1 Rainfed Agriculture – Past Trends and Future Prospects

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Introduction

The agricultural productivity has seen a rapid growth since the late 1950s due to new crop varieties, fertilizer use and expansion in irrigated agriculture. The world food production outstripped the population growth. However, there are regions of food insecurity. Of the 6.5 billion population today, about 850 million people face food insecurity. About 60% of them live in South Asia and sub-Saharan Africa. Food and crop demand is estimated to double in the next 50 years. According to a Comprehensive Assessment, it is possible to produce food – but it is probable that today's food production and environmental trends, if continued, will lead to crises in many parts of the world (Molden, 2007). The assessment has also indicated that the world's available land and water resources can satisfy future demands by taking the following steps:

- Investing to increase production in rainfed agriculture (rainfed scenario).
- Investing in irrigation (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.

Rainfed Agriculture

The importance of rainfed agriculture varies regionally but 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%, for South Asia about 60%, for East Asia 65% and for the Near East and North Africa 75% (FAOSTAT, 2005). Most countries in the world 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 still face poverty, hunger, food insecurity and malnutrition where rainfed agriculture is the main agricultural activity. These problems are exacerbated by adverse biophysical growing conditions and the poor socioeconomic infrastructure in many areas in the semi-arid tropics (SAT). The SAT is the home to 38% of the developing countries' poor, 75% of whom live in rural areas. Over 45% of the world's hungry and more than 70% of its malnourished children live in the SAT.

Even with growing urbanization, globalization and better governance in Africa and Asia, hunger, poverty and vulnerability of livelihoods to natural

Rainfed Agriculture: Unlocking the Potential (eds S.P. Wani *et al.*)

and other disasters will continue to be greatest in the rural SAT. These challenges are complicated by climatic variability, the risk of climate change, population growth, health pandemics (AIDS, malaria), degrading natural resource base, poor infrastructure and changing patterns of demand and production (Ryan and Spencer, 2001). 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 into a downward 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 for 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 0.6–1.2% decrease in the percentage of absolute poor (Thirtle *et al.*, 2002). On average for sub-Saharan Africa, agriculture accounts for 35% of gross domestic product (GDP) and employs 70% of the population (World Bank, 2000), while more than 95% of the agricultural area is rainfed (FAOSTAT, 2005), as elaborated in Box 1.1. Agriculture will continue to be the backbone of economies in Africa and South Asia in the foreseeable future. As most of the SAT poor are farmers and landless labourers, 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 labour 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 – studies have shown that research and development (R&D) investments in less-favoured semi-arid environments could provide high marginal payoffs in terms of generating new sources of economic growth. Renewed effort and innovative R&D strategies are needed to address these challenges, such as integrated natural resource management (INRM), which has been evolving within the 15 international agricultural research centres (IARC) of the Consultative Group for International Agricultural Research (CGIAR). The basic role of the 15 IARCs is to develop innovations for improving agricultural productivity and natural resource management (NRM) for addressing the problems of poverty, food insecurity and environmental degradation in developing countries. This effort has generated multiple and sizeable benefits (welfare, equity, environmental) (Kassam *et al.*, 2004). But much remains to be done in sub-Saharan Africa and less-favoured areas of South Asia.

Rainfed agriculture and water stress

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 those located in the semi-arid and dry subhumid hydroclimates in the world (Fig. 1.1), 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 predominantly are located in tropical regions (UNSTAT, 2005).

Box 1.1. Agricultural growth: an underlying factor to economic growth (after van Koppen *et al.*, 2005).

Agriculture, the sector in which a large majority of the African poor make their living, is the engine of overall economic growth and, therefore, broad-based poverty reduction (Johnston and Mellor, 1961; World Bank, 1982; IFAD, 2001; DFID, 2002; Koning, 2002). This conclusion is based on analysis of the historical development paths of countries worldwide, and recent international reports have re-affirmed this position (e.g. Inter Academy Council, 2004; Commission for Africa, 2005; UN Millennium Project, 2005). Higher farm yields enhanced producer incomes, in cash and in kind, and created demand for agricultural labour. Thus, agricultural growth typically preceded economic growth in high-income countries and recent growth in the Asian Tigers such as Thailand, Malaysia, Indonesia, Vietnam and parts of China.

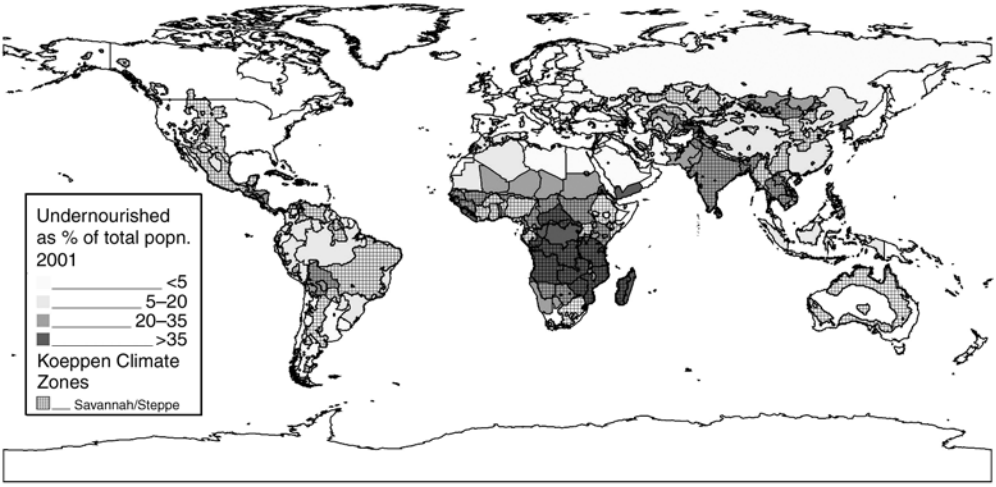


Fig. 1.1. The prevalence of undernourishment in developing countries (as percentage of population 2001–2002; UNSTAT, 2005), together with the distribution of semi-arid and dry subhumid hydroclimates in the world, i.e. savannah and steppe agroecosystems. These regions are dominated by sedentary farming subject to the world's highest rainfall variability and occurrence of dry spells and droughts.

Crop yields in rainfed areas

Since the late 1960s, agricultural land use has expanded by 20–25%, which has contributed to approximately 30% of the overall grain production growth during the period (FAO, 2002; Ramankutty *et al.*, 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 average 1.5 t/ha, compared with 3.1 t/ha for irrigated yields (Rosegrant *et al.*, 2002), and 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 of land has been nearly stagnant for these staple crops (FAOSTAT, 2005). 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, 2005). During the same period, the yield per unit of land for maize and wheat has more than doubled (Fig. 1.2). For predominantly rainfed systems, maize crops per unit of land have nearly tripled and wheat more than doubled during the same time period.

Rainfed maize yield differs substantially between regions (Fig. 1.2a). 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 USA 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 of 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 (Fig. 1.2b). 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, there appears to exist a significant potential for raised yields in rainfed agriculture, particularly in sub-Saharan Africa and South Asia.

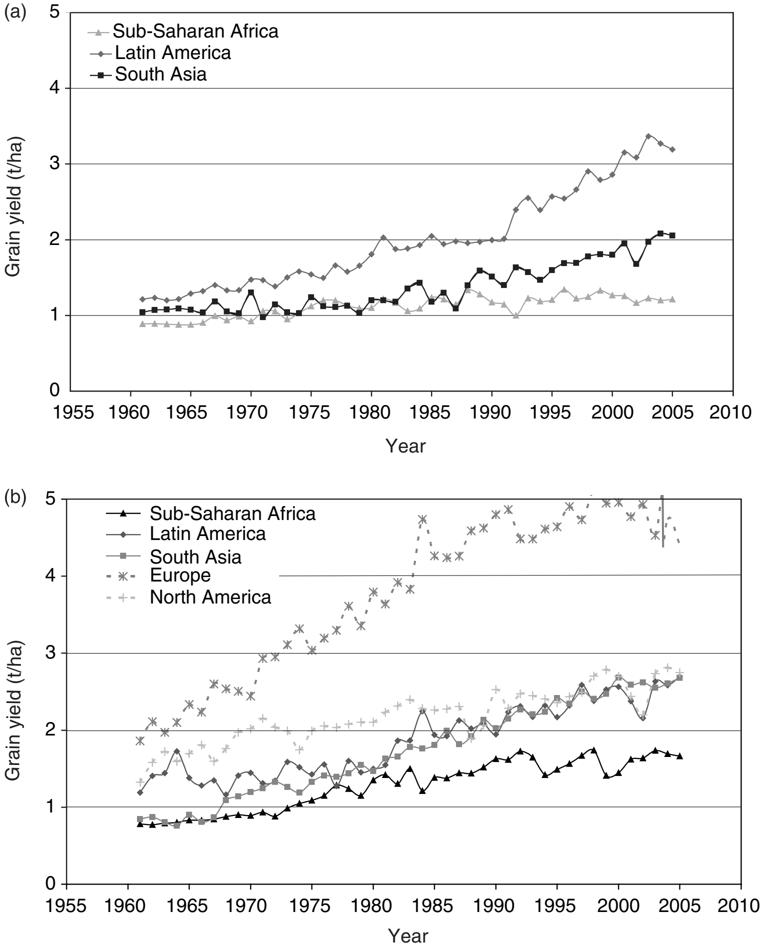


Fig. 1.2. Grain yield of predominantly rainfed maize (a) and wheat (b) for different regions during 1961–2000 (Source: FAOSTAT, 2005).

Rainfed Agriculture – a Large Untapped Potential

In several regions of the world rainfed agriculture generates among the world's highest yields. 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,b). At the same time, the dry subhumid and semi-arid regions have experienced the lowest yields and the weakest yield improvements per unit of land. Here, yields oscillate between 0.5 and 2 t/ha, with an average of 1 t/ha in sub-Saharan Africa, and 1–1.5 t/ha in South Asia, and central and west Asia and North Africa (CWANA) for rainfed agriculture (Rockström and Falkenmark, 2000; Wani *et al.*, 2003a,b).

Yield gap analyses carried out by Comprehensive Assessment for major rainfed crops in semi-arid regions in Asia and Africa and rainfed wheat in WANA reveal large yield gaps, with farmers' yields being a factor of two to four times lower than achievable yields for major rainfed crops. Detailed yield gap analysis for major rainfed crops in different parts of the world is discussed (see Chapter 6, this volume). Figure 1.3 illustrates examples of observed yield gaps in various countries in Africa, Asia and the Middle East. In countries in eastern and Southern Africa the yield gap is very large. 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).

Constraints in Rainfed Agriculture Areas

An insight into the inventories of natural resources in rainfed regions shows a grim picture of water scarcity, fragile environments, 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,c; Rockström *et al.*, 2007). Drought 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, poverty and land degradation has to be broken to meet the Millennium Development Goal of halving the number of food-insecure poor by 2015. These rainfed areas are prone to severe land degradation. 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. 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).

The root cause of land degradation is poor land use. Land degradation represents a diminished ability of ecosystems or landscapes to support the functions or services required for sustaining livelihoods. Over a period of time, continuing agricultural production, particularly in marginal and fragile lands, results in degradation of the natural resource base, with increasing impact on water resources. The following natural resources degradation and the relationship between major forms of soil degradation and water resources (Bossio *et al.*, 2007) require attention:

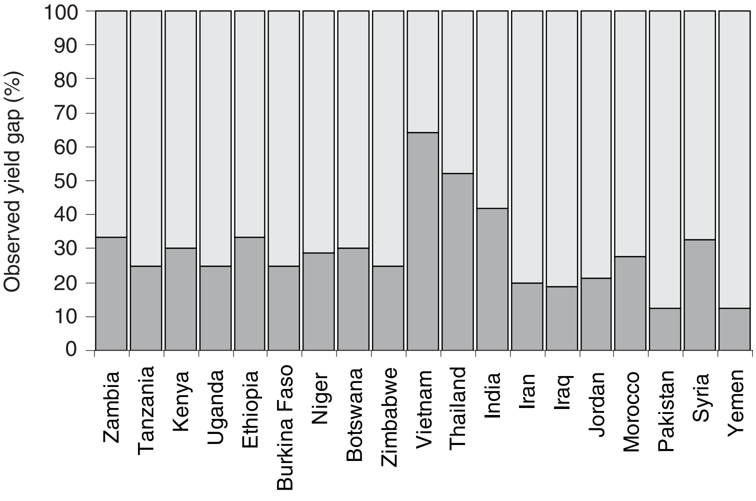


Fig. 1.3. Examples of observed yield gap (for major grains) between farmers' yields and achievable yields (100% denotes achievable yield level, and columns actual observed yield levels) (Source: derived from Rockström *et al.*, 2007).

- *Loss of organic matter and physical degradation of soil*: soil organic matter is integral to managing water cycles in ecosystems. Depleted levels of organic matter have significant negative impacts on infiltration and porosity, local and regional water cycles, water productivity, plant productivity, the resilience of agroecosystems and global carbon cycles.
- *Nutrient depletion and chemical degradation of soil*: pervasive nutrient depletion in agricultural soils is a primary cause of decreasing yields, low on-site water productivity and off-site water pollution. Salinity, sodicity and waterlogging threaten large areas of the world's most productive land and pollute groundwater.
- *Soil erosion and sedimentation*: accelerated on-farm soil erosion leads to substantial yield losses and contributes to downstream sedimentation and degradation of water bodies, a major cause of investment failure in water and irrigation infrastructure.
- *Water scarcity and pollution*: globally, agriculture is the main consumer of water, and water scarcity is a significant problem for farmers in Africa, Asia and the Near East. Agriculture is also the major contributor to non-point-source water pollution, while urbanization contributes increasingly large volumes of wastewater. Water quality problems can often be as severe as those of water availability but have yet to receive as much attention in developing countries.

Loss of organic matter and physical degradation of soil

Soil organic matter is integral to managing water cycle ecosystems. The impact of organic matter loss is not confined to production loss but also disturbs the water cycle. The decrease of soil organic matter, along with the associated faunal activities (aggravated by the use of pesticides and tillage practices), favours the collapse of soil aggregates and thus the crusting and the sealing of the soil surface. The result is reduced porosity, less infiltration and more run-off. Compaction of the soil surface by heavy machinery or overgrazing, for example, can cause overland flow, even on usually permeable soils. Such changes increase the risk of flooding and water erosion. Higher run-off concentrates in channels, causing rills and then gullies. Degradation thus changes the proportion of water flowing along pathways within catchments, with a tendency to promote rapid surface overland flow (run-off) and decrease subsurface flow. By controlling infiltration rates and water-holding capacity, soil organic matter plays a vital function in buffering yields through climatic extremes and uncertainty. Significantly, it is one of the most important biophysical elements that can be managed to improve resilience. Soil organic matter, furthermore, holds about 40% of the overall terrestrial carbon pool – twice the amount contained in the atmosphere. Poor agricultural practices are thus a significant source of carbon emissions and contribute to climate change.

Nutrient depletion and chemical degradation of soil

Globally, only half of the nutrients that crops take from the soil are replaced. This depletion of soil nutrients often leads to fertility levels that limit production and severely reduce water productivity. Shorter fallow periods do not compensate for losses in soil organic matter and nutrients, leading to the mining of soil nutrients. In many African, Asian and Latin American countries, the nutrient depletion of agricultural soils is so high that current agricultural land use is not sustainable. Nutrient depletion is now considered the chief biophysical factor limiting small-scale production in Africa (Drechsel *et al.*, 2004). Recent characterization of 4000 farmers' fields in different states across India revealed a widespread (80–100% fields) deficiency of zinc, boron and sulfur in addition to known deficiencies of macronutrients such as nitrogen and phosphorus (Sahrawat *et al.*, 2007). Such multi-nutrient deficiencies are largely due to diversion of organic manures to irrigated, high-value crops and more reliance on chemical fertilizers supplying macronutrients in pure form over a long period. Other important forms of chemical degradation are the depletion of trace metals such as zinc and iron, causing productivity declines and affecting human nutrition, acidification and salinization.

Soil erosion and sedimentation

Accelerated erosion, resulting in loss of nutrient-rich, fertile topsoil, occurs nearly everywhere where agriculture is practised and is irreversible. The torrential character of the seasonal rainfall creates high risk for the cultivated lands. In India, alone, some 150 million ha are affected by water erosion and 18 million ha by wind erosion. Soil loss ranged from 0.01 to 4.30 t/ha from sandy loam soils of Bundi district, Rajasthan, India, with the average annual rainfall of 760 mm as monitored during rainfall events over 4 years in a case study (Pathak *et al.*, 2006). Thus, erosion leaves behind an impoverished soil on the one hand and siltation of reservoirs and tanks on the other. The estimated nutrient losses in Thailand are indicated in Table 1.1 (Narongsak *et al.*, 2003). Soil erosion reduces crop yields by removing nutrients and organic matter. Erosion also interferes with soil–water relationships: the depth of soil is reduced, diminishing water storage capacity and damaging soil structure, thus reducing soil porosity. Downstream, the main impact of soil erosion is sedimentation, a major form of human-induced water pollution.

Water scarcity and pollution

Water scarcity is a significant problem for farmers in Africa, Asia and the Near East, where 80–90% of water withdrawals are used for agriculture (FAO/IIASA, 2000; Rosegrant *et al.*, 2002). Water, a finite resource, the very basis of life and the single most important feature of our planet, is the most threatened natural resource at the present time. Water is the most important driver for four of the Millennium Development Goals, as shown in Fig. 1.4. In the context of these four goals, the contribution of water resources management through direct interventions is suggested to achieve the milestones by 2015. However, in many SAT situations water quantity per se is not the limiting factor for increased productivity but its management and efficient use are the main yield determinants. Instead, the major water-related challenge for rainfed agriculture in semi-arid and dry subhumid regions is to deal with the extreme variability in rainfall, characterized by few rainfall events, high-intensity storms, and high frequency of dry spells and droughts. For example, in Kurnool district, one of the most drought-prone districts in Andhra Pradesh, India, there is a large variation in rainfall return years. The normal annual rainfall is about 660 mm, of which about 90% is received in the 6-month period of June to November. During a period of 55 years, normal rainfall (−19 to +19% in reference to normal rainfall) was received in 30 years, excess rainfall (>20% over normal rainfall) in 11 years and deficit rainfall (−20 to −59% of normal rainfall) in 14 years. It is therefore critical to understand the impact of hydroclimatic conditions and water management on yields in rainfed agriculture. Key constraints to rainwater productivity evidently differ greatly across the wide range of rainfall zones. In the arid regions, it is the absolute amount of water (so-called absolute water scarcity) that constitutes the major limiting factor in agriculture. In the semi-arid and dry subhumid tropical regions on the other hand, seasonal rainfall is generally adequate to significantly improve yields. Here, managing extreme rainfall variability in time and space is the largest water challenge. Only in the dry semi-arid and arid zones, considering mean rainfall, is absolute water stress common. In the wetter part of the semi-arid zone, and into the dry subhumid zone, rainfall generally exceeds crop water needs.

Table 1.1. Nutrient loss (t/year) in different regions of Thailand.

Region	Nitrogen	Phosphorus	Potassium
Northern	38,288	4,467	75,588
North-eastern	18,896	1,212	91,644
Eastern	17,890	1,074	30,860
Southern	17,310	453	13,254

Source: Land Development Department, Thailand.

Absolute water scarcity is thus rarely the major problem for rainfed agriculture. Still water scarcity is a key reason behind low agricultural productivity. To identify management options to upgrade rainfed agriculture it is therefore essential to assess different types of water stress in food production. Of particular importance is to distinguish between climate- and human-induced water stress, and the distinction between droughts and dry spells (Table 1.2). In semi-arid and dry subhumid

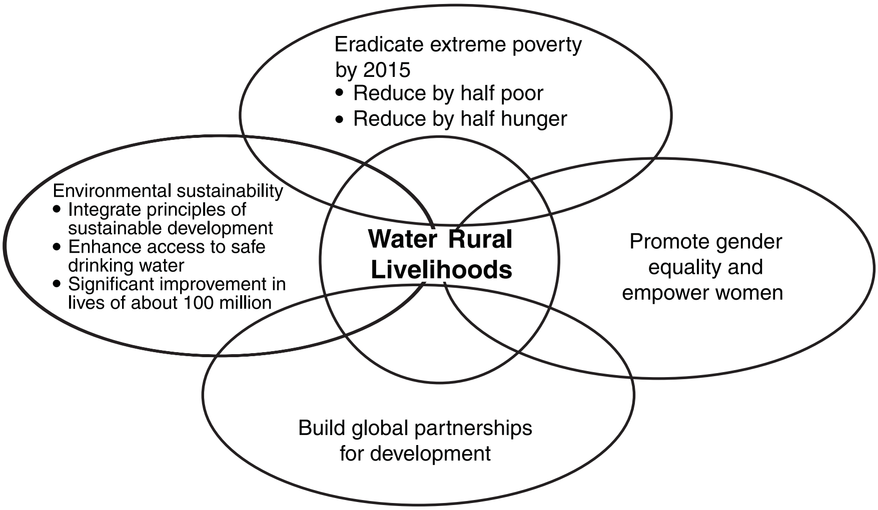


Fig. 1.4. Water is an important driver for achieving the Millennium Development Goals.

Table 1.2. Types of water stress and underlying causes in semi-arid and dry subhumid tropical environments[a].

Types of water stress	Dry spell	Drought
Meteorological	Occurrence: 2 out of 3 years Impact: yield reduction Cause: rainfall deficit of 2–5-week periods during crop growth	Occurrence: 1 out of 10 years Impact: complete crop failure Cause: seasonal rainfall below minimum seasonal plant water requirement
Agricultural (human induced)	Occurrence: >2 out of 3 years Impact: yield reduction or complete crop failure Cause: low plant water availability and poor plant water uptake capacity	Occurrence: >1 out of 10 years Impact: complete crop failure Cause: poor rainfall partitioning leads to seasonal soil moisture deficit to produce harvest

[a] Source: Falkenmark and Rockström (2004).

agroecosystems, rainfall variability generates dry spells (short periods of water stress during growth) almost every rainy season (Barron *et al.*, 2003), compared with meteorological droughts, which occur on average once every decade in moist semi-arid regions and up to twice every decade in dry semi-arid regions. When there is not enough rainfall to generate a crop, meteorological droughts result in complete crop failure. Such droughts cannot be bridged through agricultural water management, and instead social coping strategies are required, such as grain banks, relief food, local food storage and livestock sales. Dry spells, on the other hand, are manageable, i.e. investments in water management can bridge dry spells, which generally are 2–4 weeks of no rainfall during critical stages of plant growth (Box 1.2).

Even in regions with low variable rainfall, only a fraction actually forms soil moisture, i.e. green water resource, in farmers' fields. In general, only 70–80% of the rainfall is available to the plants as soil moisture, and on poorly managed land the fraction of plant-available water can be as low as 40–50% (Falkenmark and Rockström, 2004). This leads to agricultural dry spells and droughts, which are not

Box 1.2. Dry spell occurrence and yield implications in savannah agroecosystems.

Barron *et al.* (2003) studied dry spell occurrence in semi-arid locations in Kenya and Tanzania and found that meteorological dry spells of >10 days occurred in 70% of seasons during the flowering stage of the crop (maize), which is very sensitive to water stress. Regions with similar seasonal rainfall can experience different dry spell occurrence. In the semi-arid Nandavaram watershed, Andhra Pradesh, India, with approximately 650 mm of rainfall, there is a high risk of dry spell occurrence (>40% risk) during the vegetative and flowering stages of the crop, compared with semi-arid Xiaoxingcun, Southern China, receiving similar rainfall but with only a 20% risk of early season dry spells (Kesava Rao *et al.*, 2007).

caused primarily by rainfall deficiencies but instead are due to management-related problems with the on-farm water balance. The occurrence of agricultural droughts and dry spells are thus not only an indicator of poor agricultural water management but also a sign of a large opportunity to improve yields, as these droughts and dry spells are to a large degree manageable.

In addition, imbalanced use of nutrients in agriculture by the farmers results in mining of soil nutrients. Recent studies in India revealed that 80–100% of the farmers' fields were found to be critically deficient in zinc, boron and sulfur in addition to nitrogen and organic carbon (Rego *et al.*, 2005; Wani *et al.*, 2006a). Overall the constraints of rainfed production are many (Box 1.3). If the current production practices are continued, developing countries in Asia and Africa will face a serious food shortage in the very near future. The major constraints for low on-farm yields and large yield gap are:

- Inappropriate NRM practices followed by the farmers.
- Lack of knowledge.
- Low investments in rainfed agriculture.
- Lack of policy support and infrastructure including markets and credit.
- Traditional cultivars.
- Low use of fertilizers.
- Low rainwater use efficiency.
- Pests and diseases.
- Compartmental approach.

Potential of Rainfed Agriculture

In several regions of the world rainfed agriculture generates the world's highest yields. 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,b; Rockström *et al.*, 2007). Evidence from a long-term experiment at the International Crops Research Institute for the Semi-Arid

Box 1.3. Constraints identified by the stakeholders in Shekta watershed, Maharashtra, India.

- Land degradation because of felling trees, shrubs and free grazing had intensified and added to the problems of excessive run-off and soil erosion.
- Due to irregular and insufficient rainfall, there was severe scarcity of drinking water throughout the year.
- During summer, wells dried up frequently and the water table declined, leading to high intensity of water requirement in a short period and thus influencing crop failures, drought, etc.
- Livestock production in the village is limited mainly to goats, sheep, indigenous cows, buffaloes and bullocks but there is not much emphasis on breed improvement, animal nutrition and health for improving productivity.
- The socio-economic status of the people is very low and the education of children, especially female, is low although the village has set up a primary school (up to 9 years of age) in the village itself.
- The problem of market access and price fluctuations compounds the problems of inappropriate prices for the farm produce and decision making.
- At initial stages of watershed development the decision of the community to ban free grazing disturbed the livelihood of small farmers, shepherds and families owning small ruminants.

Tropics (ICRISAT), Patancheru, India, since 1976 demonstrated the virtuous cycle of persistent yield increase through improved land, water and nutrient management in rainfed agriculture. Improved systems of sorghum/pigeonpea intercrops produced higher mean grain yields (5.1 t/ha) compared with 1.1 t/ha, the average yield of sole sorghum in the traditional (farmers') post-rainy system, where crops are grown on stored soil moisture (Fig. 1.5). The annual gain in grain yield in the improved system was 82 kg/ha/year compared with 23 kg/ha/year in the traditional system. The large yield gap between attainable yield and farmers' practice as well as between the attainable yield of 5.1 t/ha and potential yield of 7 t/ha shows that a large potential of rainfed agriculture remains to be tapped. Moreover, the improved management system is still continuing to provide an increase in productivity as well as improving soil quality (physical, chemical and biological parameters) along with increased carbon sequestration of 330 kg C/ha/year (Wani *et al.*, 2003a). Yield gap analyses, undertaken for the Comprehensive Assessment of Water for Food and Water for Life, for major rainfed crops in semi-arid regions in Asia (Fig. 1.6) and Africa and rainfed wheat in WANA reveal large yield gaps, with farmers' yields being a factor of two to four lower than achievable yields for major rainfed crops grown in Asia and Africa (Rockström *et al.*, 2007). At the same time, the dry subhumid and semi-arid regions experience the lowest yields and the lowest productivity improvements. Here, yields oscillate between 0.5 and 2 t/ha, with an average of 1 t/ha, in sub-Saharan Africa, and 1–1.5 t/ha in SAT Asia, Central Asia and WANA (Rockström and Falkenmark 2000; Wani *et al.*, 2003a,b; Rockström *et al.*, 2007).

Farmers' yields continue to be very low compared with the experimental yields (attainable yields) as well as simulated crop yields (potential yields), resulting in a very significant yield gap between actual and attainable rainfed yields. The difference is largely explained by inappropriate soil, water and crop management options used at the farm level, combined with persistent land degradation.

The vast potential of rainfed agriculture needs to be unlocked through knowledge-based management of natural resources for increasing productivity and income to achieve food security in the developing world. Soil and water management play a very critical role in increasing agricultural productivity in rainfed areas in the fragile SAT systems.

New Paradigm in Rainfed Agriculture

Current rainfed agriculture cannot sustain the economic growth and food security needed.

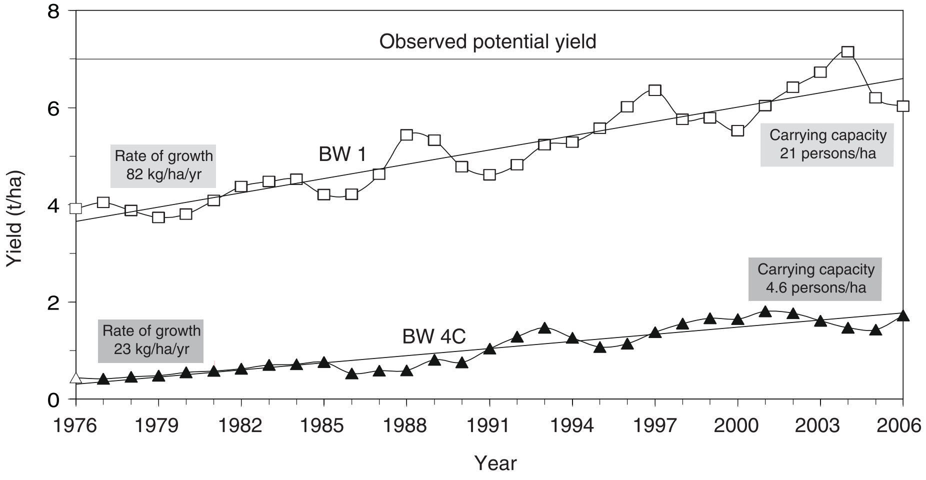


Fig. 1.5. Three-year moving average of sorghum and pigeonpea grain yield under improved and traditional management in a deep vertisol catchment at Patancheru, India.

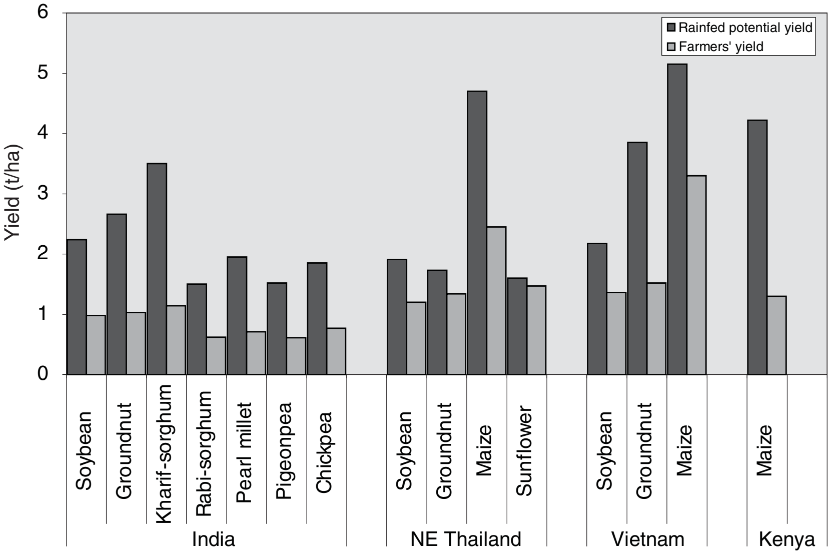


Fig. 1.6. Yield gap of important rainfed crops in different countries (Source: Rockström *et al.*, 2007).

There is an urgent need to develop a new paradigm for soil and water management. 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.

Integrated genetic and natural resource management

Traditionally, crop improvement and NRM were seen as distinct but complementary disciplines. ICRISAT is deliberately blurring these boundaries to create the new paradigm of IGNRM (integrated genetic and natural resource management) (Twomlow *et al.*, 2006). Improved varieties and improved resource management are two sides of the same coin. Most farming problems require integrated solutions, with genetic, management-related and socio-economic 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, which can respond to rapid changes in market opportunities and climatic conditions. It is time to stop debate on genetic enhancement or NRM and adopt the IGNRM approach converging genetic, NRM, social and institutional aspects with market linkages. 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 socio-economic 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.

Technologies must match not only the crop or livestock enterprise and the biophysical environment but also the market and investment environment, including seed availability. Plant breeders and NRM scientists must integrate their work with change agents (both public and private sector), and work with target groups to develop flexible cropping systems that can respond to changes in market opportunities. Rather than pursuing a single correct answer, we need to look for multiple solutions tailored to the requirements of contrasting environments and diverse sets of households. These include small and marginal farmers, female-headed households, HIV/AIDS-affected households, those lacking draft power, farmers with poor market access as well as households with good market access and better commercial production opportunities. In the rainfed areas, to improve livelihoods the approach has to be a business one through marketable surplus production through diversified farming systems with necessary market linkages and institutional arrangements.

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. These are:

- 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. For example, ICRISAT's work on community watersheds for improving livelihoods in Asia and developing groundnut markets in Malawi aims to address this issue.
- Poor research–extension–farmer linkages, which limit transfer and adoption of technology. For example, ICRISAT's work on Farmer Field Schools in Africa and the consortium approach to integrated management of community watersheds in Asia aims to strengthen these linkages.
- Need for policies and strategies on soil, water and biodiversity to offset the high rate of natural resource degradation. These issues are central to ICRISAT's consortium approach to integrated community watershed management.
- Need to focus research on soil fertility improvement, soil and water management, development of irrigation, promotion of integrated livestock–wildlife–crop systems and development of drought-mitigation strategies. These issues are addressed by several ICRISAT programmes, e.g. low-input soil fertility approaches in Africa; micronutrient research in Asia, and the Sahelian Eco-Farm.
- Need to strengthen capacities of institutions and farmers' organizations to support input and output marketing and agricultural production systems. Such capacity building is a primary goal of the Soil Water Management Network (SWMnet) of ASARECA (Association for Strengthening Agricultural Research in Eastern and Central Africa) and the Eastern and Central Africa Regional Sorghum and Millet Network (ECARSAM) in eastern and central Africa, and of seed systems/germplasm improvement networks globally.
- Poor information flow and lack of communication on rural development issues. These are being addressed by ICRISAT's VASAT Consortium (Virtual Academy for the Semi-Arid Tropics) globally and specifically ICRISAT's Bio-economic Decision Support work with partners in West Africa.
- Need to integrate a gender perspective in agricultural research and training as seen in ICRISAT's work on HIV/AIDS amelioration in India and Southern Africa.

Crop improvement plays an important role in addressing each of these issues, and thus ICRISAT has expanded the INRM paradigm to specifically emphasize the role crops and genetic improvement can play in enabling SAT agriculture to achieve its potential. Thus, the institute is seeking to embrace an overall philosophy of IGNRM. There is clear evidence from Asia and Africa (Fig. 1.7) that the largest productivity gains in the SAT can come from combining new varieties with improved crop management and NRM (Table 1.3).

A major research challenge faced in INRM is to combine the various 'information bits' derived from different stakeholders, and distil these into decision rules that they can use (Snapp and Heong, 2003). ICRISAT's participatory research in Southern Africa demonstrated that with micro-dosing alone or in combination with available animal manures farmers could increase their yields by 30–100% by applying as little as 10 kg of nitrogen per hectare (Dimes *et al.*, 2005; Ncube *et al.*, 2006; Rusike *et al.*, 2006) (Fig. 1.8).

In much of agricultural research, the multidisciplinary team approach has often run into difficulties in achieving impact because of the perceived disciplinary hierarchy. The IGNRM approach in the Community Watershed Consortium pursues integration of the knowledge and products of the various research disciplines into useful extensions messages for development workers that can sustain increased yields for a range of climatic and edaphic conditions. A similar attempt at integration

Table 1.3. Yield advantages observed with different crop cultivars and improved management in Sujala watersheds of Karnataka, India during 2005–2006 seasons.

	Yield improvement (%)		
Crop	Local Cultivar+IMP[a]	HYV+FP[b]	HYV[c]+IMP
Finger millet	74	22–52	103–123
Groundnut	27	13–36	47–83
Soybean	62	0	83
Sunflower	67	54–150	152–230
Maize	–	26	70
Sorghum	–	–	31

[a] IMP = improved management practice; [b] FP = farmers' practice; [c] HYV = high-yielding variety.

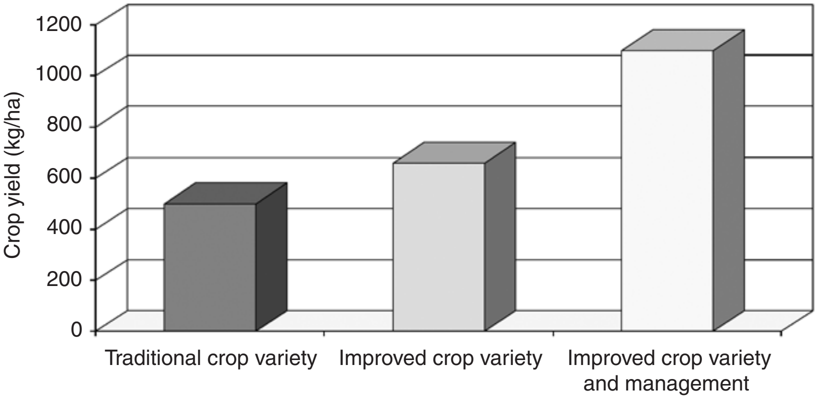


Fig. 1.7. Contribution of different technology components on sorghum yield, as observed in on-farm trials in Zimbabwe (Source: Heinrich and Rusike, 2003).

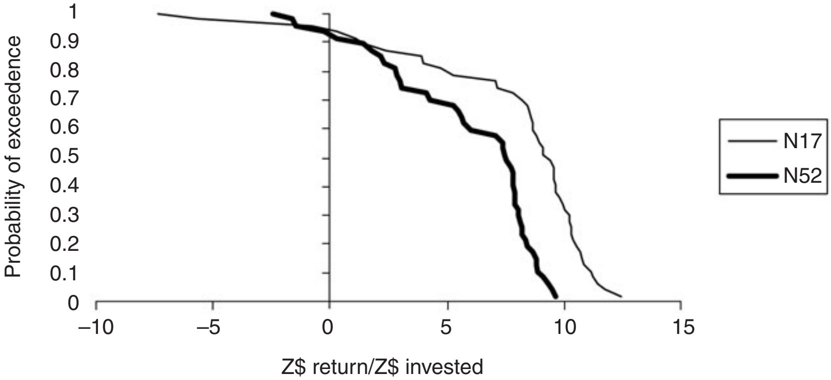


Fig. 1.8. The probability of exceeding given rates of return on nitrogen (N)-fertilizer investment on maize production at 17 and 52 kg N/ha at Masvingo, Zimbabwe (Source: Dimes, 2005).

was made for pearl millet production in Mali for a range of possible climatic scenarios (Table 1.4).

In Asia, the integrated community watershed management approach that aims to promote income-generating and sustainable crop and livestock production options as an important component of improved management of watershed landscapes is a live example of how IGNRM led to significant benefits in a poor area (Tables 1.5 and 1.6, and Fig. 1.9) and this holistic participatory approach is transforming the lives of resource-poor small and marginal farmers in the dryland areas of Asia (Wani *et al*., 2006a).

ICRISAT and the national agricultural research systems (NARS) in Asia have developed in partnership an innovative and upscalable consortium model for managing watersheds holistically. In this approach, rainwater management is used as an entry point activity starting with *in-situ* conservation of rainwater and converging the benefits of stored rainwater into increased productivity by using improved crops, cultivars, suitable nutrient and pest management practices, and land and water management practices (Table 1.6). The IGNRM approach has enabled communities not only to harness the benefits of watershed management but also to achieve much of the potential from improved varieties from a wider range of crops. The households' incomes and overall productivity have more than doubled throughout selected benchmark sites in Asia (Fig. 1.9 and Table 1.7). The benefits accrue not only to landholding households but also to the landless marginalized

Table 1.4. Effect of climate variability on pearl millet crop performance and integrated genetic natural resource management (IGNRM) options in Mali (adapted from ICRISAT, 2006).

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 re-sowing	P fertilizer at planting, water harvesting and run-off control, delay sowing (but poor growth due to N flush), exploit seedling heat and drought tolerance
Mid-season 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 run-off control
Terminal drought	Poor grain filling, fewer productive tillers	Early-maturing varieties, optimal root traits, fertilizer at planting, water harvesting and run-off control
Excessive rainfall	Downy mildew and other pests, nutrient leaching	Resistant varieties, pesticides, N fertilizer at tillering
Increased temperature	Poor crop establishment (desiccation of seedlings), increased transpiration, faster growth	Heat-tolerance traits, crop residue management, P fertilizer at planting (to increase plant vigour), 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)

Table 1.5. Effect of integrated water management interventions on run-off and soil erosion in Adarsha watershed, Andhra Pradesh, India.

		Run-off (mm)		Peak run-off rate (m^3/s/ha)		Soil loss (t/ha)	
Year	Rainfall (mm)	Untreated	Treated	Untreated	Treated	Untreated	Treated
1999	584	16	NI[a]	0.013	NI[a]	NI[a]	NI[a]
2000	1161	118	65	0.235	0.230	4.17	1.46
2001	612	31	22	0.022	0.027	1.48	0.51
2002	464	13	Nil	0.011	Nil	0.18	Nil
2003	689	76	44	0.057	0.018	3.20	1.10
2004	667	126	39	0.072	0.014	3.53	0.53
2005	899	107	66	0.016	0.014	2.82	1.20
2006	715	110	75	0.003	0.001	2.47	1.56
Mean	724	75 (10.4%)	44 (6.1%)	0.054	0.051	2.55	1.06

[a] Not installed.
Source: Sreedevi *et al.* (2007).

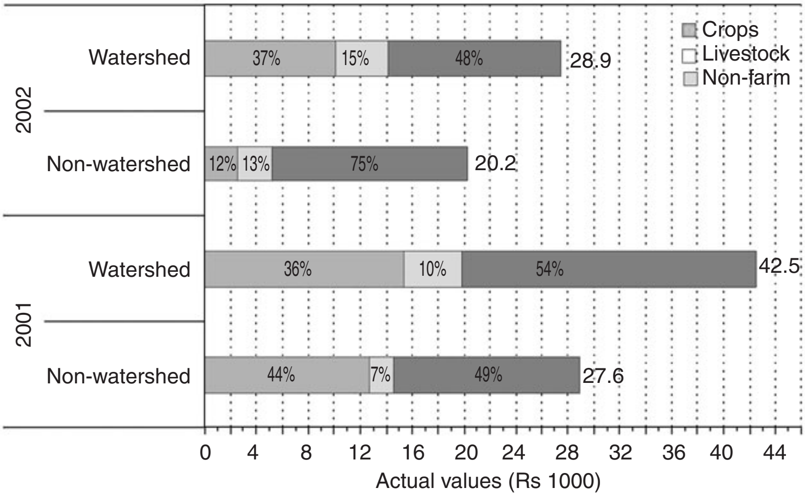


Fig. 1.9. Effect of integrated watershed management on flow of household net income (Source: ICRISAT Data – Adarsha watershed, Andhra Pradesh, India).

groups through the creation of greater employment opportunities. The greater resilience of crop income in the watershed villages during the drought year in 2002 is particularly noteworthy (Fig. 1.9). While the share of crops in household income declined from 44% to 12% in the non-project villages, crop income remained largely unchanged from 36% to 37% in the watershed village. The loss in household income in the non-project villages was largely compensated by migration and non-farm income which increased from 49% in an average year to 75% during the drought year in 2002. Much of this gain originates from improved soil fertility management and increased availability of irrigation water and integration of improved cultivars and cropping patterns into the watershed systems.

While the INRM approach has made significant contributions in re-orienting research for sustainable management of natural resources, there is now a need to create clear synergies with germplasm improvement and the income and

Table 1.6. Crop yields in Adarsha watershed, Kothapally, during 1999–2007.

Crop	1998 base-line yield	Yield (kg/ha)								Average yields	SE±
		1999–2000	2000–2001	2001–2002	2002–2003	2003–2004	2004–2005	2005–2006	2006–2007		
Sole maize	1500	3250	3750	3300	3480	3920	3420	3920	3635	3640	283.3
Improved intercropped maize	–	2700	2790	2800	3083	3129	2950	3360	3180	3030	263.0
Traditional intercropped maize	–	700	1600	1600	1800	1950	2025	2275	2150	1785	115.6
Improved intercropped pigeonpea		640	940	800	720	950	680	925	970	860	120.3
Traditional intercropped pigeonpea	190	200	180	–	–	–	–	–	–	190	–
Improved sole sorghum	–	3050	3170	2600	2425	2290	2325	2250	2085	2530	164.0
Traditional sole sorghum	1070	1070	1010	940	910	952	1025	1083	995	1000	120.7
Intercropped sorghum	–	1770	1940	2200	–	2110	1980	1960	1850	1970	206.0

Table 1.7. The effect of integrated watershed interventions on alternative sources of household income (Rs 1000).

Year	Village group[a]	Statistics	Crop income	Livestock income	Off-farm income	Household income
2001 (average year)	Non-project	Mean income	12.7	1.9	14.3	28.9
		Share of total income (%)	44.0	6.6	49.5	100.0
	Watershed project	Mean income	15.4	4.4	22.7	42.5
		Share of total income (%)	36.2	10.4	53.4	100.0
2002 (drought year)	Non-project	Mean income	2.5	2.7	15.0	20.2
		Share of total income (%)	12.2	13.3	74.5	100.0
	Watershed project	Mean income	10.1	4.0	13.4	27.6
		Share of total income (%)	36.7	14.6	48.7	100.0

[a] The sample size is n = 60 smallholder farmers in each group (ICRISAT data).

livelihood strategies of resource users. Thus the IGNRM approach espoused by ICRISAT now encompasses seed technologies and germplasm improvement as one of the important pillars for sustainable intensification and productivity improvement of agriculture in the SAT. Recent experiences at ICRISAT with projects that pursue the IGNRM approach (e.g. integrated management of community watersheds) provide optimism about the effectiveness and suitability of this approach.

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. ICRISAT's on-farm diagnostic work in different community watersheds in different states of India as well as in China, Vietnam and Thailand showed severe mining of soils for essential plant nutrients. Exhaustive analysis showed that 80–100% of farmers' fields are deficient not only in total nitrogen but also in micronutrients such as zinc and boron and secondary nutrients such as sulfur (Table 1.8). 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. Management practices that augment soil organic matter and maintain it at a threshold level are needed. Farm bunds 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 annually in addition to valuable organic matter. Also, large quantities of farm residues and other organic wastes could be converted into a valuable source of plant nutrients and organic matter through vermicomposting (Wani *et al.*, 2005). Strategic long-term catchment research at ICRISAT has shown that legume-based systems, particularly with pigeonpea, could sequester 330 kg carbon up to 150 cm depth in vertisols at Patancheru, India under rainfed conditions (Wani *et al.*, 2003a). Under the National Agricultural Technology Project (NATP), ICRISAT, the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), the Central Research Institute for Dryland Agriculture (CRIDA) and the Indian Institute of Soil Science (IISS) have identified carbon sequestering systems for alfisols and vertisols in India (ICRISAT, 2005). Integrated nutrient management strategies go a long way in improving soil health for enhancing WUE and increasing farmers' incomes.

Table 1.8. Percentage of farmers' fields deficient in soil nutrients in different states of India.

State	No. of farmers' fields	OC[a] (%)	AvP[a] (ppm)	K (ppm)	S (ppm)	B (ppm)	Zn (ppm)
Andhra Pradesh	1927	84	39	12	87	88	81
Karnataka	1260	58	49	18	85	76	72
Madhya Pradesh	73	9	86	1	96	65	93
Rajasthan	179	22	40	9	64	43	24
Gujarat	82	12	60	10	46	100	82
Tamil Nadu	119	57	51	24	71	89	61
Kerala	28	11	21	7	96	100	18

[a] OC = organic carbon; AvP = available phosphorus.

Often, soil fertility is the limiting factor to increased yields in rainfed agriculture (Stoorvogel and Smaling, 1990). 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).

In India, farmers' participatory watershed management trials in more than 300 villages demonstrated that the current subsistence farming has depleted soils not only in macronutrients but also in micronutrients such as zinc and boron and secondary nutrients such as sulfur beyond the critical limits. A substantial increase in crop yields was experienced after micronutrient amendments, and a further increase by 70–120% when both micronutrients and adequate nitrogen and phosphorus were applied, for a number of rainfed crops (maize, sorghum, mung bean, pigeonpea, chickpea, castor and groundnut) in farmers' fields (Rego *et al.*, 2005).

Therefore, investments in soil fertility directly improve water management. Rainwater productivity (i.e. total amount of grain yield per unit 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, mung bean, 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 (Rego *et al.*, 2005). Similarly, rainwater productivity increased significantly when adopting integrated land and water management options as well as use of improved cultivars in semi-arid regions of India (Wani *et al.*, 2003b).

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 additional factors than water limitation. ICRISAT's experience in rainfed areas has clearly demonstrated that, more than water quantity per se, management of water resources is the limitation in the SAT regions (Wani *et al.*, 2006a).

As indicated by Agarwal (2000), India would not have to suffer from droughts if local water balances were managed better. Even during drought years, watershed development efforts of improving rainfall management have benefited Indian farmers. For example, villages benefiting from watershed management projects increased food produce and market value by 63% compared with the non-project village even during drought years (Wani *et al.*, 2006b). An analysis in Malawi indicates that since the late 1970s only a fraction of the years that have been politically proclaimed as drought years actually were years subject to meteorological droughts (i.e. years where rainfall totals fall under minimum water needs to produce food at all) (Mwale, 2003). This is supported by Glantz (1994), who pointed out that agricultural droughts, where drought in the root zone is caused primarily by a poorly performing water balance, are more common than meteorological droughts. Furthermore, political droughts, where failures in the agricultural sector are blamed on drought, are commonplace.

Given the previous message the question arises, why is everybody blaming drought when there are famines and food shortages? The answer is that even if there is no drought in terms of rainfall, the crop may suffer from drought in the root zone, in terms of lack of green water or soil moisture. Often land degradation and poor management of soil fertility and crops are the major and more frequent causes of ‘droughts’. These are referred to as agricultural droughts – where rainfall partitioning in the farmers’ fields causes water stress. Available water as rainfall is not utilized fully for plant growth. The main cause is therefore management rather than meteorologically significant rainfall deficits.

Evidence from water balance analyses on farmers’ fields around the world shows that only a small fraction, generally less than 30% of rainfall, is used as productive green water flow (plant transpiration) supporting plant growth (Rockström, 2003). Moreover, evidence from sub-Saharan Africa shows that this range varies from 15 to 30% of rainfall, even in the regions generally perceived as ‘water scarce’ (Fig. 1.10). This range is even lower on severely degraded land or land where yields are lower than 1 t/ha. Here, as little as 5% of rainfall may be used productively to produce food. In arid areas typically as little as 10% of the rainfall is consumed as productive green water flow (transpiration) with 90% flowing as non-productive evaporation flow, i.e. no or very limited blue water generation (Oweis and Hachum, 2001). For temperate arid regions, such as WANA, a larger portion of the rainfall is generally consumed in the farmers’ fields as productive green water flow (45–55%) as a result of higher yield levels (3–4 t/ha as compared with 1–2 t/ha). Still, 25–35% of the rainfall flows as non-productive green water flow, with only some 15–20% generating blue water flow.

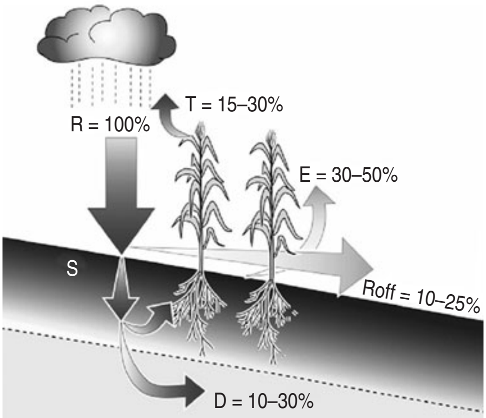


Fig. 1.10. General overview of rainfall partitioning in farming systems in the semi-arid tropics of sub-Saharan Africa, indicating the large portion of rainfall (R) which even in semi-arid farming systems is lost from the farm scale through drainage (D), surface run-off (Roff) and non-productive evaporation (E). The remainder is transpiration (T) (Source: Rockström *et al.*, 2007).

This indicates a large window of opportunity. Low current agricultural yields in rainfed agriculture, which are often blamed on rainfall deficits, are in fact often caused by other factors than rainfall. Still, what is possible to produce on-farm will not always be produced, especially not by resource-poor, small-scale farmers. The farmers’ reality is influenced by other constraints such as labour shortage, insecure land ownership, capital constraints and limitation in human capacities. All these factors influence how farming is done, in terms of timing of operations, effectiveness of farm operations (e.g. weeding and pest management), investments in fertilizers and pesticides, use of improved crop varieties, water management, etc. The final produce in the farmers’ field is thus strongly affected by social, economic and institutional conditions.

High risk and increase with climate change

Rainfed agriculture is a risky business due to high spatial and temporal variability of rainfall. Rainfall is concentrated in short rainy seasons (approximately 3–5 months), with few intensive rainfall events, which are unreliable in temporal distribution, manifested by high deviations from the mean rainfall (coefficients of variation of rainfall as high as 40% in semi-arid 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 avert risk, which in turn determines farmers' perceptions on investments in other production factors (such as labour, 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 semi-arid 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 crop, 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, 2001). 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 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 in 2080 (IIASA, 2002). In particular, sub-Saharan Africa is estimated to lose 12% of the cultivation potential, 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 by 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).

As the policy on water resource management for agriculture remains focused on irrigation, the framework for integrated water resource management at catchment and basin scales is primarily concentrated on allocation and management of blue water in rivers, groundwater and lakes. The evidence from the Comprehensive Assessment of Water for Food and Poverty Reduction indicated that the use of water for agriculture is larger than for irrigation, and there is an urgent need for a widening of the policy scope to include explicit strategies for water management in rainfed agriculture, including grazing and forest systems. However, what is needed is effective integration so as to have a focus on the investment options on water management across the continuum from rainfed to irrigated agriculture. The time is opportune 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 water management at the catchment scale (or small tributary scale of a river basin), opening up much-needed investments in water resource management in rainfed agriculture also (Rockström *et al.*, 2007).

Small catchment

It is not surprising that most of the water management investments in rainfed agriculture since the late 1950s have focused on improved management of the rain that falls on the farmer's field. Soil and water conservation or *in-situ* water-harvesting systems form the logical entry point for improved water management in rainfed agriculture.

Since *in-situ* rainwater management strategies are often relatively cheap and can be applied literally on any piece of land, they should be optimized on any field before supply of water from external sources is considered. Established but incomplete evidence indicates that investing first in management of the local field water balance increases the likelihood of success in complementing the farming systems with supplemental irrigation systems based on rainwater harvesting, river-flow diversion or groundwater sources. This indicates that farmers who successfully manage to minimize losses of the rain that falls on the crop land are more likely to successfully adopt methods for dry spell mitigation. Tangible economic benefits to individuals through *in-situ* rainwater conservation were demonstrated while studying the drivers of collective action in successful watersheds (Wani *et al.*, 2003b; Sreedevi *et al.*, 2004). In policy and investment terms, this means that the focus should be on first tapping the *in-situ* potential prior to investing in external options.

Conservation agriculture[1] systems are one of the most important strategies to enhance soil productivity and moisture conservation. Non-inversion systems, where conventional ploughs are abandoned in favour of ripping, sub-soiling and no-tillage systems using direct planting techniques, combined with mulch management, builds organic matter and improves soil structure. Conservation agriculture is practised on approximately 40% of rainfed agriculture in the USA and has generated an agricultural revolution in several countries in Latin America (Derpsch, 1998, 2005; Landers *et al.*, 2001). Large-scale adoption of conservation agriculture systems is experienced among small-scale rainfed and irrigated farmers cultivating rice and wheat on the Indo-Gangetic plains in Asia (Hobbs and Gupta, 2002).

Conservation agriculture is of key importance in efforts to upgrade rainfed agriculture among the world's resource-poor farmers. It reduces traction requirements (by tractors or animal draught power), which saves money and is strategic from a gender perspective, as it generally gives women, particularly in female-headed households, a chance to carry out timely and effective tillage. A challenge is to find alternative strategies to manage weeds, particularly in poor farm households where herbicides are not an option. Furthermore, conservation agriculture can be practised on all agricultural land, i.e. there are no limitations related to the need for watershed areas and storage capacity for water harvesting. Conservation agriculture is a particularly important soil and water management strategy in hot tropical regions subject to water constraints. Soil inversion (using ploughs) in hot tropical environments leads to rapid oxidation of organic matter and increased soil erosion, which can be avoided using conservation agriculture practices. Some drawbacks with conservation agriculture might be the high initial costs of specialized planting equipment and the need for new management skills of the farmers. In addition, the use of pesticides might be necessary during the first years; however, after a few years the need normally declines to below the level of the original farming system.

Converting from ploughing to conservation agriculture using sub-soiling and ripping has resulted in major improvements in yield and water productivity in parts of semi-arid to dry subhumid East Africa, with a doubling of yields in good years, due to increased capture of rainwater (Box 1.4). Further increases in grain yield were achieved by applying manure. Compared with irrigation, these kinds of interventions can be implemented on all agricultural lands. Moreover, eastern and Southern Africa show a large potential to reduce labour needs and improve yields in smallholder rainfed agriculture with the adoption of conservation agriculture practices (Box 1.4). Yield improvements range from 20 to 120%, with rainwater productivity improving at 10–40%.

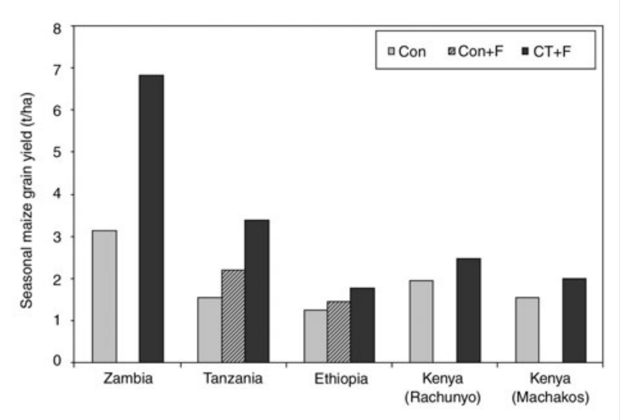
In-situ water-harvesting options also include techniques to concentrate run-off to plants, such as terracing, bunds, ridges, *khadins* and microbasins. The productivity of rain in arid environments can be substantially increased with appropriate water-harvesting techniques, which concentrate run-off to plants and trees (Box 1.5).

Shifting non-productive evaporation to productive transpiration

Rainwater use efficiency in agricultural systems in arid and SAT is 35–50%, and up to 50% of the rainwater falling on crop or pasture fields is lost as non-productive evaporation. This is a key window for improvement of green water productivity, as it entails shifting non-productive evaporation to productive transpiration, with no downstream water trade-off. This vapour shift (or transfer), where management of soil physical

Box 1.4. Conservation agriculture options in East Africa – a strategy for water and soil productivity improvement.

On-farm participatory trials on innovative conservation agriculture in semi-arid to dry subhumid Ethiopia, Kenya, Tanzania and Zambia indicate large potentials to substantially improve yields and rainwater productivity of staple food crops through conservation agriculture. Conservation agriculture involves the abandoning of soil inversion through conventional ploughing (generally mouldboard or disc ploughing), in favour of tillage systems with no turning and with minimum disturbance of the soil. Trials were carried out with farmers during 1999–2003, when yields increased significantly in all countries (see figure below). The conservation agriculture systems maximized rainfall infiltration into the soil, through ripping and sub-soiling. Draught animal traction requirements were reduced drastically (by at least 50%) and limited soil fertilization resources (manure and fertilizer) were applied along permanently ripped planting lines.



Maize yield improvements from conservation agricultural in on-farm trials in eastern and southern African countries. A conventional mouldboard ploughing system (Con) is compared with conventional ploughing with added fertilization (Con+F) and conservation agriculture using ripper and sub-soilers combined with fertilizer (CT+F).

conditions, soil fertility, crop varieties and agronomy are combined to shift the evaporative loss into useful transpiration by plants, is a particular opportunity in arid, semi-arid 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 semi-arid 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, which together result in high losses of rainwater as evaporation from soil. When yield levels increase, shading of soil improves, and when yields reach 4–5 t/ha and above, the canopy density is so high that the opportunity to reduce evaporation in favour of increased transpiration reduces, lowering the relative improvement of water productivity. This indicates that large opportunities for improving water productivity are found in low-yielding farming systems (Oweis *et al.*, 1998; Rockström, 2003), i.e. particularly in rainfed agriculture as compared with irrigated agriculture, where water productivity already is higher due to better yields.

Convergence and collective action

Convergence of actors and their actions at watershed level is needed to harness the synergies and to maximize the benefits through efficient and sustainable use of natural resources, to benefit

Box 1.5. Efficient use of *in-situ* water-harvesting techniques in arid regions.

Water-harvesting systems using small micro-basins are used to support plants and trees in arid and semi-arid environments. Small basins (*negarim*) have supported almond trees for over 17 years in the Muwaqqar area of Jordan, where the mean annual rainfall is 125 mm. The system has proved sustainable over a period of several years of drought (Oweis and Taimeh, 1996).

In the Mehasseh area of the Syrian steppe, with an average annual rainfall of 120 mm, the survival rate of rainfed shrubs is less than 10%, while those that were grown in micro-catchments had a survival rate of over 90%. Shrub survival rate can be improved between 70 and 90% with the introduction of water-harvesting interventions (semicircular bunds). In north-west Egypt, with an average annual rainfall of 130 mm, small water-harvesting basins with 200 m^2 watersheds support olive trees, and harvesting rainwater from greenhouse roofs can provide about 50% of the water required by vegetables grown inside the greenhouse (Somme *et al.*, 2004).

small and marginal farmers through increased productivity per unit of resource. We have missed out on large benefits of watershed programmes owing to a compartmental approach and there is an urgent need to bring in convergence as the benefits are manifold and it is win–win for all the stakeholders, including line departments involved in improving rural livelihoods.

New institutional mechanisms are also needed at district, state and national level to converge various watershed programmes implemented by several ministries and development agencies to enhance the impact and efficiency by overcoming duplicity and confusion. In 2005, the National Commission on Farmers recommended a holistic integrated watershed management approach, with focus on rainwater harvesting and improving soil health for sustainable development of drought-prone rainfed areas (Government of India, 2005). Recently, the Government of India has established the National Rain-fed Areas Authority (NRAA) with the mandate to converge various programmes for integrated development of rainfed agriculture in the country. These are welcome developments; however, it is just a beginning and lot more still needs to be done to provide institutional and policy support for development of rainfed areas. 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.

Enhancing partnerships and institutional innovations through the consortium approach was the major impetus for harnessing the community watershed's potential to reduce households' poverty. The underlying element of the consortium approach adapted in ICRISAT-led community watersheds is engaging a range of actors with the locales as the primary implementing unit. Complex issues were effectively addressed by the joint efforts of ICRISAT and in collaboration with key partners, namely NARSs, non-governmental organizations (NGOs), government organizations, agricultural universities, community-based organizations and other private interest groups, with farm households as the key decision makers. In self-help groups (SHGs), such as village seed-banks, these were established not just to provide timely and quality seeds. This created the venue for receiving technical support and building the capacity of members such as women for the management of conservation and livelihood development activities. Incorporating a knowledge-based entry point in the approach led to the facilitation of rapport and at the same time enabled the community to take rational decisions for their own development. 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 policy makers from the NARSs sensitized on 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.

From another aspect, the consortium approach has contributed to scaling through the nucleus–satellite scheme and building productive alliances for further research and technical backstopping. With cooperation, a balanced R&D programme was implemented rather than a 'purist model' of participation or mere adherence to government guidelines. A balanced R&D programme in community watersheds has encouraged scientific debate and at the same time promoted development through tangible economic benefits.

The other IARCs, such as the International Water Management Institute (IWMI), the International Livestock Research Institute (ILRI) and the World Wildlife Fund (WWF), have become allies because of common denominators like goal (poverty reduction) and subject (water resources). This not only maximized the use of resources but the problem situation in watersheds allowed for an integrated approach requiring the alliance of institutions and stakeholders. Similarly, the various networks such as the ASARECA and the Cereals and Legumes Asia Network (CLAN) have provided an added venue for exchange and collaboration. This led to a strong south–south partnership.

Discard artificial divide between irrigated and rainfed agriculture

Adopt an integrated water resource management approach in the watersheds by discarding the artificial divide between rainfed and irrigated agriculture. There is an urgent need to have sustainable water (rain-, ground- and surface water) use policies to ensure sustainable development. As described earlier, in the absence of suitable policies and mechanisms for sustainable use of groundwater resources, benefits of watershed programmes can easily be undone in a short period, with overexploitation of the augmented water resources. Cultivation of water-inefficient crops, like rice and sugarcane, using groundwater in watersheds needs to be controlled through suitable incentive mechanisms for rainfed irrigated crops and policy to stop cultivation of high-water-requiring crops.

Business model

Watersheds should be developed as a business model through public–private partnership using principles of market-led diversification using high-value crops, a value-chain approach and a livelihood approach rather than only a soil and water conservation approach. 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 a public–private partnership business model for watershed management.

Watershed approach for rainfed areas

In several countries, central and state governments have emphasized management of rainfed agriculture under various programmes. Important efforts, for example, have been made under the watershed development programmes in India. Originally, these programmes were implemented by different ministries such as the Ministry of Agriculture, the Ministry of Rural Development and the Ministry of Forestry, causing difficulties for integrated water management. Recently, steps were taken to unify the programme according to the 'Hariyali Guidelines' (Wani *et al.*, 2006a) and as per the common watershed guidelines developed by NRAA (Government of India, 2008).

Meta-analysis

Detailed meta-analysis of 311 watershed case studies in India revealed that watershed programmes are silently revolutionizing rainfed areas, with positive impacts (benefit–cost ratio of 1:2.14, internal rate of return of 22%, cropping intensity increased by 63%, irrigated areas increased by 34%, run-off reduced by 13% and employment increased by 181 person-days/year/ha) (Joshi *et al.*, 2005). However, 65% of the watersheds were performing below average as they lacked community participation, programmes were supply driven, equity and sustainability issues were eluding and a compartmental approach was adopted (Joshi *et al.*, 2005) (Table 1.9). Based on the knowledge gained from the meta-analysis and earlier on-farm watersheds, ICRISAT, in partnership with NARSs, developed and evaluated an innovative farmers' participatory integrated watershed consortium model for increasing agricultural productivity and later for improving rural livelihoods (Wani *et al.*, 2003b).

Table 1.9. Benefits of watersheds – summary of meta-analysis.

Indicator	Particulars	Unit	No. of studies	Mean	Mode	Median	Min	Max	t- value
Efficiency	Benefit–cost ratio	Ratio	128	2.14	1.70	1.81	0.82	7.06	21.25
	IRR[a]	%	40	22.04	19.00	16.90	1.68	94.00	6.54
Equity	Employment	person-days/ha/year	39	181.50	75.00	127.00	11.00	900.00	6.74
Sustainability (%)	Irrigated area	%	97	33.56	52.00	26.00	1.37	156.03	11.77
	Cropping intensity	%	115	63.51	80.00	41.00	10.00	200.00	12.65
	Rate of run-off	%	36	–13.00	–33.00	–11.00	–1.30	–50.00	6.78
	Soil loss	t/ha/year	51	–0.82	–0.91	–0.88	–0.11	–0.99	39.29

[a]IRR = internal rate of return.

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 and upstream–downstream linkages.

Pilot-scale model community watershed

Based on detailed studies and synthesis of the results, impacts, shortcomings and knowledge gained from a large number of watershed programmes and on-farm experiences, an ICRISAT-led consortium developed an innovative farmers' participatory consortium model for integrated watershed management (Wani *et al.*, 2002, 2003b,c). ICRISAT has launched several pilot-scale models of community watersheds based on the knowledge gained over 25 years of strategic and on-farm development research using CGIAR priorities as its guide. The ICRISAT-led watershed espouses the IGNRM approach, where activities are implemented at landscape level. Research and development interventions at landscape level were conducted at benchmark sites representing the different agroecoregions of the SAT. The entire process revolves around the four Es (empowerment, equity, efficiency and environment), which are addressed by adopting specific strategies prescribed by the four Cs (consortium, convergence, cooperation and capacity building). The consortium strategy brings together institutions from the scientific, non-government, 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.*, 2003a).

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

- Collective action by farmers and participation from the beginning through cooperative and collegiate mode in place of contractual mode.
- Integrated water resource management and holistic system approach through convergence for improving livelihoods as against traditional compartmental approach.
- A consortium of institutions for technical backstopping.
- Knowledge-based entry point to build rapport with community and enhanced 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.
- Low-cost and environment-friendly soil and water conservation measures throughout the toposequence for more equitable benefits to a large number of farmers.
- Income-generating activities for the landless and women through allied sector activities and rehabilitation of wastelands for improved livelihoods and protecting the environment.

Integrated watershed management deals with conservation and efficient use of rainwater, groundwater, land and other natural resources for increasing agricultural productivity and improving livelihoods. Watershed management is used as an entry point to increase cropping intensity and also to rehabilitate degraded lands in the catchments in order to increase productivity, enhance biodiversity, increase incomes and improve livelihoods. Such an approach demands integrated and holistic solutions from seed to final produce, with involvement of various institutions and actors with diversified expertise varying across technical, social, financial, market and human resource development, and so on. The programme outputs are tuned to reduce poverty, minimize land degradation, increase productivity and production, and build communities' resilience to shocks due to natural calamities such as drought and flood as well as the climate variability due to global warming.

Multiple benefits and impacts

Through the use of new science 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, ICRISAT-led watersheds effected remarkable impacts on SAT resource-poor farm households.

Reducing rural poverty – in the watershed communities, this is evident in the transformation of their economies. The ICRISAT model ensured improved productivity with the adoption of cost-efficient water-harvesting structures (WHS) as an entry point for improving livelihoods. Crop intensification and diversification with high-value crops is one leading example that allowed households to achieve production of basic staples and surplus for modest incomes. The model has provision for improving the capacity of farm households through training and networking and for improved livelihood-enhanced participation, especially of the most vulnerable groups such as women and the landless. For example, the SHGs common in the watershed villages of India and an improved initiative in China provide income and empowerment of women. The environmental clubs, whose conceptualization is traced from Bundi watershed in Rajasthan, India, inculcated environmental protection, sanitation and hygiene among the children.

Building on social capital made the huge difference in addressing rural poverty of watershed communities. This is evident in the case of Kothapally watershed in Andhra Pradesh, India. Today, it is a prosperous village on the path of long-term sustainability and has become a beacon for science-led rural development. In 2001, the average village income from agriculture, livestock and non-farming sources was US$945 compared with the neighbouring non-watershed village income of US$613 (Fig. 1.9). 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 on households owning five tractors, seven lorries and 30 autorickshaws. People from surrounding villages come to Kothapally for on-farm employment. With more training on livelihood and enterprise development, migration is bound to cease. Between 2000 and 2003, investments in new livelihood enterprises such as a seed oil mill, a tree nursery and worm composting increased average income by 77% in Powerguda, a tribal village in Andhra Pradesh.

Crop–livestock integration is another facet harnessed for poverty reduction. The Lucheba watershed, Guizhou province of southern China, has transformed its economy through modest injection of capital-allied contributions of labour and finance, to create basic infrastructures such as access to roads and drinking water supply. With technical support from the consortium, the farming system was intensified from rice and rape seed to tending livestock (pig raising) and growing horticultural crops (fruit trees such as *Ziziphus*; vegetables such as beans, peas and sweet potato) and groundnuts. In forage production, wild buckwheat was specifically important as an alley crop as it was a good forage grass for pigs. 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 such as breed improvement (artificial insemination and natural means) and livestock centre/health camp establishment (Wani *et al.*, 2006b).

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.

Increasing crop productivity – this is a common objective in all the watershed programmes, and the 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 yield by two and a half times (Table 1.6) and sorghum yield by threefold (Wani *et al.*, 2006a). Overall, in the 65 community watersheds (each measuring approximately 500 ha), implementing best-bet practices resulted in significant yield advantages in sorghum (35–270%), maize (30–174%), pearl millet (72–242%), groundnut (28–179%), sole pigeonpea (97–204%) and intercropped pigeonpea (40–110%). 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 (0.5–1.0 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 in north-eastern Thailand, maize yield increased by 27–34% with improved crop management.

Improving water availability – in the watersheds this was attributed to efficient management of rainwater and *in-situ* conservation, establishment of WHS and improved groundwater levels. Findings in most of the watershed sites reveal that open wells located near WHS have significantly higher water levels compared with those away from the WHS. Even after the rainy season, the water level in wells nearer to WHS sustained good groundwater yield. In the various watersheds of India such as Lalatora (in Madhya Pradesh), the 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 to 343 ha. In Kothapally watershed in Andhra Pradesh, the groundwater level rise was 4.2 m in open wells (Fig. 1.11). The various WHS resulted in an additional groundwater recharge per year of approximately 428,000 m^3 on average. 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. Earlier every farmer's household used to spend 2–3 h per day fetching drinking water. This was the main motivation for the excellent farmers' participation in the project. On the other hand, collective pumping out 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 used to carry water on their heads from a long distance. Pumping of water from the river as a means of irrigating watermelon has provided maximum income for households in Thanh Ha watershed (in Vietnam) (Wani *et al.*, 2006b).

Supplemental irrigation – this can play a very important role in reducing the risk of crop failures and in optimizing the productivity in the SAT. In these regions, there is good potential for delivering excess rainwater to storage structures or groundwater, because even under improved systems there is loss of 12–30% of the rainfall as run-off. 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 post-rainy seasons showed that chickpea yield (1.25 t/ha) increased by 127% over the control yield (0.55 t/ha), and groundnut pod yield (1.3 t/ha) increased by 59% over the control yield (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 centre in Patancheru. Our results showed that crops on light-textured soils such as alfisols respond better with supplemental irrigation. Clearly, there is potential to enhance productivity and reduce the risks of crop failures through application of harvested water through supplemental irrigation at the critical stage of the crop (for more details *see* Chapter 11, this volume).

Sustaining development and protecting the environment – these are the two-pronged

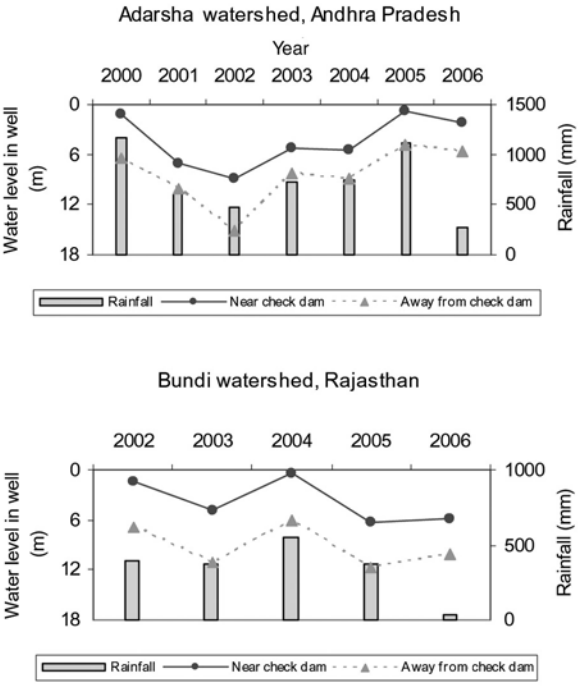


Fig. 1.11. The impact of watershed interventions on groundwater levels at two benchmark sites in India. (Note: estimated additional groundwater recharge due to watershed interventions is 675,000 m^3/year in Bundi watershed and 427,800 m^3/year in Adarsha watershed.)

achievements of the watersheds. The effectiveness of improved watershed technologies was evident in reducing run-off volume, peak run-off rate and soil loss and improving groundwater recharge. This is particularly significant in Tad Fa watershed, where interventions such as contour cultivation at mid-slopes, vegetative bunds planted with *Vetiver*, fruit trees grown on steep slopes and relay cropping with rice bean reduced seasonal run-off to less than half (194 mm) and soil loss to less than one-seventh (4.21 t/ha) as compared with the conventional system (473 mm run-off and soil loss 31.2 t/ha). This holds true with peak run-off rate, where the reduction is approximately one-third (Table 1.10).

A large number of fields (80–100%) in the SAT were found to be severely deficient in zinc, boron and sulfur as well as nitrogen and phosphorus. Amendment of soils with the deficient micro- and secondary nutrients increased crop yields by 30–70%, resulting in overall increase in water and nutrient use efficiency. Introduction of integrated pest management (IPM) and improved cropping systems decreased the use of pesticides worth US$44 to 66 per ha. Crop rotation using legumes in Wang Chai watershed (Thailand) substantially reduced the nitrogen requirement for rainfed sugarcane. 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.

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 carbon sequestration of 7.4 t/ha in 24 years was observed with improved management options in a long-term

Table 1.10. Seasonal rainfall, run-off and soil loss from different benchmark watersheds in India and Thailand.

Watershed	Seasonal rainfall (mm)	Run-off (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

watershed experiment at ICRISAT. By adopting fuel-switch for carbon, women SHGs in Powerguda (a remote village of Andhra Pradesh, India) have pioneered the sale of carbon units (147 t CO_2 C) to the World Bank from their 4500 *Pongamia* trees, seeds of which are collected for producing saplings for distribution/promotion of biodiesel plantation. 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 NO_3-N in run-off water (8 versus 14 kg nitrogen per ha). Introduction of IPM in cotton and pigeonpea substantially reduced the number of chemical insecticidal sprays during the season and thus reduced the pollution of water bodies with harmful chemicals. Reduced run-off and erosion reduced risk of downstream flooding and siltation of water bodies, which directly improved environmental quality in the watersheds (Pathak *et al.*, 2005; Sahrawat *et al.*, 2005; Wani *et al.*, 2005).

Conserving biodiversity – in the watersheds, this 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. Similarly, rehabilitation of the common property resource land in Bundi watershed through the collective action of the community ensured the availability of fodder for all the households and income of US$1670 per year for the SHG through sale of grass to the surrounding villages. Above-ground diversity of plants (54 plant species belonging to 35 families) as well as below-ground diversity of microorganisms (21 bacterial isolates, 31 fungal species and 1.6 times higher biomass C) was evident in rehabilitated CPR as compared with the degraded CPR land (9 plant species, 18 bacterial isolates and 20 fungal isolates, of which 75% belong to the *Aspergillus* genus) (Wani *et al.*, 2005).

Promoting NRM at the landscape level – this enabled the study of impact factors of NRM, such as sustainability of production, soil and water quality, and other environment resources have been looked at from a landscape perspective. This accounts for some successes in addressing concerns on equity issues such as benefits for the poorest people, for example the landless, who are unable to take advantage of improved soil/water conditions, and expansion of water-intensive crops triggering renewed water stress. These remain as legitimate challenges to a holistic thinking, which can be better unravelled from a landscape scale. To date, the articulation of this recognition is to be seen in policy recommendations for serious attention to capacity building and not just for planning activities.

Equal importance was given to on-site and off-site impacts. The effects of water conservation at the upper ridge to downstream communities were factored in. Water-harvesting structures, specifically the rehabilitation of the *nala* (drain) bund at the upper portion in Bundi watershed (Rajasthan), allowed irrigation of 6.6 ha at the downstream part. Another case is the Aniyala watershed, located at the lower toposequence of Rajasamadhiyala watershed in Gujarat, India. Excess water flows of the 21 WHS in Rajasamadhiyala cascades into Aniyala. This increased groundwater recharge by 25% and improved the groundwater source by 50% in a normal rainfall year. Because of this, there was an increase in crop production by 25–30% (Sreedevi *et al.*, 2006). The quality and number of livestock in the village improved because of water and fodder availability. Off-site effects of watershed-specific equity issues is one area that needs to be strengthened for enhanced impact.

Scaling-up

Factors such as low soil fertility, inappropriate soil and water management practices causing land degradation, lack of improved varieties, pest and disease attack, resource-poor farmers, declining land:man ratio and poor rural communities, who are unable to meet even minimum standards of health and nutrition, add to the burgeoning problem of rural poverty (Wani *et al.*, 2001). The adoption of the new paradigm in rainfed agriculture has shown that with proper management of natural resources the system's productivity can be enhanced and poverty can be reduced without causing further degradation of the natural resource base. The scaling-up of these innovations has been attempted in Andhra Pradesh, India, through the Andhra Pradesh Rural Livelihoods Programme (APRLP).

The approach of the APRLP puts the people living in the watershed at the centre of development and involves not only conservation of soil and water but also the efficient and sustainable use of natural resources to improve the livelihoods of everyone living in the watershed, with a special emphasis on the marginalized groups of people, such as those with little or no land, women and the poorest of the community (APRLP, 2006, 2007). The project has adopted a participatory 'Sustainable Rural Livelihoods' strategy (SRL), which is based on an analysis of the capital assets (physical, social, human, natural and financial) from which the rural poor derive their livelihoods. The approach also takes into consideration the vulnerability and risks that people face, local policies and constraints and the institutional environment. Since sustainable livelihoods approaches are based on empowerment, gender and equity have been mainstreamed in all the activities of the project. It is important to note that the APRLP is not a stand-alone project; it works within the watershed programme to bring about change which will ensure that the poorest people benefit from watershed programme interventions as well as gain access to new livelihood opportunities. The APRLP promoted activities which are off-farm and non-farm as well as those which are land based, building on what people already do and enhancing the skills they have. In order to achieve sustained development, the APRLP followed a participatory approach that ensured demand-driven planning and implementation and promoted convergence with other rural development programmes, government schemes and other government line departments in the state as well as other institutions and programmes run by NGOs.

Apart from the APRLP there are also other efforts to scale up these innovations, particularly the consortium model of integrated watershed management with backstopping and technical support from ICRISAT. The major efforts are the Sujala watershed programme in Karnataka, India, supported by the World Bank; watershed programmes in three districts of Madhya Pradesh and Rajasthan, with support from the Sir Dorabji Tata Trust, Mumbai, India; and in four countries in Asia (India, Thailand, Vietnam and China), with the support of the Asian Development Bank (ADB), the Philippines (for more details on upscaling strategies for IWM, see Chapter 12, this volume).

Conclusions

Rural development through sustainable management of land and water resources gives a plausible solution for alleviating rural poverty and improving the livelihoods of the rural poor. In an effective convergence mode for improving the rural livelihoods in the target districts, with watersheds as the operational units, a holistic integrated systems approach by drawing attention to the past experiences, existing opportunities and skills, and supported partnerships can enable change and improve the livelihoods of the rural poor. The well-being of the rural poor depends on fostering their fair and equitable access to productive resources. The rationale behind convergence through watersheds has been that these watersheds help in 'cross-learning' and drawing on a wide range of experiences from different sectors. A significant conclusion is that there should be a balance between attending to needs and priorities of rural livelihoods and enhancing positive directions of change by building effective and sustainable partnerships. Based on the experience and performance of the existing integrated community watersheds in different socio-economic environments, appropriate exit strategies, which include proper sequencing of interventions, building up of financial, technical and organizational capacity of local communities to internalize and sustain interventions, and the requirement for any minimal external technical and organizational support need to be identified.

Note

[1] Conservation agriculture, often defined as conservation tillage or conservation farming, includes tillage systems with no inversion of soil, i.e. without conventional ploughing, and ranges from no-tillage to minimum tillage and tillage systems aimed at opening the soil for rainfall capture without inversion. These systems include crop rotations and a mulch cover, which according to the convention should allow at least an average 30% cover of the soil throughout the year. For many farming systems in arid, semi-arid and dry subhumid tropical regions a permanent mulch cover is difficult to sustain. Despite this difficulty, conservation agriculture systems, often adopted as a strategy for *in-situ* water harvesting, show much promise, even though difficulties with weed management are a more prominent challenge than when securing a mulch cover. The Comprehensive Assessment has chosen to adopt a wide definition of conservation agriculture focused on non-inversion tillage for improvement of soil and water management (including sub-soiling, ripping, pitting and no-till systems).

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