Unlocking the potential of rainfed agriculture

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8 Managing water in rainfed agriculture

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Overview

Facing the food and poverty crises in developing countries will require a new emphasis on small-scale water management in rainfed agriculture involving the redirection of water policy and large new investments. Rainfed systems dominate world food production, but water investments in rainfed agriculture have been neglected over the past 50 years. Upgrading rainfed agriculture promises large social, economic, and environmental paybacks, particularly in poverty reduction and economic development. Rainfed farming covers most of the world's cropland (80%) and produces most of the world's cereal grains (more than 60%), generating livelihoods in rural areas and producing food for cities. Estimates suggest that about 25% of the increased water requirement needed to attain the 2015 hunger reduction target of the Millennium Development Goal can be contributed from irrigation. The remaining 75% will have to come from water investments in rainfed agriculture.

There is a close correlation between hunger, poverty, and water: most hungry and poor people live in regions where water challenges pose a particular constraint to food production. The world's hotspots for hunger and poverty are concentrated in the arid, semiarid, and dry subhumid regions of the world. There, water is a key challenge for food production due to the extreme variability of rainfall, long dry seasons, and recurrent droughts, floods, and dry spells. These regions cover some 40% of the world's land area and host roughly 40% of the world's population. The water challenge in these rainfed areas is to enhance yields by improving water availability and the water uptake capacity of crops.

Investments in rainfed agriculture have large payoffs in yield improvements and poverty alleviation through income generation and environmental sustainability. This is an important conclusion of the Comprehensive Assessment of Water Management in Agriculture, given that rainfed agriculture, particularly in the world's most water-challenged regions, is a risky business, with current yields generally less than half of those in irrigated systems and in temperate regions where water risks are much lower.

> Small investments for supplemental irrigation in combination with improved soil, nutrient, and crop management can more than double water productivity and yields in small-scale rainfed agriculture

The key challenge is to reduce water-related risks posed by high rainfall variability rather than coping with an absolute lack of water. There is generally enough rainfall to double and often even quadruple yields in rainfed farming systems, even in water-constrained regions. But it is available at the wrong time, causing dry spells, and much of it is lost. Apart from water, upgrading rainfed agriculture requires investments in soil, crop, and farm management. However, to achieve these, rainfall-related risks need to be reduced, which means that investments in water management are the entry point to unlock the potential in rainfed agriculture.

A new era of water investments and policy is required for upgrading rainfed agriculture. The focus of the past 50 years on managing rainfall in farmers' fields, through soil and water conservation, cannot alone reduce the risk of frequent dry spells. Needed are investments in water resources management in smallholder rainfed farming systems that add new freshwater through local management of rainfall and runoff. Upgrading rainfed agriculture thus involves investments in the continuum between rainfed and irrigated agriculture.

The Comprehensive Assessment shows that the potential for improving water productivity is particularly high in smallholder rainfed agriculture, with water savings of 15%–20% already possible over the coming decade. Such large water savings are possible because water productivity is very low in rainfed agriculture in poverty-stricken rural areas. Small investments (providing 1,000 cubic meters of extra water per hectare per season) for supplemental irrigation in combination with improved soil, nutrient, and crop management can more than double water productivity and yields in small-scale rainfed agriculture.

Investments in rainfed agriculture can improve environmental sustainability. Expansion of land under agriculture, particularly rainfed crops and grazing, is a key driver of the severe degradation of ecosystem services over the past 50 years. Poor management of rainwater in rainfed systems generates excessive runoff, causing soil erosion and poor yields due to a shortage of soil moisture. Investments to maximize rainfall infiltration and the water-holding capacity of soils minimize land degradation while increasing the water available in the soil for crop growth. This will result in improvements in the quality of natural ecosystems and of water in aquatic ecosystems.

There is an urgent need for widening the policy scope to include explicit strategies for water management in rainfed agriculture, including grazing and forest systems. Policy on water resources management for agriculture remains focused on irrigation, while the framework for integrated water resources management at watershed and basin scales concentrates primarily on allocation and management of blue water in rivers, groundwater, and lakes. What is needed is effective integration that focuses on investment options for water management across the continuum from rainfed to irrigated agriculture. Now is the time to abandon the sectoral divide between irrigated and rainfed agriculture and to place water

IWMI Part 4 Ch8-16 final.indd 316 2/28/07 11:06:31 AM

resources management and planning more centrally in the policy domain of agriculture at large. The current focus on water resources planning at the river basin scale does not put enough emphasis on water management in rainfed agriculture, which overwhelmingly occurs below the river basin scale, on farms of less than 5 hectares (ha), at the scale of small catchments. Therefore, an equally strong focus is needed on managing water at the watershed level and at the basin scale. This shift in focus opens up space for much needed investments in water resources management in rainfed agriculture.

Even where the potential gains from water investments in rainfed agriculture are greatest, improving water management alone is not enough to achieve significant and sustainable increases in yield. At the farming systems level full response to water investments is achievable only if other production factors, such as soil fertility, crop varieties, and tillage practices, are improved simultaneously. Important yield improvements can be achieved through synergies, particularly when water management is linked to organic fertilization from agroforestry and livestock systems, for example. Attention to land tenure, water ownership, and market access is also needed to ensure the full benefits from water management interventions.

Rainfed agriculture will continue to produce the bulk of the world's food. And because water productivity is very low in rainfed agriculture, there are significant opportunities for producing more food with less freshwater

The knowledge already exists to at least double yields in rainfed agriculture, even where water poses a particular challenge: the key is adaptation and adoption strategies. Needed for success are human capacity building and stronger institutions. Due to the general perception that water takes care of itself in rainfed systems, the emphasis has been on on-farm management of soil, plants, trees, and animals. Thus, farmers in many regions of the world still practice rainfed farming with no explicit water management strategies. Investments are needed in institutional and human capacities to plan and manage water for rainfed agriculture at the catchment scale, where local runoff water resources can be diverted, stored, and managed. The Comprehensive Assessment has found that while many countries have written off rainfed agriculture in arid, semiarid, and dry subhumid areas as marginal with limited potential, and invested little in institutional and human capacities to support water investments by farmers, other countries have invested in tapping the potential that lies in the availability of an adequate but erratic water resource provided by the rain.

Major water investments required in rainfed agriculture

When it comes to ensuring food security for all, two major water realities face humankind. Rainfed agriculture will continue to produce the bulk of the world's food. And water productivity is very low in rainfed agriculture, thus providing significant opportunities for producing more food with less freshwater. Rainfed agriculture is practiced in 80% of the world's physical agricultural area and generates 62% of the world's staple food (FAOSTAT 2005).

Addressing malnourishment and poverty requires a new green revolution (Conway 1997) in small-scale rainfed agriculture in arid, semiarid, and dry subhumid regions of the world (Falkenmark and Rockström 2004). A key to success is to invest in the often untapped potential of upgrading rainfed agriculture through integrated water investments. The Comprehensive Assessment indicates that water investments in rainfed agriculture are required to attain the Millennium Development Goals, as most hungry people live in

IWMI Part 4 Ch8-16 final.indd 317 2/28/07 11:06:32 AM

regions subject to frequent water stress and extreme water shocks, such as droughts, floods, and dry spells (short periods of water stress during critical growth stages).

Water management to upgrade rainfed agriculture encompasses a wide spectrum, from water conservation practices for improving rainwater management on the farmer's field to managing runoff water (surface and subsurface) for supplying supplemental irrigation water to rainfed food production. There is no clear demarcation between rainfed and irrigated systems (see conceptual framework annex). This chapter addresses water management in all agricultural systems where direct rainwater is the main water source for crop production. It describes the major trends, drivers, and current conditions for key water management challenges facing rainfed agriculture from the perspectives of water productivity, wealth creation and poverty eradication, and environmental sustainability. While applying a global outlook, the chapter focuses on temperate and tropical arid, semiarid, and dry subhumid regions in developing countries, regions where rainfed farming systems and agriculture-based livelihoods are common, where water stress–related constraints in agriculture are concentrated, and where rural poverty and malnourishment are greatest. Since the most unreliable and often scarce resource in agricultural production in these areas is soil moisture for plant growth ("green water"), the challenge is to enhance the availability and productivity of water used for biomass production.

> Most food for poor communities in developing countries is produced in rainfed agriculture

The chapter first details the gaps in the management of water under rainfed systems. It then evaluates opportunities for investment in managing water in rainfed systems together with evidence on the potential returns on these investments with respect to livelihoods and environmental sustainability. The final section assesses the policy shifts needed to support the necessary investments.

Most food is produced in rainfed agriculture

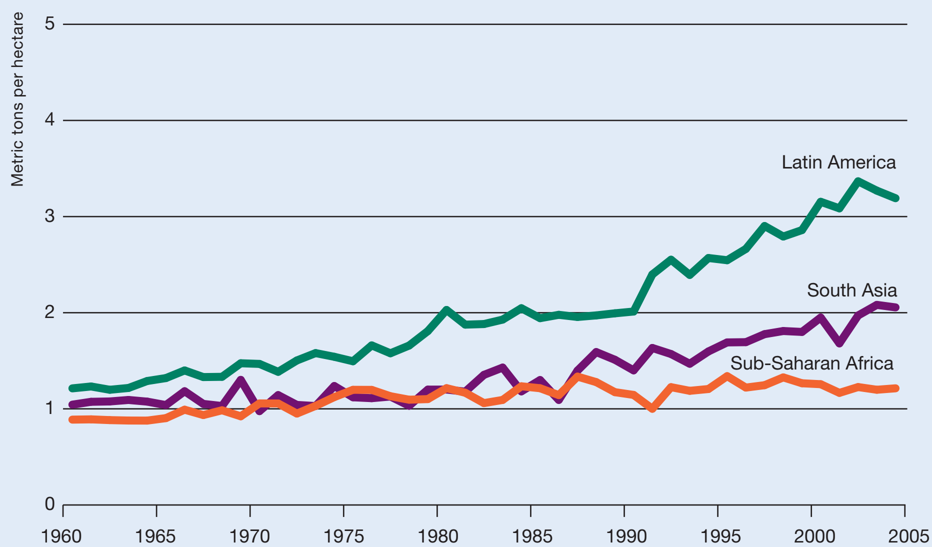
The importance of rainfed agriculture varies regionally, but most food for poor communities in developing countries is produced in rainfed agriculture. Some 93% of farmed land is rainfed in Sub-Saharan Africa, 87% in Latin America, 67% in the Near East and North Africa, 65% in East Asia, and 58% in South Asia (FAO 2002). Most countries depend primarily on rainfed agriculture for their grain food.

Yield increase is the key to future food production from rainfed agriculture. In the past 40 years agricultural land use has expanded 20%–25%, contributing approximately 30% of the overall growth in grain production during the period (FAO 2002; Ramankutty, Foley, and Olejniczak 2002). The remaining yield gains originated from intensification through yield increases per unit of land area. However, regional variation is large, as are the differences between irrigated and rainfed agriculture. In developing countries rainfed grain yields are on average 1.5 metric tons per hectare, compared with 3.1 metric tons per hectare for irrigated yields (Rosegrant and others 2002), and increases in production from rainfed agriculture have originated mainly from land expansion.

Trends differ by region. Sub-Saharan Africa, with 97% rainfed production of staple cereals such as maize, millet, and sorghum, has doubled cultivated cereal area since 1960, while yield per unit of land has barely changed (figures 8.1 and 8.2; FAOSTAT 2005).

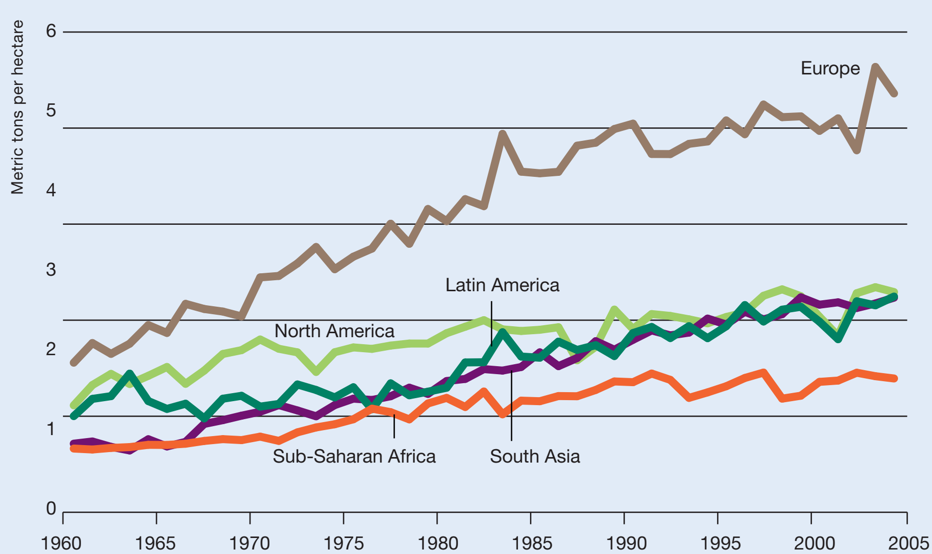
IWMI Part 4 Ch8-16 final.indd 318 2/28/07 11:06:32 AM

figure **8.1** | **Yields vary widely by region for predominantly rainfed maize...**



Source: FAOSTAT 2005.

figure **8.2** | **...and for wheat**



Source: FAOSTAT 2005.

IWMI Part 4 Ch8-16 final.indd 319 2/28/07 11:06:33 AM

South Asia has experienced a major shift from more drought-tolerant low-yielding crops such as sorghum and millet, to wheat and maize, for which area planted and yield per unit of land have doubled since 1961 (FAOSTAT 2005). In Latin America and the Caribbean area expansion of 25% in the last 40 years has been less than the gain in yield per unit of land (FAOSTAT 2005). In many predominantly rainfed regions of the world grain yields have doubled or tripled during the same period (see figures 8.1 and 8.2).

Rainfed maize yields differ substantially across regions from just over 1 metric ton per hectare in Sub-Saharan Africa to 3 metric tons per hectare in Latin America and the Caribbean (see figure 8.1). By comparison, in the United States and Europe, yields are 7–10 metric tons per hectare. Similar variation is found for wheat (see figure 8.2). In view of these regional differences in yield development there appears to be significant potential for boosting yields in rainfed agriculture, particularly in South Asia and Sub-Saharan Africa.

A majority of poor people in the world are dependent on rainfed agriculture for food, incomes, and thus livelihood security

Rainfed agriculture—large untapped potential. In several regions of the world rainfed agriculture has some of the highest yields. These are predominantly temperate regions, with relatively reliable rainfall and inherently productive soils. But even in tropical regions, particularly in subhumid and humid zones, agricultural yields in commercial rainfed agriculture exceed 5–6 metric tons per hectare (Rockström and Falkenmark 2000; Wani and others 2003a, b). At the same time the dry subhumid and semiarid regions have experienced the lowest yields and weakest yield improvements per unit of land. Yields for rainfed agriculture are in the range of 0.5–2 metric tons per hectare, with an average of 1 metric ton per hectare in Sub-Saharan Africa, and 1–1.5 metric tons per hectare in South Asia and Central and West Asia and North Africa (Rockström and Falkenmark 2000; Wani and others 2003a, b).

Analyses by the Comprehensive Assessment of major rainfed crops in semiarid regions in Africa and Asia and rainfed wheat in North Africa and West Asia reveal large yield gaps, with farmers' yields being 2–4 times lower than achievable yields for major rainfed crops (figure 8.3). Historic trends show a growing yield gap between farmers' practices and farming systems that benefit from management advances (Wani and others 2003a).

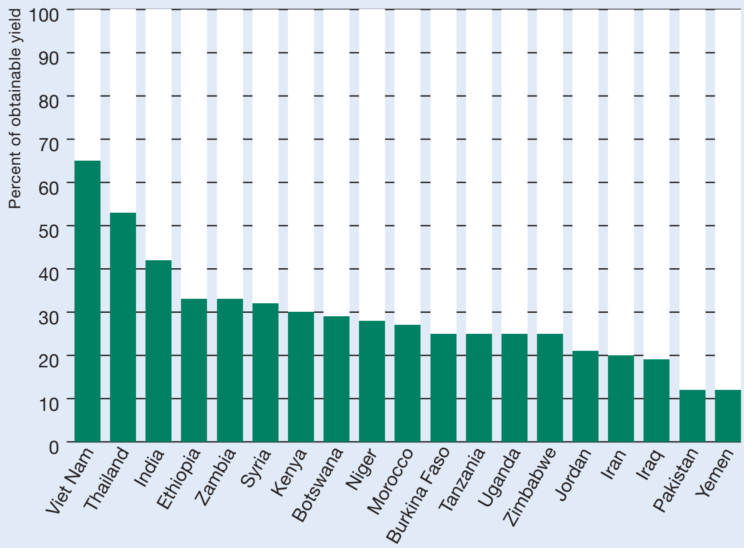
Upgrading rainfed agriculture—a key to poverty reduction?

Rainfed agriculture generates most of the food in the world *[well established]* and plays a key role in poverty reduction *[established but incomplete]*. A majority of poor people in the world are dependent on rainfed agriculture for food, incomes, and thus livelihood security *[established but incomplete]*. The importance of rainfed sources of food weighs disproportionately on women, who make up some 70% of the world's poor (WHO 2000). Agriculture plays a key role in economic development (World Bank 2005) and poverty reduction (Irz and Roe 2000), with every 1% increase in agricultural yields translating into a 0.6–1.2 percentage point decrease in the absolute poor by some estimates (Thirtle and others 2002). In Sub-Saharan Africa agriculture accounts for 35% of GDP and employs 70% of the population (World Bank 2000), and more than 95% of the agricultural area is rainfed (box 8.1; FAOSTAT 2005).

There is a correlation between poverty, hunger, and water stress (Falkenmark 1986). The UN Millennium Project (2005) has identified "hotspot" countries suffering from the

IWMI Part 4 Ch8-16 final.indd 320 2/28/07 11:06:34 AM

figure **8.3** **Observed gaps for major grains are large between farmers' yields and achievable yields for selected African, Asian, and Middle Eastern countries**



Source: Analysis done for the Comprehensive Assessment of Water Management in Agriculture.

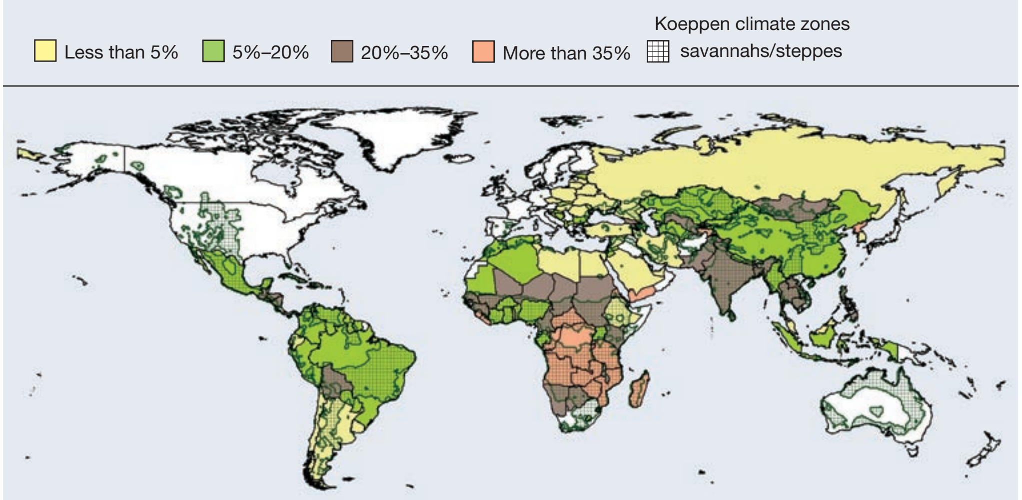
highest prevalence of malnutrition. These countries coincide closely with those that contain the major semiarid and dry subhumid hydroclimates in the world (savannahs and steppe ecosystems), where rainfed agriculture is the dominant source of food and where water constitutes a key limiting factor to crop growth (map 8.1; SEI 2005). Nearly all of the world's 850 million undernourished people live in poor developing countries, which are located predominantly in tropical regions (FAO 2004b).

box **8.1** **Agricultural growth is an underlying factor for economic growth**

Agriculture, the sector in which a large majority of poor people in Africa make their living, is the engine of overall economic growth and, therefore, of broad-based poverty reduction (Johnston and Mellor 1961; World Bank 1982; Timmer 1988; Abdulai and Hazell 1995; IFAD 2001; DFID 2002; Koning 2002). Recent international reports have reaffirmed this conclusion, which is based on analysis of the historical development paths of countries worldwide (IAC 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 labor. Thus, agricultural growth typically preceded economic growth in the high-income industrial countries and the more recent growth in the Asian Tigers such as Indonesia, Malaysia, Thailand, Viet Nam, and parts of China.

Source: van Koppen, Namara, and Stafilios-Rothschild 2005.

map 8.1 **Undernutrition is high in semiarid and dry subhumid climates subject to variable rainfall, dry spells, and droughts**
(Undernourished as share of total population, 2001/02)



Note: Semiarid and dry subhumid hydroclimates include 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.
Source: UNStat 2005.

Lack of focus on water management has led to missed opportunities

Increasingly, evidence shows that the amount of water is not the key limiting factor for improved yields, even in so-called drylands (Klaij and Vachaud 1992; Agarwal 2000; Wani and others 2003b; Hatibu and others 2003) *[established but incomplete]*. Savannah regions have rainfall levels that sometimes exceed rainfall in the temperate zone—500–1,000 millimeters (mm) per growing season compared with 500–700 mm per growing season for temperate regions. Instead, the major water-related challenge for rainfed agriculture in semiarid and dry subhumid regions is the extreme variability in rainfall, characterized by few rainfall events, high-intensity storms, and high frequency of dry spells and droughts. It is therefore critical to understand how hydroclimatic conditions and water management affect yields in rainfed agriculture.

Water availability has shaped rainfed agriculture. Farming systems have adapted to hydroclimatic gradients, from pastoral systems in arid environments to multiple-cropping systems in humid agroecosystems (table 8.1). Though based on the same fundamental principles across the world, farming systems also exhibit variations based in history and culture that result in differences in crops, tillage systems, and soil and water management systems.

Even if rainfed agriculture can be categorized generically, it is critical to distinguish among hydroclimatic zones, which vary widely from a few hundred millimeters of rainfall per year to more than 1,000 mm, with aridity index values ranging from below 0.2 to

IWMI Part 4 Ch8-16 final.indd 322 2/28/07 11:06:39 AM

table 8.1 Classification of hydroclimatic zones by aridity index, typical agricultural land use, and ecosystem gradients

	Arid		Semiarid	
	Temperate	**Tropical**	**Temperate**	**Tropical**
Area (%)	0.5	4.0	2.6	13.0
Population (%)	2.5	9.5	5.6	11.7
Major production constraints	■ Precipitation amount ■ Precipitation distribution ■ Soil chemistry	■ Precipitation amount ■ Precipitation distribution ■ Potential greater than actual evapotranspiration ■ Soil chemistry	■ Precipitation amount ■ Precipitation distribution ■ Temperature	■ Precipitation amount ■ Precipitation distribution ■ Precipitation intensity ■ Potential greater than actual evapotranspiration ■ Soil physiology and chemistry
Hotspots	■ West Asia ■ North Africa	■ Sub-Saharan Africa ■ Northeast Brazil ■ Mexico	■ Central and West Asia ■ North Africa ■ Southern Europe ■ Mongolia ■ Northern China	■ Sub-Saharan Africa ■ South Asia ■ Northeast Brazil ■ Southern China
Ecosystem gradient	■ Desert ■ Desert shrubland	■ Desert	■ Steppe ■ Grassland	■ Grassland ■ Savannah ■ Parkland savannah
Typical rainfed farming systems	■ Pastoral ■ Rainfed winter crop	n.a.	■ Pastoral ■ Rainfed winter crop ■ Rainfed mixed	■ Pastoral ■ Rainfed cereal, mixed, rice-wheat

	Subhumid		Humid	
	Temperate	**Tropical**	**Temperate**	**Tropical**
Area (%)	7.3	9.0	19.3	41.9
Population (%)	5.7	7.1	9.2	26.8
Major production constraints	■ Precipitation distribution ■ Temperature	■ Precipitation distribution ■ Precipitation intensity ■ Soil physiology and chemistry	■ Temperature	■ Precipitation intensity
Hotspots	■ Central Asia	■ Sub-Saharan Africa ■ South Asia ■ Southeast Asia ■ Latin America		■ Southeast Asia
Ecosystem gradient	■ Steppe ■ Shrubland ■ Forest	■ Parkland savannah ■ Woodland savannah	■ Forest	■ Forest ■ Rain forest
Typical rainfed farming systems	■ Rainfed winter crop ■ Rainfed mixed	■ Rainfed cereal ■ Rainfed mixed ■ Rice-wheat	n.a.	■ Rainfed rice-wheat

n.a. is not available

Note: Climate is defined according to the aridity index: precipitation/potential evapotranspiration less than 0.2 arid (including hyperarid); 0.2 to less than 0.5 semiarid; 0.5 to less than 1 subhumid; more than 1 humid (Deichmann and Eklundh 1991). Temperature classification follows FAO/IIASA (2000) climatic zones, with temperate meaning at least one month with monthly mean temperatures, corrected to sea level, below 5° Celsius (C) and four or more months above 10°C, and tropical and subtropical as all months with monthly mean temperatures, corrected to sea level, above 18°C, and one or more months with monthly mean temperatures, corrected to sea level, below 18°C but above 5°C.

Source: Compiled for the Comprehensive Assessment of Water Management in Agriculture using population data from LandScan (2004) and aggregated farming systems classification as defined by Dixon, Gulliver, and Gibbon (2001).

IWMI Part 4 Ch8-16 final.indd 323 2/28/07 11:06:40 AM

more than unity. Key constraints to rainwater productivity (total amount of rainfall per grain yield) will differ greatly across this wide range of rainfall zones. In the arid regions it is the absolute amount of water that constitutes the major limiting factor in agriculture. In the semiarid and dry subhumid tropical regions seasonal rainfall is generally adequate to significantly improve yields, and managing extreme rainfall variability over time and space is the largest water challenge. Only in the dry semiarid and arid zones, even when considering the standard deviation around the mean, is absolute water stress common (figure 8.4). In the wetter part of the semiarid zone and into the dry subhumid zone, rainfall generally exceeds crop water needs.

> "Agricultural" droughts are due primarily to management-related problems with the on-farm water balance and are an indicator of large opportunities to improve yields through better water management

Thus, the large observed differences between farmers' yields and attainable yields cannot be explained by differences in rainfall. Rather, they are a result of differences in water, soil, and crop management. In a global analysis of more than 100 agricultural development projects, Pretty and Hine (2001) found that in projects that focused on improving rainfed agriculture, yields doubled on average and often increased several hundred percent. This illustrates the large potential for investments in upgrading rainfed agriculture.

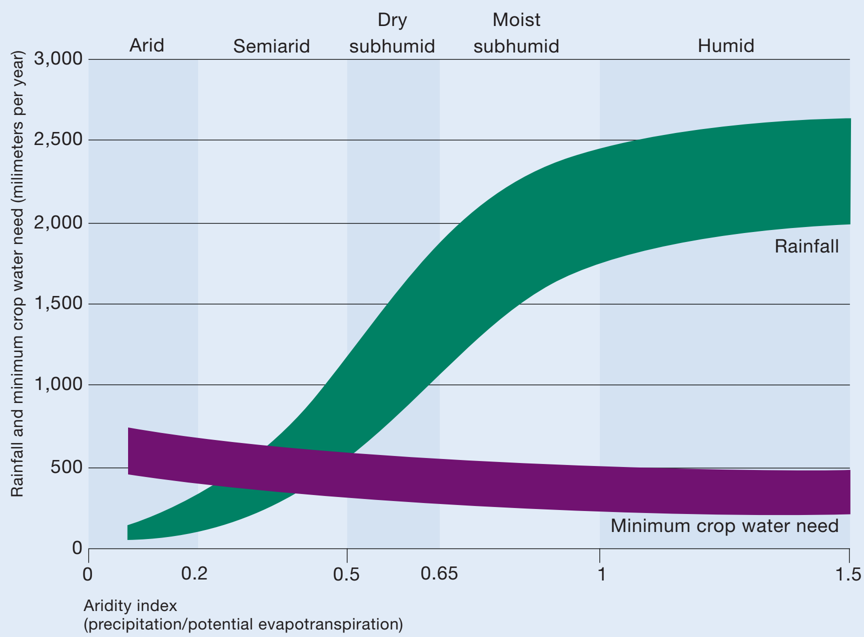
Meteorological and agricultural droughts: water stress in agriculture is often human induced. Though the absolute amount of water scarcity is rarely the major problem for rainfed agriculture, water scarcity is a key reason behind low agricultural productivity. To identify management options for upgrading rainfed agriculture, it is essential to assess different types of water stress in food production. Especially important is distinguishing between climate- and human-induced water stress and between droughts and dry spells (table 8.2). In semiarid and dry subhumid agroecosystems rainfall variability generates dry spells (short periods of water stress during critical growth stages) almost every rainy season (Barron and others 2003). Meteorological droughts (periods of inadequate rainfall to grow a crop), by contrast, occur on average only once every decade in moist semiarid regions and up to twice every decade in dry semiarid regions. Investments in water management can bridge dry spells, which generally last two to four weeks (Barron and others 2003). Meteorological droughts cannot be bridged through agricultural water management and instead require social coping strategies, such as cereal banks, relief food, local food storage, and livestock sales.

Even in regions with low variability in rainfall, not all of the rain reaches farmers' fields as soil moisture. In general, only 70%–80% of the rainfall is available to plants as soil moisture, and on poorly managed land the share 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 due primarily to management-related problems with the on-farm water balance and are thus an indicator of large opportunities to improve yields through better water management.

Agarwal (2000) argues that India would not have to suffer from droughts if local water balances were better managed. Even during drought years better rainfall management has benefited Indian farmers; villages benefiting from watershed management projects increased food production and market value by 63% compared with those without such projects (Wani and others 2006b). In Malawi over the past three decades only a few of the years that

IWMI Part 4 Ch8-16 final.indd 324 2/28/07 11:06:40 AM

figure **8.4** **Range of rainfall variability across hydroclimatic zones from arid to humid agroecosystems**



Note: The ecosystem gradient is shown as the aridity index (ratio of annual precipitation to annual potential evapotranspiration). The range in total rainfall is expressed as plus or minus one standard deviation.
Source: Minimum crop water need is estimated from Doorenbos and Pruitt (1992) and adjusted for aridity index.

table **8.2** **Types of water stress and underlying causes in semiarid and dry subhumid tropical environments**

	Dry spell	Drought
Meteorological		
Frequency	Two out of three years	One out of ten years
Impact	Yield reduction	Complete crop failure
Cause	Rainfall deficit of two- to five-week periods during crop growth	Seasonal rainfall below minimum seasonal plant water requirement
Agricultural		
Frequency	More than two out of three years	One out of ten years
Impact	Yield reduction or complete crop failure	Complete crop failure
Cause	Low plant water availability and poor plant water uptake capacity	Poor rainfall partitioning, leading to seasonal soil moisture deficit for producing harvest (where poor partitioning refers to a high proportion of runoff and nonproductive evaporation relative to soil water infiltration at the surface)

Source: Falkenmark and Rockström 2004.

IWMI Part 4 Ch8-16 final.indd 325 2/28/07 11:06:41 AM

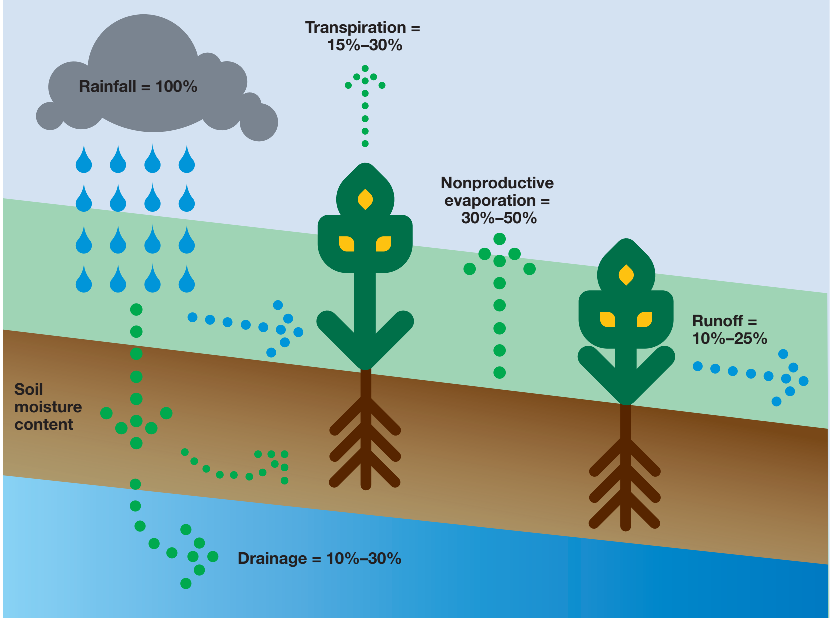
were politically proclaimed to be drought years actually suffered meteorological droughts (Mwale 2003). Glantz (1994) has pointed out that agricultural droughts, caused primarily by a poorly performing water balance, are more common than meteorological droughts.

Why is drought so commonly blamed when there are famines and food shortages? The answer is that even if there is no shortage of rain, crops may suffer from drought in the root zone. Often, land degradation and poor management of soil fertility and crops are the major causes of "droughts." These are referred to as agricultural droughts when available water as rainfall is not fully used for plant growth.

> Evidence from water balance analyses on farmers' fields around the world shows that generally less than 30% of rainfall is used as plant transpiration supporting plant growth

Evidence from water balance analyses on farmers' fields around the world shows that only a small fraction of rainfall (generally less than 30%) is used as productive green water flow (plant transpiration) supporting plant growth (Rockström 2003). In Sub-Saharan Africa this varies from 15% to 30% of rainfall, even in regions generally perceived as water scarce (figure 8.5). On severely degraded land or land where yields are lower than 1 metric ton per hectare, as little as 5% of rainfall may be used productively to produce food. In arid areas typically as little as 10% of rainfall is consumed as productive green water flow, with most of the remainder going to nonproductive evaporation flow (Oweis and Hachum 2001). For temperate arid regions, such as North Africa and West Asia, a larger portion of the rainfall is generally consumed in the farmers' fields as productive transpiration (45%–55%) as a result of higher yield levels (3–4 metric tons per hectare compared with 1–2 metric tons per hectare). Still, 25%–35% of the rainfall flows as nonproductive evaporation, with only some 15%–20% generating blue water flow (runoff).

figure **8.5** | **Rainfall partitioning in the semiarid tropics indicating rainfall losses from the farm scale through drainage, surface runoff, and nonproductive evaporation**



IWMI Part 4 Ch8-16 final.indd 326 2/28/07 11:06:42 AM

Many factors limit yields in rainfed agriculture. Often, soil fertility is the limiting factor (Stoorvogel and Smaling 1990). Soil degradation, through nutrient depletion and loss of organic matter, causes serious yield decline closely related to water determinants. It affects water availability for crops through poor rainfall infiltration and plant water uptake due to weak roots. Nutrient mining is a serious problem in smallholder rainfed agriculture, particularly in Sub-Saharan Africa. An estimated 85% of African farmland experienced a loss of more than 30 kilograms per hectare of nutrients annually in 2002–04 (Henao and Baanante 2006).

Investments in soil fertility directly improve water management. In India watershed management trials in more than 300 villages found that subsistence farming practices had depleted soils not only of macronutrients but also of such micronutrients as zinc and boron and secondary nutrients such as sulphur beyond critical limits. When both micronutrients and adequate nitrogen and phosphorus were applied, crop yields increased substantially for a number of rainfed crops (maize, sorghum, mung bean, pigeonpea, chickpea, castor, and groundnut) (Rego and others 2005). Rainwater productivity for maize, groundnut, greengram, castor, and sorghum increased 70%–100% as a result of the micronutrient amendment, and net economic returns were 1.5–1.75 times higher (Rego and others 2005). Similarly, rainwater productivity increased significantly when integrated land and water management options were adopted along with the use of improved cultivars in semiarid regions of India (Wani and others 2003b).

The temporal and spatial variability of climate, especially rainfall, is a major constraint to yield improvements, competitiveness, and commercialization of rainfed crops, and evidence is emerging that climate change is increasing rainfall variability

What *can* be produced on farms *will* not always be produced, however, especially by resource-poor small-scale farmers. The farmers' reality is influenced by other constraints such as labor shortages, insecure land ownership, capital constraints, and limitations in human capacities. All these factors affect how farming is done, in terms of the timing of operations, the effectiveness of farm operations, investments in fertilizers and pesticides, use of improved crop varieties, and water management. What is produced in the field is thus strongly affected by social, economic, and institutional conditions.

Risks are high and will increase with climate change. Rainfall is concentrated in short rainy seasons (3–5 months), with a few intensive rainfall events that are unreliable in temporal distribution and with high deviations from the mean (coefficients of variation as high as 40% in semiarid regions; Wani and others 2004). Even if water is not always the key limiting yield factor, rainfall is the only truly random agricultural production factor.

The temporal and spatial variability of climate, especially rainfall, is a major constraint to yield improvements, competitiveness, and commercialization of rainfed crops, tree crops, and livestock systems in most of the tropics. The high risk for water-related yield loss makes farmers risk averse, influencing their other investment decisions, including labor, improved seed, and fertilizers *[established but incomplete]*. Smallholder farmers are usually aware of the effects of the shortage and variability of soil moisture on the variety, quantity, and quality of production, leading to a narrow range of options for commercialization. Combined with the fluctuations in yields, this makes it hard for resource-poor men and women in semiarid areas to respond effectively to opportunities made possible by

IWMI Part 4 Ch8-16 final.indd 327 2/28/07 11:06:43 AM

emerging markets, trade, and globalization. Management options should therefore start by focusing on reducing rainfall-induced risks.

Evidence is emerging that climate change is increasing rainfall variability and the frequency of extreme events such as drought, floods, and hurricanes (IPCC 2001). In a recent study of rainfed cereal potential under different climate change scenarios and varying rainfall, losses of rainfed production potential in the most vulnerable developing countries was predicted under most scenarios. Losses were estimated at 10%–20% of production area, with some 1–3 billion people possibly affected in 2080 (Fischer, Shah, and van Velthuizen 2002). In particular, Sub-Saharan Africa is estimated to lose 12% of its cultivation potential, mostly in the Sudan-Sahelian zone, which is already subject to high climate variability and adverse crop conditions. Because of the risk associated with climate variability, smallholder farmers generally (and rationally) prefer to reduce the risk of crop failure due to dry spells and drought before investing in soil fertility, improved crop varieties, and other yield-enhancing inputs (Hilhost and Muchena 2000).

Even with improvements in water productivity, investments in upgrading rainfed agriculture will require assessing tradeoffs with downstream users and ecosystems

Large new investments needed in water management in rainfed agriculture

The largest amount of new consumptive water use in crop production needed to attain the Millennium Development Goal for reducing hunger (more than 900 cubic kilometers a year; see chapter 3 on scenarios) will have to take place on current farmland through investments in upgrading rainfed agriculture or on land converted from natural ecosystems and grazing lands to agriculture. Land conversion would correspond to an expansion of rainfed agriculture of at least 70 million hectares, and possibly much more (see chapter 3).

Closing basins (when more water is being used than is environmentally desirable or renewably available) leave fewer degrees of freedom for blue water development and may redirect attention to green water flows upstream, before rainfall turns into blue runoff flow. Even with expansion of agricultural land, development of irrigated agriculture, and significant improvements in green water productivity, rainfed agriculture will have to shoulder the largest burden of providing food in developing countries, and large water investments are required for success. This calls for increased efforts to upgrade rainfed systems.

At the same time, even with improvements in water productivity, investments in upgrading rainfed agriculture, including technologies such as small-scale supplemental irrigation and conservation agriculture (as described later), will result in the capture of local blue water resources and an increased consumption of green water. Thus, tradeoffs with downstream users and ecosystems will have to be assessed.

The challenges of broadening the reach of investments and policies

Past investments in agricultural research in savannah agroecosystems have been disappointing (Seckler and Amarasinghe 2004). One reason is the lack of focus on water resources management in rainfed agriculture. Instead, the focus over the past 50 years at the farm level has been mainly on crop research, soil conservation, and to a lesser extent in-situ water conservation (maximizing rainfall infiltration) through various strategies of terracing, bunding, and ridging.

IWMI Part 4 Ch8-16 final.indd 328 2/28/07 11:06:43 AM

Failure of innovation to achieve widespread adoption. Upgrading rainfed agriculture requires that technologies be adapted to local biophysical and sociocultural conditions and that institutional and behavioral transformations accompany the technological changes (Harris, Cooper, and Pala 1991; van Duivenbooden and others 2000). As researchers have noted, it is difficult to assess the impact of natural resources management interventions using the econometric methods applied for assessing the impact of commodity-based interventions (Shiferaw, Freeman, and Swinton 2004).

Social and ecological crises often spur the adoption of new ways of thinking and of system transformation *[established]*. The adoption of conservation agriculture in several parts of the world was driven by crises—in the United States as a response to the Dust Bowl in the 1930s, in parts of Latin America as a response to an agrarian yield crisis, and in Zambia as a response to droughts. Recent widespread adoption of soil and water management practices in Burkina Faso and Niger forms part of a response to crisis-related land degradation and possible climate change *[established but incomplete].*

Water management for rainfed agriculture requires a landscape perspective and involves cross-scale interactions from farm households to watersheds

There are many challenges to investments in rainfed agriculture. Large numbers of households are small, with marginal farmers. Most rainfed areas have poor infrastructure facilities because large investments have historically tended to go to high-potential irrigated areas. Local institutions engaged in agricultural development and extension have limited capacity to promote rainwater management. This knowledge-intensive extension effort suffers from limited information of the options available, social and economic constraints to adoption, lack of enabling environments and backup services, poor market linkages, and weak infrastructure.

Focus on blue water has led to weak policies for water investments in rainfed agriculture. One result of the historic focus on blue water in agricultural policy is a legacy of weak water governance and policies for rainfed agricultural development. Water resources management is normally governed under ministries for water affairs and focuses on developing and allocating water for large-scale irrigation, drinking water, and hydropower. This has resulted in a downstream focus, with upper catchment areas, where rainfed agriculture is generally practiced, being seen primarily as runoff or blue water–generating zones. Ministries of agriculture have focused on the "dry" parts of agricultural development and tended to give priority to erosion control over water management in general (box 8.2). Thus, although proven knowledge for better management of rainwater exists, investments for turning this knowledge into innovations in governance, policy, institutions, practices, and technologies to support smallholder farmers have been very limited.

Recently, management of green water resources and other investments to upgrade rainfed agriculture have begun to receive increased priority from state and central governments (see box 8.2). Important efforts have been made under watershed development programs in India, for example. Originally, these programs were implemented by different ministries (Agriculture, Rural Development, Forestry) making integrated water management difficult. Recently, steps were taken to unify the program (Wani and others 2006b). In 2005 the National Commission on Farmers adopted an integrated watershed management approach, with a focus on harvesting rainwater and improving soil health for sustainable development of drought-prone rainfed areas (India 2005).

box 8.2 | **Water was often left out in soil and water conservation programs**

In Kenya, Tanzania, and Uganda national food security is achieved largely by smallholder farmers in rainfed agricultural-livestock systems. Population growth rates are high, and land for agricultural expansion is no longer abundant. Traditionally, national water management has been the responsibility of different ministries—agriculture, water, environment, tourism, and energy—with adverse impacts on local strategies to improve water management for cultivation and food production. A review by the Comprehensive Assessment of water and food policy-related documents in Kenya, Tanzania, and Uganda found that there was no clear policy on rainwater harvesting for agricultural production to improve food security among the rural poor.

Tanzania implemented a major soil and water conservation program in the semiarid central part of the country in 1973–95. An evaluation in 1995 noted several weaknesses of the program, including these (Hatibu and others 1999):

- The program was oriented toward the land rather than the people in the project area.
- The work on croplands focused on water runoff disposal and addressed rainwater productivity only in marginal ways.
- Key extension messages were quite conventional (improved seed, row planting), and soil-water conservation did not figure prominently among the messages.
- There should have been more emphasis on rainwater management than on erosion control considering that shortage of soil moisture was the bigger problem for crop yields in the dry land of central Tanzania.
- On-farm soil and water conservation measures promoted by the project have done very little to increase land productivity.
- The strategy needs to shift from a narrow focus on erosion control to a broader, holistic land husbandry approach.

The 2002 National Water Policy in Tanzania sets a goal of making more water available to rural communities through rainwater harvesting technologies (Tanzania Ministry of Agriculture and Food Security 2002). The Agricultural Sector Development Strategy recognizes integrated soil-water management as the solution to the drought problems of semiarid areas (Tanzania Ministry of Agriculture and Food Security 2001). This comprehensive program includes integrated soil and water conservation, rainwater harvesting and storage, irrigation, and drainage. As a result, rainwater harvesting forms an important part of the national irrigation master plan adopted in 2003 (Tanzania Ministry of Agriculture and Food Security 2003).

There is thus growing evidence of the importance of water investments in rainfed agriculture and of the gradual redirection of water governance and management toward upgrading rainfed agriculture as a key strategy for reducing poverty and increasing agricultural production. It is further becoming increasingly clear that water management for rainfed agriculture requires a landscape perspective and involves cross-scale interactions from farm households to watersheds.

Investing in rainfed agriculture to improve livelihoods and environmental sustainability

Although proven knowledge for better management of rainwater exists, investments in turning this knowledge into innovations in governance, policy, institutions, practices,

IWMI Part 4 Ch8-16 final.indd 330 2/28/07 11:06:44 AM

and technologies to support smallholder farmers have been limited. Opportunities within rainfed systems include increasing the productivity of green water depleted in rainfed systems and increasing yields in rainfed systems by capturing more soil moisture for plant water uptake. Taking advantage of both opportunities requires large investments in rainfed agriculture. While the focus here is on management options at the farm level to upgrade rainfed agriculture, the required policy, governance, and market strategies have to operate at a higher scale, from the watershed to national and regional levels.

Investing in water management in rainfed agriculture

There are several rainwater management strategies to improve crop yields and green water productivity (table 8.3; Critchley and Siegert 1991). One set of strategies aims at maximizing plant water availability in the root zone (maximizing the green water resource) through practices that reduce surface runoff (blue water flow) and that redirect upstream runoff to the farm (local storage of blue water for supplemental irrigation). A second set aims at maximizing plant water uptake capacity, which involves crop and soil management practices that increase root water uptake (and thus minimize drainage to the water table). There is a wide spectrum of integrated land and water management options to achieve these aims. Some focus on increasing water productivity, such as mulch practices, drip irrigation techniques, and crop management to enhance canopy cover, while most aim at improving crop production by capturing more water (water productivity increases

table **8.3** **Rainwater management strategies and corresponding management options to improve yields and water productivity**

Aim	Rainwater management strategy	Purpose	Management options
Increase plant water availability	External water harvesting systems	Mitigate dry spells, protect springs, recharge groundwater, enable off-season irrigation, permit multiple uses of water	Surface microdams, subsurface tanks, farm ponds, percolation dams and tanks, diversion and recharging structures
	In-situ water-harvesting systems, soil and water conservation	Concentrate rainfall through runoff to cropped area or other use	Bunds, ridges, broad-beds and furrows, microbasins, runoff strips
		Maximize rainfall infiltration	Terracing, contour cultivation, conservation agriculture, dead furrows, staggered trenches
	Evaporation management	Reduce nonproductive evaporation	Dry planting, mulching, conservation agriculture, intercropping, windbreaks, agroforestry, early plant vigor, vegetative bunds
Increase plant water uptake capacity	Integrated soil, crop and water management	Increase proportion of water balance flowing as productive transpiration	Conservation agriculture, dry planting (early), improved crop varieties, optimum crop geometry, soil fertility management, optimum crop rotation, intercropping, pest control, organic matter management

Source: Authors' compilation.

IWMI Part 4 Ch8-16 final.indd 331 2/28/07 11:06:45 AM

simultaneously because the on-farm water balance is used more effectively) as crop production increases.

The focus of the water management strategies discussed here is on water harvesting, because most of the new, innovative investment options are in this area. There is a particular emphasis therefore on external water-harvesting systems. Moreover, the description of in-situ water-harvesting techniques is limited to what has been assessed as a particularly promising avenue, namely conservation agriculture systems. A comprehensive assessment of in-situ soil and water-conservation methods is given in Liniger and Critchley (forthcoming).

Capturing local runoff upstream in water-harvesting systems addresses problems of frequent drought and prevailing poverty in upper watersheds

Reinventing small-scale water harvesting. Rainwater harvesting (concentrating runoff from watersheds for beneficial use) was practiced in the Negev Desert as early as the 10th century (Evanari, Shanan, and Tadmor 1971). Encompassing any practice that collects runoff for productive purposes (Siegert 1994), rainwater harvesting includes three components: a watershed area to produce runoff, a storage facility (soil profile, surface reservoirs, or groundwater aquifers), and a target area for beneficial use of the water (agriculture, domestic, or industry). The classification varies depending on the spatial scale of runoff collection, from in-situ practices managing rain on farmland (often defined as water conservation) to external systems collecting runoff from watersheds outside the cultivated area (Oweis, Prinz, and Hachum 2001). Rainwater harvesting practices are further defined by storage strategies, from direct runoff concentration in the soil (photo 8.1) to collection and storage of water in structures (surface, subsurface tanks, and small dams; Fox and Rockström 2000).

In India water development policies aimed at large-scale water infrastructure and motorized pumping of surface and groundwater for agriculture resulted in the abandoning of a widespread historic water-harvesting legacy (Agarwal and Narain 1997) *[established*

Photo by Lisa Schipper

Photo 8.1 Small-scale rainwater harvesting can bridge intraseasonal dry spells and stabilize food supplies in periods of poor rainfall

IWMI Part 4 Ch8-16 final.indd 332 2/28/07 11:06:46 AM

but incomplete]. The situation is now changing. Watershed programs are being recognized as a potential engine for agricultural growth and development in fragile and marginal rainfed areas. Several factors explain the shift. Blue water investments are located mainly downstream in watersheds and basins, because they depend on the concentration of large volumes of stable runoff (in lakes and rivers). Large-scale irrigation therefore benefits predominantly downstream communities, while water harvesting offers an appropriate water management complement for agriculture for wide spatial coverage across watersheds and basins. Capturing local runoff upstream in water-harvesting systems addresses problems of frequent drought and prevailing poverty in upper watersheds.

Supplemental irrigation is a key strategy, still underused, for unlocking rainfed yield potential and water productivity

Increasing and stabilizing yields through drought proofing and dry spell mitigation. Supplemental irrigation systems are external rainwater-harvesting systems that collect runoff from watershed areas external to the cultivated land and add it to the rainfed cropland. These systems, developed in different parts of the world, collect runoff at different watershed scales and use various methods to store it. Supplemental irrigation is a key strategy, still underused, for unlocking rainfed yield potential and water productivity (box 8.3).

Since rainfall is the principal source of water for rainfed crops, supplemental irrigation is applied only when rainfall fails to provide essential moisture for improved and stable production (photo 8.2). The amount and timing of supplemental irrigation, particularly in water-scarce areas, are not scheduled to provide moisture-stress-free conditions throughout the growing season but to ensure a minimum amount of water during critical stages of crop growth to permit optimal (in water use or in economic terms) rather than maximum yield (as limited by external conditions that cannot be influenced by management). Supplemental irrigation systems can provide multiple irrigation opportunities during the course of a rainy season (microdams can be filled and emptied several times) and can be used for full-scale off-season irrigation of small gardens for market crops such as vegetables (box 8.4).

Photo by Jennie Barron

Photo 8.2 Supplemental irrigation supports normal yields among crops ruined by insufficient rainfall

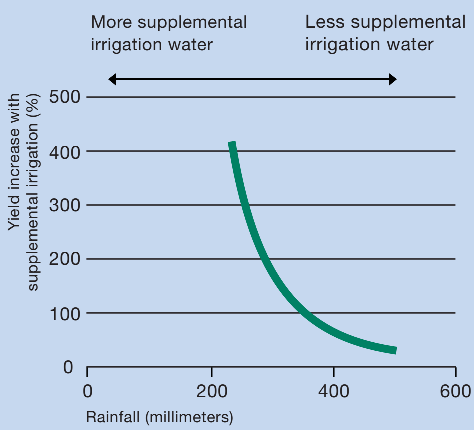
The critical importance of supplemental irrigation lies in its capacity to bridge dry spells and thereby reduce risks in rainfed agriculture. In many farming systems supplemental irrigation provides the only strategy for dry spell mitigation in rainfed agriculture. In-situ management of rainwater, for example, through water conservation methods to increase rainfall infiltration, cannot provide plants with adequate water through dry spells long enough to cause water stress. Evidence indicates that supplemental irrigation of 50–200 mm (500–2,000 cubic meters per hectare) a season is sufficient to bridge critical yield-reducing dry spells and stabilize yield levels (Oweis 1997). Such small amounts can be collected using water in local springs, shallow groundwater, or conventional water resource schemes during the rainy season. By reducing risk, supplemental irrigation may provide the necessary incentive for investments in other production factors such as crop varieties, fertilizer, labor, and tillage techniques and for diversification (staple food crops and cash crops).

Several studies have shown that supplemental irrigation systems are affordable and appropriate for single household or small community investments. A cost-benefit study on supplemental irrigation of maize-tomato cropping systems in Burkina Faso and Kenya found net profits of $73 and $390 per hectare annually, compared with net income losses

box 8.3 **Supplemental irrigation increases yields and water productivity in rainfed systems**

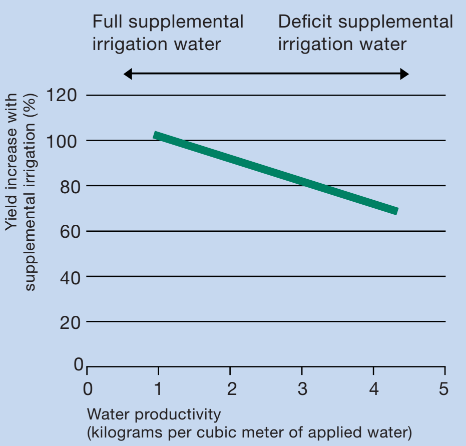
When rainfall is scarce, supplemental irrigation can increase yields significantly compared with completely rainfed systems (figure 1), and in arid regions this increase can be substantial. In water-scarce regions deficit irrigation (only partly meeting plant water demand when adding water) may also be practiced. Experiments in arid regions show that water productivity is higher using deficit supplemental irrigation than with full supplemental irrigation (figure 2). However, yield improvements are greater with full supplemental irrigation. Thus, there is a tradeoff between maximizing yield and maximizing water productivity.

Figure 1 Yield increase with supplemental irrigation at different rainfall amounts



Source: Oweis 1997.

Figure 2 Relationship between yield increase with supplemental irrigation and water productivity



Source: Ilbeyi and others 2006.

The implications of dry spell occurrence in smallholder farming systems were investigated using a crop-soil water simulation model (APSIM) in semiarid Kenya and Tanzania. In more than half of crop seasons the conventional maize system resulted in poor yields (less than 200 kilograms per hectare). Improved water management alone, using supplemental irrigation for dry spell mitigation, was not enough to improve farmers' yields. When supplemental irrigation was combined with fertilizer (60 kilograms of nitrogen per hectare), however, yields doubled (from 0.4 to 0.9 metric tons per hectare per season), and water productivity was also significantly improved. The number of seasons with crop failure decreased by 25%, with potentially strong impacts on household food security among the smallholder farming systems prevalent in tropical savannah agroecosystems (Barron forthcoming).

of $165 and $221 in traditional systems (Fox, Rockström, and Barron 2005). Moreover, the study found a strong mutual dependence between investments in supplemental irrigation and fertilizers. Studies of supplemental irrigation of maize and cabbage using farm ponds in Kenya (Ngigi and others 2005a, b) and a rice-mustard cropping system in India (Panigrahi, Panda, and Agrawal 2005) also concluded that supplemental irrigation was an economically viable option for improving livelihoods of smallholder farmers. In general,

IWMI Part 4 Ch8-16 final.indd 334 2/28/07 11:06:47 AM

box 8.4 | Successful implementation of supplemental irrigation in India

In Rajasthan, India, an arid region receiving 200–300 mm of rainfall, farmers commonly harvest runoff from large field areas upstream. The runoff is concentrated into smaller areas at lower elevations for use in growing crops. In most of South India tanks are traditionally used to harvest and store runoff water. The stored water is used communally for supplemental irrigation during dry spells or for growing a post–rainy season crop.

A promising technology that has been widely adapted in India is the percolation tank, a small reservoir that captures runoff and holds the water for percolation into shallow water tables. The water is subsequently pumped onto the fields when needed. Groundwater storage avoids the high evaporation losses of surface storage and provides a low-cost water distribution system to farms. However, since groundwater is a limited and shared resource, there is a risk for unequal distribution among farmers unless water withdrawal is regulated.

Source: Sreedevi and others 2006; Wani and others 2006b.

investments in rainfed agriculture exhibit higher marginal returns from additional investments in technology and infrastructure compared with investments in irrigated agriculture (Fan, Hazell, and Haque 2000).

Although supplemental irrigation has great potential, realizing maximum benefits depends on its proper application as one element in a package that includes other farm inputs and management practices. Consequently, farmers need to be involved in the development and testing of the technology within the local community and possibly also at the water basin level. Water-harvesting systems have been widely adopted by commercial farmers. Examples include farm ponds in the upper Murray Darling Basin in Australia and on vineyards (for supplemental irrigation of grape production) and livestock farms (for drinking) in the relatively water-scarce Western Cape region in South Africa (van Dijk and others 2006). In India smallholder farmers in several semiarid regions have adopted water harvesting on a large scale.

Using the local field-water balance more effectively. Most water management investments in rainfed agriculture over the past 50 years have focused on improving management of the rain that falls on farmers' fields. Soil and water conservation or in-situ water-harvesting systems (see table 8.3) 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 on any piece of land, they should be optimized before water from external sources is considered. Investing first in management of the local field-water balance increases the likelihood of success with supplemental irrigation systems based on rainwater harvesting, river-flow diversion, and groundwater sources *[established but incomplete]*. Studies of the drivers of collective action in successful watersheds found tangible economic benefits to farmers through in-situ rainwater conservation (Wani and others 2003b; Sreedevi, Shiferaw, and Wani 2004).

IWMI Part 4 Ch8-16 final.indd 335 2/28/07 11:06:48 AM

Conservation agriculture is one of the most important strategies for enhancing soil productivity and moisture conservation *[well established]*. Noninversion systems, which replace conventional plowing with ripping, subsoiling, and no-till systems using direct planting techniques, combined with mulch management, build organic matter and improve soil structure. Conservation agriculture is practiced in approximately 40% of rainfed agriculture in the United States and has generated an agricultural revolution in several countries in Latin America (Derpsch 1998, 2005; Landers and others 2001). There has been wide adoption of conservation agriculture systems among small-scale rainfed and irrigated farmers cultivating rice and wheat on the Indo-Gangetic plains in Asia (Hobbs and Gupta 2002).

> Soil and water conservation or in-situ water-harvesting systems form the logical entry point for improved water management in rainfed agriculture

Conservation agriculture is of key importance for upgrading rainfed agriculture among the world's resource-poor farmers. It reduces traction requirements (by tractors or draft animals), 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. Conservation agriculture can be practiced on all agricultural land, since it does not suffer from limitations related to the need for watershed areas and storage capacity for water harvesting. A particularly important soil and water management strategy in hot tropical regions subject to water constraints, conservation agriculture avoids the rapid oxidation of organic matter and increased soil erosion that occur with soil inversion (using plows) in hot tropical environments *[established but incomplete]*. Some drawbacks of the method are the high initial costs of specialized planting equipment and the need for new management skills. Another challenge is to find strategies to control weeds, particularly for poor farm households for which herbicides are not an option. However, while the use of pesticides might be necessary during the first years, the level normally falls below that of the original farming system after several years.

Converting from plowing to conservation agriculture using subsoiling and ripping has resulted in major improvements in yield and water productivity in parts of semiarid to dry subhumid East Africa, with a doubling of yields in good years due to increased capture of rainwater (box 8.5). Further increases in grain yield have been achieved by applying manure. These interventions can be implemented on all agricultural land. Evidence from East Africa and Southern Africa shows that conservation agriculture can reduce labor needs and improve yields in smallholder rainfed agriculture (box 8.5) *[established but incomplete]*. Yield improvements range from 20% to 120%, with rainwater productivity improving 10%–40%.

Photo by Jennie Barron

Photo 8.3 Supplemental irrigation: furrow irrigation and gravitational water supply

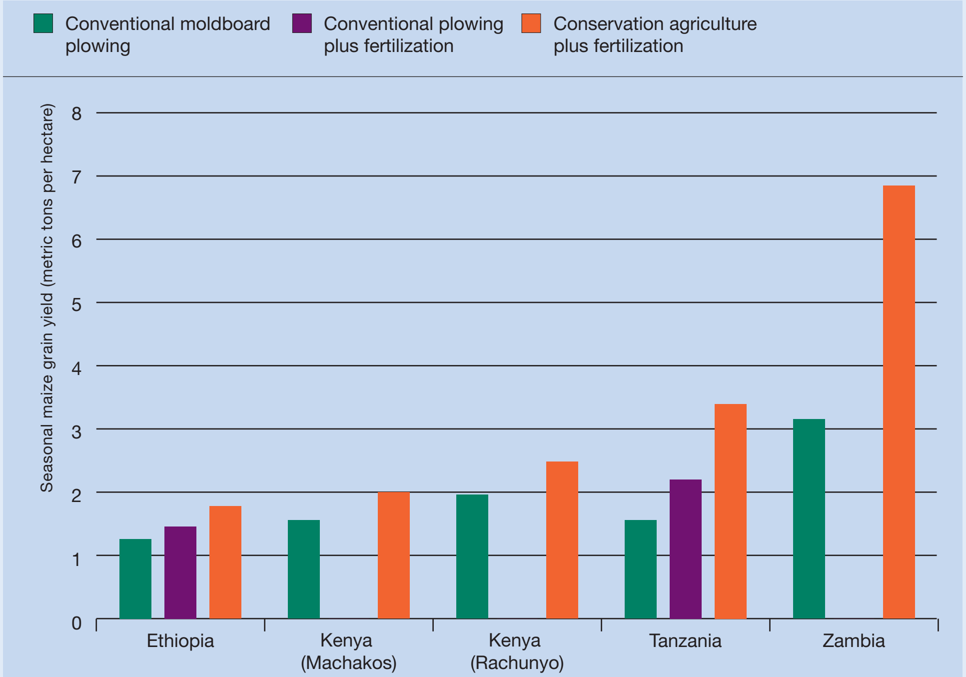
In-situ water-harvesting options also include techniques to concentrate runoff to plants, such as terracing, bunds, ridges, and microbasins. The productivity of rain in arid environments can be substantially increased with water-harvesting techniques that concentrate runoff to plants and trees (photo 8.3). Small basins *(negarim)* have supported almond trees for more than 17 years in the Muwaqqar area of Jordan, where the mean annual rainfall is 125 mm, even during 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 rose from less than 10% to more than 90% when the shrubs were grown in microcatchments. In northwest Egypt, with an average annual rainfall of

IWMI Part 4 Ch8-16 final.indd 336 2/28/07 11:06:48 AM

box 8.5 **Water and soil productivity improvement through conservation agriculture in East Africa**

Trials with farmers on innovative conservation agriculture in semiarid to dry subhumid areas in Ethiopia, Kenya, Tanzania, and Zambia during 1999–2003 indicate large potential to substantially improve yields and rainwater productivity of staple food crops (Rockström and others forthcoming). Limited fertilizer (manure and chemical fertilizer) was applied along permanently ripped planting lines. Yields increased significantly in all countries (see figure). The conservation agriculture systems maximized rainfall infiltration into the soil and cut the need for draft animal traction by at least half.

Maize yield improvements from conservation agriculture in on-farm trials



Source: Rockström and others forthcoming.

130 mm, small water-harvesting basins with 200 square meter watersheds support olive trees, and rainwater harvested from greenhouse roofs can provide about half the water required by vegetables grown inside the greenhouse (Somme and others 2004).

Shifting nonproductive evaporation to productive transpiration. In semiarid areas up to half the rainwater falling on agricultural land is lost as nonproductive evaporation. This is a key window for improving green water productivity through shifting nonproductive evaporation to productive transpiration, with no downstream blue water tradeoff, through management of soil physical conditions, soil fertility, crop varieties, and agronomy. This vapor shift (or transfer) of the evaporative loss into useful transpiration by plants is a particular opportunity in arid, semiarid, and dry subhumid regions.

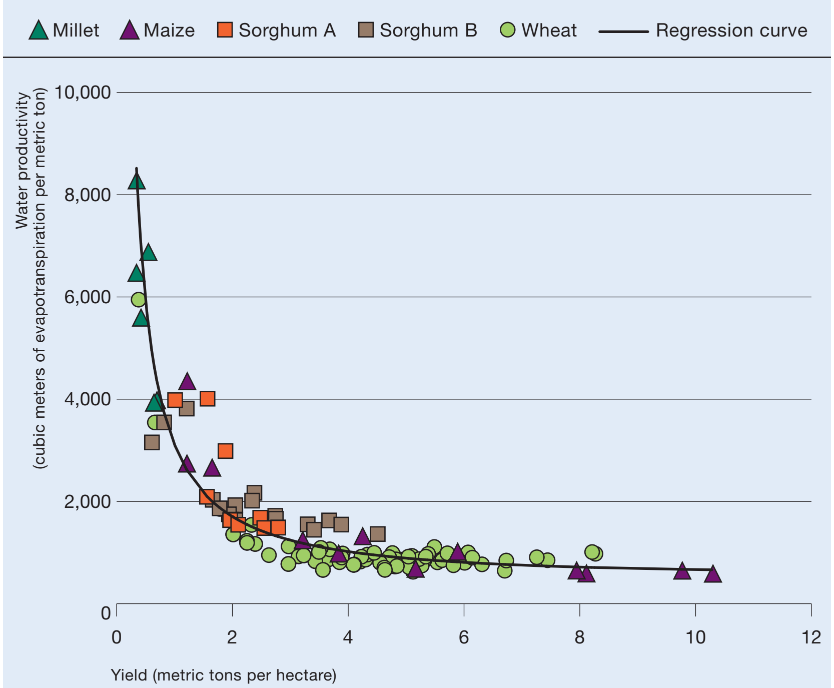
IWMI Part 4 Ch8-16 final.indd 337 2/28/07 11:06:49 AM

Field measurements of rainfed grain yields and green water flows (evapotranspiration) indicate that when yields double from 1 to 2 metric tons per hectare in semiarid tropical agroecosystems, green water productivity may improve from approximately 3,500 cubic meters per metric ton to less than 2,000 cubic meters per metric ton (figure 8.6; Rockström 2003; Oweis, Pala, and Ryan 1998), a result of the dynamic nature of water productivity improvements when moving from very low yields to higher yields. At low yields evaporative losses of water from the soil are high because the sparse canopy coverage of the soil. When yield levels increase, soil shading improves (thanks to larger canopies), and when yields reach 4–5 metric tons per hectare and greater, the canopy density is so high that the opportunity to reduce evaporation in favor of increased transpiration declines, lowering the relative improvement of water productivity. This indicates that large opportunities for improving water productivity are found in low-yielding farming systems, particularly in rainfed agriculture (water productivity is already higher in irrigated agriculture because of better yields).

In semiarid areas up to half the rainwater falling on agricultural land is lost as nonproductive evaporation

In arid areas evidence shows that adoption of in-situ (microcatchment) water harvesting for rainfall infiltration can raise productive transpiration from 10%–30% to 60%, a

figure **8.6** **Dynamic relationship between water productivity and yield for cereal crops under various management and climate conditions**



Source: Millet, Rockström, Jansson, and Barron 1998; maize, Stewart 1988; sorghum A, Dancette 1983; sorghum B, Pandey, Maranville, and Admou 2000; durum wheat, Zhang and Oweis 1999; regression line after Rockström 2003.

IWMI Part 4 Ch8-16 final.indd 338 2/28/07 11:06:50 AM

substantial change. Moreover, with supplemental irrigation for dry spell mitigation nonproductive evaporation can be reduced to 50% of total green water flow.

Crop breeding is important for improving the response to water availability. Using both Mendelian breeding techniques and modern genetic engineering, new crop varieties can be developed that can increase water productivity while maintaining or even increasing yield.

In sum, there seems to be ample room for improvements in water productivity through management. Reducing nonproductive water losses can make more water available in the root zone without sacrificing blue water formation. Moreover, increasing yield results in a simultaneous increase in water productivity, although in this case more blue water is diverted to evapotranspiration.

Applying a holistic approach to agroecosystems

Investments in rainfed and irrigated agriculture are important for meeting not only the Millennium Development Goal on reducing hunger but also the goals on reducing poverty and ensuring environmental sustainability. Increased yields in agriculture have raised consumptive water use dramatically (from approximately 1,000 cubic kilometers a year in 1960 to 4,500 cubic kilometers a year today) and have resulted in large expansions of agricultural area in developing countries (from some 26–32 million square kilometers to 56 million square kilometers over the past 45 years; FAOSTAT 2005). As the Millennium Ecosystem Assessment notes, changes in land use due to expansion of agriculture were the main reason behind the degradation of 65% of ecosystem services over the past 50 years (MEA 2005). Thus, investments in upgrading rainfed agriculture need to take a holistic approach to agroecosystems.

Evidence shows not only large opportunities to upgrade rainfed agriculture, but also substantial payoffs for society

Investments in rainfed agriculture promise substantial payoffs. Evidence shows not only large opportunities to upgrade rainfed agriculture, but also substantial payoffs for society. An exhaustive review of 311 case studies on watershed programs in India focusing on rainwater management found that the mean cost-benefit ratio of watershed programs was relatively high, at 1:2.14 (Joshi and others 2005). The watershed programs generated large employment opportunities, augmented irrigated area and cropping intensity, and conserved soil and water resources.

Returns to labor and profitability at the farm household scale are key drivers behind decisions to invest in rainfed agriculture, especially in water management. An evaluation of farming practices in water harvesting in Tanzania found that upgrading rainwater management is a critical factor in increasing returns to labor and thus for poverty reduction (Hatibu and others 2006). Similarly, case studies in Asia have amply demonstrated that investments in managing rainwater and enhancing its use efficiency increased profitability for the farmers (Wani and others 2006b). In the Adarsha watershed, Kothapally, India, returns to family labor and land (net income) from rainfed cereals and pulses almost doubled in large part because of a watershed development approach based on integrated genetic and natural resources management (Wani and others 2006b). Per capita income was 1,900 rupees ($43) in villages without investments in upgrading rainfed farming and 3,400 rupees ($77) in the Adarsha watershed. These examples show clearly that continued failure to bridge the gap between potential yields, returns to labor, and profitability and

IWMI Part 4 Ch8-16 final.indd 339 2/28/07 11:06:51 AM

those achieved on farmers' fields in rainfed farming is a major factor explaining the perpetuation of poverty.

Water management is a key investment for diversification of agricultural income. Off-farm employment in rural areas usually expands in parallel with agricultural growth *[established but incomplete]*. Each 1% growth in agricultural yields brings about an estimated 0.5%–0.7% reduction in number of poor people (World Bank 2005). Thus rural employment, both on and off the farm, is strongly conditioned by the rate of agricultural growth.

Investments in water management in rainfed systems can have important additional benefits that arise from the multiple roles of water for livelihoods and health

A recent study in the developed Rajasamadhiyala watershed in Gujarat, India, revealed that public investments in rainwater harvesting enabled farmers to invest in wells, pump sets, sprinkler sets, and drip irrigation systems in addition to fertilizers and improved pest and disease management (Wani and others 2006a; Sreedevi and others 2006). Development in integrated watersheds triggered a shift toward commercial cereal crop production, such as maize, whereas in the surrounding villages without watershed development farmers continued to grow low-value cereals like sorghum. In addition, farmers in the developed watershed village in Andhra Pradesh put more area under vegetables and horticultural crops than did farmers in the surrounding villages, contributing to income stability and resilience (figure 8.7; Wani and others 2006b). A prerequisite for such diversification is access to markets. In India the output from rainfed agriculture, including that from high yielding varieties, has increased rapidly in many areas and at the same pace as in irrigated areas (Kerr 1996).

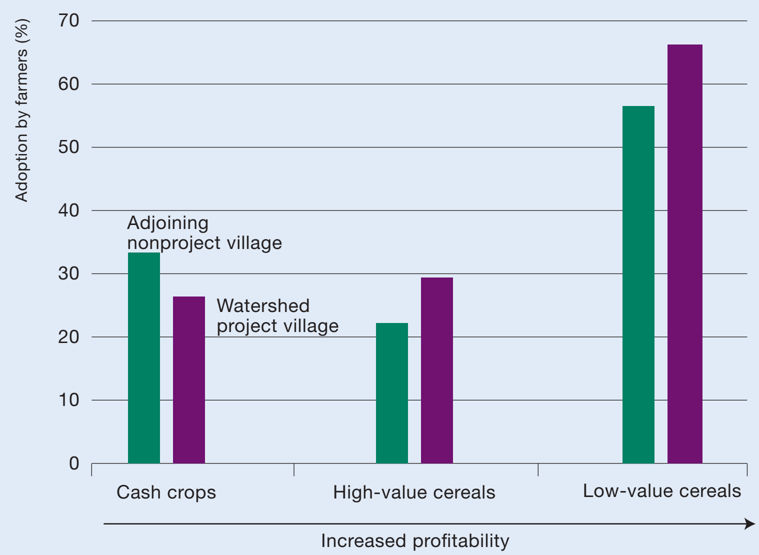
In many parts of Tanzania rainwater harvesting has enabled farmers in semiarid areas to upgrade rainfed farming by growing a marketable crop, thus helping to reduce poverty. Farmers upgraded from sorghum and millet to rice or maize with follow-up legume crops that exploit residual moisture in the field. Currently, production of rice in semiarid areas using rainwater harvesting accounts for more than 35% of the rice produced in the country (Gowing and others 1999; Meertens, Ndgege, and Lupeja 1999).

Farm-scale water management improvements yield multiple benefits. Investments in water management in rainfed systems can have important additional benefits that arise from the multiple roles of water for livelihoods and health. In supporting all forms of biomass growth for cultivated crops—pasture for livestock, noncultivated food plants, and fuel and construction wood—rainwater influences the resilience of rural communities practicing rainfed agriculture. Rural livelihoods also depend on nonagricultural incomes (remittances, seasonal off-farm work, rural complementary sources of income) that reduce vulnerability to variations in rainfall.

A study in East Africa shows that strategies for reducing poverty to meet the Millennium Development Goals require investments that promote productivity growth in three areas (ASARECA and IFPRI 2005). Major staples were found to be the key for overall economic growth and poverty reduction. Rainfed systems dominate the production of staples, underscoring the importance of investing in the upgrading of rainfed systems. The livestock sector, which consists predominantly of rainfed systems, is a key livelihood source for people in South Asia. And many nonfarm rural enterprises are linked to value-adding processing of crop and livestock products.

IWMI Part 4 Ch8-16 final.indd 340 2/28/07 11:06:51 AM

figure **8.7** **Watershed development in rainfed areas boosts output in semiarid Kothapally, Andhra Pradesh, India**



Source: Wani and others 2006b.

There are also other options for generating more benefits from systems such as forests and rangelands, which deplete rainwater naturally. They include investments to add further value to rain, such as the development of microenterprises associated with natural resources such as vermicomposting, plant nurseries, biodiesel plantations, oil extraction, and processing of farm produce. These help to ensure diversified livelihood options for women and youth and increase resilience during drought years (Wani and others 2003a; Joshi and others 2005; Wani and others 2006b).

Intensified rainfed agriculture requires balancing water for food and for ecosystems. Every increase in water used in agriculture will affect water availability for other uses, both for direct human use (water supply) and for ecosystem use (terrestrial and aquatic ecosystems). In overcommitted watersheds upgrading rainfed agriculture through investments in water-harvesting systems may result in severe water tradeoffs with downstream users and ecosystems (Calder 1999), although other evidence points to limited or no downstream impacts on stream flow even from broad implementation of small-scale water storage systems (Evanari, Shanan, and Tadmor 1971; Schreider and others 2002; Sreedevi and others 2006) *[competing explanations]*. Investing in water management in rainfed agriculture can have positive environmental impacts on other ecosystems as a result of reduced land degradation and improvements in water quality downstream.

Basinwide gains are possible from investments in upstream water harvesting in rainfed agricultural systems. Improvements in water productivity, which are expected to

IWMI Part 4 Ch8-16 final.indd 341 2/28/07 11:06:52 AM

be particularly large in rainfed agricultural areas where yields often are low (see figure 8.6), partially offset the reduction of water availability downstream that would have resulted without any improvements in water productivity. Thus, although blue water availability downstream will likely decrease, the total amount of green water consumed per unit of crop yield is lower from a basin perspective. Moreover, capturing water close to the source (where the raindrop hits the ground), as is common in water-harvesting systems, reduces evaporative losses of blue water during its journey from field to watershed to river basin. Energy savings is another important advantage in investing in storage of water as close as possible to the source. Storage investments as far upstream as possible in a watershed permit using gravitational energy, whereas storage downstream may require new energy to lift water back to the farm land. However, more research is needed to assess the downstream water effects of upgrading rainfed agriculture.

> The evidence on rainfed agriculture conveys two key messages: rainfed agriculture will play a major role in global food security and sustainable economic growth, and there are large opportunities for gains from new investments in water management

The dramatic increase in land degradation over the past half century as a result of deforestation and poor land use, often in upstream locations in river basins, has upset hydrological performance (chapter 15 on land; Vörösmarty, Lévêque, and Revenga 2005). The reduced water-holding capacity of upper watersheds and disrupted partitioning of rainfall between green and blue water flows (lower green flows and higher blue storm flows) have affected both upstream rural communities (more recurrent water stress) and downstream communities (faster runoff because of lower base flow and higher surface flow; siltation of dams; Bewket and Sterk 2005). Investments in upgrading rainfed agriculture in upper watersheds, by slowing the release of water and thus taming the erosive flows of blue water, can reduce land degradation. Furthermore, good management of water in rainfed agriculture will increase slow subsurface water flows in the landscape. This improves the release of freshwater downstream over time and reduces land degradation from water-induced soil erosion.

Investments in improved water and land management upstream yield economic payoffs for communities downstream *[established but incomplete]*. Most documented experiences have so far considered afforestation in the upstream watershed (Perrot-Maître and Davis 2001; Landell-Mills and Porras 2002), but examples are emerging in different parts of the world of downstream communities compensating upstream communities for the economic gains of environmental services received downstream as a result of water management investments upstream (FAO 2004a).

New investment opportunities and policy options

The evidence on rainfed agriculture presented in this chapter conveys two key messages: rainfed agriculture will play a major role in global food security and sustainable economic growth, and there are large opportunities for gains from new investments in water management. Furthermore, the knowledge exists to substantially increase long-term yields in rainfed agriculture in regions subject to recurrent water-related productivity challenges. But there is a gap in the uptake and use of this knowledge among all stakeholders, from policymakers to small-scale farmers. A number of constraints interfere, including technical, socioeconomic, and policy factors, but inadequate investment in knowledge sharing and scaling-up of best practices is the major impediment.

IWMI Part 4 Ch8-16 final.indd 342 2/28/07 11:06:52 AM

A new approach to agricultural water policy is needed that views rainfall as the freshwater resource and that considers both green and blue water for livelihood options at the appropriate scale for local communities. Unlocking the potential in rainfed agriculture requires large new investments in human capacity, supporting research, and institutional development as well as specific technologies. A new set of extension services are needed, with staff trained to support farmers in water management investments at the smaller rainfed farming scale (water management skills are now embedded in water resource development for large-scale irrigation). The knowledge-intensive nature of this undertaking means that successful dissemination will require large investments.

A policy focus on rainwater management, not just runoff management

Rainfed agriculture has suffered from insufficient policy and institutional support for improving water management for production. Investments have focused on remediating the negative effects of water upstream (erosion control and water conservation) to reduce the downstream impact. In recent decades, however, the focus has shifted from water management for conservation to water management for production upstream, changing the perception from water as a foe, to be disposed of through erosion control measures, to water as a friend, to be supplied for productive purposes at the local scale.

Water investments in rainfed agriculture involve management of water that is not considered to be water: rainfall also needs to be viewed as an economic water resource

A green and blue water paradigm for strategic investments. Today, the focus of water policy is primarily at the river basin or large watershed scale, while agricultural policy often targets the individual farm, but not in terms of water investments. A new water policy paradigm needs to focus more explicitly at the smaller watershed scale, which often corresponds to the community, small township, or village (tens to thousands of hectares). This scale corresponds to the relevant water resource management scale of rainfed farmers, where a new green revolution will have to occur over the next decades in order to achieve the Millennium Development Goal of reducing poverty and hunger by half and ensuring environmental sustainability.

Introducing a water policy focus on green water resources widens the scope to include water planning in upper watersheds and land use impacts on blue water availability downstream. Conventionally, in policy, management, and legal terms, only liquid, blue water in rivers, groundwater, lakes, wetlands, and estuaries is included in water resources management. Water investments in rainfed agriculture involve management of water that is not considered to be water. The green water resource needs to be placed centrally in water resource investments. This requires a shift in water policy focus from permanent blue water flow in rivers, lakes, and groundwater to rainfall and intermittent and local surface runoff flow in rills and gullies, local shallow water tables, and temporary impoundments of surface water. Rainfall needs to be viewed as an economic water resource, rather than only the blue water component.

Such a shift in policy perspective took place recently in India, in recognition of the importance of rainfed agriculture for development and its contribution to the overall economic growth of the country. The government established an independent National

IWMI Part 4 Ch8-16 final.indd 343 2/28/07 11:06:53 AM

Authority for Development of Rainfed Agriculture in 2005. This shift has also reached the state level. The government of Tamil Nadu, for example, established a Mission on Rainfed Agriculture in 2005.

A new meso-scale for water management. Water resources management focuses mainly on the larger watershed or river basin scale, while agricultural interventions for rainfed agriculture remain focused at the farm or field level. To capitalize on the untapped potential of rainfed agriculture for small-scale farmers, water management investments are required at the small watershed scale—the tributary scale in river basins—where runoff often flows only during short periods after rainfall events.

A new water policy framework for integrated water resources management is required for planning and allocating rainwater at the watershed scale

A new water policy framework for integrated water resources management is required for planning and allocating rainwater at the watershed scale. Moving toward the gray area between rainfed and irrigated agriculture at the watershed scale requires new skills and data on water availability and use at the meso-scale. Essential data on important processes, especially runoff, are needed to properly design and implement landscape or community-level approaches to water harvesting and delivery systems for integrated water management. New approaches to legal ownership of rainwater at the watershed levels will also have to be developed. Water policies and regulations are designed for allocating irrigation water from large rivers, groundwater, and dams and not for collecting rainfall at the meso-watershed scale in small microdams, farm ponds, and percolation tanks. To succeed a new water paradigm in agriculture is required, which promotes water investments at the appropriate scale for particularly small-scale farmers in tropical and subtropical developing countries.

New efforts to promote innovation and adaptive adoption

Upgrading rainfed agriculture requires integrated approaches to social and ecological management. A challenge facing low-productive rainfed agriculture is the need for innovations in management of water that require novel technologies and practices such as water harvesting and conservation agriculture. Both innovation and adaptation are needed for successful adoption and out-scaling. One promising approach is adaptive comanagement between local communities and knowledge agents, in which knowledge sharing and transformation occur as an iterative process. Important tools for adaptive comanagement include participatory approaches, farmer field schools, and action research methods.

An integrated approach to rainwater management must address links between investments and risk reduction, between rainwater management and multiple livelihood strategies, and between land, water, and crops. Strategies for upgrading, including technologies and management, are generally known. However, the missing links for scaling-up and scaling-out are social and economic processes and institutions that can link to suitable policies.

India has experienced important success from integrated watershed management, with local ownership combined with tangible economic benefits among rural households (Wani and others 2003c). However, India's experience also highlights the limitation of a compartmental approach. The benefits of increased productivity were not realized to the desired extent, equity issues were not addressed, and community participation was not achieved, resulting in neglect of the various water-harvesting structures in the watersheds.

IWMI Part 4 Ch8-16 final.indd 344 2/28/07 11:06:54 AM

An integrated approach to land, water, and crop management is required on farm at the same time that watershed and basin development strategies are employed to increase yields in rainfed agriculture. Successes are not directly transferable to other socioecological contexts but require adaptation and comanagement. Investments in upgrading rainfed agriculture need to consider the wide range of benefits from rainwater that contribute to the overall resilience of rural communities—support for all forms of biomass growth, including cultivated crops, pasture for livestock, noncultivated food plants, and fuel and construction wood.

Strategies to enable investments in rainwater management

Governance of agricultural development should give more attention to resource management and intersectoral approaches, including at the local level, to counteract the focus on inputs that has dominated in the past. This is challenging, as it requires the integration of socioecological understanding in institutional capacity so that the rain, land, and crop complexities, potentials, and risks involved in rainfed agriculture are integrated in economic planning. Broader knowledge is needed for investments at national, regional, and district levels.

In rainfed areas strategic public investments in rainwater management are urgently needed to encourage the private sector to take investment risks

Institutional reform is required at the national level to bridge the divide in governance of water resources, agriculture, and the environment. Relevant departments and ministries need to be more closely connected in legal, policy, and management areas.

Investments are required in local institutions for resource management. Opportunities to make investments in rainfed agriculture bankable need to be promoted. Land tenure reforms and development of local markets and transport infrastructure are crucial. Farmer organizations, small-scale credit schemes, private banking partnerships, and other institutional arrangements need to go hand in hand with policy advances.

Microcredit schemes for water management investments are especially important. Farm households generally cannot afford the large (relative to financial capacity) initial investments required even for small-scale water-harvesting systems for crop production, despite high benefit to cost ratios and the positive impact on long-term risk reduction.

Enabling environments are important. Well targeted economic support is essential in agriculture development. Improved water management needs to be supported by investments in infrastructure, markets, access roads, and secure land tenure.

Providing complementary public sector investments. To support farmers' efforts of gradual intensification, participatory approaches should be combined with public investments in governance, management, and infrastructure.

In rainfed areas strategic public investments in rainwater management are urgently needed to encourage the private sector (individual as well as corporate) to take investment risks. India has demonstrated that once public investments in rainwater harvesting have ensured soil moisture and increased groundwater availability, individuals and industries will increase their investments in rainfed agriculture (Wani and others 2006a). As private investments tend to follow the path of minimum risk, once the highest risk for growing economic biomass—rainfall variability—was reduced, private investments flowed.

Investments in infrastructure supporting agricultural development are important. Evidence shows that investments in roads and education targeted to rainfed areas had a larger

IWMI Part 4 Ch8-16 final.indd 345 2/28/07 11:06:55 AM

effect on poverty than those directed to irrigated areas (Fan, Hazell, and Haque 2000; Fan, Zhang, and Zhang 2002). Work by Hatibu and Rockström (2005) has shown that investments in rainwater management generate significant impacts on poverty if accompanied by linkages to profitable markets. In the Machakos District in Kenya the social and economic success over the past 50 years among rainfed farming communities originated in investments in soil and water conservation, particularly terracing (Tiffen, Mortimore, and Gichuki 1994), combined with investments in infrastructure that enabled farmers to diversify and penetrate local markets (Zaal and Oostenrup 2002). Linking crop and livestock producers in semiarid areas with markets and marketing systems enables them to obtain high returns on their investments in rainwater management, increasing the benefits from existing systems while promoting wider adoption. This agrees with findings in India that complementary investments in road infrastructure in rainfed areas resulted in much higher impacts on poverty (Wani and others 2006b).

Linking crop and livestock producers in semiarid areas with markets and marketing systems enables them to obtain high returns on their investments in rainwater management

Increasing the profitability of private sector investments. Profitability is a key factor determining all investment. Rainfed agriculture has suffered from particularly low profitability as a result of the strong focus on staple grains and the trend of declining world market prices for grain. By contrast, irrigated agriculture has diversified into specialized commercial crops such as cut flowers and other horticultural crops. Rainfed agriculture similarly needs to shift toward greater diversification to boost investment. This could be achieved through investments in water resources management *[established but incomplete]*. Investment in small water-harvesting structures for storage of local runoff for supplemental irrigation, for example, could support diversification by enabling off-season full irrigation of high-value vegetables and fruits.

Investmenting in capacity building. Agricultural extension services and other service institutions need to adjust their skills mix to meet the needs of rainfed agriculture. Today, capacity is focused on the local field scale (agriculture, livestock, and soil and water conservation at the local farm scale) or the larger watershed or river basin scale for irrigation development, management, and planning. The capacity to upgrade rainfed agriculture through water investments, which requires skill at the meso-watershed scale, is very limited.

Adaptation to climate change to increase resilience

There is growing confidence in the scientific predictions of the impacts of anthropogenic climate change. Water resources are severely affected, and evidence indicates, despite large standard deviations, that rainfall in tropical regions will become even more unreliable. Larger and more intensive storms will become more common, and several regions, including Southern Africa, will suffer from reduced rainfall. Furthermore, advances in climate science over the past five years also point with growing certainty to the unavoidability of climate change impacts in the coming decades, not just in a distant future.

Increasingly, this has resulted in a growing concern for the need to adapt to climate change. Investments in water management in rainfed agriculture should form a cornerstone of any country's strategy for adapting to climate change, particularly in developing countries in tropical regions where rainfed agriculture plays such an important economic

IWMI Part 4 Ch8-16 final.indd 346 2/28/07 11:06:55 AM

role. Poor countries are more vulnerable to climate change, and poor communities are hit hardest by social and environmental shocks. Investments that reduce water-related risks build more resilient communities better able to face increased occurrence of floods, droughts, and dry spells under a changing climate. The National Adaptation Programmes of Action under the UN Framework Convention on Climate Change need to address both small- and large-scale investments in water management to meet a future with a higher frequency of water-related climate shocks. For agricultural water management this includes a strategic balance between investments to reduce vulnerability to droughts and floods at the local scale through small water storage systems as well as large-scale infrastructure investments. Building water resilience to climate change adds a new and urgent dimension to the need for large new investments in water management to upgrade rainfed agriculture.

Investments in water management in rainfed agriculture should form a cornerstone of any country's strategy for adapting to climate change

Comprehensive evidence for action to improve livelihoods

Diverse forces and comprehensive evidence point to the urgency of concerted and strategic investments in upgrading rainfed agriculture in developing countries where water is a constraint to food production. They also highlight the large opportunities. Achieving the Millennium Development Goals of reducing poverty and hunger by half and ensuring environmental sustainability is not possible without major contributions from rainfed agriculture. Low yields today are an opportunity for the future, given the wide evidence of large volumes of unused water, even in water-scarce regions, and the wide knowledge base of appropriate, effective, and affordable water management practices ready to be adopted by farmers at a large scale. Nothing less than a new green revolution is required in Sub-Saharan Africa, and significant agricultural productivity improvements are needed in large parts of South, Southeast, and East Asia as well as in parts of Latin America.

Water alone will not do the job. But this chapter shows that in rainfed farming, where water is a highly variable production factor, risk reduction through water management is a key to unlocking the potential of managing crops, soil fertility, and pests and allowing for diversification. A crucial finding is the possibility of improving livelihoods as well as water productivity through water management in rainfed agriculture. More food can be produced with relatively less water, particularly in the low-yielding farming systems of the world.

It is time for governments and development organizations to abandon the notion that rainfed farming in semiarid and dry subhumid regions is a marginal activity practiced on drylands and instead invest in tapping the potential for doubling and often tripling or quadrupling productivity in these systems. This will contribute to fighting poverty, reducing environmental degradation, and building resilience to climate change; allow for a more balanced rural-urban development; and ultimately contribute to sustainability.

Reviewers

Chapter review editor: Jean Boroto.
Chapter reviewers: Mintesinot Behailu, Meena Bilgi, Eline Boelee, James Chimphamba, Guy Evers, John Gowing, Dorothy Hamada, Ingrid Hartman, Peter Hobbs, Dyno Keatinge, Henry Mahoo, Douglas J. Merrey, Tony Peacock, Bharat R. Sharma, Jonathan Woolley, and Yali E. Woyessa.

IWMI Part 4 Ch8-16 final.indd 347 2/28/07 11:06:56 AM

References

Abdulai, A., and P. Hazell. 1995. "The Role of Agriculture in Sustainable Development in Africa." *Journal of Sustainable Agriculture* 7 (2/3): 101–19.

Agarwal, A. 2000. *Drought? Try Capturing the Rain*. Briefing Paper. New Delhi: Centre for Science and Environment.

Agarwal, A., and S. Narain. 1997. *Dying Wisdom: Rise, Fall and Potential of India's Traditional Water Harvesting System*. Faridabad, India: Thomson Press Ltd.

ASARECA (Association for Strengthening Agricultural Research in Eastern and Central Africa) and IFPRI (International Food Policy Research Institute). 2005. "Strategic Priorities for Agricultural Research-for-Development in Eastern and Central Africa." Entebbe, Uganda, and Washington, D.C.

Barron, J. Forthcoming. "Water Productivity and Rainwater Management in Smallholder Farming Systems: Simulations for Cereals in Semiarid Sub-Sahara Africa with APSIM." Contribution to the Comprehensive Assessment project "Water Use in Agriculture on Water Scarcity and Food Security in Tropical Rainfed Water Scarcity Systems: A Multi-level Assessment of Existing Conditions, Response Options and Future Potentials." International Crops Research Institute for the Semi-Arid Tropics, Andhra Pradesh, India.

Barron, J., J. Rockström, F. Gichuki, and N. Hatibu. 2003. "Dry Spell Analysis and Maize Yields for Two Semiarid Locations in East Africa." *Agricultural and Forest Meteorology* 117 (1–2): 23–37.

Bewket, W., and G. Sterk. 2005. "Dynamics in Land Cover and its Effect on Stream Flow in the Chemoga Watershed, Blue Nile Basin, Ethiopia." *Hydrological Processes* 19 (2): 445–58.

Calder, I.R. 1999. *The Blue Revolution: Land Use and Integrated Water Resources Management*. London: Earthscan.

Commission for Africa. 2005. *Our Common Interest: Report of the Commission for Africa*. Accessed May 2005. [www.commissionforafrica.org/english/report/introduction.html].

Conway, G. 1997. *The Doubly Green Revolution: Food for All in the Twenty-first Century*. London: Penguin Books.

Critchley, W., and K. Siegert. 1991. *Water Harvesting: A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production*. Rome: Food and Agriculture Organization.

Dancette, C. 1983. "Estimation des besoins en eau des principales cultures pluviales en zone soudano-sahélienne." *L'Agronomie Tropicale* 38 (4): 281–94.

Deichmann, U., and L. Eklundh. 1991. "Global Digital Data Sets for Land Degradation Studies: A GIS Approach." GRID Case Study Series 4. United Nations Environment Programme, Global Environmental Monitoring System and Global Resource Information Database, Nairobi. Accessed February 2006. [http://geodata.grid.unep.ch/].

Derpsch, R. 1998. "Historical Review of No-tillage Cultivation of Crops." In J. Benites, E. Chuma, R. Fowler, J. Kienzle, K. Molapong, J. Manu, I. Nyagumbo, K. Steiner, and R. van Veenhuizen, eds., *Conservation Tillage for Sustainable Agriculture*. Proceedings from an International Workshop, Harare, 22–27 June. Part II (Annexes). Eschborn, Germany: Deutsche Gesellschaft fur Technische Zusammenarbeit.

———. 2005. "The Extent of Conservation Agriculture Adoption Worldwide: Implications and Impact." Keynote Paper at the 3rd World Congress on Conservation Agriculture, Regional Land Management Unit, World Agroforestry Centre, 3–7 October, Nairobi.

DFID (Department for International Development). 2002. "Better Livelihoods for Poor People: The Role of Agriculture." Issues Paper. Consultation Document Draft A4. Rural Livelihoods Department, London.

Dixon, J., A. Gulliver, and D. Gibbon. 2001. *Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World*. Rome and Washington, D.C.: Food and Agriculture Organization and World Bank.

Doorenbos, J., and W.O. Pruitt. 1992. *Crop Water Requirements*. FAO Irrigation and Drainage Paper. Rome: Food and Agriculture Organization.

Evenari, M., L. Shanan, and N.H. Tadmor. 1971. *The Negev: The Challenge of a Desert*. Cambridge, Mass.: Harvard University Press.

Falkenmark, M. 1986. "Fresh Water—Time for a Modified Approach." *Ambio* 15 (4): 192–200.

Falkenmark, M., and J. Rockström. 2004. *Balancing Water for Humans and Nature: The New Approach in Ecohydrology*. London: Earthscan.

Fan, S., P. Hazell, and T. Haque. 2000. "Targeting Public Investments by Agro-ecological Zone to Achieve Growth and Poverty Alleviation Goals in Rural India." *Food Policy* 25 (4): 411–28.

Fan, S., L. Zhang, and X. Zhang. 2002. *Growth, Inequality, and Poverty in Rural China*. Research Report 125. Washington, D.C.: International Food Policy Research Institute.

FAO (Food and Agriculture Organization). 2002. *World Agriculture: Towards 2015/2030: Summary Report*. Rome.

———. 2004a. *Payment Schemes for Environmental Services in Watersheds*. Regional Forum, 9–12 June 2003 in Arequipa, Peru. Land and Water Discussion Paper 3. Rome.

IWMI Part 4 Ch8-16 final.indd 348 2/28/07 11:06:56 AM

———. 2004b. *The State of Food Insecurity in the World 2004.* Rome.
FAO (Food and Agriculture Organization)/IIASA (International Institute for Applied Systems Analysis). 2000. *Global Agro-Ecological Zones (Global-AEZ)*. CD-ROM. Rome and Laxenburg, Austria. Accessed February 2006. [www.iiasa.ac.at/Research/LUC/GAEZ].
FAOSTAT. 2005. Database. Food and Agriculture Organization, Rome. Accessed November 2005. [http://faostat.fao.org/].
Fischer, G., M. Shah, and H. van Velthuizen. 2002. *Climate Change and Agricultural Vulnerability*. Special report for the UN World Summit on Sustainable Development, 26 August–4 September, Johannesburg. Laxenburg, Austria: International Institute for Applied Systems Analysis. [www.iiasa.ac.at/Research/LUC/JB-Report.pdf].
Fox, P., and J. Rockström. 2000. "Water Harvesting for Supplemental Irrigation of Cereal Crops to Overcome Intra-seasonal Dry-spells in the Sahel." *Physics and Chemistry of the Earth, Part B Hydrology, Oceans and Atmosphere* 25 (3): 289–96.
Fox, P., J. Rockström, and J. Barron. 2005. "Risk Analysis and Economic Viability of Water Harvesting for Supplemental Irrigation in Semiarid Burkina Faso and Kenya." *Agricultural Systems* 83 (3): 231–50.
Glantz, M.H. 1994. *Drought Follows the Plough: Cultivating Marginal Areas*. Cambridge, UK: Cambridge University Press.
Gowing, J.W., H. Mahoo, O.B. Mzirai, and N. Hatibu. 1999. "Review of Rainwater Harvesting Techniques and Evidence for Their Use in Semiarid Tanzania." *Tanzania Journal of Agriculture Science* 2 (2): 171–80.
Harris, H.C., P.J.M. Cooper, and M. Pala. 1991. *Soil and Crop Management for Improved Water Use Efficiency in Rainfed Areas*. Proceedings of an International Workshop sponsored by the Ministry of Agriculture, Forestry, and Rural Affairs, International Center for Agricultural Research in the Dry Areas, and International Maize and Wheat Improvement Center, 15–19 May, 1989. Ankara: International Center for Agricultural Research in the Dry Areas.
Hatibu, N., and J. Rockström. 2005. "Green-Blue Water System Innovations for Upgrading of Smallholder Farming Systems—A Policy Framework for Development." *Water Science and Technology* 51 (8): 121–32.
Hatibu, N., E.A. Lazaro, H.F. Mahoo, F.B. Rwehumbiza, and A.M. Bakari. 1999. "Soil and Water Conservation in Semiarid Areas of Tanzania: National Policies and Local Practices." *Tanzania Journal of Agricultural Sciences* 2 (2): 151–70.
Hatibu, N., M.D.B. Young, J.W. Gowing, H.F. Mahoo, and O.B. Mzirai. 2003. "Developing Improved Dryland Cropping Systems for Maize in Semiarid Tanzania. Part 1: Experimental Evidence of the Benefits of Rainwater Harvesting." *Journal of Experimental Agriculture* 39 (3): 279–92.
Hatibu, N., K. Mutabazi, E.M. Senkondo, and A.S.K. Msangi. 2006. "Economics of Rainwater Harvesting for Crop Enterprises in Semiarid Areas of East Africa." *Agricultural Water Management* 80 (1–3): 74–86.
Henao, J., and C. Baanante. 2006. *Agricultural Production and Soil Nutrient Mining in Africa: Implications for Resource Conservation and Policy Development*. IFDC Technical Bulletin. Muscle Shoals, Ala: International Fertilizer Development Center.
Hilhost, T., and F. Muchena. 2000. *Nutrients on the Move: Soil Fertility Dynamics in African Farming Systems*. London: International Institute for Environment and Development.
Hobbs, P.R., and R.K. Gupta. 2002. "Rice-wheat Cropping Systems in the Indo-Gangetic Plains: Issues of Water Productivity in Relation to New Resource Conserving Technologies." In J.W. Kijne, ed., *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. Wallingford, UK: CABI Publishing.
IAC (InterAcademy Council). 2004. *Realizing the Promise and Potential of African Agriculture: Science and Technology Strategies for Improving Agricultural Productivity and Food Security in Africa*. Amsterdam: InterAcademy Secretariat.
IFAD (International Fund for Agricultural Development). 2001. *Rural Poverty Report 2001: The Challenge of Ending Rural Poverty*. Oxford, UK: Oxford University Press.
Ilbeyi, A., H. Ustun, T. Oweis, M. Pala, and B. Benli. 2006. "Wheat Water Productivity and Yield in a Cool Highland Environment: Effect of Early Sowing with Supplemental Irrigation." *Agricultural Water Management* 82 (3): 399–410.
India, Government of. 2005. *Serving Farmers and Saving Farming—2006: Year of Agricultural Renewal*. Third Report. New Delhi: Ministry of Agriculture, National Commission on Farmers.
IPCC (Intergovernmental Panel on Climate Change). 2001. *Climate Change 2001*. Third Assessment Report. Cambridge, UK: Cambridge University Press.
Irz, X., and T. Roe. 2000. "Can the World Feed Itself? Some Insights from Growth Theory." *Agrekon* 39 (3): 513–28.
Johnston, D.G., and J.W. Mellor. 1961. "The Role of Agriculture in Economic Development." *American Economic Review* 51 (4): 566–93.
Joshi, P.K., A.K. Jha, S.P. Wani, L. Joshi, and R.L. Shiyani. 2005. *Meta-analysis to Assess Impact of Watershed Program and People's Participation*. Comprehensive Assessment of Water Management in Agriculture Research Report 8. Colombo: International Water Management Institute.

IWMI Part 4 Ch8-16 final.indd 349 2/28/07 11:06:57 AM

Kerr, J. 1996. "Sustainable Development of Rainfed Agriculture in India." EPTD Discussion Paper 20. International Food Policy Research Institute, Environment and Production Technology Division, Washington, D.C. [www.ifpri.org/divs/eptd/dp/papers/eptdp20.pdf].

Klaij, M.C., and G. Vachaud. 1992. "Seasonal Water Balance of a Sandy Soil in Niger Cropped with Pearl Millet, Based on Profile Moisture Measurements." *Agricultural Water Management* 21 (4): 313–30.

Koning, N. 2002. "Should Africa Protect Its Farmers to Revitalise its Economy?" Working Paper North-South Centre. Wageningen University and Research Centre, Wageningen, Netherlands.

Landell-Mills, N., and T.I. Porras. 2002. *Silver Bullet or Fools' Gold? A Global Review of Markets for Forest Environmental Services and Their Impact on the Poor*. Instruments for Sustainable Private Sector Forestry Series. London: International Institute for Environment and Development. [www.iied.org/pubs/pdf/full/9066IIED.pdf].

Landers, J.N., H. Mattana Saturnio, P.L. de Freitas, and R. Trecenti. 2001. "Experiences with Farmer Clubs in Dissemination of Zero Tillage in Tropical Brazil." In L. García-Torres, J. Benites, and A. Martínez-Vilela, eds., *Conservation Agriculture, A Worldwide Challenge.* Rome: Food and Agriculture Organization.

LandScan. 2004. Global Population Database. Oak Ridge National Laboratory, Oak Ridge, Tenn. Accessed November 2005.

Liniger, H.P., and W. Critchley. Forthcoming. *Where the Land Is Greener: Case Studies and Analysis of Soil and Water Conservation Initiatives Worldwide*. Berne, Switzerland: World Overview of Conservation Approaches and Technologies.

MEA (Millennium Ecosystem Assessment). 2005. *Ecosystems and Human Wellbeing: Synthesis*. Washington, D.C.: Island Press.

Meertens, H., L. Ndege, and P. Lupeja. 1999. "The Cultivation of Rainfed Lowland Rice in Sukumaland, Tanzania." *Agriculture, Ecosystems, and Environment* 76 (1): 31–45.

Mwale, F. 2003. "Drought Impact on Maize Production in Malawi." UNESCO–IHE Report. United Nations Educational, Scientific and Cultural Organization Institute for Water Education, Delft, Netherlands.

Ngigi, S.N., H.H.G. Savenije, J. Rockström, and C.K. Gachene. 2005a. "Hydro-economic Evaluation of Rainwater Harvesting and Management Technologies: Farmers' Investment Options and Risks in Semiarid Laikipia District of Kenya." *Physics and Chemistry of the Earth* 30 (11–16): 772–82.

Ngigi, S.N., H.H.G. Savenije, J.N. Thome, J. Rockström, and F.W.T. Penning de Vries. 2005b. "Agro-hydrological Evaluation of On-farm Rainwater Storage Systems for Supplemental Irrigation in Laikipia District, Kenya." *Agricultural Water Management* 73 (1): 21–41.

Oweis, T. 1997. *Supplemental Irrigation: A Highly Efficient Water-use Practice*. Aleppo, Syria: International Center for Agricultural Research in the Dry Areas.

Oweis, T., and A. Hachum. 2001. "Reducing Peak Supplemental Irrigation Demand by Extending Sowing Dates." *Agricultural Water Management* 50 (2):109–23.

Oweis, T., and A. Taimeh. 1996. "Evaluation of a Small Basin Water-Harvesting System in the Arid Region of Jordan." *Water Resources Management* 10 (1): 21–34.

Oweis, T., M. Pala, and J. Ryan. 1998. "Stabilizing Rainfed Wheat Yields with Supplemental Irrigation and Nitrogen in a Mediterranean Climate." *Agronomy Journal* 90 (5): 672–81.

Oweis, T., D. Prinz, and A. Hachum. 2001. *Water Harvesting: Indigenous Knowledge for the Future of the Drier Environments*. Aleppo, Syria: International Center for Agricultural Research in the Dry Areas.

Pandey, R.K., J.W. Maranville, and A. Admou. 2000. "Deficit Irrigation and Nitrogen Effects on Maize in a Sahelian Environment: I. Grain Yield and Yield Components." *Agricultural Water Management* 46 (1): 1–13.

Panigrahi, B., S.N. Panda, and A. Agrawal. 2005. "Water Balance Simulation and Economic Analysis for Optimal Size of On-farm Reservoir." *Water Resources Management* 19 (3): 233–50.

Perrot-Maître, D., and P. Davis. 2001. *Case Studies: Developing Markets for Water Services from Forests*. Washington D.C.: Forest Trends.

Pretty, J., and R. Hine. 2001. *Reducing Food Poverty with Sustainable Agriculture: A Summary of New Evidence*. Final Report of the "Safe World" Research Project. University of Essex, UK.

Ramankutty, N., J.A. Foley, and N.J. Olejniczak. 2002. "People and Land: Changes in Global Population and Croplands during the 20th Century." *Ambio* 31(3): 251–57.

Rego, T.J., S.P. Wani, K.L. Sahrawat, and G. Pardhasardhy. 2005. *Macro-benefits from Boron, Zinc, and Sulphur Application in Indian SAT: A Step for Grey to Green Revolution in Agriculture*. Global Theme on Agroecosystems Report 16. Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Rockström, J. 2003. "Water for Food and Nature in Drought-prone Tropics: Vapour Shift in Rain-fed Agriculture." *Royal Society Transactions B Biological Sciences* 358 (1440): 1997–2009.

Rockström, J., and M. Falkenmark. 2000. "Semiarid Crop Production from a Hydrological Perspective: Gap between Potential and Actual Yields." *Critical Reviews in Plant Science* 19 (4): 319–46.

IWMI Part 4 Ch8-16 final.indd 350 2/28/07 11:06:57 AM

Rockström, J., P-E. Jansson, and J. Barron. 1998. "Seasonal Rainfall Partitioning under Runon and Runoff Conditions on Sandy Soil in Niger. On-farm Measurements and Water Balance Modelling." *Journal of Hydrology* 210 (1–4): 68–92.

Rockström, J., P. Kaumbutho, J. Mwalley, A.W. Nzabi, M. Temesgen, L. Mawenya, J. Barron, and S. Damgaard-Larsen. Forthcoming. "Conservation Farming Strategies in East and Southern Africa: A Regional Synthesis of Crop and Water Productivity from On-farm Action Research." Submitted to *Soil and Tillage Research*.

Rosegrant, M., C. Ximing, S. Cline, and N. Nakagawa. 2002. "The Role of Rainfed Agriculture in the Future of Global Food Production." EPTD Discussion Paper 90. International Food Policy Research Institute, Environment and Production Technology Division, Washington, D.C. [www.ifpri.org/divs/eptd/dp/papers/eptdp90.pdf].

Schreider, S.Y., A.J. Jakeman, R.A. Letcher, R.J. Nathan, B.P. Neal, and S.G. Beavis. 2002. "Detecting Changes in Streamflow Response to Changes in Non-climatic Catchment Conditions: Farm Dam Development in the Murray-Darling Basin, Australia." *Journal of Hydrology* 262 (1–4): 84–98.

Seckler, D., and U. Amarasinghe. 2004. "Major Problems in the Global Water-Food Nexus." In C. Scanes and J. Miranowski, eds., *Perspectives in World Food and Agriculture 2004*. Ames, Iowa: Iowa State Press.

SEI (Stockholm Environment Institute). 2005. "Sustainable Pathways to Attain the Millennium Development Goals—Assessing the Role of Water, Energy and Sanitation." Document prepared for the UN World Summit, 14 September, New York. Stockholm.

Shiferaw, B., H.A. Freeman, and S. Swinton. 2004. *Natural Resource Management in Agriculture: Methods for Assessing Economic and Environmental Impacts*. Wallingford, UK: CABI Publishing.

Siegert, K. 1994. "Introduction to Water Harvesting: Some Basic Principles for Planning, Design and Monitoring." In *Water Harvesting for Improved Agricultural Production*. Proceedings of the FAO Expert Consultation, 21–25 November 1993, Cairo. Water Report 3. Rome: Food and Agriculture Organization.

Somme, G., T. Oweis, Q. Abdulal, A. Bruggeman, and A. Ali. 2004. *Micro-catchment Water Harvesting for Improved Vegetative Cover in the Syrian Badia*. On-farm Water Husbandry Research Reports Series 3. Aleppo, Syria: International Center for Agricultural Research in the Dry Areas.

Sreedevi, T.K., B. Shiferaw, and S.P. Wani. 2004. *Adarsha Watershed in Kothapally: Understanding the Drivers of Higher Impact*. Global Theme on Agroecosystems Report 10. Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Sreedevi, T.K., S.P. Wani, R. Sudi, M.S. Patel, T. Jayesh, S.N. Singh, and T. Shah. 2006. *On-site and Off-site Impact of Watershed Development: A Case Study of Rajasamadhiyala, Gujarat, India*. Global Theme on Agroecosystems Report 20. Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Stewart, J.I. 1988. *Response Farming in Rainfed Agriculture*. Davis, Calif.: The WHARF Foundation Press.

Stoorvogel, J.J., and E.M.A. Smaling. 1990. *Assessment of Soil Nutrient Depletion in Sub-Saharan Africa: 1983–2000*. Vol. 1, Main Report. Report 28. Wageningen, Netherlands: Winand Staring Centre.

Tanzania, Ministry of Agriculture and Food Security. 2001. "Agricultural Sector Development Strategy." Dar es Salaam.

———. 2002. "Water Policy." Dar es Salaam.

———. 2003. "Study on Irrigation Master Plan." Dar es Salaam.

Thirtle, C., L. Beyers, L. Lin, V. Mckenzie-Hill, X. Irz, S. Wiggins, and J. Piesse. 2002. *The Impacts of Changes in Agricultural Productivity on the Incidence of Poverty in Developing Countries*. DFID Report 7946. London: Department for International Development.

Tiffen, M., M. Mortimore, and F. Gichuki. 1994. *More People, Less Erosion—Environmental Recovery in Kenya*. Nairobi: ACTSPRESS, African Centre for Technology Studies.

Timmer, C.P. 1988. "The Agricultural Transformation." In H. Chenery, and T.N. Srinivasan, eds., *Handbook of Development Economics*. Vol. 1. Amsterdam: Elsevier.

UN Millennium Project. 2005. *Investing in Development: A Practical Plan to Achieve the Millennium Development Goals*. New York. Accessed May 2005. [www.unmillenniumproject.org].

UNStat. 2005. United Nations Statistics Division, Statistical databases. Accessed December 2005. http://unstats.un.org/unsd/default.htm.

Van Dijk, A., R. Evans, P. Hairsine, S. Khan, R. Nathan, Z. Paydar, N. Viney, and L. Zhang. 2006. *Risks to the Shared Water Resources of the Murray-Darling Basin*. Part II. Prepared for the Murray-Darling Basin Commission. MDBC Publication 22/06. Clayton South, Victoria, Australia: Commonwealth Scientific and Industrial Research Organization.

Van Duivenbooden, N., M. Pala, C. Studer, C.L. Bielders, and D.J. Beukes. 2000. "Cropping Systems and Crop Complementarity in Dryland Agriculture to Increase Soil Water Use Efficiency: A Review." *Netherlands Journal of Agricultural Science* 48 (3/4): 213–36.

IWMI Part 4 Ch8-16 final.indd 351 2/28/07 11:06:58 AM

Van Koppen, B., R. Namara, and C. Stafilios-Rothschild. 2005. "Reducing Poverty through Investments in Agricultural Water Management: Poverty and Gender Issues and Synthesis of Sub-Saharan Africa Case Study Reports." Working Paper 101. International Water Management Institute, Colombo.

Vörösmarty, C.J., C. Lévêque, and C. Revenga. 2005. "Fresh Water." In R. Hassan, R. Scholes, and N. Ash, eds., *Millenium Ecosystem Assessment*. Ecosystems and Human Well-being Vol. 1. Current Status and Trends. Washington, D.C.: Island Press.

Wani, S.P., S.S. Balloli, A.V.R. Kesava Rao, and T.K. Sreedevi. 2004. "Combating Drought through Integrated Watershed Management for Sustainable Dryland Agriculture." Presented at Regional Workshop on Agricultural Drought Monitoring and Assessment Using Space Technology, 4 May, National Remote Sensing Agency, Hyderabad, India.

Wani, S.P., M. Reddy, T.K. Sreedevi, and D. Raju, eds. 2006a. "Corporate Science and Technology Institutions—Partnerships for Inclusive and Sustainable Development and Economic Growth." Proceedings of the CII-ICRISAT Workshop, 27 February, International Crops Research Institute for the Semi-Arid Tropics, Andhra Pradesh, India.

Wani, S.P., P. Pathak, L.S. Jangawad, H. Eswaran, and P. Singh. 2003a. "Improved Management of Vertisols in the Semiarid Tropics for Increased Productivity and Soil Carbon Sequestration." *Soil Use and Management* 19 (3): 217–22.

Wani, S.P., P. Pathak, T.K. Sreedevi, H.P. Singh, and P. Singh. 2003b. "Efficient Management of Rainwater for Increased Crop Productivity and Groundwater Recharge in Asia." In J.W. Kijne, R. Barker, and D. Molden, eds., *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. Wallingford, UK, and Colombo: CABI Publishing and International Water Management Institute.

Wani, S.P., H.P. Singh, T.K. Sreedevi, P. Pathak, T.J. Rego, B. Shiferaw, and S.R. Iyer. 2003c. "Farmer-participatory Integrated Watershed Management: Adarsha Watershed, Kothapally India. An Innovative and Scalable Approach." In R.R. Harwood and A.H. Kassam, eds., *Research towards Integrated Natural Resources Management: Examples of Research Problems, Approaches and Partnerships in Action in the CGIAR*. Washington, D.C.: Consultative Group on International Agricultural Research, Interim Science Council.

Wani, S.P., Y.S. Ramakrishna, T.K. Sreedevi, T.D. Long, T. Wangkahart, B. Shiferaw, P. Pathak, and A.V.R. Kesava Rao. 2006b. "Issues, Concepts, Approaches and Practices in Integrated Watershed Management: Experience and Lessons from Asia." In B. Shiferaw and K.P.C. Rao, eds., *Integrated Management of Watersheds for Agricultural Diversification and Sustainable Livelihoods in Eastern and Central Africa: Lessons and Experiences from Semi-Arid South Asia*. Proceedings of the International Workshop held at International Crops Research Institute for the Semi-Arid Tropics, Nairobi, 6–7 December 2004. Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

WHO (World Health Organization). 2000. "Gender, Health and Poverty." Factsheet 251. June. [www.who.int/mediacenter/factsheets/fs251/en/].

World Bank. 1982. *World Development Report 1982*. New York: Oxford University Press.

———. 2000. "Spurring Agricultural and Rural Development." In *Can Africa Claim the 21st Century?* Washington, D.C.

———. 2005. *Agricultural Growth for the Poor: An Agenda for Development.* Washington, D.C.: World Bank.

Zaal, F., and R.H. Oostenrup. 2002. "Explaining a Miracle: Intensification and the Transition towards Sustainable Small-scale Agriculture in Dryland Machakos and Kitui Districts, Kenya." *World Development* 30 (7): 1221–87.

Zhang, H., and T. Oweis. 1999. "Water-yield Relations and Optimal Irrigation Scheduling of Wheat in the Mediterranean Region." *Agricultural Water Management* 38 (3): 195–211.

IWMI Part 4 Ch8-16 final.indd 352 2/28/07 11:06:59 AM