency and productivity can improve food security. A sectoral approach to managing water is a cause of low water use efficiency.

9.3.2 WATER ALONE CANNOT ACHIEVE FOOD SECURITY

9.3.2.1 Soil Health: An Important Driver for Enhancing Water Use Efficiency

Soil health is severely affected due to land degradation and is in need of urgent attention. Often, soil fertility is the limiting factor to increased yields in rainfed agriculture [Stoorvogel and Smaling 1990; Rego et al. 2005]. Soil degradation through nutrient depletion and loss of organic matter causes serious yield decline, closely related to water determinants as it affects water availability for crops due to poor rainfall infiltration and plant water uptake due to weak roots. Nutrient mining is a serious problem in smallholder rainfed agriculture. In sub-Saharan Africa, soil nutrient mining is particularly severe. It is estimated that approximately 85% of African farmland in 2002–2004 experienced a loss of more than 30 kg/ha of nutrients per year [IFDC 2006].

The International Crops Research Institute for the Semi-Arid Tropics' (ICRISAT) on-farm diagnostic work in different community watersheds in different states of India as well as in Southern China, North Vietnam, and Northeast Thailand showed severe mining of soils for essential plant nutrients. Exhaustive analysis in selected states in India showed that 80%–100% of farmers' fields are deficient not only in total nitrogen but also micronutrients like zinc, boron, and secondary nutrients such as sulfur beyond the critical limits (Table 9.2a and b) [Rego et al. 2007; Sahrawat et al. 2007].

A substantial increase in crop yields was experienced after micronutrient amendments, and a further increase of 70% to 120% occurred when both micronutrients and adequate nitrogen and phosphorus were applied to a number of rainfed crops (maize, sorghum, mung bean, pigeonpea, chickpea, castor, and groundnut) in farmers' fields [Rego et al. 2005; Sahrawat et al. 2007; Srinivasarao et al. 2010]. Evidence from on-farm participatory trials in different rainfed areas in India clearly indicated that investments in soil fertility improvement directly improved water management, resulting in increased rainwater productivity. Rainwater productivity (i.e., for grain yield per mm of rainfall) was significantly increased in the example above as a result of micronutrient amendment. The rainwater productivity for grain production was increased by 70%–100% for maize, groundnut, mungbean, castor, and sorghum by adding boron, zinc, and sulfur [Rego et al. 2005]. In terms of net economic returns, rainwater productivity was substantially higher by 1.50 to 1.75 times. Similarly, rainwater productivity was increased significantly when integrated land, nutrient, and water management options were adopted as well as use of improved cultivars in semiarid regions of India [Wani et al. 2003; Sreedevi and Wani 2009]. Gains in rainwater-use efficiency with improved land, nutrient, and water management options were far higher in low rainfall years (Figure 9.9).

TABLE 9.2a

Percent of Farmers' Fields Deficient in Available Nutrients in Various States (Districts within States) of India

State	District	No. of Farmers	OC[a] %	Av P ppm	Av K ppm	Av S ppm	Av B ppm	Av Zn ppm
Andhra Pradesh	Adilabad, Ananthapuram, Kadapa, Khammam, Kurnool, Mahabubnagar, Medak, Nalgonda, Prakasam, Rangareddy, Warangal	3650	76[b]	38	12	79	85	69
Chattisgarh	Kanker	40	–	63	10	90	95	50
Gujarat	Junagadh	82	12	60	10	46	100	85
Jharkhand	Gumla, Kharsawan	115	42	65	50	77	97	71
Karnataka	Bengaluru, Rural, Bijapur, Chamrajanagar, Chikballapur, Chitradurga, Dharwad, Haveri, Kolar, Raichur, Tumkur	17,712	70	46	21	84	67	55
Kerala	Kollam, Pathanamthitta, Thiruvananthapuram	28	11	21	7	96	100	18
Madhya Pradesh	Badwani, Dewas, Guna, Indore, Jhabua, Mandla, Raisen, Rajagarah, Sagar, Sehore, Shajapur, Vidisha	341	22	74	1	74	79	66
Rajasthan	Alwar, Banswara, Bhilwara, Bundi, Dungarpur, Jhalwar, Sawai Madhopur, Tonk, Udaipur	421	38	45	15	71	56	46
Tamilnadu	Kanchipuram, Karur, Salem, Tirunelveli, Vellore	119	57	51	24	71	89	61
Total		22,508	69	45	19	83	70	58

Source: Rego, T.J., et al., *Journal of Plant Nutrition*, 30, 1569–1583, 2007; Sahrawat, K.L., et al., *Current Science*, 93(10), 1–6, 2007; Wani, S.P., et al., In *Conservation Farming: Enhancing Productivity and Profitability of Rain-Fed Areas*, Soil Conservation Society of India, New Delhi, 163–178, 2008; and unpublished data sets of ICRISAT.

[a] OC = organic carbon; AvP = available phosphorus; AvK = available potash; AvS = available sulfur; AvB = available boron, AVZn = available zinc.

[b] = Per cent of farmers fields deficient, i.e., below critical limit for a particular nutrient.

* = Extensive soil sampling undertaken to interpolate analysis at district level using GIS.

TABLE 9.2b
Mean and Range Values of Nutrient Content in Soil Samples in Various States (Districts within States) of India

State	District	No. of Farmers	OC[a] %	Av P ppm	Av K ppm	Av S ppm	Av B ppm	Av Zn ppm
Andhra Pradesh	Adilabad, Ananthapuram, Kadapa, Khammam, Kurnool, Mahabubnagar, Medak, Nalgonda, Prakasam, Rangareddy, Warangal	3650						
Mean			0.41	9.1	129	9.6	0.34	0.81
Range			0.08–3.00	0.0–247.7	0–1,263	0.0–801.0	0.02–4.58	0.08–35.60
Chattisgarh	Kanker	40						
Mean			–	6.99	128.9	6.53	0.25	0.91
Range			–	0.0–63.6	4.1–11.66	1.4–34.6	0.1–0.78	0.4–3.07
Gujarat	Junagadh	82						
Mean			0.77	6.9	104	16.0	0.22	0.44
Range			0.21–1.90	0.4–42.0	30–635	1.1–150.4	0.06–0.49	0.18–2.45
Jharkhand	Gumla, Kharsawan	115						
Mean			0.53	5.3	63	7.8	0.17	0.68
Range			0.19–1.13	0.0–72.4	8–247	1.3–50.0	0.06–0.80	0.24–2.90
Karnataka	Bengaluru, Rural, Bijapur, Chamrajanagar, Chikballapur, Chitradurga, Dharwad, Haveri, Kolar, Raichur, Tumkur	17712						
Mean			0.43	12.3	133	13.2	0.57	0.97
Range			0.01–3.60	0.0–480.0	4–3750	0.1–4647.4	0.02–26.24	0.06–235.00
Kerala	Kollam, Pathanamthitta, Thiruvananthapuram	28						
Mean			1.04	22.0	101	3.4	0.31	1.88
Range			0.36–2.57	1.2–137.0	33–313	1.0–11.0	0.18–0.48	0.56–7.20

(*continued*)

TABLE 9.2b (Continued)

Mean and Range Values of Nutrient Content in Soil Samples in Various States (Districts within States) of India

State	District	No. of Farmers	OC[a] %	Av P ppm	Av K ppm	Av S ppm	Av B ppm	Av Zn ppm
Madhya Pradesh	Badwani, Dewas, Guna, Indore, Jhabua, Mandla, Raisen, Rajagarah, Sagar, Sehore, Shajapur, Vidisha	341						
Mean			0.65	5.0	190	9.6	0.43	0.72
Range			0.28–2.19	0.1–68.0	46–716	1.8–134.4	0.06–2.20	0.10–3.82
Rajasthan	Alwar, Banswara, Bhilwara, Bundi, Dungarpur, Jhalwar, Sawai Madhopur, Tonk, Udaipur	421						
Mean			0.72	8.1	116	10.6	0.60	1.27
Range			0.09–2.37	0.2–44.0	14–1,358	1.9–274.0	0.08–2.46	0.06–28.60
Tamilnadu	Kanchipuram, Karur, Salem, Tirunelveli, Vellore	119						
Mean			0.51	9.2	122	11.3	0.34	0.78
Range			0.14–1.37	0.2–67.2	13–690	1.0–93.6	0.06–2.18	0.18–5.12
Total		22,508						
Mean			0.44	11.5	133	12.4	0.53	0.94
Range			0.01–3.60	0.0–480.0	0–3750	0.0–4647.4	0.02–26.24	0.06–235.00

Source: Rego, T.J., et al., *Journal of Plant Nutrition*, 30, 1569–1583, 2007; Sahrawat, K.L., et al., *Current Science*, 93(10), 1–6, 2007; Wani, S.P., et al., In *Conservation Farming: Enhancing Productivity and Profitability of Rain-Fed Areas*, Soil Conservation Society of India, New Delhi, 163–178, 2008; and unpublished data sets of ICRISAT.

[a] OC = Organic Carbon; AvP = Available Phosphorus, AvK = Available Potash, AvS = Available Sulfur, AvB = Available Boron, AVZn= Available Zinc.

* = Extensive soil sampling undertaken to interpolate analysis at district level using GIS.

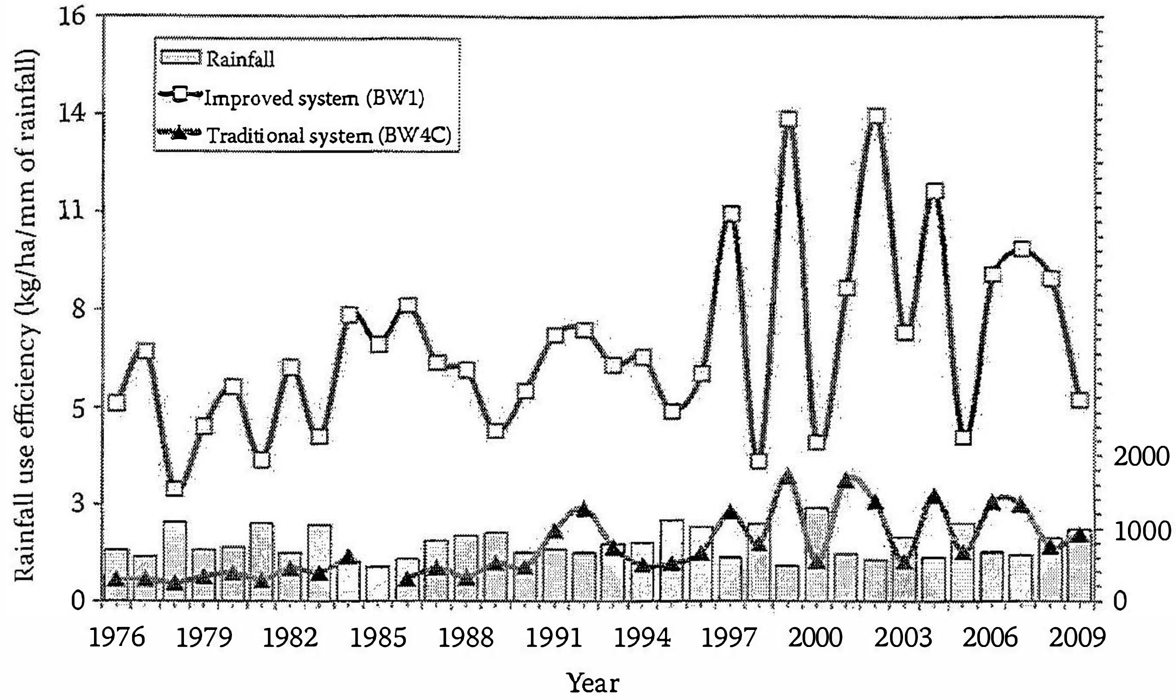


FIGURE 9.9 Increased rainwater use efficiency in low rainfall years.

In addition, soil organic matter—an important driving force for supporting biological activity in soil—is very much in short supply, particularly in tropical countries. In addition to its importance for sustainable crop production, low soil organic matter in tropical soils is a major factor contributing to their poor productivity [Lee and Wani 1989; Syers et al. 1996; Katyal and Rattan 2003], the accelerated decomposition of soil organic carbon (SOC) due to agriculture and release of carbon (C) in the atmosphere also contributes to global warming [IPCC 1990; Lorenz and Lal 2005]. Management practices that augment soil organic matter and maintain it at a threshold level are needed. Sequestration of C in soil has attracted the attention of researchers and policymakers alike as an important mitigation strategy for minimizing impacts of climate change [Lal 2004; Velayutham et al. 2000; ICRISAT 2005; Bhattacharya et al. 2009; Srinivasarao et al. 2009]. Agricultural soils are among the earth's largest terrestrial reservoirs of C and hold potential for expanded C sequestration [Lal 2004]. Improved agricultural management practices in the tropics such as intercropping with legumes, application of balanced plant nutrients, suitable land and water management, and use of stress-tolerant high-yielding cultivars improved SOC content and also increased crop productivity [Wani et al. 1995, 2003a, 2005, 2007; Lee and Wani 1989; ICRISAT 2005; Srinivasarao et al. 2009]. Farm bunds and degraded common lands in the villages could be productively used for growing nitrogen-fixing shrubs and trees to generate nitrogen-rich loppings. For example, growing *Gliricidia sepium* at a close spacing of 75 cm on farm bunds could provide 28–30 kg nitrogen per ha in addition to valuable organic matter. Also, large quantities of farm residues and other organic wastes could be converted into valuable sources of plant nutrients and organic matter through vermicomposting [Nagavallama et al. 2005]. Vermicompost is a good source of plant nutrients along with organic C addition

TABLE 9.3
Nutrient Composition of Vermicompost and Garden Compost

Nutrient Element	Vermicompost (%)	Garden Compost (%)
Organic carbon	9.8–13.4	12.2
Nitrogen	0.51–1.61	0.8
Phosphorus	0.19–1.02	0.35
Potassium	0.15–0.73	0.48
Calcium	1.18–7.61	2.27
Magnesium	0.093–0.568	0.57
Sodium	0.058–0.158	<0.01
Zinc	0.0042–0.110	0.0012
Copper	0.0026–0.0048	0.0017
Iron	0.2050–1.3313	1.1690
Manganese	0.0105–0.2038	0.0414

Source: Nagavallemma, K.P., et al., *Vermicomposting: Recycling Wastes into Valuable Organic Fertilizer, Global Theme on Agroecosystems Report No. 8*, ICRISAT, Patancheru, Andhra Pradesh, India, 2004.

to the soil (Table 9.3). Through collective action, women self-help groups in the watersheds are earning additional income with vermicomposting [Wani et al. 2008; Sreedevi et al. 2007; Sreedevi and Wani 2009] and also contributing to enhancement of agricultural productivity and disposal of agricultural wastes thru environment-friendly processes.

9.3.3 WATER RESOURCES MANAGEMENT

For enhancing rainwater use efficiency in rainfed agriculture, the management of water alone cannot result in enhanced water productivity as the crop yields in these areas are limited by factors additional to water limitation. ICRISAT's experience in rainfed areas has clearly demonstrated that more than water quantity per se, management of water is the limitation in the SAT regions [Wani et al. 2005]. An analysis in Malawi indicates that over the past three decades, only a fraction of the years that have been politically proclaimed as drought years were actually years subject to meteorological droughts (i.e., years where rainfall totals fall under minimum water needs to produce food at all) [Mwale 2003]. As indicated by Agarwal [2000], India would not have to suffer from droughts if local water balances were managed properly. Even during drought years, watershed development efforts of improving rainfall management have benefited Indian farmers [Shiferaw et al. 2006].

Evidence from water balance analyses on farmers' fields around the world shows that only a small fraction, less than 30% of rainfall, is used as productive green water flow (plant transpiration) supporting plant growth [Rockström 2003]. In arid areas, typically as little as 10% of the rainfall is consumed as productive green water flow (transpiration), 90% flows as nonproductive evaporation flow, i.e., no or very limited blue water generation [Oweis and Hachum 2001]. In temperate arid regions, such as WANA, a large portion of the rainfall is generally consumed in the farmers' fields as productive green water flow (45%–55%) that results in higher yield levels (3–4 t/ha as compared to 1–2 t/ha) and 25%–35% of the rainfall flows as nonproductive green water flow. The remaining 15%–20% generate blue water flow. These indicate a large scope of opportunity. Low agricultural yields in rainfed agriculture, often blamed as rainfall deficits, are in fact caused by other factors than rainfall. Still, what is possible to produce on-farm will not always be produced by resource-poor small-scale farmers. The farmers' reality is influenced by other constraints such as labor shortage, insecure land ownership, capital constraints, and limitation in human capacities.

9.3.4 Shifting Nonproductive Evaporation to Productive Transpiration

Rainwater use efficiency in agricultural systems in arid and SAT is 35% to 50%. This suggests a scope for improvement of green water productivity, as it entails shifting nonproductive evaporation to productive transpiration, with no downstream water trade-off. This vapor shift (or transfer) through improved management options is a particular opportunity in arid, semiarid, and dry subhumid regions [Rockström et al. 2007].

Field measurements of rainfed grain yields and actual green water flows indicate that by doubling yields from 1 to 2 t/ha in semiarid tropical agroecosystems, green water productivity may improve from approximately 3500 m^3/t to less than 2000 m^3/t. This is a result of the dynamic nature of water productivity improvements when moving from very low yields to higher yields. At low yields, crop water uptake is low and evaporative losses are high, as the leaf area coverage of the soil is low. This results in high losses of rainwater as evaporation from soil. When yield levels increase, shading of soil improves.

9.4 NEW PARADIGM IS A MUST FOR UNLOCKING THE POTENTIAL OF RAINFED AGRICULTURE

9.4.1 New Paradigm for Water Management in Rainfed Agriculture

Business as usual in managing rainfed agriculture as subsistence agriculture with low resource use efficiency cannot sustain the economic growth and needed food security. There is an urgent need to develop a new paradigm for upgrading rainfed agriculture. The conventional sectoral approach to water management produced low water use efficiencies resulting in increased demand for water to produce food. We need to have a holistic approach based on converging all the necessary aspects of natural resource conservation—their efficient use, production functions, and income enhancement avenues through value chain and enabling policies and much needed investments in rainfed areas [Wani et al. 2003b, 2009; Rockström et al. 2007].

Policy on water resource management for agriculture remains focused on irrigation, and the framework for integrated water resource management (IWRM) at catchment and basin scales are primarily concentrated on allocation and management of blue water (irrigation water) in rivers, groundwater, and lakes. The evidence from the CA indicated that water for agriculture is larger than irrigation, and there is an urgent need for a widening of the policy scope to include explicit strategies for water (green and blue) management in rainfed agriculture, including grazing and forest systems. Effective integration is a must to have a focus on the investment options of water management across the continuum (range) from rainfed to irrigated agriculture. This is the time to abandon the obsolete sectoral divide between irrigated and rainfed agriculture, which would place water resource management and planning more centrally in the policy domain of agriculture at large and not, as today, as a part of water resource policy [Molden et al. 2007].

Furthermore, the current focus on water resource planning at the river basin scale is not appropriate for water management in rainfed agriculture, which overwhelmingly occurs on farms of <5 ha at the scale of small catchments, below the river basin scale. Therefore, the focus should be on managing water at the catchment scale (or small tributary scale of a river basin), and opening for much needed investments in water resource management and also in rainfed agriculture [Rockström et al. 2007].

Evidence collected during the CA of water for food and water for life revealed that business as usual in global agriculture would not be able to meet the goal of food security and poverty reduction. If the situation continues, it will lead to crises in many parts of the world [Molden et al. 2007]. However, the world's available land and water resources can satisfy future demands by taking the following steps:

- Upgrading rainfed agriculture by investing more to enhance agricultural productivity (rainfed scenario)
- Discarding the artificial divide between rainfed and irrigated agriculture and adopting an IWRM approach for enhancing resource efficiency and agricultural productivity
- Investing in expanding irrigation where the scope exists and improving the efficiency of the existing irrigation systems (irrigation scenario)
- Conducting agricultural trade within and between countries (trade scenario)
- Reducing gross food demand by influencing diets and reducing postharvest losses, including industrial and household waste

To upgrade rainfed agriculture in the developing countries community, a participatory and integrated watershed management approach is recommended and is found effective through a number of islands of success in Asia and Africa [Wani et al. 2002, 2003; Rockström et al. 2007; Wani et al. 2008]. In the rainfed areas of the tropics, water scarcity and growing land degradation cannot be tackled thru farm-level interventions alone, and community-based management of natural resources for enhancing productivity and improving rural livelihoods are urgently needed [Wani et al. 2003, 2009; Rockström et al. 2007]. We need to have a holistic approach based on converging all the necessary aspects of natural resource conservation, their efficient use, production functions, and income enhancement avenues through value chain and enabling policies and much needed investments in rainfed areas. A major research and development challenge in upgrading rainfed agriculture is to establish convergence among different stakeholders and scientific disciplines by coming out of disciplinary compartments and translating available blueprints into operational plans and implementing them [Wani et al. 2003, 2006, 2009a; Rockström et al. 2007]. We know what to do but we face the challenge of how to do it.

The community-based management of natural resources calls for new approaches (technical, institutional, and social) that are knowledge-intensive and need strong capacity-building measures for all the stakeholders, including policymakers, researchers, development agents, and farmers. The small and marginal farmers are deprived of the new knowledge and materials produced by the researchers. There is a disconnect between the farmers and the researchers as the extension systems in most developing countries are not functioning at the desired level. There is an urgent need to bring in change in the way we are addressing the issues of rainfed agriculture to achieve food security and alleviate poverty to meet the MDGs.

9.4.2 HOLISTIC WATERSHED APPROACH THROUGH INTEGRATED GENETIC AND NATURAL RESOURCE MANAGEMENT (IGNRM)

Traditionally, crop improvement and natural resource management (NRM) were seen as distinct but complementary disciplines. ICRISAT has deliberately blurred these boundaries to create the new paradigm of IGNRM [Twomlow et al. 2006] to solve farming problems. Improved varieties and improved resource management are two sides of the same coin. The systems approach looks at various components of the rural economy—traditional food grains, new potential cash crops, livestock and fodder production, as well as socioeconomic factors such as alternative sources of employment and income. Crucially the IGNRM approach is participatory, with farmers closely involved in technology development, testing, and dissemination.

ICRISAT's studies in Africa and Asia have identified several key constraints to more widespread technology adoption [Ryan and Spencer 2001]. Other institutes have independently reached similar conclusions for other agroecosystems. So there is general agreement on the key challenges before us:

- Lack of a market-oriented smallholder production system where research is market-led, demand-driven, and follows the commodity chain approach to address limiting constraints along the value chain.
- Poor research-extension–farmer linkages, which limit transfer and adoption of technology.
- Need for policies and strategies on soil, water, and biodiversity to offset the high rate of natural resource degradation.
- Need to focus research on soil fertility improvement, soil and water management, development of irrigation, promotion of integrated livestock–tree–crop systems, and development of drought mitigation strategies.
- Need to strengthen capacities of institutions and farmers' organizations to support input and output marketing and agricultural production systems.
- Poor information flow and lack of communication on rural development issues.

- Need to integrate a gender perspective in agricultural research and training as seen in ICRISAT's work on community watershed, VASAT, and village-level studies.

In much of agricultural research, the multidisciplinary team approach has often run into difficulties in achieving impact because of the perceived disciplinary hierarchy [Shambhu et al. 2005]. The IGNRM approach in The Community Watershed Consortium pursues integration of the knowledge and products of the various

TABLE 9.4
Effect of Climate Variability on Pearl Millet Crop Performance and IGNRM Options in Mali

Climate Parameters	Effects on Crops and Natural Resources	IGNRM Options
Late onset of rains	Shorter rainy season, risk that long-cycle crops will run out of growing time	Early-maturing varieties, exploitation of photoperiodism, P fertilizer at planting
Early drought	Difficult crop establishment and need for partial or total resowing	P fertilizer at planting, water harvesting and runoff control, delay sowing (but poor growth due to N flush), exploit seedling heat and drought tolerance
Midseason drought	Poor seed setting and panicle development, fewer productive tillers, reduced grain yield per panicle/plant	Use of pearl millet variability: differing cycles, high tillering cultivars, optimal root traits, etc., water harvesting and runoff control
Terminal drought	Poor grain filling, fewer productive tillers	Early-maturing varieties, optimal root traits, fertilizer at planting, water harvesting and runoff control
Excessive rainfall	Downy mildew and other pests, nutrient leaching	Resistant varieties, pesticides, N fertilizer at tillering
Increased temperature	Poor crop establishment (dessication of seedlings), increased transpiration, faster growth	Heat tolerance traits, crop residue management, P fertilizer at planting (to increase plant vigor), large number of seedlings per planting hill
Unpredictability of drought stress	See above	Phenotypic variability, genetically diverse cultivars
Increased CO_2 levels	Faster plant growth through increased photosynthesis, higher transpiration	Promote positive effect of higher levels through better soil fertility management
Increased occurrence of dust storms at onset of rains	Seedlings buried and damaged by sand particles	Increase number of seedlings per planting hill, mulching, ridging (primary tillage)
Increased dust in the atmosphere	Lower radiation, reduced photosynthesis	Increase nutrient inputs (i.e., K)

research disciplines into useful extension messages for development workers that can sustain increased yields for a range of climatic and edaphic conditions (Table 9.4).

9.4.3 WATERSHED DEVELOPMENT—A GROWTH ENGINE FOR DEVELOPMENT OF RAINFED AREAS

In several countries, central and state governments and development investors have emphasized management of rainfed agriculture under various programs. Important efforts, for example, have been made under the watershed development programs in India, Thailand, Vietnam, and China in Asia, and Ethiopia and Rawanda in Africa. Originally, these programs in India were implemented until 2008 by different ministries such as the Ministry of Agriculture, the Ministry of Rural Development, and the Ministry of Environment and Forestry, causing difficulties for integrated watershed management. Recently, steps were taken to unify the program according to the common watershed guidelines developed by the Government of India in 2008 [GoI 2008].

9.4.4 COMMON FEATURES OF THE WATERSHED DEVELOPMENT MODEL

Government agencies, development thinkers, donors, researchers, and NGOs have gradually learned one from another, though some are ahead of the field and others are deficient in some aspect or other, principally in people participation or in the science. But generally, the better models of today have some or all of the following features in common:

- Participation of villagers as individuals, as groups, or as a whole, increasing their confidence, enabling their empowerment, and their ability to plan for the future and for self determination
- Capturing the power of group action in the village, between villages, and from federations, e.g., capturing economies of scale by collective marketing
- The construction of basic infrastructure with contributions in cash or labor from the community
- Better farming techniques, notably the improved management of soil, water, diversifying the farming system and integrating the joint management of communal areas and forest
- The involvement of the landless, often in providing services
- Arrangements for the provision of basic services and infrastructure
- The establishment of village institutions and links with the outside world
- Improved relationships between men and women
- Employment and income generation by enterprise generation in predominantly, but not exclusively, agriculture-related activities

And sometimes:

- The fusion of research and development (R&D) by capturing the extraordinary power of participatory technology development, including variety selection with direct links to germplasm collections

- Complete avoidance of corruption so that trust is engendered and all the benefits pass to the community
- Involvement with enforced migration

9.4.5 RECENT ADDITIONS TO THE WATERSHED MODEL

More recently, the following features have been added:

- The pragmatic use of scientific knowledge as the entry point rather than money, leading to tangible economic benefits from low-cost interventions that generate rapid and substantial returns at an acceptable low level of risk. Among these are novel interventions focusing on soil health, participatory evaluation of improved cultivars, integrated pest management (IPM), use of micronutrients, and soil conservation and water table recharge structures.
- A broad-based approach to income generation involving private sector links associated with scientific advances and markets: e.g., in the remediation of micronutrients deficiencies; in the marketing of medicinal and aromatic plants; with premium payments paid by industrial processors for aflatoxin-free maize and groundnut; with high sugar sorghum, soybean, and selected crops sold to industry for processing; and with the production for sale of commercial seed, hybrid varieties, and biopesticides.
- Using new science methodologies to improve performance: remote sensing for monitoring and feedback to farmers; yield gap analysis; and rapid assessment of the fertility status of the watershed.
- Building productive partnerships and alliances in a consortium for research and technical backstopping with the members brought together from the planning stage.
- A desire to create resilience in the watershed and its community to climate change and to events occurring after program intervention.

Where best applied, the model has led to profound farming system changes, improved food self sufficiency, expanded employment and commerce, and enhanced incomes. Where indifferently executed, the approach has led to no better than ad hoc development schemes as we shall see. There is indeed something here analogous to the yield gap exhibited between research stations and farmers' yields. Much of the difference can be captured by implementing agencies catching up with best practices. The more recent linking of natural resource science with the private sector, markets, and with peoples' broader livelihoods in consultation with them, is transforming the dynamics and success rate of development efforts.

The watershed approach is a paradigm that works in all rainfed circumstances, has delivered important benefits and impacts, and needs to be implemented on a large scale. But watershed impact covers a spectrum from no better than ad hoc development schemes to impressive improvements of the natural resource endowment and agricultural production and a transformation of the socioeconomy.

To consolidate and build upon the foundation already laid and universally gain the impact that is possible requires governments doing some difficult things, most noticeably introducing a new mind set or different form of approach that accepts that:

- Watershed development is not just a means to increase production or to conserve soil and water, but an opportunity for the fully integrated and sustained development of human and natural resources.
- The approach is valid across various rainfall regimes over vast tracts of tropical rainfed areas and can contribute in large measure to the simultaneous achievement of government's production, environmental, and social goals.
- Sustainability and better social impact and equity are very important issues with pro-poor interventions, not as a spin-off or afterthought, but planned and integral to the whole.
- There are vast opportunities to reduce costs and increase output by improving the appropriateness and reach of technology.

There is obvious value in converging different schemes in the interest of impact and sustainability, rather than a spread of activity: this is particularly important in the case of water and of schemes aimed to reach the poor.

9.4.6 LEARNING FROM META-ANALYSIS OF WATERSHEDS IN INDIA

The descriptive summary of multiple benefits derived from 636 watersheds, as indicated in numerous studies, is shown in Table 9.5. It is obvious that watershed programs are silently revolutionizing the rainfed areas with a mean benefit/cost ratio of 2.0 with the benefits ranging from 0.82 to 7.30. It indicates that, on average, even in fragile and high-risk rainfed environments, watershed programs were able to generate benefits that were more than double their costs. In many of the watersheds, benefits were even higher. About 18% of watersheds generated benefit/cost ratios above 3, which is fairly modest (Figure 9.10). However, 68% of watersheds performed below average (B/C ratio of 2.0) and indicated a large scope to enhance the impact of watershed projects in the country. Merely 0.6% of watersheds failed commensurate with the cost of the project [Joshi et al. 2008].

The mean internal rate of return of 27.43% was significantly high and comparable with any successful government programs (Table 9.5). The internal rates of return in 41% of watersheds were in the range of 20% to 30%, whereas about 27% of watersheds yielded an internal rate of return (IRR) of 30% to 50% (Figure 9.11). The watersheds with IRRs below 10% were only 1.9%.

Another important purpose of the watershed programs was to generate employment opportunities to address the equity concerns of landless laborers and marginal and small farmers. The results of meta-analysis indicated that watershed programs have generated significant and substantial employment opportunities in the watershed areas. The mean additional annual employment generation in the watershed area on various activities and operations was about 154 person days/ha/yr (Table 9.5). It was as high as 900 person days/ha/yr in those watersheds that included multiple activities. Generating employment opportunities for the rural poor means raising

TABLE 9.5
Summary of Benefits from the Sample Watersheds Using Meta-Analysis

	Particulars	Unit	No. of Studies	Mean	Mode	Median	Minimum	Maximum	*t* Value
Efficiency	B/C ratio	Ratio	311	2.01	1.70	1.70	0.82	7.30	35.09
	IRR	%	162	27.43	25.90	25.00	2.03	102.70	21.75
Equity	Employment	Person days/ha/yr	99	154.53	286.67	56.50	0.05	900.00	8.13
Sustainability	Increase in irrigated area	%	93	51.55	34.00	63.43	1.28	204	10.94
	Increase in cropping intensity	%	339	35.51	5.00	21.00	3.00	283.00	14.96
	Runoff reduced	%	83	45.72	43.30	42.53	0.38	96.00	9.36
	Soil loss saved	t/ha/yr	72	1.12	0.91	0.99	0.11	2.05	47.21

Source: Joshi, P.K., et al., In *Global Theme on Agroecosystems, Report No. 46*; ICRISAT, Patancheru, Andhra Pradesh, India, 2008.

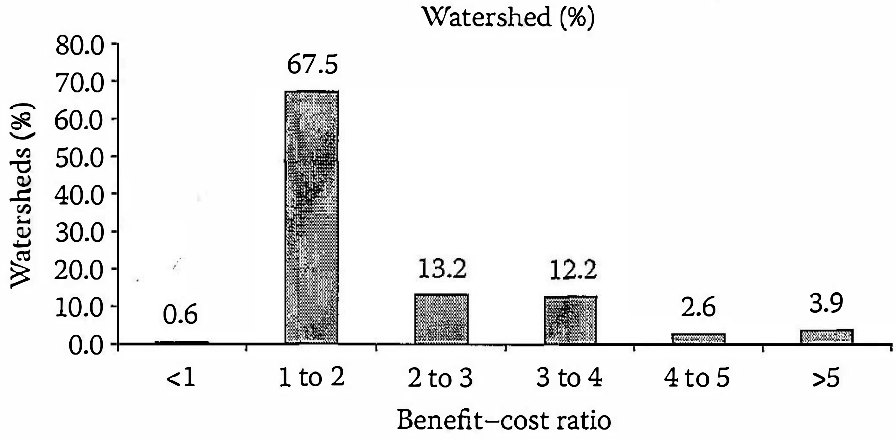


FIGURE 9.10 Distribution (%) of watersheds according to benefit/cost ratio (BCR). (From Joshi, P.K., et al., In *Global Theme on Agroecosystems, Report No. 46*, ICRISAT, Patancheru, Andhra Pradesh, India, 2008. With permission.)

their purchasing power and, in turn, alleviating rural poverty and income disparities. This has an important implication in that the watershed investment may be characterized as a poverty alleviation program in the fragile ecosystem areas.

The important objective of the watershed programs is to improve the livelihood of poor rural households, who encounter disproportionate uncertainties in rainfed agriculture due to precarious environments, acute degradation of soil, and water scarcity. The estimates show that watershed programs were quite effective in addressing the problems of land degradation due to soil erosion and loss of water due to excessive runoff. Soil loss of about 1.12 t/ha/yr was saved due to interventions in the watershed framework. Conserving soil means raising farm productivity and transferring good soils to the next generation. It was noted that, on average, about 38 ha m additional water storage capacity was created in a watershed of 500 ha as a result of the watershed program. Augmenting water storage capacity contributed in (i) reducing the rate of runoff, and (ii) increasing groundwater recharge. On average, runoff loss was

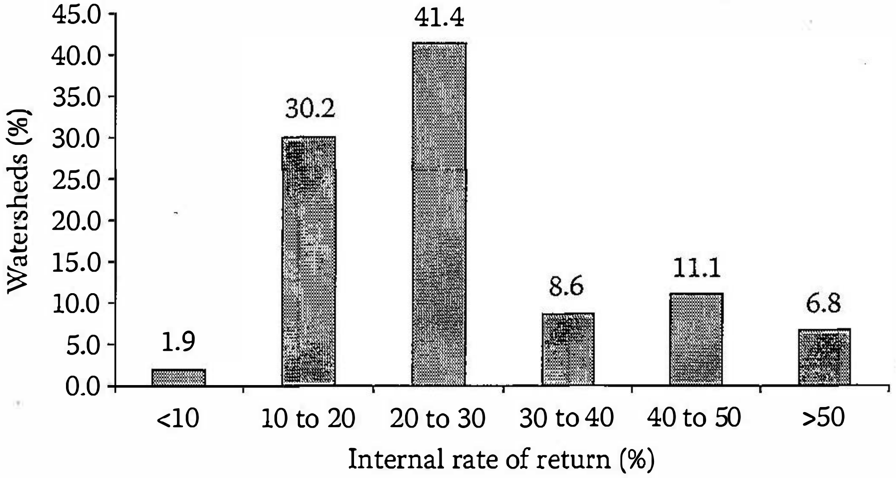


FIGURE 9.11 Distribution (%) of watersheds according to IRR. (From Joshi, P.K., et al., In *Global Theme on Agroecosystems, Report No. 46*, ICRISAT, Patancheru, Andhra Pradesh, India, 2008. With permission.)

reduced by 46% because of various watershed interventions, and the groundwater table was also augmented by 3.6 m in the watershed areas. These improvements have direct impacts in expanding the irrigated area, increasing cropping intensity, and diversifying systems with high-value crops. On an average, the irrigated area increased by about 52%, while the cropping intensity increased by 35.5%. In some cases, the irrigated area increased up to 204%, while the cropping intensity increased by 283%. Such an impressive increase in the cropping intensity was not realized in many surface irrigated areas in the country. These benefits confirm that the watershed programs perform as a viable strategy to overcome several externalities arising due to soil and water degradation [Joshi et al. 2008].

The above evidence suggests that watershed programs, which have been specifically launched in rainfed areas with the sole objective of improving the livelihood of poor rural households in a sustainable manner, have paid rich dividends and were successful in raising income levels, generating employment opportunities, and augmenting natural resources in the rainfed areas. These benefits have far-reaching implications for rural masses in the rainfed environment [Wani et al. 2008].

9.4.7 RESULTS OF META-ANALYSIS REGRESSION

The results of meta-analysis regression further showed that the benefits vary depending upon the location, size, type, rainfall, implementing agency, and people's participation, among other factors. The coefficient of multiple determination (R^2) shows the variables included in the model and explains the more than 56% variation in the benefit:cost ratio. The positive value of intercept also indicates a positive impact of watershed programs on augmentation of income. A number of factors determine the economic efficiencies of watershed programs. Geographical location, rainfall pattern, focus of watershed program, implementing agency, status of target population, and people's participation are some of the critical factors that play a deterministic role in the performance and efficiency of watersheds [Joshi et al. 2008]. Consideration of the time gap between implementation and evaluation of the program is also important. However, the effect of the time gap between implementation and evaluation could not be captured, as the variable was statistically nonsignificant. However, a positive sign of the variable indicates a larger benefit associated with intervention with time and suggests that performance of the watershed program should not be judged immediately after the implementation [Wani et al. 2008a].

Macrowatersheds (>1200 ha) achieved better impact than micros of 500 ha. Development needs to be undertaken in clusters of at least four to six microwatersheds together (2000–3000 ha) and the common guidelines has addressed this [GoI 2008], adopting sizes of 1000 to 5000 ha by selecting microwatersheds in a cluster. Macrounits offer economies of scale, more technical options, and greater hydrological efficiency and would ease collaboration between agencies and their interface with the community.

Between 700 mm and 1100 mm of rainfall, there is good technology available. Above and below these amounts, the appropriateness and range of current technologies is not good enough and needs to be researched in concert with watershed communities to enhance the impact of watershed programs in all rainfed regions.

Use of new scientific tools such as crop simulation and water balance models, GIS, remote sensing and information and communication technology (ICT), participatory research and development (PR&D), and collective action for planning, implementation, monitoring, and evaluation is needed to manage natural resources more efficiently and sustainably in the watersheds.

The drivers of success are tangible economic benefits to large number of people, empowerment through knowledge, equal partnership, trust and shared vision, good local leadership, transparency and social vigilance in financial dealings, equity through low-cost structures, a predisposition to work collectively, activities targeted at the poor and women, increased drinking water availability, and income-generating activities for women.

The current allocations are insufficient to treat a complete watershed or to adopt the livelihoods approach. Higher investments are a must to make watersheds engines of growth. The new IWMP of the Government of India has increased investments from Rs.6000 (US $133) to Rs.12000 (US $266) per ha in plains and Rs.15000 (US $333) in hilly areas [GoI 2008] and has adopted a livelihood approach to ensure tangible economic benefits to people in a watershed.

There is opportunity to reduce costs: more cost-effective water structures; economies of scale from using the macrowatershed as the development unit; convergence of action to avoid duplication; getting things right the first time to avoid repeat expenditures; and avoiding the adverse costs of environmental deterioration. The cost/benefit ratio would be much improved by more efficient use of technology to increase productivity, by bringing wasteland into productive use, and by a total accounting of socioeconomic and environmental benefits.

Interventions are needed to benefit women and vulnerable groups and help them to develop social capital and increased sustainability. National and state planning for and selection of watersheds might best be based on a matrix of the potentials for impact on production, poverty, the environment, and community involvement.

Moving forward requires that a lack of capacity to effectively implement programs is addressed. Implementing agencies need to expand and broaden their capacities and skills and reach and communities need to strengthen their institutions and their skills. This will require a longer implementation period of 7 to 8 years with more time spent in preparation and in postintervention support. Additional funds and more flexibility in using budgets and the engagement of specialist service providers will also be required. The new common guidelines [GoI 2008] have addressed these recommendations and project duration is increased up to 7 years and 5% of the total budget is earmarked for capacity-building using quality service providers.

One of the weakest aspects lies in the generation and dissemination of technology. A big improvement is needed in making appropriate technology and information accessible to the watershed community. The remedy lies in devising technology for the drier and wetter parts of the rainfed area and in more PR&D in forming consortia and employing agencies to provide specialist technical backstopping.

There is a crucial need to improve monitoring and evaluation (M&E) and the feedback of the information obtained to constantly improve performance. Only a few key indicators need to be monitored in all watersheds. At one or two representative watersheds in each district, a broad range technical and socioeconomic parameters should be measured to provide a scientific benchmark and a better economic valuation of impact than is currently possible.

9.4.8 BUSINESS MODEL

Watersheds should be seen and developed as a business model. This calls for a shift in approach from subsidized activities to knowledge-based entry points and from subsistence to marketable surplus ensuring tangible economic benefits for the population of the watershed at large. This is being done with productivity enhancement, diversification to high-value enterprises, income-generating activities, market links, public–private partnerships, microentrepreneurship, and broad-based community involvement. Strengths of rainfed areas using available water resources efficiently through involvement of private entrepreneurs and value addition can be harnessed by linking small and marginal farmers to markets through public–private partnership business model for watershed management [Wani et al. 2008, 2008a].

9.4.9 PROMOTING COLLECTIVE ACTION IN THE COMMUNITY

Collective action occurs when the benefits from lower transaction costs of doing business are higher than the additional costs involved (sacrifices made) in complying with collective rules. When the anticipated benefits of cooperation are lower than the expected costs, households are unlikely to engage in collective efforts. For example, this may be the case for very marginal farmers who produce very small quantities such that the benefits per unit of transaction are small and do not warrant additional costs from cooperation. Previous studies have shown that these costs and benefits are likely to differ from one household to another depending on location, volume of production, endowment of assets, education, managerial skills, etc. [Kerr et al. 2002]. This shows that the benefits of collective action are likely to be unequally distributed and it may not be useful to some households unless some interventions are designed to enhance their participation.

9.4.9.1 Convergence and Collective Action

Convergence of actors and their actions at the watershed level is needed to harness the synergies to unlock the potential of rainfed agriculture and maximize the benefits through efficient and sustainable use of natural resources. The integrated watershed management approach is science-based and knowledge-driven; it demands synthesis of knowledge from different sectors and translation into messages that small and marginal farmers could understand and adopt. The convergence approach to benefit small and marginal farmers through increased productivity per unit of resource is recommended as a large benefit of watershed programs has been missed due to a compartmentalized approach [Wani et al. 2003, 2003b, 2008].

New institutional mechanisms are also needed at district, state, and national levels to converge various watershed programs implemented by several ministries and development agencies to enhance the impact and efficiency by overcoming duplicity and confusion. For example, in 2005, the National Commission on Farmers in India recommended a holistic, integrated watershed management approach, with a focus on rainwater harvesting and improving soil health for sustainable development of drought-prone rainfed areas [GoI 2005]. Recently, the Government of India has established National Rain-fed Areas Authority (NRAA) with the mandate to converge various programs for integrated development of rainfed agriculture in the country. The common watershed guidelines issued by the Government of India have also emphasized the need for convergence and collective action [GoI 2008]. Thus, it has become increasingly clear that water management for rainfed agriculture requires a landscape perspective, and involves cross-scale interactions from farm household scale to watershed/catchment scale.

9.4.9.2 Consortium for Technical Backstopping

Enhancing partnerships and institutional innovations through a consortium approach was a major impetus for harnessing community watershed's potential to reduce household poverty [Wani et al. 2003b]. Complex issues were effectively addressed by a efforts of ICRISAT in collaboration with key partners, namely National Agricultural Research Systems (NARSs), nongovernmental organizations (NGOs), government organizations, agricultural universities, community-based organizations (CBOs), and other private interest groups with farm households as the key decision-makers. Self-help groups (SHGs) like village seedbanks were established not just to provide timely and quality seeds, but also to provide technical support and build the capacity of members, including women, for management, conservation, and livelihood-development activities. Incorporating knowledge-based entry points in the approach led to the facilitation of rapport and, at the same time, enabled the community to make rational decisions for their own development [Wani et al. 2008b]. As demonstrated by ICRISAT, the strongest merit of the consortium approach is in the area of capacity-building, where farm households are not the sole beneficiaries. Researchers, development workers, and students of various disciplines are also trained, and policymakers from the NARSs are sensitized to the entire gamut of community watershed activities. Private–public partnership has provided the means for increased investments, not only for enhancing productivity but also for building institutions as engines for people-led NRM [Wani et al. 2008b].

9.4.9.3 Discard Artificial Divide between Irrigated and Rainfed Agriculture

There is an urgent need to have sustainable water-use policies to ensure sustainable development and adopt an IWRM approach in the watersheds by discarding the artificial divide between rainfed and irrigated agriculture. In the absence of suitable policies and mechanisms for sustainable use of groundwater resources, benefits of watershed programs can be undone—quickly and easily—by overexploitation of the augmented water resources [Sreedevi et al. 2006]. Cultivation of water inefficient crops like rice and sugarcane needs to be controlled through suitable incentive mechanisms for rainfed irrigated crops and policies must be evolved to stop cultivation of high water requiring crops [Wani et al. 2008a].

9.4.9.4 Pilot-Scale Model Community Watershed—A Site of Learning

Based on detailed studies and synthesis of the results, impacts, shortcomings, lessons learned from many watershed programs, and on-farm experiences gained, the ICRISAT-led consortium developed an innovative farmers' participatory consortium model for integrated watershed management [Wani et al. 2002, 2003b, 2003c]. ICRISAT-led watershed espouses the IGNRM approach, where activities are implemented at the landscape level at benchmark sites representing the different agroecoregions of the SAT. The entire process revolves around the four E's (empowerment, equity, efficiency, and environment), which are addressed by adopting specific strategies prescribed by the four C's (consortium, convergence, collective action, and capacity-building). The consortium strategy brings together institutions from the scientific, nongovernment, government, and farmers' groups for knowledge management. Convergence allows integration and negotiation of ideas among actors. Cooperation enjoins all stakeholders to harness the power of collective actions. Capacity-building engages in empowerment for sustainability [Wani et al. 2003b].

The important components of the new model, which are distinct from the earlier ones, are the following:

- Collective action by farmers and participation from the beginning through cooperative and collegiate modes in place of contractual modes—a PR&D approach.
- Principle of "users pay" adopted from the beginning; no free rides in the program.
- Demand-driven approach and no supply-driven technologies; users have to pay in cash/kind.
- Integrated water resource management and holistic system approach through convergence for improving livelihoods vs. a traditional compartmental approach.
- A consortium of institutions for technical backstopping.
- Knowledge-based entry point to build rapport with community and enhance participation of farmers and landless people through empowerment.
- Tangible economic benefits to individuals through on-farm interventions enhancing efficiency of conserved soil and water resources and targeted income-generating activities for women and vulnerable groups through allied sector activities and rehabilitation of wastelands for improved livelihoods and environmental protection.
- Low-cost and environment-friendly soil and water conservation measures throughout the toposequence for more equitable benefits to large numbers of farmers.

9.4.10 MULTIPLE BENEFITS AND IMPACTS

Through the use of new tools [i.e., remote sensing, geographical information systems (GIS), and simulation modelling) along with an understanding of the entire food production–utilization system (i.e., food quality and market) and genuine involvement of stakeholders, the ICRISAT-led consortium approach effected remarkable impacts on SAT resource-poor farm households.

9.4.10.1 Reducing Rural Poverty

Reduction of rural poverty in the watershed communities is evident in the transformation of their economies. The ICRISAT model ensured improved productivity with the adoption of cost-efficient water harvesting structures (WHSs) as an entry point for improving livelihoods. Crop intensification and diversification with high-value crops is an example of allowing households to achieve production of basic staples and surplus for modest incomes. The model has provisions for improving the capacity of farm households through training and networking and for alleviating poverty, improved livelihood, and enhanced participation, especially of the most vulnerable groups like women and the landless.

Building on social capital made a huge difference in addressing the rural poverty of watershed communities. This is evident in the case of Adarsha Watershed, Kothapally, in Andhra Pradesh, India. Today, it is a prosperous village on the path to long-term sustainability and has become a beacon for science-led rural development. In 2001, the average family income from agriculture, livestock, and nonfarming sources was US$945, compared with the neighboring nonwatershed village income of US$613 (Figure 9.12). The villagers proudly professed: "We did not face any difficulty for water even during the drought year of 2002. When surrounding villages had no drinking water, our wells had sufficient water." To date, the village prides itself in households owning 6 tractors, 8 lorries, 7 cars, and 30 auto-rickshaws. People from surrounding villages come to Kothapally for on-farm employment. With more training in livelihood and enterprise development, migration is bound to cease. Additional income of Rs.2000 to Rs.5000 per ha was obtained by the dryland farmers through in situ rainwater conservation, farm ponds, and suitable cropping systems [Venkateswarlu et al. 2008; Rao et al. 2010].

Crop–livestock integration is another facet harnessed for poverty reduction. The Lucheba watershed in Guizhou province of southern China has transformed its economy through modest injection of capital-allied contributions of labor and finance to create basic infrastructures like access to roads and drinking water supply. With

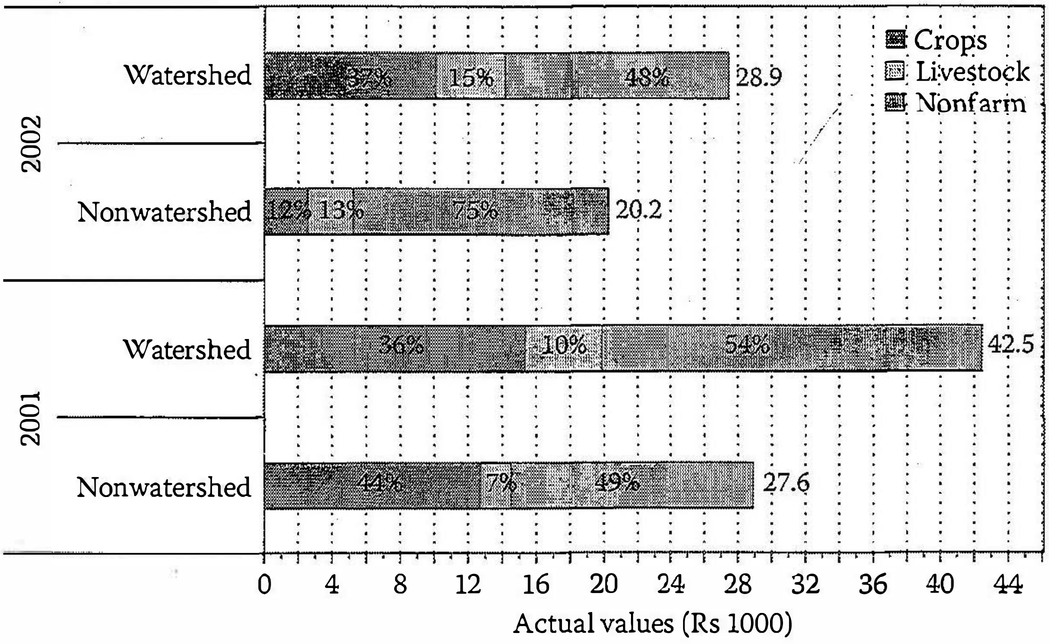


FIGURE 9.12 Effect of integrated watershed management on flow of household net income. (From Shiferaw, B., et al., *Journal of SAT Agricultural Research*, 2, 1, 2006. With permission.)

technical support from the consortium, the farming system was intensified from rice and rape seed to tending livestock (raising pigs) and growing horticultural crops (fruit trees like *Ziziphus*; vegetables like beans, peas, chillies, and sweet potatoes) and groundnuts. In forage production, wild buckwheat was specifically important as an alley crop, as it was good forage grass for pigs [Sreedevi and Wani 2009]. This cropping technology was also effective in controlling erosion and increasing farm income in sloping lands. This holds true in many watersheds of India, where the improvement in fodder production has intensified livestock activities like breed improvement (by artificial insemination and natural means) and livestock center/health camp establishment [Wani et al. 2006]. In Tad Fa and Wang Chai watersheds in Thailand, there was a 45% increase in farm income within 3 years. Farmers earned an average net income of US$1195 per cropping season. A complete turnaround in the livelihood system of farm households was inevitable in ICRISAT-led watersheds. In the Kothapally, Adarsha watershed, milk production increased substantially over the past 6 years, resulting in a marketable surplus of 800 L day^{-1}. At present, Reliance Industries, a supermarket chain, has established a milk procurement center at Kothapally and farmers get good value for milk based on its fat content.

9.4.10.2 Increasing Crop Productivity

Increasing crop productivity is a common objective of all the watershed programs, and enhanced crop productivity is achieved after the implementation of soil and water conservation practices, along with appropriate crop and nutrient management. For example, the implementation of improved crop management technology in the benchmark watersheds of Andhra Pradesh increased the maize yields 2.5 times (Table 9.6) and sorghum yields threefold [Wani et al. 2006]. Overall, in the 65 community watersheds (each measuring approximately 500 ha), implementing best-bet practices resulted in significant yield advantages, varying with crops from 63%–197% (Table 9.7). The crop responses varied with location as well as with crops, the increases ranged in sorghum from 35%–270%, in maize from 30%–174%, in pearl millet from 72%–242%, in groundnut from 28%–179%, in sole pigeonpea from 97%–204%, and in intercropped pigeonpea from 40%–110% [Sreedevi and Wani 2009]. In Thanh Ha watershed of Vietnam, yields of soybean, groundnut, and mung bean increased by threefold to fourfold (2.8–3.5 t/ha) as compared with baseline yields (0.5 to 1.0 t/ha), reducing the yield gap between potential farmers' yields. A reduction in nitrogen fertilizer (90–120 kg urea per ha) by 38%, increased maize yield by 18%. In Tad Fa watershed of northeastern Thailand, maize yield increased by 27%–34% with improved crop management [Wani et al. 2006].

9.4.10.3 Improving Water Availability

Improving water availability in the watersheds was attributed to efficient management of rainwater and in situ conservation, establishment of WHS, and improved groundwater levels. Even after the rainy season, the water level in wells nearer to WHS sustained good groundwater yields. In the various watersheds of India like Lalatora (in Madhya Prdesh), treated area registered a groundwater level rise of 7.3 m. At Bundi, Rajasthan, the average rise was 5.7 m and the irrigated area increased from 207 ha to 343 ha. In Kothapally watershed in Andhra Pradesh, the groundwater

TABLE 9.6

Average Crop Yields (kg ha^{-1}) with Equivalent of Maize Crop with Different Cropping Systems at Adarsha Watershed, Kothapally, 1999–2008

	Yield (kg ha^{-1})													
Cropping Systems	**Before 1998**	**1999–2000**	**2000–2001**	**2001–2002**	**2002–2003**	**2003–2004**	**2004–2005**	**2005–2006**	**2006–2007**	**2007–2008**	**2008–2009**	**Mean**	**CV%**	**SE**
						Improved systems								
Sole maize	–	3250	3760	3300	3480	3920	3420	3920	3630	4680	4810	3820	17.8	80
Maize/pigeonpea intercrop system	–	5260	6480	5600	5650	6290	4990	6390	6170	6120	6680	5960	16.7	116
Sorghum/pigeonpea intercrop system	–	5010	6520	5830	–	5780	4790	5290	5310	–	–	5500	13.4	154
Sole sorghum	–	4360	4590	3570	2960	2740	3020	2860	2500	–	–	3330	23.9	141
						Farmers practice								
Sole maize	1500	1700	1600	1600	1800	2040	1950	2250	2150	–	–	1890	17.2	53
Sorghum/pigeonpea intercrop system	1980	2330	2170	2750	3190	3310	3000	3360	3120	–	–	2900	19.2	110
Hybrid cotton	–	2295	7050	6600	6490	6950	–	–	–	–	–	5880	37.0	511
BT cotton	–	–	–	–	–	–	–	6210	5590	7310	9380	7120	26.1	315
Mean		3477	4970	3833	4018	4814	3651	4584	4320	6268	7396			
CV%		11.9	31.4	10.7	8.0	14.5	20.3	10.8	12.2	16.7	16.2			
SE		415	1559	410	323	698	742	495	525	1049	1201			

Note: The farmers practice sorghum/pigeonpea intercrop system; improved pigeonpea variety ICPL 87119 was grown along with local sorghum variety (Pacha Jonna) from 2001 onward. The old variety, which was highly susceptible for fusarium wilt, was discontinued.

TABLE 9.7
Crop Yields as Influenced by Best-Bet Options in Districts of Andhra Pradesh under APRLP–ICRISAT Watersheds and Karnataka under Sujala–ICRISAT Project

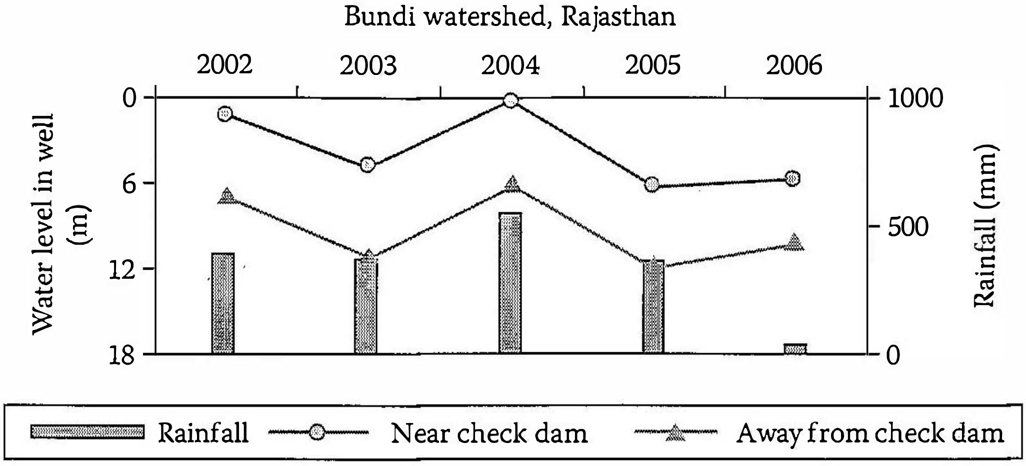
Crop	Grain Yield ($t\ ha^{-1}$) Farmers' Practice	Grain Yield ($t\ ha^{-1}$) Improved Practice	% Increase over Farmers' Practice
	Andhra Pradesh		
Groundnut	0.95	1.52	63
Greengram	0.98	1.67	70
Pearl millet	0.88	2.13	142
Maize	3.10	5.24	69
Sorghum	1.13	2.30	104
	Karnataka		
Groundnut	1.00	1.97	97
Finger millet	1.15	1.93	68
Sunflower	0.76	2.26	197
Maize	3.45	5.87	70
Soybean	1.35	2.47	82

Source: Sreedevi, T.K., and Wani, S.P. In *Rain-Fed Agriculture: Unlocking the Potential, Comprehensive Assessment of Water Management in Agriculture Series*, CAB International, Wallingford, UK, 222–257, 2009.

level rise was 4.2 m in open wells (Figure 9.13). The various WHSs resulted in an additional groundwater recharge per year of approximately 428,000 m^3, on average, in a watershed. With this improvement in groundwater availability, the supply of clean drinking water was guaranteed. In Lucheba watershed in China, a drinking water project, which constitutes a water storage tank and pipelines to farm households, was a joint effort of the community and the watershed project. This solved the drinking water problem for 62 households and more than 300 livestock. Previously, every farmer's household spent 2–3 hours per day fetching drinking water. This was the main motivation for the excellent participation by farmers in the project. On the other hand, in Thanh Ha watershed in Vietnam, collective pumping of well water established an efficient water distribution system and enabled the farmers' group to earn more income by growing watermelon with reduced drudgery as women previously had to carry water a long distance on their heads to irrigate watermelon crops [Wani et al. 2006].

9.4.10.4 Supplemental Irrigation

Supplemental irrigation can play a very important role in reducing the risk of crop failures and in optimizing productivity in the SAT. In these regions, there is a good potential for delivering excess rainwater to storage structures or groundwater because, even under improved systems, there is a loss of 12%–30% of the rainfall as



Estimated additional groundwater recharge was 6,75,0000 m^3 per year.

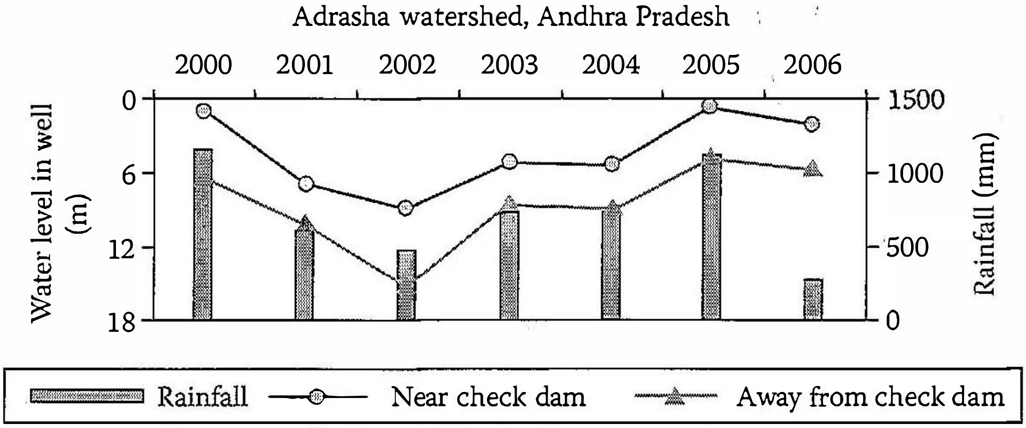


FIGURE 9.13 The impact of watershed interventions on groundwater levels at two benchmark sites in India. (Note: Estimated additional groundwater recharge due to watershed interventions is 675,000 m^3/yr in Bundi watershed and 427,800 m^3/yr in Adarsha Watershed.)

runoff. Striking results were recorded from supplemental irrigation on crop yields in ICRISAT benchmark watersheds in Madhya Pradesh. On-farm studies made during the 2000–2003 postrainy seasons showed that chickpea yields (1.25 t/ha) increased by 127% over the control yields (0.55 t/ha), and groundnut pod yields (1.3 t/ha) increased by 59% over the control yields (0.82 t/ha) by application of two supplemental irrigations of 40 mm. Similar yield responses in mung bean and chickpea crops were obtained from supplemental irrigation at the ICRISAT center in Patancheru [Pathak et al. 2009].

9.4.10.5 Sustaining Development and Protecting the Environment

Sustaining development and protecting the environment are the two-pronged achievements of the watersheds. The effectiveness of improved watershed technologies was evident in reducing runoff volume, peak runoff rate and soil loss, and improving groundwater recharge. This is particularly significant in Tad Fa watershed where interventions such as contour cultivation at midslopes, vegetative bunds planted with *Vetiver*, fruit trees grown on steep slopes, and relay cropping with rice bean reduced seasonal runoff to less than half (194 mm) and soil loss to less than one-seventh (4.21 t/ha) of the conventional system (473 mm runoff and soil loss of 31.2 t/ha). This holds true with the peak runoff rate, where the reduction is approximately one-third (Table 9.8).

A large number of fields (80%–100%) in the SAT were found severely deficient in zinc, boron, and sulfur, as well as nitrogen and phosphorus (Tables 9.2a and b). Amendment of soils with the deficient micronutrients and secondary nutrients increased crop yields by 30% to 70%, resulting in an overall increase in water and nutrient use efficiency (Table 9.9) [Rego et al. 2007]. The Introduction of IPM in cotton and pigeonpea substantially reduced the number of chemical insecticidal sprays in Kothapally, India during the season and thus reduced the pollution of water bodies with harmful chemicals. Introduction of IPM and improved cropping systems decreased the use of pesticides to 66 per ha, saving US$44 [Ranga Rao et al. 2007]. Crop rotation using legumes in Wang Chai watershed in Thailand and Than Ha Watershed in Vietnam substantially reduced nitrogen requirements for rainfed sugarcane in Wang Chai and maize in Than Ha watersheds. The IPM practices, which brought into use local knowledge using insect traps of molasses, light traps, and tobacco waste, led to extensive vegetable production in Xiaoxingcun (China) and Wang Chai (Thailand) watersheds [Wani et al. 2006].

Improved land and water management practices, along with integrated nutrient management comprising application of inorganic fertilizers and organic amendments (such as crop residues, vermicompost, farm manures, and *Gliricidia* loppings) as well as crop diversification with legumes, not only enhanced productivity but also improved soil quality. Increased C sequestration of 7.4 t/ha in 24 years was observed with improved management options in a long-term watershed experiment at ICRISAT [Wani et al. 2003a]. By adopting a fuel-switch for C, women SHGs in Powerguda (a remote village of Andhra Pradesh, India) have pioneered the sale of C units (147 t CO_2 C) to the World Bank from their 4500 *Pongamia* trees, the seeds of which are collected for producing saplings for distribution and promotion of the biodiesel plantation. A normalized difference vegetation index (NDVI) estimation from the satellite images showed that within 4 years, vegetation cover could increase by 35% in Kothapally. The IGNRM options in the watersheds reduced loss of

TABLE 9.8

Seasonal Rainfall, Runoff, and Soil Loss from Different Benchmark Watersheds in India and Thailand

Watershed	Seasonal Rainfall (mm)	Runoff (mm)		Soil Loss (t/ha)	
		Treated	Untreated	Treated	Untreated
Tad Fa (Khon Kaen, NE Thailand)	1284	169	364	4.21	31.2
Kothapally (Andhra Pradesh, India)	743	44	67	0.82	1.9
Ringnodia (Madhya Pradesh, India)	764	21	66	0.75	2.2
Lalatora (Madhya Pradesh, India)	1046	70	273	0.63	3.2

TABLE 9.9

Yield and Nutrient Uptake of Maize, Castor, Groundnut, and Mung Bean in Response to Fertilization in Andhra Pradesh, India, 2002–2004

			Total Uptake of Nutrients					
	Grain Yield	Total Dry Matter	kg ha^{-1}				g ha^{-1}	
Treatment	kg ha^{-1}	kg ha^{-1}	N	P	K	S	B	Zn
			Maize					
2002								
Farmer inputs (FI)	2730	6200	59.5	15.0	45.2	4.5	16.4	111.8
FI + SBZn	4560 (67%)	8850 (42%)	86.4	20.8	57.1	7.0	19.2	191.8
LSD (0.05)	419	633	8.8	4.1	5.7	0.7	3.8	25.4
2003								
FI	2790	6370	48.3	48.3	39.0	4.4	8.7	113.1
FI + SBZn	4130 (48%)	9040 (41%)	73.9	73.9	47.2	6.9	17.1	228.1
FI + SBZn + NP	4880 (74%)	10,377 (62%)	108.1	108.1	55.6	9.3	19.4	266.7
LSD (0.05)	271	580	8.4	8.4	6.3	0.7	3.6	41.0
2004								
FI	2430	5820	60.0	60.0	59.9	5.3	19.0	89.6
FI + SBZn	3110 (27%)	7060 (21%)	69.4	69.4	63.9	5.7	23.6	165.1
FI + SBZn + NP	4230 (74%)	9470 (62%)	93.0	93.0	85.8	9.0	42.1	191.9
LSD (0.05)	417	1054	13.4	13.4	13.9	1.3	7.8	38.3

(continued)

TABLE 9.9 (Continued)

Yield and Nutrient Uptake of Maize, Castor, Groundnut, and Mung Bean in Response to Fertilization in Andhra Pradesh, India, 2002–2004

			Total Uptake of Nutrients					
	Grain Yield	Total Dry Matter	kg ha^{-1}				g ha^{-1}	
Treatment	kg ha^{-1}	kg ha^{-1}	N	P	K	S	B	Zn
			Castor					
2002								
Farmer inputs FI	590	1400	23.2	3.1	22.1	2.2	18.1	40.0
FI + SBZn	890 (50%)	2070 (47%)	34.2	5.1	30.3	3.6	26.5	62.2
LSD (0.05)	143	360	6.9	1.4	6.6	0.7	4.9	14.2
2003								
FI	690	1610	27.5	6.3	14.4	2.6	11.3	47.8
FI + SBZn	1000 (44%)	2270 (40%)	37.9	7.6	24.3	3.9	15.7	70.4
FI + SBZn + NP	1190 (72%)	2770 (72%)	46.4	7.5	26.6	4.7	22.2	79.4
LSD (0.05)	186	403	8.0	1.4	6.4	0.8	4.6	13.7
2004								
FI	990	2220	33.8	5.3	31.7	2.4	18.1	41.0
FI + SBZn	1240 (25%)	2710 (22%)	54.2	7.4	32.1	3.8	23.3	73.0
FI + SBZn + NP	1370 (38%)	3350 (27%)	54.4	7.7	38.9	4.3	30.6	86.6
LSD (0.05)	285	484	13.0	2.2	13.2	0.9	4.2	18.2

Groundnut								
2002								
Farmer inputs (FI)	700	2690	74.9	7.3	29.3	4.4	40.1	50.2
FI + SBZn	940 (34%)	3420 (27%)	95.1	11.3	41.9	6.4	52.1	80.9
LSD (0.05)	103	145	4.1	2.4	3.7	0.7	3.1	5.1
2003								
FI	560	2920	57.7	6.6	27.5	3.7	38.6	59.0
FI + SBZn	810 (44%)	4150 (42%)	86.3	7.2	38.1	5.5	56.8	151.5
FI + SBZn + NP	980 (75%)	4740 (62%)	114.9	10.6	39.5	6.5	68.4	116.8
LSD (0.05)	59	183	5.6	1.2	3.6	0.5	3.9	13.2
2004								
FI	920	4080	107.8	9.2	47.6	6.8	78.9	87.3
FI + SBZn	1190 (29%)	4930 (20%)	124.1	10.8	56.9	6.3	65.1	141.5
FI + SBZn + NP	1280 (39%)	5060 (24%)	139.4	15.4	60.9	7.0	106.8	129.6
LSD (0.05)	96	262	8.4	2.3	6.3	0.7	7.6	52.0

(continued)

TABLE 9.9 (Continued)
Yield and Nutrient Uptake of Maize, Castor, Groundnut, and Mung Bean in Response to Fertilization in Andhra Pradesh, India, 2002–2004

			Total Uptake of Nutrients					
	Grain Yield	Total Dry Matter	kg ha^{-1}				g ha^{-1}	
Treatment	kg ha^{-1}	kg ha^{-1}	N	P	K	S	B	Zn
			Mung bean					
2002								
Farmer inputs FI	770	1500	36.7	4.6	25.4	2.3	20.4	45.6
FI + SBZn	1110 (44%)	2110 (40%)	53.3	7.4	36.3	4.0	30.4	69.6
LSD (0.05)	145	280	8.2	1.0	5.5	0.4	5.6	5.6
2003								
FI	900	2900	54.7	6.9	52.1	3.0	37.6	59.8
FI + SBZn	1390 (54%)	4840 (66%)	87.9	13.7	80.4	7.8	73.0	129.2
FI + SBZn + NP	1540 (71%)	5420 (86%)	103.9	13.2	95.3	6.4	79.9	208.4
LSD (0.05)	160	417	14.2	2.1	16.6	1.0	9.4	23.8
2004								
FI	740	2800	59.6	9.0	57.7	3.1	40.2	53.5
FI + SBZn	920 (24%)	3200 (14%)	58.7	8.0	55.3	4.8	66.6	69.1
FI + SBZn + NP	1160 (56%)	4050 (44%)	71.6	9.0	66.7	5.7	77.8	79.7
LSD (0.05)	131	580	17.4	2.2	11.8	1.1	15.0	16.8

NO_3–N in runoff water (8 vs 14 kg nitrogen per ha). Reduced runoff and erosion reduced risk of downstream flooding and siltation of water bodies that directly improved environmental quality in the watersheds [Pathak et al. 2005; Sahrawat et al. 2005; Wani et al. 2005].

9.4.10.6 Conserving Biodiversity

Conserving biodiversity in the watersheds was engendered through participatory NRM. The index of surface percentage of crops (ISPC), crop agrobiodiversity factor (CAF), and surface variability of main crops changed as a result of integrated watershed management interventions. Pronounced agrobiodiversity impacts were observed in Kothapally watershed, where farmers now grow 22 crops in a season with a remarkable shift in cropping pattern from cotton (200 ha in 1998 to 100 ha in 2002) to a maize/pigeonpea intercrop system (40 ha in 1998 to 180 ha in 2002), thereby changing the CAF from 0.41 in 1998 to 0.73 in 2002. In Thanh Ha, Vietnam the CAF changed from 0.25 in 1998 to 0.6 in 2002 with the introduction of legumes [Wani et al. 2005]. Similarly, in Bundi watershed in Rajasthan, in rehabilitated degraded common land above- and below-ground biodiversity (flora and fauna) has been recorded [Dixit et al. 2005].

9.4.11 SCALING-UP

Most farming problems require integrated solutions, with genetic, management-related, and socioeconomic components. In essence, plant breeders and NRM scientists must integrate their work with that of private and public sector change agents to develop flexible cropping systems that can respond to rapid changes in market opportunities and climatic conditions. ICRISAT, in partnership with NARSs, has conceived, developed, and successfully evaluated an innovative farmers' participatory consortium model for integrated watershed management. The model includes the consortium approach and adopts the concept of convergence in every activity in the watershed [Sreedevi and Wani 2009].

Watersheds are only management units for sustainable development of NRs and agriculture is the backbone of rural development. Watersheds need to be used as planning units for developing area plans by adopting a bottom-up approach for sustainable inclusive growth using water management as an entry point activity. Watershed management is just a beginning for holistic area development and improving livelihoods and not an end in itself. The watershed plans can be converged to make district and state plans for development of rainfed and drought-prone districts to reduce poverty. These plans can be used for implementing various programs such as Mahatma Gandhi Rural Employment Guarantee Scheme (MGREGS), food for work, watersheds, various crop missions (e.g., pulses mission, oil seeds mission, etc.), food security mission, Millennium Development Goal area plans, rural knowledge centers, etc. It calls for convergence of actors and actions at village, district, state, and country levels but it should not result in a race for defending operational territories.

The new paradigm for upgrading rainfed agriculture can double the productivity in Asia and also reduce poverty without causing further degradation of natural resource base. Based on the success of the participatory consortium watershed management model at Kothapally, the Andhra Pradesh Rural Livelihoods Program (APRLP), Sir Dorabji Tata Trust, Mumbai, the World Bank's Sujala Project in Karntaka, India, and the Asian Development Bank (ADB) have selected this model for scaling up the benefits in Andhra Pradesh, Madhya Pradesh, and Rajasthan in India, and Northeast Thailand, Northern Vietnam, and South China. As most of NRM technologies are agroecoregion- and site-specific, the representative benchmark watersheds allow transferring the findings from benchmark nucleus watersheds to the satellite watersheds in the similar target ecoregion. In the target ecosystems, project implementing agencies (PIAs) are selected based on their strengths and available current knowledge base. Nucleus watersheds were selected for development and critical monitoring as the sites for undertaking participatory action research, as sites of learning and training in a district, and as sites to study the processes to select different partners in the consortium. An innovative model with a consortium of institutions, as opposed to single institution approach, for technical backstopping was initiated (Figure 9.14) for project implementation [Wani et al. 2003b]. All the partners have worked in partnership with another institution to manage the watershed sustainably.

A successful partnership based on a strong commitment with state and local agencies, community leaders, and people is desirable. Involvement of the state government departments, agricultural research and education institutions in the area, and, most importantly, the policymakers along with the farmers is critical from the beginning. To establish and operationalize the consortium, the transaction costs (time and financial resources) are more; however, once it is established, the scaling-out process is quite rapid, economical, and impact-oriented [Wani et al. 2008b]. To promote community participation in the watershed for site selection as well as implementation and assessment of activities, various committees/groups were formed. It was

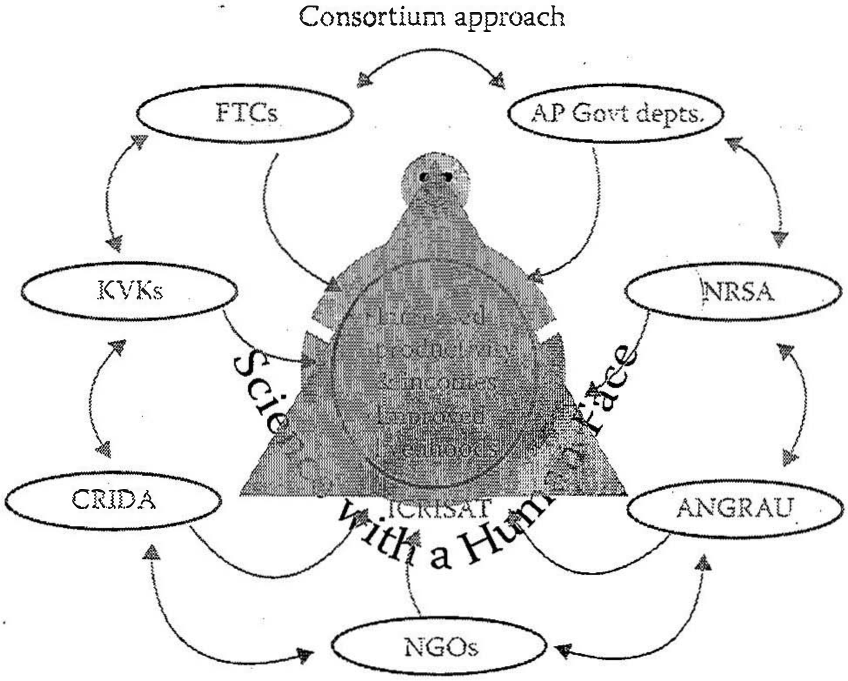


FIGURE 9.14 Farmer participatory consortium approach for integrated watershed development in Andhra Pradesh.

recognized that to shift the community participation from a contractual to a consultative and collegiate mode, tangible private economic benefits to individuals were a must. Such tangible benefits to individuals could come from in situ rainwater conservation and translation through increased farm productivity by adopting an IGNRM approach. The farmers need to be graduated slowly after initiation to take on or participate in collective action. First, in rainfed areas in the tropics where subsistence agriculture is the rule, it is urgent that the immediate needs of individuals be met through the program rather than fixing the lofty goals of community participation for common societal benefits. Adopting the principle that "users pay" and providing no subsidies for investments on individuals' farms for technologies, inputs, and conservation measures force development researchers to provide demand-driven options rather than supply-driven options. Once the individuals realize the benefits of soil and water conservation, they came forward to participate in community activities in the watershed through various organized groups and also sustain the initiatives that benefit them to improve their livelihoods. This approach builds the ownership, accountability, and sustainability vs. the target-driven conventional approach, which has not worked in tropical rainfed areas.

9.4.12 UNLOCKING THE POTENTIAL OF RAINFED AGRICULTURE—A BEGINNING IS MADE IN INDIA

Lately, increasing attention is being paid to management of green water (soil moisture) resources to upgrade rainfed agriculture. In the past few years, there has been an increased priority on developing policies and building capacities in favor of increased investments in water management in rainfed agriculture.

There is, thus, growing evidence of the importance of water investments in rainfed agriculture, and governance and management is gradually being redirected in certain regions of the world toward water management for upgrading rainfed agriculture as a key strategy for reducing poverty and increasing agricultural production [World Bank 2005]. It is further increasingly clear that water management for rainfed agriculture requires a landscape perspective and involves cross-scale interactions from the farm household scale to the watershed scale.

In India, the initiation of IWMP by converging all watershed schemes under Department of Land Resources (DoLR) in the Ministry of Rural Development (MoRD), establishing the NRAA, the renaming the National Rural Employment Guarantee Scheme (NREGS) as the Mahatma Gandhi Employment Guarantee Scheme of MoRD by the Ministry of Agriculture as well as their establishing the National Food Security Mission (NFSM), Rashtriya Kisan Vikas Yojana (RKVY), and the pulses and oil seeds production enhancement initiatives, and the Ministry of Water Resources encouraging more crop per drop through farmers' participatory action research trials are examples of upgrading the rainfed agriculture in India. All these programs are targeted to increase productivity of rainfed crops and improve livelihoods of the rural poor. The Indian Council of Agricultural Research (ICAR-GoI) has initiated a network project on climate change impacts on agriculture in India, as well as adaptation and mitigation strategies in the country [Venkateswarlu and Shankar 2009].

The initiation of a mission project to upgrade rainfed agriculture in 25 rainfed districts of Karnataka, with technical backstopping provided by an ICRISAT-led consortium, is an example of science-led development to unlock the potential of rainfed agriculture [ICRISAT 2010]. The Department of Agriculture is converging all the schemes targeted for rainfed agriculture through this mission and has pooled together the expertise of state agricultural universities and different departments of agriculture, community-based organizations, and input suppliers to benefit the farmers.

ACKNOWLEDGMENTS

We gratefully acknowledge the help of all the consortium partners in Asia, including the farmers who have enabled us to contribute this chapter. We also thank Asian Development Bank, Manila, Philippines, Sir Dorabji Tata Trust, Mumbai, and Sir Ratan Tata Trust, Mumbai, for their financial support for undertaking activities in various regions on which this chapter is based.

REFERENCES

Agarwal, A. 2000. *Drought? Try capturing the rain.* Briefing paper for members of parliament and state legislatures—An occasional paper from the Centre for Science and Environment (CSE), New Delhi: CSE.

Bhattacharyya, T., Ray, S.K, Pal, D.K., et al. 2009. Soil carbon stocks in India—Issues and priorities. 2009. *Journal of the Indian Society of Soil Science* 57(4):461–468.

Dixit, S., Tewari, J.C., Wani, S.P., et al. 2005. *Participatory biodiversity assessment: Enabling rural poor for better natural resource management.* Global Theme on Agroecosystems Report no. 18. Patancheru 502324. Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Falkenmark, M. 1986. Fresh water—Time for a modified approach. *Ambio* 15(4):192–200.

Falkenmark M., Karlberg L., and J. Rockström. 2009. Present and future water requirements for feeding humanity. *Food Sec.* 1:59–69.

Food and Agriculture Organization (FAO). 2002. Agriculture: Towards 2015/30. *Technical interim report.* http://www.fao.org/es/esd/at2015/toc-e.htm.

FAOStat. 2010. AQUASTAT: FAO's Information System on Water and Agriculture. http://www.fao.org/nr/aquastat.

FAOStat. 2010. FAOStat. http://faostat.fao.org/site/567/DesktopDefauly.aspx?pageID=567#ancor.

Fisher, G., Harrij, V.V., Eva H., et al. 2009. *Potentially obtainable yields in the semiarid tropics.* Global Theme on Agroecosystems Report no. 54. Patancheru 502 324, Andhra Pradesh, India; International Crops Research Institute for the Semi-Arid Tropics.

GoI. 2005. *Serving farmers and saving farming–2006: Year of agricultural renewal.* Third Report, National Commission on Farmers, Ministry of Agriculture. New Delhi: GoI.

GoI. 2008. *Common guidelines for watershed development projects.* New Delhi: Ministry of Agriculture, Government of India.

Hilhost, T., and F. Muchena. 2000. *Nutrients on the move: Soil fertility dynamics in African farming systems.* London: International Institute for Environment and Development.

Holmen, H. 2004. Why no green revolution in Africa? *Currents* 34:12–16.

ICRISAT. 2005. *Identifying systems for carbon sequestration an increased productivity in semiarid tropical environments.* A Project Completion Report, National Agricultural Technology Project. New Delhi: Indian Council of Agricultural Research.

ICRISAT. 2010. Bhoo Chetana—Boosting rainfed agriculture in Karnataka. In *Mission mode: Bridging yield gaps in dryland crops*. Karnataka State Department of Agriculture, Government of Karnataka and Global Theme on Agroecosystems. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

IIASA. 2002. *Climate change and agricultural vulnerability*. Special report for the UN World Summit on Sustainable Development. Johhanesburg, 2002. http://www.iiasa.ac.at/Research/LUC/JB-Report.pdf.

IFDC. 2006. Agricultural production and soil nutrient mining in Africa: Implications for resource conservation and policy development. *IFDC Technical Bulletin*. Muscle Shoals, AL:IFDC.

Intergovernmental Panel on Climate Change (IPCC). 1990. *Climate change*, eds. J.T. Houghton, G.J. Jenkinson, and J.J. Ephraums. Cambridge: Cambridge University Press.

IPCC. 2007. Climate change-impacts: Adaptation and vulnerability. In *Technical Summary of Working Group II to Fourth Assessment Report Intergovernmental Panel on Climate Change*, ed. M.L. Parry, O.F. Canziani, J.P. Paultikof, P.J. van der Linden, and C.E. Hanon, 23–78. Cambridge: Cambridge University Press.

Irz, X., and Roe, T. 2000. Can the world feed itself? Some insights from growth theory. *Agrekon* 39:513–528.

Joshi, P.K., Jha, A.K., Wani, S.P., et al. 2008. Impact of watershed program and conditions for success: A meta-analysis approach. In *Global theme on agroecosystems, Report no. 46*. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Katyal, J.C., and R.K. Rattan. 2003. Secondary and micronutrients: Research gaps and future needs. *Fert. News* 48(4):9–14, 17–20.

Kerr, J., Pangare, G., and V. Lokur. 2002. *Watershed development projects in India. Research Report 127*. Washington, DC: IFPRI.

Lal, R. 2004. Soil carbon sequestration to mitigate climate change. *Geoderma* 123:1–22.

Lee, K.K., and S.P. Wani. 1989. Significance of biological nitrogen fixation and organic manures in soil fertility management. In *Soil fertility and fertility management in semi-arid tropical India*, ed. C.B. Christianson, 89–108. Muscle Shoals, AL: IFDC.

Lorenz, K., and R. Lal. 2005. The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. *Advances in Agronomy* 88:35–66.

Molden, D., Frenken, K., Barker, R., et al. 2007. Trends in water and agricultural development In *Water for food, water for life—A comprehensive assessment of water management in agriculture,* ed. D. Moden, 57–89. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Mwale, F. 2003. Drought impact on maize production in Malawi. *Unesco-IHE Report*. Delft: the Netherlands.

Nagavallemma, K.P., Wani, S.P., Lacroix, S., et al. 2004. *Vermicomposting: Recycling wastes into valuable organic fertilizer. Global Theme on Agroecosystems Report No. 8*. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropic.

Nagavallemma, K.P., Wani, S.P., Lacroix, S., et al. 2005. Vermicomposting: Recycling wastes into valuable organic fertilizer. *Journal of Agriculture and Environment for International Development* 99:188–204.

Oweis, T., and Hachum, A. 2001. Reducing peak supplemental irrigation demand by extending sowing dates. *Agricultural Water Management* 50:109–123.

Pathak, P., Sahrawat, K.L., Rego, T.J., et al. 2005. Measurable biophysical indicators for impact assessment: Changes in soil quality. In *Natural resource management in agriculture: Methods for assessing economic and environmental impacts*, eds. B. Shiferaw, H.A. Freeman, and S.M. Swinton, 53–74. Wallingford, UK: CAB International.

Pathak, P., Sahrawat, K.L., Wani, S.P., et al. 2009. Opportunities for water harvesting and supplemental irrigation for improving rain-fed agriculture in semi-arid areas. In *Rain-fed agriculture: Unlocking the potential.* Comprehensive Assessment of Water Management in Agriculture Series, eds. S.P. Wani, J. Rockström, and T. Oweis, 197–221. Wallingford, UK: CAB International.

Ranga Rao, G.V., Rupela, O.P., Wani, S.P., et al. 2007. Bio-intensive pest management reduces pesticide use in India. Pesticides News. *Journal of Integrated Pest Management.* 76:16–17.

Rao, K.V., Venkateswarlu, B., Sahrawat, K.L., Wani, S.P., Mishra, P.K., Dixit, S., Reddy, K.S., Kumar, M., and Saikia, U.S. (eds.). 2010. *Proceedings of National Workshop-cum-Brainstorming on Rainwater Harvesting and Reuse through Farm Ponds: Experiences, issues and strategies.* April 21–22, 2009, CRIDA, Hyderabad.

Rego, T.J., Sahrawat, K.L., Wani, S.P., et al. 2007. Widespread deficiencies of sulfur, boron and zinc in Indian semi-arid tropical soils: On-farm crop responses. *Journal of Plant Nutrition* 30:1569–1583.

Rego, T.J., Wani, S.P., Sahrawat, K.L., et al. 2005. Macro-benefits from boron, zinc, and sulphur application in Indian SAT: A step for grey to green revolution in agriculture. *Global Theme on Agroecosystems Report no. 16.* Patancheru, Andhra Pradesh, India: ICRISAT.

Rockström, J. 2003. Water for food and nature in the tropics: Vapour shift in rain-fed agriculture. Invited paper to the Special issue 2003 of *Royal Society Transactions B Biology, Theme Water Cycle as Life Support Provider* 358(1440):1997–2009.

Rockström, J., and Falkenmark, M. 2000. Semiarid crop production from a hydrological perspective: Gap between potential and actual yields. *Critical Reviews in Plant Science* 19(4):319–346.

Rockström, J., Falkenmark, M., Karlberg, L., et al. 2009. Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resources Research* 45:W00A12, doi:10.1029/2007WR006767.

Rockström, J., Hatibu, N., Oweis, T., et al. 2007. Managing water in rain-fed agriculture. In *Water for food, water for life: A comprehensive assessment of water management in agriculture*, ed. D. Molden, 315–348. London: Earthscan and Colombo, Sri Lanka: International Water Management Institute (IWMI).

Rosegrant, M., Ximing, C., Cline, S., et al. 2002. *The role of rain-fed agriculture in the future of global food production.* EPTD Discussion Paper No. 90, Washington, DC: IFPRI, Environment and Production Technology Division.

Ryan, J.G., and Spencer, D.C. 2001. *Challenges and opportunities shaping the future of the semi-arid tropics and their implications*. Patancheru, Andhra Pradesh, India: ICRISAT.

Sahrawat, K.L., Bhattacharyya, T., Wani, S.P., et al. 2005. Long-term lowland rice and arable cropping effects on carbon and nitrogen status of some semi-arid tropical soils. *Current Science* 89(12):2159–2163.

Sahrawat, K.L., Wani, S.P., Rego, T.J., et al. 2007. Widespread deficiencies of sulphur, boron and zinc in dryland soils of the Indian semi-arid tropics. *Current Science* 93(10):1–6.

Sanchez, P., Swaminathan, M.S., Dobie, P., and Yuksel, N. 2005. *Halving hunger: It can be done*. Summary version of the report of the Task Force on Hunger. New York: The Earth Institute at Columbia University.

SEI. 2005. *Sustainable pathways to attain the millennium development goals—Assessing the role of water, energy and sanitation.* Document prepared for the UN World Summit, Sept 14, 2005, New York, NY. Stockholm: SEI. http://www.sei.se/mdg.htm.

Shambu Prasad, C., Hall, A.J., and Wani, S.P. 2005. *Institutional history of watershed research: The evolution of ICRISAT's work on natural resources in India. Global Theme on Agroecosystems Report No. 12*. Patancheru, Andhra Pradesh, India: ICRISAT.

Shiferaw, B., Anupama, G.V., Nageswara Rao, G.D., et al. 2006. Socioeconomic characterization and analysis of resource-use patterns in community watersheds in semi-arid India. *Journal of SAT Agricultural Research* 2(1).

Singh, P., Aggarwal, P.K., Bhatia, V.S., et al. 2009. *Yield gap analysis: Modeling of achievable yields at farm level in rain-fed agriculture: Unlocking the potential*, eds. S.P. Wani, J. Rockstorm, and T. Oweis, 81–123. Wallingford, UK: CAB International.

Sreedevi, T.K., and Wani, S.P. 2009. Integrated farm management practices and up-scaling the impact for increased productivity of rain-fed systems. In *Rain-fed agriculture: Unlocking the potential*, ed. S.P. Wani, J. Rockström, and T. Oweis, 222–257. Comprehensive Assessment of Water Management in Agriculture Series. Wallingford, UK: CAB International.

Sreedevi, T.K., Wani, S.P., and Pathak, P. 2007. Harnessing gender power and collective action through integrated watershed management for minimizing land degradation and sustainable development. *Journal of Financing Agriculture* 36:23–32.

Sreedevi, T.K., Wani, S.P., Sudi, R., et al. 2006. On-site and off-site impact of watershed development: A case study of Rajasamadhiyala, Gujarat, India. *Global Theme on Agroecosystems Report No. 20.* Patancheru, Andhra Pradesh, India: ICRISAT.

Srinivasa Rao, Ch., Vittal, K.P.R., Venkateswarlu, B., et al. 2009. Carbon stocks in different soil types under diverse rainfed production systems in tropical India. *Communications in Soil Science and Plant Analysis* 40:2338–2356.

Srinivasa Rao, Ch., Wani, S.P., Sahrawat, K.L., et al. 2010. Effect of balanced nutrition on yield and economics of vegetable crop in participatory watersheds in Karnataka. *Indian Journal of Fertilizers* 6:39–42.

Stoorvogel, J.J., and E.M.A. Smaling. 1990. *Assessment of soil nutrient depletion in sub-Saharan Africa: 1983–2000, 1: Main report.* Report No. 28. Wageningen, the Netherlands: Winand Staring Centre.

Syers, J.K., Lingard J., Pieri J., et al. 1996. Sustainable land management for the semiarid and sub-humid tropics. *Ambio* 25:484–491.

Thirtle, C., Beyers, L., Lin, L., et al. 2002. *The impacts of changes in agricultural productivity on the incidence of poverty in developing countries.* DFID Report No. 7946. London: Department for International Development (DFID).

Twomlow, S., Shiferaw, B., Cooper, P., et al. 2006. *Integrating genetics and natural resource management for technology targeting and greater impact of agricultural research in the semi-arid tropics.* Patancheru Andhra Pradesh, India: ICRISAT.

UNEP. 1997. *World atlas of desertification,* 2nd ed. Nairobi, Kenya: UNEP.

UNStat. 2005. www.unstat.com.

Velayutham, M., Pal, D.K., and Bhattacharyya, T. 2000. Organic carbon stock in soils of India. In *Global climate change and tropical ecosystems.* Advances in Soil Science, eds. R. Lal, J.M. Kible, and B.A. Stewart, 71–95. Boca Raton, FL: CRC Press.

Venkateswarlu, B., Ramakrishna, Y.S., Reddy, S., et al. 2008. *Rainfed farming—A profile of doable technologies.* Technical Bulletin. Hyderabad, Andhra Pradesh, India: CRIDA.

Venkateswarlu, B., and Shanker, A.K. 2009. Climate change and agriculture: Adaptation and mitigation strategies. *Indian Journal of Agronomy* 54(2):226–230.

Walker, T. 2010. *Challenges and opportunities for agricultural R & D in the semi-arid tropics.* Internal document for strategic planning. Patancheru, Andhra Pradesh, India: ICRISAT.

Wani, S.P., Balloli, S.S., Kesava Rao, A.V.R., et al. 2004. Combating drought through integrated watershed management for sustainable dryland agriculture. In *Regional workshop on agricultural drought monitoring and assessment using space technology*, 39–48. May 4, 2004. Hyderabad, India: National Remote Sensing Agency (NRSA).

Wani, S.P., Joshi, P.K., Raju, K.V., et al. 2008a. *Community watershed as a growth engine for development of dryland areas. A comprehensive assessment of watershed programs in India.* Global Theme on Agroecosystems Report No. 47. Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Wani, S.P., Joshi, P.K., Ramakrishna, Y.S., et al. 2008. A new paradigm in watershed management: A must for development of rain-fed areas for inclusive growth. In *Conservation farming: Enhancing productivity and profitability of rain-fed areas*, eds. A. Swarup, S. Bhan, and J.S. Bali, 163–178. New Delhi: Soil Conservation Society of India.

Wani, S.P., Maglinao, A.R., Ramakrishna, A. et al. 2003. *Integrated watershed management for land and water conservation and sustainable agricultural production in Asia. Proceedings of the ADB-ICRISAT-IWMI annual project review and planning meeting.* December 10–14, 2001, Hanoi, Vietnam. Patancheru, Andhra Pradesh, India: ICRISAT.

Wani, S.P., Pathak, P., Jangawad, L.S., et al. 2003a. Improved management of Vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration. *Soil Use and Management* 19:217–222.

Wani, S.P., Pathak, P., Sreedevi, T.K., et al. 2003b. Efficient management of rainwater for increased crop productivity and groundwater recharge in Asia. In *Water productivity in agriculture: Limits and opportunities for improvement,* eds. J.W. Kijne, R. Barker, and D. Molden, 199–215. Wallingford, UK: CAB International and Colombo, Sri Lanka: IWMI.

Wani, S.P., Pathak, P., Tam, H.M., et al. 2002. Integrated watershed management for minimizing land degradation and sustaining productivity in Asia. In *Integrated land management in dry areas. Proceedings of a joint UNU-CAS international workshop,* ed. Z. Adeel, 207–230. September 8–13, 2001, Beijing, China.

Wani, S.P., Ramakrishna, Y.S., Sreedevi, T.K., et al. 2006. Issues, concepts, approaches and practices in integrated watershed management: Experience and lessons from Asia. In: *Integrated management of watersheds for agricultural diversification and sustainable livelihoods in Eastern and Central Africa,* 17–36. Proceedings of the international workshop held at ICRISAT, December 6–7, 2004, Nairobi, Kenya. Patancheru, Andhra Pradesh, India: ICRISAT.

Wani, S.P., Rego, T.J., Rajeswari, S., et al. 1995. Effect of legume-based cropping systems on nitrogen mineralisation potential of Vertisol. *Plant and Soil* 175:265–274.

Wani, S.P., Rockström, J., and Oweis, T. (eds.). 2009a. *Rain-fed agriculture: Unlocking the potential.* Comprehensive Assessment of Water Management in Agriculture Series. Wallingford, UK: CAB International.

Wani, S.P., Sahrawat, K.L., Sreedevi, T.K., et al. 2007. Carbon sequestration in the semi-arid tropics for improving livelihoods. *International Journal of Environmental Studies* 64(6):719–727.

Wani, S.P., Singh, P., Dwivedi, R.S., et al. 2005. Biophysical indicators of agro-ecosystem services and methods for monitoring the impacts of NRM technologies at different scale. In *Natural resource management in agriculture: Methods for assessing economic and environmental impacts,* eds. B. Shiferaw, H.A. Freemen, and S.M. Swinton, 97–123. Wallingford, UK: CAB International.

Wani, S.P., Singh, H.P., Sreedevi, T.K., et al. 2003c. Farmer-participatory integrated watershed management: Adarsha Watershed, Kothapally India. An innovative and up-scalable approach. A Case Study. In *Research towards integrated natural resources management: Examples of research problems, approaches and partnerships in action in the CGIAR,* eds. R.R. Harwood and A.H. Kassam, 123–147. Washington, DC: Interim Science Council, Consultative Group on International Agricultural Research.

Wani, S.P., Sreedevi, T.K., Rockström, J., et al. 2009. Rain-fed agriculture—Past trend and future prospects. In *Rain-fed agriculture: Unlocking the potential,* eds. S.P. Wani, J. Rockström, and T. Oweis, 1–35. Comprehensive Assessment of Water Management in Agriculture Series. Wallingford, UK: CAB International.

Wani, S.P., Sreedevi, T.K., Vamsidhar Reddy, T.S., et al. 2008b. Community watersheds for improved livelihoods through consortium approach in drought prone rainfed areas. *Journal of Hydrological Research and Development* (23)55–77.

World Health Organization (WHO). 2000. *Gender, health and poverty. Factsheet No. 25*, http://www.who.int/mediacenter/factsheets/fs251/en/.

World Bank. 2000. Spurring agricultural and rural development. In *Can Africa claim the 21st century?*, 170–207. Washington, DC: World Bank.

World Bank. 2005. *Agricultural growth for the poor: An agenda for development*. Washington, DC: The International Bank for Reconstruction and Development/The World Bank.