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The path to success is not a single vector from the current status

Artist: Nathanael Kang, Malaysia

3

Looking ahead to 2050: scenarios of alternative investment approaches

Coordinating lead authors: Charlotte de Fraiture and Dennis Wichelns

Lead authors: Johan Rockström and Eric Kemp-Benedict

Contributing authors: Nishadi Eriyagama, Line J. Gordon, Munir A. Hanjra, Jippe Hoogeveen, Annette Huber-Lee, and Louise Karlberg

Overview

Food production requires enormous amounts of water and land. Yearly, some 7,130 cubic kilometers of water are consumed by crops to meet global food demand, the equivalent of 90 times the annual runoff of the Nile River, or more than 3,000 liters per person per day. Most of it (78%) comes directly from the rain, and 22% from irrigation. Already, 1.2 billion people live in river basins characterized by absolute physical water scarcity, while another 1.6 billion live in basins where economic constraints limit the pace of much-needed investments in water management. Today, food production requires about 2,500 square meters of cropland and 5,500 square meters of grazing land per person per year. Without proper investments water shortages, water quality deterioration, and land degradation are expected to intensify, particularly in resource-poor countries.

World food demand, and thus the consumption of agricultural water, will continue to increase during the coming decades, even though the rate of population growth is declining. With a growing population, rising incomes, and changes in diets, food demand may grow by 70%–90% by 2050. Without improvements in the efficiency of agricultural water use, crop water consumption would have to grow by the same order of magnitude.

Competition between water for food production and water for other sectors will intensify, but food production will remain the largest water user worldwide. Because of urbanization, demand for water in domestic and industrial sectors is expected to grow by a factor of 2.2 by 2050. With the increasing scarcity of water, reuse of urban wastewater will become more important in water-short areas. Crop production for energy generation also is increasing in several areas, with potentially substantial implications for land and water use in agriculture. While major tradeoffs will occur between all water using sectors, the tradeoffs will be particularly pronounced between agriculture and the environment, the two largest water-demanding sectors. Climate change will further increase pressures on water resources management.

Investments to improve productivity in rainfed areas are needed to increase food production, stimulate economic development, and protect the environment. Many rural poor people depend on rainfed agriculture. Assisting the poor often implies focusing on smallholders in rainfed areas. Investment costs per hectare to upgrade rainfed areas tend to be relatively low, particularly in Sub-Saharan Africa, where most rural poor people live in rainfed areas and more poor people may be lifted out of poverty by focusing investment on rainfed areas. An optimistic outlook on yield growth shows that rainfed agriculture could meet food demand in 2050. The potential is particularly high in low-yielding farming systems, which tend to be where poor people live. Realizing the yield growth potential of existing rainfed areas reduces the need for new large-scale irrigation development. But improving rainfed production through water harvesting and supplemental irrigation also requires infrastructure, though smaller and less centralized. In addition, impacts on downstream water resources are more disperse and difficult to assess. Harvesting rainwater increases the amount of water consumed by crops, leaving less water for runoff to rivers and lakes. Intensifying rainfed agriculture throughout a large region will affect surface water and groundwater resources. This negative impact on downstream water availability is partly offset by improvements in water productivity. Relying largely on rainfed agriculture is also risky and needs the right incentives and measures to mitigate risks to individual farmers to realize its full potential.

> There is greater scope for increasing food production by improving output per unit of water in existing irrigated areas than by expanding irrigated area

There is greater scope for increasing food production by improving output per unit of water in existing irrigated areas than by expanding irrigated area. In an optimistic yield growth scenario, in which 80% of the gap between actual and obtainable irrigated yields is bridged, more than half of additional food demand can be met by improving output per unit of water on existing irrigated lands. In South Asia, where more than 50% of the cropped area is irrigated and productivity is low, additional food demand can be met by improving output per unit of water in irrigated agriculture rather than by expanding area under production. Bridging 80% of the irrigated yield gap contributes 540 million metric tons of grains, or 75% of additional global demand by 2050. Expanding irrigated area by 35% contributes only 260 million metric tons of grain. Yield improvements increase required water diversions by 30%, but irrigated area expansion requires an increase of 55%. This would have serious impacts on water scarcity and the provision of environmental services. Further, the capital cost of improving water productivity is smaller than the cost of new construction for area expansion. The largest gains in value per unit of water likely will be achieved through diversification and by using water for many productive purposes, such as fisheries, livestock, home gardens, and other small enterprises.

Optimal investment strategies will require an appropriate mix of strategies, depending on the potential and constraints in different regions. With inevitable increases in world food demand agriculture will require more land and water resources. Part of the increase in food production can be achieved by improving crop yields and increasing output per unit of water, through appropriate investments in both irrigated and rainfed agriculture. However, even in an optimistic investment scenario, cropped area will increase by 9% and water withdrawals for agriculture will increase by 13% by 2050. One challenge is to manage this additional water in a way that minimizes adverse impacts on—and where possible enhances—environmental services, while providing the necessary gains in food production and poverty alleviation.

Drivers of agricultural water use

Competing claims on water resources will increase with rising demands from agriculture, households, and industry. Recent forecasts warn of impending global problems unless appropriate action is taken to improve water management and increase water use efficiency (Seckler and others 1998; Seckler and others 2000; Alcamo and others 1997; Rosegrant, Cai, and Cline 2002; Shiklomanov 2000; Vörösmarty and others 2004; Bruinsma 2003; SEI 2005; Falkenmark and Rockström 2004; Rosegrant and others 2006). About 1.2 billion people live in water-scarce river basins (closed basins), and another 500 million where the limit to water resources is fast approaching (closing basins; see chapters 2 on trends and 16 on basins). Another 1.6 billion people live in basins where economic constraints limit the pace of much-needed investments in water management.

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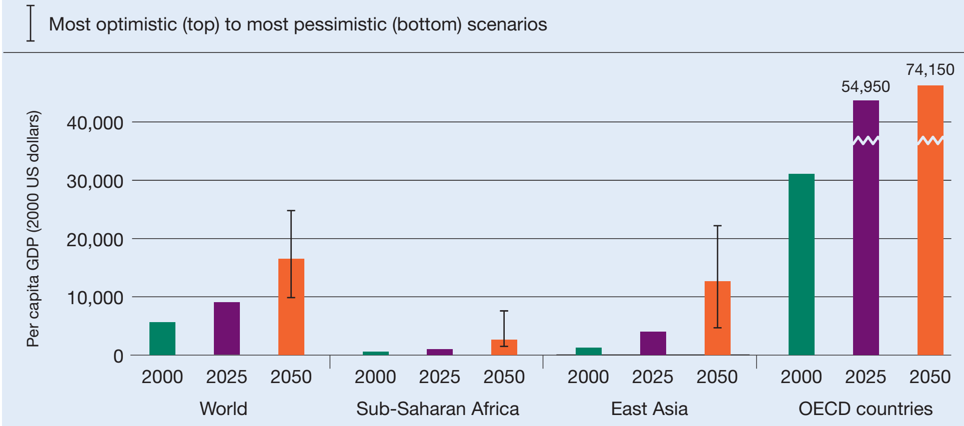
Food supply and demand

With continuing population growth, rising incomes, and urbanization, food demand will roughly double in the next 50 years.

Changing diets. As incomes rise, food habits change in favor of more nutritious and more diversified diets. Rising incomes throughout much of Asia over the last three decades led not only to more consumption of staple cereals but also to a shift in consumption patterns among cereal crops and away from cereals toward livestock products and high-value crops. In middle-income countries (such as Thailand) per capita rice consumption stabilized or slightly declined while wheat consumption increased. Meat consumption more than tripled, while dairy demand more than doubled from 1967 to 1997. Consumption of high-value crops, such as fruit, sugar, and edible oils, also increased substantially (FAOSTAT 2006).

In the years ahead urbanization and income growth will continue to drive food demand toward higher per capita food intake and richer diets, particularly in low- and middle-income countries. The base scenario of the Comprehensive Assessment of Water Management in Agriculture estimates that more than 25% of the increase in grain demand will be due to changes in diets—mainly for the production of animal products—rather than to population growth. Such changes influence future agricultural water demand because livestock products, sugar, and oil typically require more water to produce than cereals and roots and tubers (see chapter 7 on water productivity).

While the changes in diets follow similar patterns (Rosegrant, Cai, and Cline 2002; Pingali 2004), regional and cultural differences are pronounced—and are expected to remain so in coming decades. Meat consumption will rise slower in India than in China, but figure **3.1** **The world will get richer, but large income gaps will remain**



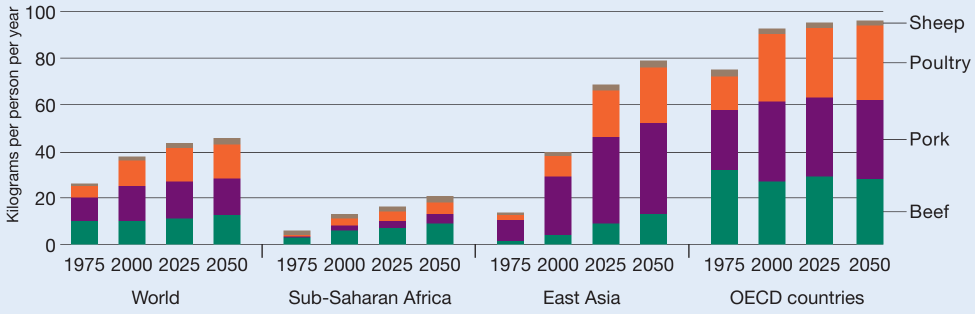
Source: MEA 2005; Alcamo and others 2005.

demand for dairy products will increase rapidly, with profound impacts on water resources (Singh and others 2004). In China per capita pork consumption is slightly higher than in the United States and increasing quickly, while per capita beef consumption is only 10% of that in the United States. Meat consumption in much of Sub-Saharan Africa is not directly related to income, because many pastoralists eat livestock products and bushmeat out of necessity.

Figures 3.1, 3.2, and 3.3 illustrate trends in income and per capita food consumption. Table 3.1 provides estimates of agricultural commodity demands used in this study, comparing them with projections published by others.

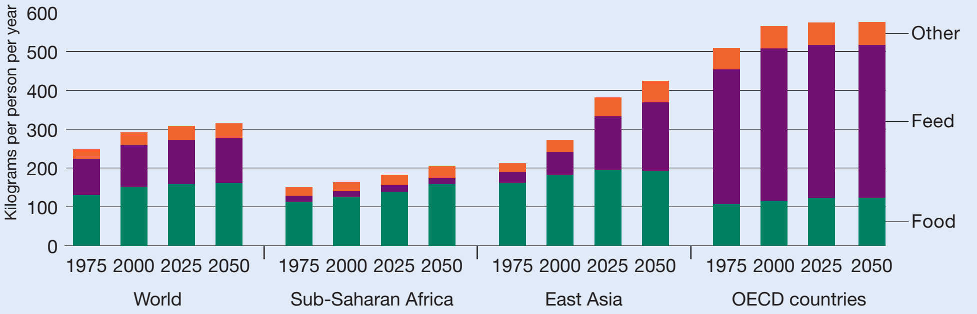
Income is a major driver of changes in diets. The income gap between rich and poor countries will decline, but remain large**.** In 2000 per capita GDP was estimated at $5,630 worldwide, $31,650 in Organisation for Economic Co-operation and Development (OECD) countries, $1,230 in East Asia, and $560 in Sub-Saharan Africa. According to projections by the Millennium Ecosystem Assessment, none of the developing regions will reach the OECD level by 2050. Projections exhibit great uncertainty. The I bars in figure 3.1 indicate the difference between the most optimistic and pessimistic among that assessment's scenarios. The colored bars depict the income projections we use in our scenario analysis (borrowed from the Millennium Ecosystem Assessment scenario TechnoGarden).

Global average meat consumption is estimated at 37 kilograms (kg) per capita per year in 2000, increasing to 48 kg in 2050 (see figure 3.2). Regional variation is large—meat consumption in Sub-Saharan Africa is about 12 kg per capita, less than one-sixth the meat consumption in OECD countries. With economic growth East Asia will move toward the same consumption level as OECD countries. Our estimates are comparable to those of other studies. The Millennium Ecosystem Assessment estimates global average annual meat demand by 2050 in the range of 41–70 kg per capita: 100–130 kg per capita for the OECD and 18–27 for Sub-Saharan Africa (Alcamo and others 2005). The Food figure **3.2** **Meat consumption per person will roughly double in East Asia**



Source: For 1975 and 2000, FAOSTAT 2006; for 2025 and 2050, International Water Management Institute analysis done for the Comprehensive Assessment of Water Management in Agriculture using the Watersim model.

figure **3.3** **Feed demand drives future demand for grains**



Source: For 1975 and 2000, FAOSTAT 2006; for 2025 and 2050, International Water Management Institute analysis done for the Comprehensive Assessment of Water Management in Agriculture using the Watersim model.

and Agriculture Organization's (FAO) interim report *Agriculture: Towards 2030/2050* provisionally estimates a global average of 52 kg per capita by 2050 (FAO 2006). Expected growth in per capita meat consumption in East Asia and the OECD will be much slower in the next 25 years than in the past 25 years (Alexandratos 1997, 2005). In OECD countries meat consumption will stabilize or decline, due partly to health considerations.

In high-income countries the growth rate in cereal consumption per capita declines over time, approaching zero by 2050 (see figure 3.3). In growing economies in East Asia (including China) cereal consumption continues to increase due to increasing feed grain demand, while per capita food consumption stabilizes. In Sub-Saharan Africa cereal food consumption continues to increase, but at a modest rate.

Increasing consumption of livestock products leads to higher feed grain demand, though the extent is subject to debate. Livestock are fed primarily by a combination of grass (grazing), crop residuals, and feedstuffs (primarily grains). Red meats require twice as much feed grain as white meats (Seckler and others 2000; Verdegem, Bosma, and Verreth 2006). In OECD countries, where cattle are raised largely on feed grains, cattle feeding accounts for two-thirds of the average per capita grain consumption. In Sub-Saharan Africa and India, where grazing is common and livestock are fed crop residuals and by-products, less than 10% of the grain supply is used for feed. Producing 1 kg of meat requires 2.3 kg of maize in the United States but only 0.1 kg in India (derived from FAOSTAT 2006).

An important question is how livestock will be fed in the future (Seckler and others 2000). Some argue that cattle will be raised largely on grass and crop residuals (as today) and that increases in feed demand will largely be offset by improving feed efficiency

table **3.1** **Comparison of global demand projections**

Variable	FAOSTAT 2006 Base year 2000	Comprehensive Assessment of Water Management in Agriculture 2025
Calories per capita (kilocalories per person per day)	2,790	3,100
Rice (millions of metric tons)	349	545
Wheat (millions of metric tons)	570	805
Maize (millions of metric tons)	610	870
Cereals for food (millions of metric tons)	940	1,230
Cereals for feed (millions of metric tons)	645	890
Cereals total[c] (millions of metric tons)	1,840	2,560
Roots and tubers (millions of metric tons)	685	625
Vegetables (millions of metric tons)	750	1,020
Oil crops (millions of metric tons)	370	585
Meat (millions of metric tons) demand[d]	220	360
Sugar[e] (millions of metric tons)	146	195
Aquaculture (millions of metric tons)	41	80
Milk and dairy (millions of metric tons)	476	720
Milk cows[g] (millions)	625	805
Beef cows[g] (millions)	300	405
Pigs[g] (millions)	1,150	1,500
Grazing land (millions of hectares)	3,450	4,660

a. Based on per capita gross food consumption including losses during processing and consumption. Most people actually consume fewer calories.

b. Production in millions of tons

c. Total cereals include cereals for food, feed, and other purposes

d. Beef, pork, poultry, and sheep.

e. Raw sugar equivalent.

f. Verdegem, Bosma, and Verreth 2006.

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(Rosegrant, Cai, and Cline 2002) or by switching to other types of feed (Verdegem, Bosma, and Verreth 2006). Others claim that grain feeding will gain importance with decreasing opportunities to expand grazing land. In addition, with urbanization, livestock production will become more intensive and concentrated near cities (Keyzer and others 2005).

Figure 3.3 shows the potential impact on feed consumption, assuming that livestock feeding remains largely as it is today. Ways to improve livestock water productivity are described in chapter 13 on livestock.

General trends toward more diversified and meat-based diets are well documented (Pingali 2004; Alexandratos 1997, 2005), but considerable uncertainties remain regarding food and feed demand projections. Environmental concerns and emerging health

International Water Management Institute 2025	International Food Policy Research Institute 2025	Food and Agriculture Organization 2030	Comprehensive Assessment of Water Management in Agriculture 2050	Food and Agriculture Organization 2050	Millennium Ecosystem Assessment 2050
2,950		3,050	2,970[a]	3,130	2,970–3,600
	510	533	580	524[b]	
	770	851	890	908[b]	
	905		1,000		
1,175	1,240	1,406	1,480	1,445	
940	1,012	1,148	1,010		
2,435	2,606	2,838	2,980	3,012	2,864–3,229
	630	615	810	670	
			1,570		
			780		
	336	373	440	465	377–567
		216	250	240	
			122[f]		
		746	925	895	
		1,858[h]	1,070		
			510		
			1,790		
			5,220		

g. Assuming no changes in yield and extraction rates.

h. This is the total for milk and beef cows.

Source: For International Water Management Institute, Seckler and others 2000; for International Food Policy Research Institute, Rosegrant, Cai, and Cline 2002; for Food and Agriculture Organization 2030, FAO 2002, and for 2050, FAO 2006; for Millennium Ecosystem Assessment, MEA 2005; for grazing land, Stockholm Environment Institute projections done for the Comprehensive Assessment of Water Management in Agriculture.

problems related to obesity might generate new trends, particularly in high-income countries. Outbreaks of diseases such as mad cow disease and, more recently, avian flu might frighten consumers away from meat consumption. In addition, future feed grain requirements per kilogram of meat, milk, and eggs (see figure 3.3) and income projections that drive changes in diets are uncertain (see figure 3.1).

Assuming production of 120 million metric tons of fish from aquaculture by 2050 and 1.6 cubic meters of water per kilogram, 192 cubic kilometers of water would be required, or about 8% of current irrigation withdrawals

Changes in fish production. As fish stocks in oceans and fresh water bodies decline (Kura and others 2004; Worm and others 2006), the importance of aquaculture in meeting world fish demand will increase (see chapter 12 on inland fisheries). Between 1998 and 2003 global production from capture fisheries fluctuated between 87.7 and 95.5 million metric tons. In the same period aquaculture production increased steadily from 30.6 to 41 million metric tons (Verdegem, Bosma, and Verreth 2006). Projections of global fish production from aquaculture range from 15.6 kg per capita in 2030 to 22.5 kg per capita in 2030 (Ye 1999). The higher estimate corresponds to global aquaculture production of 186 million metric tons.

In many areas environmental flow regulations are needed to ensure adequate volumes and seasonal water patterns in rivers to maintain fisheries and other ecosystem services (Poff and others 1997; Arthington and others 2006). In water-scarce basins during the dry season aquacultural production and environmental requirements might compete with water diversions for irrigation. However, in some areas fish production is an integral part of an irrigated agricultural production system (Nguyen-Khoa and Smith 2004 and chapter 12 on inland fisheries).

And in some areas aquaculture is linked with capture fisheries. For example, production of high-value commodities such as shrimp and salmon can require up to 3 kg of fishmeal per kilogram of output (Naylor and others 1998, 2000). However, aquacultural production of shrimp and salmon accounts for a small portion of worldwide fish production. In aggregate, aquaculture is a net producer, generating 3–4 kg of food fish per kilogram of feed fish used in production (Tidwell and Allan 2001).

Assessments of the impacts of aquaculture on freshwater demand vary by an order of magnitude. Verdegem, Bosma, and Verreth (2006) estimate that aquaculture requires on average between 0.4 and 1.6 cubic meters of water per kilogram of fish produced from open water evaporation and seepage from ponds. Where fish are fed grains, this adds to the water requirements. Extensive aquaculture can require up to 45 cubic meters of water per kilogram of fish. Assuming production of 120 million metric tons of fish from aquaculture by 2050 and 1.6 cubic meters per kilogram (Verdegem, Bosma, and Verreth 2006), 190 cubic kilometers of water would be required, or about 8% of current irrigation withdrawals. This estimate does not account for seepage water that might recharge groundwater and be reused. Additional water for fish when aquaculture is combined with canals and reservoirs for irrigation is negligible at a global scale (see chapter 7 on water productivity). However, problems might arise locally if water is retained in an irrigation delivery system during peak demand. Integrating fisheries with irrigation is an important way to increase output and value per unit of water (see chapter 12 on inland fisheries).

Food, feed, and energy crops. Food production requires large amounts of water. On average, 1 kg of grain requires 1,600 liters of water, but estimates vary from 400 to more than 5,000 liters per kilogram of grain. The amount of water required to produce crops varies by crop and region, depending on climate, mode of cultivation (rainfed or irrigated, high-input or low-input agriculture), crop variety and length of growing season, and crop yields (see chapter 7 on water productivity). Following the water productivity framework in the livestock chapter, the water account for livestock includes water used to produce both feed crops and grass for grazing. By contrast, food wastes and crop residues are by-products, for which the water requirements have already been accounted. It is estimated that 7,130 cubic kilometers are consumed by crops globally, including both feed and food crops (table 3.2).

Nonfood crops such as cotton occupy 3% of the cropped area and 9% of irrigated area. The demand for cotton is expected to more than double by 2050. Crop production for energy also is increasing in several areas, with potentially substantial implications for land and water use in agriculture (Koplow 2006).

> **Even with improvements in water productivity, agriculture will continue to consume a large portion of the world's developed water supply in 2050**

Water for food production

Suppose improvements in land and water productivity or major shifts in production patterns do not take place. The amount of crop water consumption in 2050 would increase by 70%–90% depending on actual growth in population and income, and assumptions regarding the water requirements of livestock and fisheries. If that occurs, crop water consumption will reach 12,050–13,500 cubic kilometers, up from 7,130 cubic kilometers today. This estimated range includes crop water depletion for food and feed production, plus losses through evaporation from soil and open water. Evaporation from flooded rice paddies, irrigation canals, and reservoirs also is included, while evaporation from grasslands and aquaculture ponds is not. The estimate also excludes the impact of likely improvements in water productivity (see chapter 7 on water productivity). However, even with improvements in water productivity, agriculture will continue to consume a large portion of the world's developed water supply.

Only some of the water consumed by crops is diverted from surface and groundwater resources through irrigation—blue water. A large portion comes directly from rainfall that infiltrates the soil to generate soil moisture—green water (see chapters 1 on setting the scene and 8 on rainfed agriculture). Assessments of future water withdrawals for agriculture depend on assumptions regarding water sources. According to our estimates, 78% of the water consumed in agriculture is met from rain falling directly on land in both rainfed and irrigated areas.[1] The other 22% (1,570 cubic kilometers) is met by consumptive use of water withdrawn from rivers, lakes, and aquifers. To provide this 1,570 cubic kilometers, an estimated 2,630 cubic kilometers are withdrawn from surface water and groundwater resources. This means that 60% of the water withdrawn for agriculture is consumed (rendered unusable for further use) by crops and evaporation losses from soils and open water bodies, while 40% returns to surface water or groundwater.[2]

The ratio of consumption to withdrawals is commonly referred to as the consumptive or depleted fraction (Seckler and others 2000).[3] Consumptive fractions tend to be

table **3.2** **Crop water consumption and water needed for grazing in 2000**
(cubic kilometers unless otherwise indicated)

	Crops				
Region	**Total cereals[a]**	**Roots and tubers**	**Sugar**	**Vegetables and fruits**	**Soybeans**
Sub-Saharan Africa	557	154	25	26	7
East Asia	960	99	67	172	68
South Asia	896	18	135	84	37
Central Asia & Eastern Europe	525	44	14	7	4
Latin America	336	29	163	35	176
Middle East & North Africa	166	4	6	32	1
OECD countries	640	12	24	15	134
World	4,089	363	434	370	427

Note: Water for aquaculture or inland fisheries is not included in these estimates.

a. Includes cereals used for feed.

b. Estimating the water transpired on grazing land is a fairly new exercise and relies on several uncertain factors—the feed energy supplied per kilogram of grass, feed energy requirements per animal, the mix of feeds for different kinds of livestock, and the water-use efficiency of grass production. The estimates for the composition of livestock feed from grazing are produced using the same assumptions as in chapter 13 on livestock of 5 kg of grass per tropical livestock unit per day and a water-use efficiency of 1.3 kg of dry matter per cubic meter of water, which corresponds to 750 liters per kilogram. This estimate is much lower than the amount of water evaporated from pastureland estimated

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low in water-abundant areas, where intensive water management is not cost effective, and higher in water-scarce areas, where plants use shallow groundwater and farmers reuse drainage water. In the Middle East and North Africa region we estimate a consumptive fraction of 77%, with peak values close to 100%. In water-abundant areas the consumptive fraction can be as low as 35%. Generally it is not feasible or desirable to achieve a consumptive fraction higher than 70% at the basin scale, due to substantial infrastructure and environmental costs (Molden, Sakthivaldivel, and Habib 2000 and chapter 16 on river basins).

Our estimate of 2,630 cubic kilometers withdrawn for agriculture in 2000 is consistent with estimates in other studies (box 3.1).

Ways to meet the demand for water for food. The estimated amount of additional water required to produce enough food in the future is large, given current trends in population, income, and diet. In addition, the increasing demand for nonagricultural water will intensify competition for limited resources. Without increases in productivity an additional 5,000 cubic kilometers of water will be required for crop production to meet future food demand, while the land area used for crops and livestock will increase by 50%–70% (Kemp-Benedict 2006b).

There are several ways to satisfy future food demands with the world's available land and water resources:

- Expanding rainfed croplands.

Crops			Livestock		
Other	Total	Share of water from rivers and aquifers (%)	Feed crops	Grazing[b]	Share of water for grazing (%)
312	1,071	6	68	218	76
325	1,661	22	277	96	26
335	1,505	41	16	27	63
193	772	20	277	61	18
169	895	12	190	240	56
30	225	61	59	13	18
181	990	17	426	185	30
1,547	7,130[c]	22	1,312	840	39

by Postel (1998): 5,800 cubic kilometers. Our estimates describe the amount of evaporation for grass actually consumed, rather than for the total area reported as "permanent pasture." Two factors explain the difference: in extensive grazing lands only a small portion of the grass biomass is consumed, and reported permanent pasture land tends to be overestimated, with part of the pasture land underused (Kemp-Benedict 2006b).

c. This estimate is comparable to other estimates, such as Rockström and others (1999), 6,800 cubic kilometers; Chapagain (2006), 6,390 cubic kilometers; and Postel (1998), 7,500 cubic kilometers.

Source: For crops, Watersim simulations, and for grazing, Stockholm Environment Institute computations, both done for the Comprehensive Assessment of Water Management in Agriculture.

- Increasing water productivity and upgrading rainfed areas by enhancing management of rainwater and local runoff through in-situ and ex-situ water harvesting (adding small amounts of irrigation water where feasible).
- Increasing annual irrigation water supplies by developing new surface water storage facilities and increasing groundwater withdrawals and use of wastewater.
- Increasing water productivity in irrigated areas and the value per unit of water by integrating livestock and fisheries in irrigated systems.
- Promoting agricultural trade from water-abundant and water-efficient producing areas to water-scarce areas.
- Changing food demand patterns (influencing diets toward more water-efficient food mixes, such as less meat) and reducing waste (post-harvest losses).

Much effort has been devoted to agricultural water management in irrigated areas, while water management in rainfed areas has received less attention.[4] Yet there are notable opportunities to improve yields and water productivity in rainfed areas. The Comprehensive Assessment presents evidence on the opportunities to more than double yields for major rainfed crops in tropical developing countries through integrated soil, water, and crop management (see chapters 8 on rainfed agriculture and 15 on land).

Water productivity can be enhanced in rainfed areas by integrating in-situ management of rainfall (maximizing rainfall infiltration on farm fields), and soil fertility management with external management of local runoff (for supplemental irrigation). For example, farmers can use improved tillage methods (in-situ water harvesting),

box **3.1** Estimates of water withdrawals vary

The concerns that water is a finite resource and that inappropriate uses of water can harm the environment are not new. Many researchers have estimated actual and future global water withdrawals and depletion for human purposes. Studies conducted in the 1960s and 1970s projected that by 2000 global water withdrawals would climb to 6,000–8,000 cubic kilometers of the 12,500 cubic kilometers of accessible resources, with dire consequences for the world's water resources (Gleick 1999). More recent assessments suggest that current annual global water withdrawals by all sectors are 3,100–3,700 cubic kilometers. Thus some of the earlier forecasts are two times the water demands actually observed (Gleick 1999), largely because water productivity improvements were not taken into account. The analysis in this chapter accounts for potential improvements in water productivity.

Estimates of water demands also vary because of differing definitions of *water use*. Some writers use the term to describe total withdrawals, while others refer to crop water depletion. In addition, data describing irrigation and basin efficiency are sparse, and estimates are subject to judgments about the amount of reuse of return flows (Seckler and others 2000; Molden, Sakthivaldivel, and Habib 2000). Furthermore, past projections have focused almost exclusively on withdrawals from rivers and groundwater, and consumptive use for irrigation, domestic, and industrial sectors. Recent estimates account more clearly for water consumption in rainfed agriculture (Rockström and others 1999; Falkenmark and Rockström 2004; Gordon and others 2005).

The following table presents some recent best estimates on water withdrawals for agriculture in 2025.

Projected increases in water withdrawals for irrigation, various sources
(cubic kilometers unless otherwise indicated)

Source	1995	2025	Increase (%) 1995–2025
Shiklomanov (2000)	2,488	3,097	24
Seckler and others (2000)	2,469	2,915	18
Faurès, Hoogeveen, and Bruinsma (2002)	2,128	2,420[a]	14

a. This estimate uses 2030 as the projection year and covers projects for developing countries only, constituting 75%–80% of global withdrawals.

Source: Molden and de Fraiture 2004.

fertilization methods, and higher yielding varieties to enhance yields and water productivity in rainfed agriculture (see chapters 8 on rainfed agriculture and 15 on land). Farmers can also implement soil and water conservation measures that reduce surface runoff and soil evaporation, while increasing the proportion of rainfall used effectively in crop production.

International trade is important in achieving national food security goals, with potentially interesting implications for global water resources. In 1995, without international trade in cereal crops, irrigation water consumption would have been higher by 11% (de Fraiture and others 2004; Oki and others 2003).

Post-harvest losses globally are estimated at 10%–35% of total production (WRI 1998). In the United States food waste in processing, retailing, and consumer use is about 27% of the food supply (WRI 1998). Preventing post-harvest losses in Africa—an estimated 10% of total production is lost on the farm[5]—might reduce crop water consumption by 95 cubic kilometers a year with current crop water productivity. Reducing pest and disease damage could improve water productivity substantially: 40% of potential output in Africa and Asia, and about 20% in the developed world, is lost to pests and pathogens (Somerville and Briscoe 2001). Much of the loss occurs after plants are fully grown, after most or all of the water required to produce a crop has been consumed. So, reducing losses to pests and pathogens will improve productivity per unit of evapotranspiration, generating a net water savings. But this will require chemicals that may reduce water quality.

Modifying diets, though difficult, can have large impacts on future food demands and water requirements (SIWI and IWMI 2004). Projections of global meat demand by 2050, as reported in the Millennium Ecosystem Assessment scenarios, vary from 41 to 70 kg per person per year depending on income, price, and public perceptions about health risks and environmental concerns (Alcamo and others 2005). The lower bound estimate (41 kg per person) might require 950 cubic kilometers (15%) less crop water consumption than the upper bound estimate (70 kg per person).

Withdrawals for nonagricultural sectors are expected to more than double by 2050, increasing competition for water between sectors

Nonagricultural water use

More water to domestic and industrial purposes. The demand for water in industrial and domestic uses increases with urbanization. Withdrawals for nonagricultural sectors are expected to more than double by 2050, increasing competition for water between sectors (table 3.3). In most countries water for cities receives priority over water for agriculture—by law or by custom (Molle and Berkoff 2006). Greater competition for water will leave less for agriculture, particularly near large cities in water-short areas (such as the Middle East and North Africa, Central Asia, India, Pakistan, Mexico, and northern China). The estimates show also that while the proportion of water diverted for nonagricultural sectors increases, agriculture remains the largest water user among the productive sectors globally. While major tradeoffs will occur between all water-using sectors, they will be particularly pronounced between agriculture and the environment as the two largest water demanding sectors (Rijsberman and Molden 2001).

Only a small part of the water diverted for domestic and industrial purposes is consumed, with 75%–85% of water diverted to urban areas flowing back to rivers, lakes, and groundwater as return flow. In many urban areas, particularly in water-scarce developing countries, wastewater is used for high-value vegetable production, a livelihood activity for millions of city dwellers (Gupta and Gangopadhyay 2006; Hussain and others 2001, 2002; Raschid-Sally, Carr, and Buechler 2005; and chapter 11 on marginal-quality water).

The use of urban wastewater for irrigation will increase as water becomes more scarce in urbanizing areas. If by 2050 half the return flows from cities are reused, 200 cubic kilometers of wastewater might be used for irrigation. This would represent only 6%–8% of future agricultural withdrawals, but the economic values generated might be table **3.3**

Withdrawals by nonagricultural sector will increase by a factor of 2.2 by 2050
(cubic kilometers unless otherwise indicated)

	Agriculture	Domestic		Manufacturing	
Region	**2000**	**2000**	**2050**	**2000**	**2050**
Sub-Saharan Africa	68	7	35	2	8
East Asia	518	48	185	21	159
South Asia	1,095	15	90	4	29
Central Asia & Eastern Europe	244	40	88	68	236
Latin America	175	31	78	12	42
Middle East & North Africa	173	14	51	3	10
OECD countries	233	121	152	135	131
World	2,630	278	681	245	617

Note: Seckler and others (2000) estimate domestic use at 265 cubic kilometers in 1995,with a 2.1% growth rate to 2025, and industrial use at 590 cubic kilometers, with a 1.6 % growth rate. Rosegrant, Cai, and Cline (2002) estimate growth in nonirrigation consumptive water use of 1.6% a year for 1995–2025 (withdrawals not reported). Shiklomanov (2000) estimates annual growth of 1.7% for 1995–2025 for domestic and industrial use.

(continues on facing page)

substantial. Much of the wastewater would be used to produce highly valued vegetables, helping sustain the livelihoods of millions of small farmers (Hussain and others 2001, 2002). While reuse of city wastewater for agriculture poses environmental and health risks, these can be minimized with proper management (see chapter 11 on marginal-quality water).

In many countries rising incomes are correlated with increasing demands for restoring and maintaining environmental services. The demand for environmental amenities adds pressure on scarce water resources. The environment has become a new competitor for water in some areas, as reflected in changing policies for water allocation and pricing (see chapter 6 on ecosystems). A first-cut estimate by Smakthin, Revenga, and Döll (2004) indicates that 20%–45% of long-term annual flows must be preserved to maintain essential ecosystem services.[6]

UNESCO (2006) suggests that 100 cubic kilometers need to be added to estimates of future water demands to account for current overexploitation of groundwater and 30 cubic kilometers must be added to account for the mining of fossil groundwater.

Exploring alternative strategies

The policies and investment strategies chosen to increase food production will affect water use, the environment, and rural and urban poverty. Feeding 3 billion more people by 2050 will require water development and management decisions that address tradeoffs between food and environmental security. Three broad investment strategies are to:

- Improve productivity in rainfed settings.

Thermo-cooling		Total nonagricultural				
2000	2050	2000	Share of total (%) 2000	2050	Share of total (%) 2050	Annual increase (%) 2000–50
1	18	10	13	60	47	3.7
32	75	101	16	419	50	2.9
15	55	34	3	175	16	3.3
48	52	156	39	377	55	1.8
10	134	53	23	254	61	3.2
7	22	24	12	82	35	2.5
262	307	518	69	590	77	0.3
376	664	902	25	1,963	42	1.6

Source: Stockholm Environment Institute 2006 estimates done for the Comprehensive Assessment of Water Management in Agriculture.

- Increase production in irrigated areas.
- Expand international trade.

We examine these strategies and conclude with a plausible scenario that combines the best elements of the three: the Comprehensive Assessment scenario (table 3.4).

We use scenarios to illustrate the tradeoffs in these investment strategies. To explore the potential outcomes and impacts of each strategy, we highlight each alternative and contrast one with another. For example, we compare a scenario that emphasizes area expansion with a scenario that emphasizes productivity improvement. Actual improvements in agricultural water management will consist of more balanced combinations of measures rather than one set. The impacts of policy choices involve a complex web of feedback mechanisms. Our aim is not to describe the future in all of its complexities and manifestations in this analysis, but rather to illustrate tradeoffs by examining the potential implications of changes in a limited number of variables most amenable to policy changes. We present alternative policy choices and water management strategies, concluding with an optimistic scenario that builds on the regional relevance and opportunities of those strategies.

In constructing the scenarios, we use Watersim (de Fraiture forthcoming), a quantitative model consisting of two fully integrated modules: a food production and demand module based on a partial equilibrium framework, and a water supply and demand module based on a water balance and water accounting framework. Several relevant issues, such as impacts on the environment and poverty reduction, are difficult to model or quantify. Hence, we combine quantitative analysis with qualitative interpretations based on detailed analysis of the current situation in chapters 4–16.

table **3.4** **Overview of scenarios of irrigation, crop water use, crop yields, and water productivity in 2050**

	Base year	Rainfed scenarios 2050	
Variable	**2000**	**High yield**	**Low yield**
Rationale		Emphasizes investments in rainfed areas: water harvesting and supplemental irrigation	Simulates the pessimistic case where upgrading rainfed agriculture is not successful
Irrigated area (millions of hectares)	340	340	340
Growth (%)		0	0
Rainfed area (millions of hectares)	860	920	1,320
Growth (%)		7	53
Irrigated cereal yield (metric tons per hectare)	3.70	5.02	4.94
Growth (%)		34	30
Rainfed cereal yield (metric tons per hectare)	2.46	4.24	2.96
Growth (%)		72	20
Water productivity, irrigated (kilograms per cubic meter)	0.68	0.84	0.83
Growth (%)		24	22
Water productivity, rainfed (kilograms per cubic meter)	0.49	0.66	0.54
Growth (%)		35	10
Cereals traded (millions of metric tons)	262	510	620
Share of consumption traded (%)	14	17	22
Crop water consumption, rainfall (cubic kilometers)	5,560	7,415	9,040
Growth (%)		33	63
Crop water consumption, irrigation (cubic kilometers)	1,570	1,870	1,870
Growth (%)		19	19
Withdrawals for irrigation (cubic kilometers)	2,630	3,155	3,160
Growth (%)		19	19
Share of value from irrigated area (%)	46	40	40
Investments costs (billions of US dollars)		40–250	30–210

Note: Scenarios were constructed using the Watersim model (de Fraiture forthcoming).

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Can upgrading rainfed agriculture meet future food demand?

Rainfed areas generate about 62% of global cereal production on 71% of the area harvested in cereals. More generally, rainfed areas generate an estimated 54% of the gross value of worldwide crop production on 72% of the harvested area (Watersim estimates for the Comprehensive Assessment). With rising concerns over the high cost of expanding large-scale irrigation and the environmental impacts of large dams, upgrading rainfed agriculture is gaining increased attention (see chapter 8 on rainfed agriculture and box 3.2).

There are several compelling reasons to invest in water management in rainfed agriculture. There is high potential to improve productivity, especially where yields are low. A majority of the rural poor are smallholders who depend on rainfed rather than irrigated agriculture, so assisting the poor often implies focusing on smallholders in rainfed areas.

Irrigation scenarios 2050		Trade scenario	Comprehensive Assessment of Water Management in Agriculture scenario
Area expansion	**Yield improvement**	**2050**	**2050**
Emphasizes food self-sufficiency and stable food supply through expansion of irrigated areas	Emphasizes improving the performance of existing irrigated areas: increase in yield and water productivity	Simulates increased agricultural trade from water-abundant countries to water-scarce countries	Emphasizes optimal strategies that vary among regions: an optimistic, but plausible scenario
450 33	370 9	340 0	394 16
1,100 28	1,140 33	1,040 22	920 7
5.04 35	6.55 77	4.94 33	5.74 55
2.95 20	2.97 21	3.90 59	3.88 58
0.83 22	0.97 43	0.83 22	0.93 38
0.54 10	0.55 11	0.62 33	0.64 31
430	480	700	490
14	16	23	16
8,080 45	7,880 42	7,260 31	6,570 19
2,420 54	2,255 44	1,650 5	1,945 24
4,120 57	3,460 32	2,760 5	2,975 13
51	45	39	40
415	300	25–110	250–370

Realizing the potential of existing rainfed areas reduces the need for new large-scale irrigation development, which can generate adverse environmental impacts. And the cost of upgrading rainfed areas is generally lower than the cost of constructing irrigation schemes, particularly in Sub-Saharan Africa.

Nevertheless, the potential contribution of rainfed agriculture to world food production is the subject of debate, and forecasts of the relative roles of irrigated and rainfed agriculture vary considerably. Adoption rates of water-harvesting techniques are low, and extending successful local techniques over larger areas has proven difficult in the past. Relying on rainfed agriculture also involves considerable risk. Water-harvesting techniques are useful for bridging short dry spells, and investments in water management are thus a way to decrease risk in rainfed agriculture. But longer dry spells may lead to crop failure, and rainfed agriculture is generally more risky than fully irrigated agriculture.

box 3.2 What is upgrading rainfed agriculture?

Upgrading rainfed agriculture through improved water management consists of:

- In-situ soil and water management and water harvesting techniques (conservation agriculture, bunds, terracing, contour cultivation, furrows, land leveling).
- Ex-situ water harvesting for supplemental irrigation (surface microdams, subsurface tanks, farm ponds).

These measures are implemented primarily by farmers, without external interventions or detailed engineering analysis. The measures are less technology intensive, more labor intensive and environmentally less disruptive than conventional large-scale irrigation.

Some of these measures might be considered as irrigation by some observers. However, we find it helpful to describe a continuum of partially irrigated areas between the extremes of areas completely dependent on rainfall and areas that are fully irrigated (Rockström 2003).

Source: Chapter 8 on rainfed agriculture.

box 3.3 The GAEZ method and exploitable yield gaps

The Food and Agriculture Organization and the International Institute for Applied Systems Analysis have developed a method for assessing land suitability classes and maximum attainable yields under different input regimes using the Global Agro-Ecological Zones (GAEZ) concept (www.iiasa.ac.at/Research/LUC/GAEZ/index.htm).

The literature on yield gaps distinguishes two components: agroenvironmental and other non-transferable factors, and differences in crop management practices such as suboptimal use of inputs and other cultural practices. The portion of the gap due to the first component cannot be narrowed. The portion pertaining to the second component can be narrowed and is termed the "exploitable yield gap." Duwayri, Tran, and Nguyen (1999) suggest the theoretical maximum obtainable yields of wheat and rice might be as high as 20 metric tons per hectare. Yields of 17 metric tons per hectare have been achieved on experiment stations in subtropical climates and 10 metric tons per hectare in tropical climates. Wide yield differences are present even among countries with fairly similar agroecological environments. In such cases differences in the socioeconomic and policy environments play a major role (Bruinsma 2003, p. 297–303).

Rainfed scenarios: optimistic and pessimistic. To assess the potential of improving rainfed agriculture, we analyze two yield projections, low and high. We apply the Global Agro-Ecological Zones (GAEZ) methodology and use information describing exploitable yield gaps, the difference between actual and maximum attainable yields (box 3.3). The maximum attainable yield assumes high input levels and best suited varieties, depending on the quality of land. This approach provides realistic estimates based on known techniques, without assuming major breakthroughs (Fischer and others 2002; Bruinsma 2003).

The yield growth scenarios are formulated based on exploitable yield gaps (table 3.5). The high-yield scenario assumes—rather optimistically—that 80% of the gap will be bridged within the time horizon. This implies successful institutional reform, well functioning markets and credit systems, mechanization, improved use of fertilizers and

table **3.5** **Yield scenarios for rainfed agriculture**
(tons per hectare unless otherwise indicated)

Crop and region	Actual yield 2000	Maximum potential yield	Low-yield scenario		High-yield scenario		Historical annual growth rate,[a] irrigated plus rainfed (%)
			Simulated yield 2050	Annual growth rate (%) 2000–50	Simulated yield 2050	Annual growth rate (%) 2000–50	
Wheat							
Sub-Saharan Africa	1.3	3.4	1.9	0.7	3.2	1.8	2.6
Middle East & North Africa	0.8	3.5	1.2	0.7	1.6	1.3	2.4
Central Asia & Eastern Europe	2.0	5.1	2.4	0.4	3.8	1.3	1.1
South Asia	1.6	2.7	1.7	0.2	2.5	1.0	2.8
East Asia	3.0	4.6	3.3	0.2	4.5	0.8	4.4
Latin America	2.2	3.9	2.6	0.3	3.7	1.0	1.4
OECD countries	3.4	5.6	3.8	n.a.	5.5	1.0	1.6
World	2.4	5.0	2.7	0.3	3.8	0.7	2.2
Rice							
Sub-Saharan Africa	1.0	4.0	1.5	0.8	3.2	2.4	0.4
Middle East & North Africa	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.4
Central Asia & Eastern Europe	n.a.	2.4	n.a.	n.a.	n.a.	n.a.	0.2
South Asia	1.6	3.5	2.1	0.6	3.3	1.5	1.7
East Asia	1.8	4.5	2.4	0.5	4.3	1.7	2.0
Latin America	1.4	4.5	2.1	0.8	3.8	2.0	2.0
OECD countries	n.a.	2.9	n.a.	n.a.	n.a.	n.a.	0.8
World	1.6	4.2	2.0	0.5	3.6	1.6	1.7
Maize							
Sub-Saharan Africa	1.4	6.6	2.1	0.7	4.1	2.1	0.8
Middle East & North Africa	0.9	4.3	1.3	0.6	1.7	1.2	3.0
Central Asia & Eastern Europe	3.2	3.8	3.3	0.1	3.5	0.2	1.9
South Asia	1.6	6.9	2.5	0.9	4.3	2.0	1.4
East Asia	3.6	5.5	3.9	0.2	5.0	0.7	3.2
Latin America	2.7	5.3	3.3	0.4	4.9	1.2	2.5
OECD countries	8.3	10.1	8.7	0.1	9.1	0.2	2.0
World	4.0	7.8	4.3	0.2	6.2	0.9	2.0

n.a. is not applicable because crop not grown under rainfed conditions.

a. Historical growth rates include the effects of conversion from rainfed to irrigated production, particularly in South and East Asia during the green revolution. Achieving these growth rates in purely rainfed systems will be difficult. Time series data disaggregated for irrigated and rainfed yields are not available.

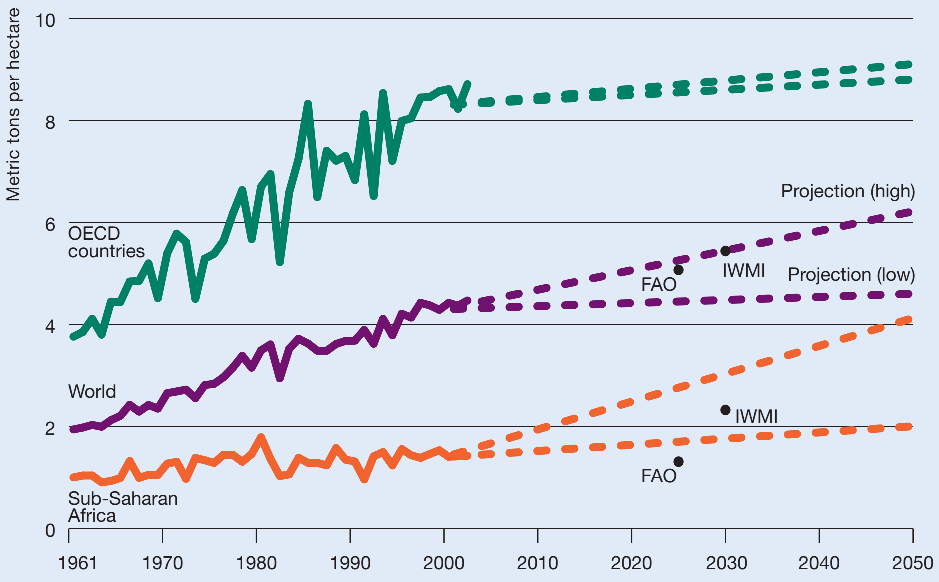
Source: Actual yields in 2000 based on data underlying Bruinsma (2003); maximum attainable rainfed yields (high input) derived from GAEZ country-level data.

high-yielding varieties, and rapid adoption of water-harvesting techniques. The pessimistic yield scenario assumes that only 20% of the gap will be bridged, due to a slow rate of adoption of soil fertility and crop improvements, in-situ soil and water management, and external water-harvesting measures. Where yields are already high and the exploitable gap is small, as in OECD countries, projected growth rates are low. Where yields are low, as in Sub-Saharan Africa, potential improvements are large. In some cases productivity improves at a higher rate than historically observed.

The potential for growth is high in Sub-Saharan Africa, where yields are low and have been more or less stagnant during the past 40 years. Observed yields are less than one-third of the maximum attainable yields, suggesting considerable scope for improvement. In OECD countries, where yields have been increasing rapidly, the scope for further improvements is likely smaller (figure 3.4).

Improved water management in rainfed areas is essential. Bridging the yield gap in rainfed areas will happen only with the right mix of physical and institutional infrastructure. This requires effort and investment additional to business-as-usual scenarios developed by the International Water Management Institute (Seckler and others 2000) and the FAO study, *World Agriculture: Towards 2015/2030* (Bruinsma 2003).

figure **3.4** **Past growth of maize yields and the potential for growth vary considerably by region**



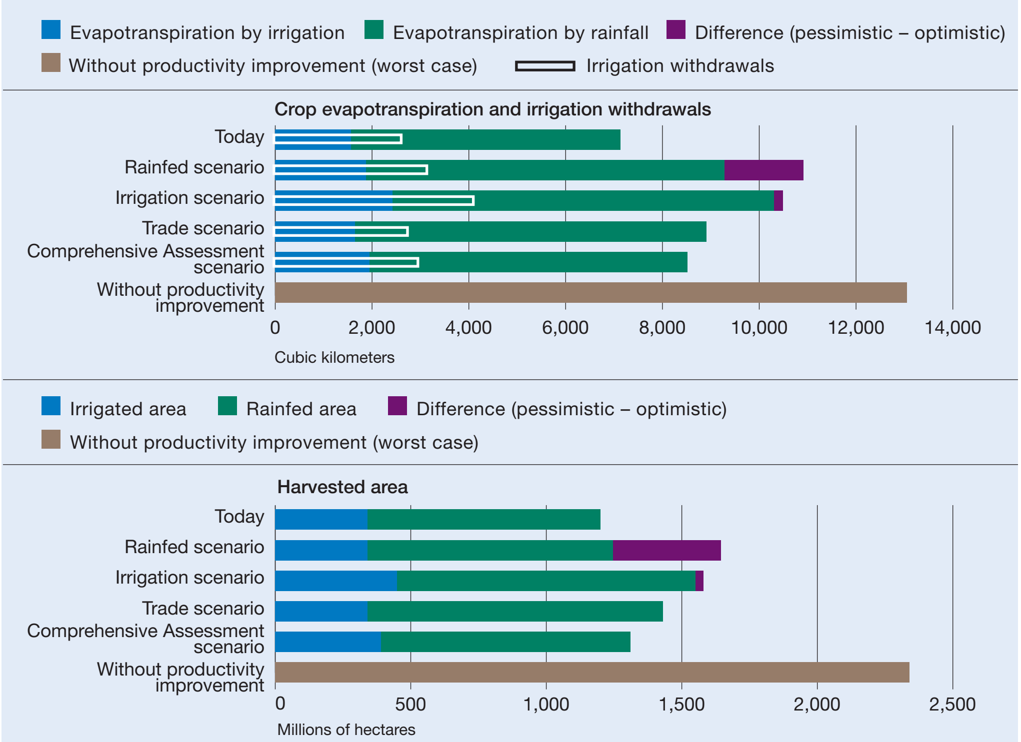
Note: Points marked FAO (Food and Agriculture Organization) are based on projections in Bruinsma (2003); those marked IWMI (International Water Management Institute) are based on projections in Seckler and others (2000).

Source: For 1960–2003, FAOSTAT 2006; for 2000–50, International Water Management Institute analysis done for the Comprehensive Assessment of Water Management in Agriculture using the Watersim model.

Great potential—great uncertainties. The rainfed scenario that assumes zero growth in irrigated area shows that the potential of rainfed agriculture is sufficient to meet additional food requirements globally. Nearly all the additional food demand projected to 2050 can be met by increases in productivity. In an optimistic yield growth scenario in which cereal yields grow by 72%, the demand for agricultural commodities is met by increasing rainfed harvested area by only 7% (figure 3.5). The contribution of rainfed agriculture to the total gross value of food supply increases from 52% in 2000 to 60% in 2050. In the optimistic yield scenario Sub-Saharan Africa, Asia, and Latin America can be largely self-sufficient in producing major food crops. But East Asia must import maize to meet the large increase in feed demand. In addition, the Middle East and North Africa must import food because of lack of suitable lands for rainfed production. Global food trade increases from 14% to 17% of total production.

But the scenario analysis also demonstrates the risks inherent in a rainfed-based strategy. In the pessimistic scenario with a low rate of adoption of water harvesting

figure **3.5** **An optimistic yield scenario requires less land (400 million fewer hectares) and less crop water depletion (1,625 fewer cubic kilometers) than a pessimistic scenario**



Note: The figure shows projected amounts of water and land requirements under different scenarios. The Comprehensive Assessment scenario combines elements of the other approaches. The purple segments of the bars show the difference between optimistic and pessimistic assumptions for the two rainfed and two irrigated scenarios. The brown bar shows the worst cases scenario of no improvement in productivity.

Source: International Water Management Institute analysis done for the Comprehensive Assessment for Water Management in Agriculture using the Watersim model.

and only modest improvements in rainfed yields, the area in rainfed production must increase by 53% to meet future food demands (an additional 400 million hectares as compared with the optimistic yield scenario; see figure 3.5). Globally, the land is available (table 3.6), but such a large expansion might have negative environmental consequences if production is extended to marginally suitable areas. Erosion and soil degradation might cause long-term declines in productivity. The large-scale conversion of forested and grazing areas to farmland also might have undesirable environmental consequences.

FAO estimates suggest ample scope to increase the area under crops except in South Asia and the Middle East and North Africa (see table 3.6). In Sub-Saharan Africa and Latin America only one-fifth of the potential land area is already in use. However, more than half of the land marked as potential is now under forests or protected areas (Alexandratos 2005). Furthermore, some of the land might be marginal in quality (Bruinsma 2003) or not suitable for cereal crops.

In the pessimistic yield scenario, countries without potential to expand rainfed areas—due either to lack of suitable land or to unreliable rainfall—must increase food imports. The Middle East and North Africa will import more than two-thirds of its agricultural needs. South and East Asia, due to land limitations, will become major importers of maize and other grains, importing 30%–50% of their domestic needs. Latin America, developed countries, and Central Asia and Eastern Europe, having the potential to expand land in agriculture, will increase their exports. Globally, food trade will increase from 14% of total agricultural production today to 22% in 2050. Large grain imports from East and South Asia will put upward pressure on food prices (the model results suggest an increase of 11%). There is a risk that poor countries may not be able to afford food imports, and household-level food insecurity and inequity might worsen.

Climate change, which is expected to increase the variability and intensity of weather events, exacerbates the risks of rainfed production, particularly in semiarid areas vulnerable to drought (Kurukulasuriya and others 2006). Floods may damage infrastructure (roads, bridges), with negative implications for marketing farm output.

table **3.6** **Potential land suitable for agricultural expansion**
(millions of hectares unless otherwise indicated)

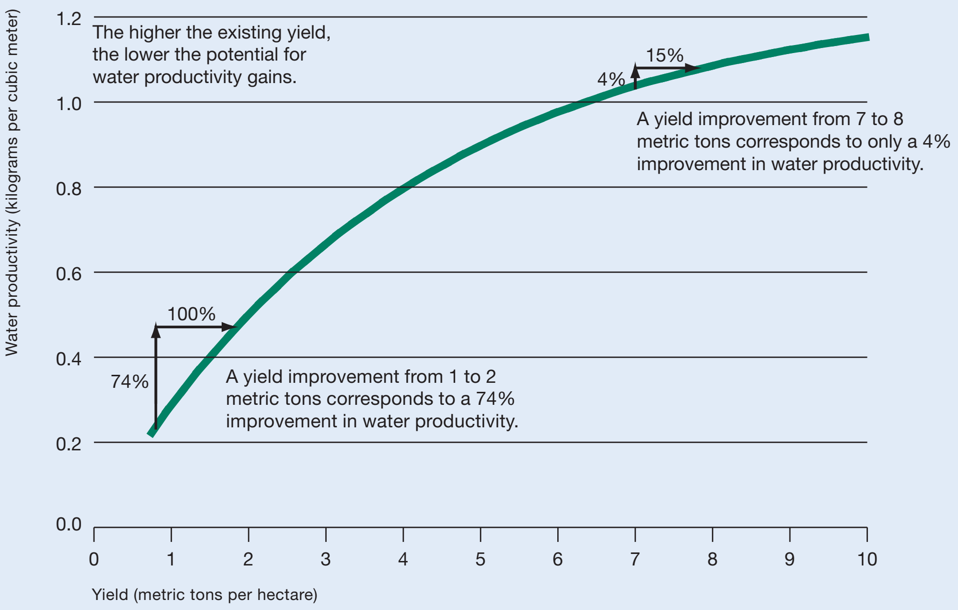
Region	Area currently cropped[a] (irrigated plus rainfed)	Total area suitable for rainfed production
Sub-Saharan Africa	228	1,031
Middle East & North Africa	86	99
Central Asia & Eastern Europe	265	497
South Asia	207	220
East Asia	232	366
Latin America	203	1,066
Developed countries	387	874

a. Estimates of total cropped areas vary between 1.2 and 1.6 billion hectares depending on definitions of crop categories.
Source: Based on FAO (2002, p. 40).

Both the optimistic and pessimistic rainfed scenarios lead to substantial increases in soil water consumption. Improved water management (including small amounts of supplemental irrigation) is a prerequisite for the yield improvements in the high-yield scenario. With higher yields water transpiration by crops must increase to produce enough biomass and economic yield. Part of the increased evapotranspiration might be offset by increasing water productivity, by improving the harvest index, by reducing losses from soil evaporation, or by increasing transpiration while reducing evaporation. When yields are low (below 50% of the potential), the scope to improve water productivity is high, but if yields are high, additional water is required to achieve even higher yields (figure 3.6). Thus the higher the initial yield, the lower the potential for water productivity gains.

In the optimistic rainfed yield scenario total evapotranspiration on cropland increases by 30%, from 7,130 to 9,280 cubic kilometers. While the global average of rainfed cereal yield improves by 72%, crop water productivity improves by 35%. In the pessimistic yield scenario global rainfed cereal yields improve by 20% and water productivity by 10%, while total crop water consumption increases by 54% to 10,980 cubic kilometers, an additional 3,850 cubic kilometers after the year 2000. Increases in soil water depletion of that order of magnitude will have impacts on river flows and groundwater recharge, with implications for downstream water users and those relying on groundwater resources. There might

figure **3.6** **Water productivity is subject to diminishing returns**



Source: Based on the yield–water productivity relationship for rainfed cereals in Rockström (2003); see also chapter 7 on water productivity.

also be implications for atmospheric properties (Foley and others 2005, Gordon and Folke 2000; chapter 6 on ecosystems).

The estimated cost of improving rainfed agriculture varies substantially according to the situation. Assuming an investment cost range of $50–$250 per hectare and $2–$5 per 1,000 cubic meters of water (see chapter 8 on rainfed agriculture), the estimated capital cost of the low-yield scenario is between $30 billion and $210 billion and that of the high-yield scenario between $40 billion and $250 billion. While the impacts are described to 2050, the scenario assumes that investments are made in the next 20 years. Capital investments must come largely from public sources. Individual farmers complement these with private investments in enhanced farm inputs. Financing this scenario may prove difficult because donor investments tend to favor large infrastructure projects typically associated with large-scale irrigation rather than small, dispersed investments in rainfed agriculture.

> Upgraded rainfed agriculture can produce the food required in the future, but multiple conditions must be met for successful implementation, including substantial investments in water harvesting, agricultural research, supporting institutions, and rural infrastructure

Conclusion: upgrading rainfed agriculture offers good potential to meet future food demand. Upgraded rainfed agriculture can produce the food required in the future, but conditions must be met for successful implementation of a "rainfed strategy." The required productivity increases will not occur without substantial investments in water harvesting, agricultural research, supporting institutions, and rural infrastructure. In addition, crop yields will vary with economic incentives and crop prices, as farmers respond to those parameters when choosing key inputs. A high-yield scenario will evolve only if generating high yields is profitable for farmers. Resources are available to improve rainfed agriculture, but the institutional structure must encourage farm-level adoption of the recommended production practices. If incentives are missing or inappropriate, the environmental costs of achieving greater production could be substantial: 54% more crop water consumption and 38% more land (see figure 3.5). Such large increases in crop water consumption will likely have consequences for downstream ecosystems and water users. Moreover, a large expansion of agricultural land might reduce biodiversity and damage ecosystem services.

More irrigation?

Irrigated agriculture now provides 40% of the global cereal supply (60% of the cereals produced in developing countries). About 46% of the gross value of agricultural production (total production multiplied by world market prices in 2000) comes from irrigated areas, which make up 28% of the harvested area (Watersim estimates for the Comprehensive Assessment). Many expect that the contribution of irrigated agriculture to food production and rural development will increase in the coming decades (Seckler and others 2000; Bruinsma 2003).

After a decade of decline, international donors have shown renewed interest in irrigation investments, particularly in Sub-Saharan Africa, where irrigation development has remained well below its physical potential (see chapter 9 on irrigation). The Commission for Africa (2005) and the New Partnership for Africa's Development have described the need to invest in doubling the irrigated area in Sub-Saharan Africa to achieve the Millennium Development Goals.

In India the groundwater boom, with millions of smallholders investing in private tubewells, continues despite environmental problems with groundwater overdraft and fossil groundwater mining (see chapter 10 on groundwater). Irrigation with wastewater is expanding in developing countries in areas near major cities (see chapter 11 on marginal-quality water). In India and Pakistan large investments are planned for rehabilitating and modernizing the Ganges and Indus River irrigation systems (Briscoe and others 2005).

The evidence suggests that despite environmental concerns about large-scale irrigation development (see chapter 6 on ecosystems), there remain good reasons to invest in irrigation development, improvement, and modernization. These include the potential for poverty alleviation, high potential to improve irrigation performance, maintenance of irrigation capacity, and concerns about climate change and its effects on rainfall variability (see chapter 9 on irrigation).

We examine scenarios that describe the implications of irrigated area expansion and the gains from enhancing the output per unit of water in irrigated areas.

Expanding irrigated areas. This scenario emphasizes food self-sufficiency and access to agricultural water for more people, particularly in Asia and Sub-Saharan Africa. Irrigated area increases by 0.6% per year from 340 million hectares (ha) in 2000 to 450 million ha in 2050,[7] simulating the expansion of the groundwater boom in South Asia, the intensification of irrigated areas in the Middle East and North Africa and in East Asia, and a doubling of irrigated area in Sub-Saharan Africa from 6.4 million ha to 12.8 million ha (table 3.7). Irrigated and rainfed yields increase at a modest pace—between 20% and 35% over 50 years.

With the expansion of irrigated area South and East Asia become largely self-sufficient in maize and other grains, while importing small amounts of wheat. East Asia continues exporting rice, but vegetable exports decline due to rapid increases in domestic demand. Sub-Saharan Africa becomes largely food self-sufficient, though it cannot

table **3.7** **Assumptions underlying the irrigated area expansion scenario**

	Area irrigated and harvested (millions of hectares)			**Irrigated wheat yields** (metric tons per hectare)		
Region	**2000**	**2050**	**Cumulative growth** (%) **2000–50**	**2000**	**2050**	**Cumulative growth** (%) **2000–50**
Sub-Saharan Africa	6.4	12.8	101	3.0	3.8	27
Middle East & North Africa	20.7	22.8	10	3.4	4.2	23
Central Asia & Eastern Europe	32.8	37.3	14	3.0	4.0	32
South Asia	104.3	135.2	30	2.8	4.0	44
East Asia	116.5	169.6	46	4.1	6.0	47
Latin America	16.5	23.4	42	4.8	6.3	31
OECD countries	45.4	49.8	10	4.4	4.9	10
World	341.3	454.4	33	3.4	4.7	38

maintain pace with the rapidly increasing domestic demand for maize. The rural economy in Sub-Saharan Africa is boosted as smallholders benefit from the opportunity to produce irrigated vegetables for the growing domestic market. As a result, Sub-Saharan Africa becomes largely self-sufficient in vegetables. Global trade in agricultural products remains at about the current level.

National food security and rural incomes are enhanced in this scenario, but pressure on water resources increases. Harvested area increases by 110 million ha, partly by increasing irrigation intensity (growing more crops per season) and partly by expanding the area by 76 million ha. Without improvements in application efficiency agricultural water diversions for irrigation increase from 2,630 cubic kilometers per year today to 4,100 cubic kilometers per year in 2050 (see figure 3.5). The increase is equivalent to 30 times the amount of water stored behind the Aswan Dams. With improvements in application efficiency global diversions might increase to only 3,650 cubic kilometers.

> Under the irrigated area expansion scenario the number of people who live in physically water-scarce basins rises from 1.2 billion to 2.6 billion in 2050

The cost of building, maintaining, and managing the required water infrastructure will be substantial, particularly in Sub-Saharan Africa, where irrigation costs are high and public funds are severely limited. At least $400 billion will be required to expand the harvested area by 110 million ha, a rough estimate based on incomplete data (table 3.8). Building the supporting infrastructure and creating the institutional capacity to manage newly built irrigation schemes, roads, and marketing facilities will add further to costs. Substantial investments will be required by public agencies, development banks, and other donor organizations.

Much of the irrigated area expansion in South Asia will involve groundwater development, which typically is privately funded. In Sub-Saharan Africa irrigation development will come largely from public investments. The average construction cost per hectare is higher in Sub-Saharan Africa than in South Asia, due partly to high transaction costs and partly to the high failure rate of irrigation projects. In a global sample of 314 publicly funded irrigation projects analyzed by Inocencio and others (2006), about half the projects in Sub-Saharan Africa were partial failures, the highest rate among regions in the sample. The authors argue that if only successful projects are considered, the investments costs in Sub-Saharan Africa are similar to those in other regions. An estimated $30–$40 billion are needed to double the area equipped with irrigation infrastructure, and additional funds are needed for complementary investments in roads, storage and processing facilities, communications, and institutions (Rosegrant and others 2005).

Physical water scarcity might increase while economic water scarcity declines. Already, 1.2 billion people (20% of the world's population) live in physically water-scarce basins. In the irrigated area expansion scenario this number increases to about 2.6 billion (28% of world population) in 2050 (map 3.1). Competition among sectors (agriculture, fisheries, cities, and industry) and transboundary water conflicts will likely intensify. In 36 of 128 basins minimum environmental flow requirements will not be satisfied, implying a potential increase in the adverse environmental impacts of agricultural water withdrawals on ecosystems and fisheries. Expanding irrigation infrastructure also increases the potential for aquaculture development, but we are unable to evaluate this tradeoff with data currently available.

table 3.8 Capital investment cost of irrigated area expansion

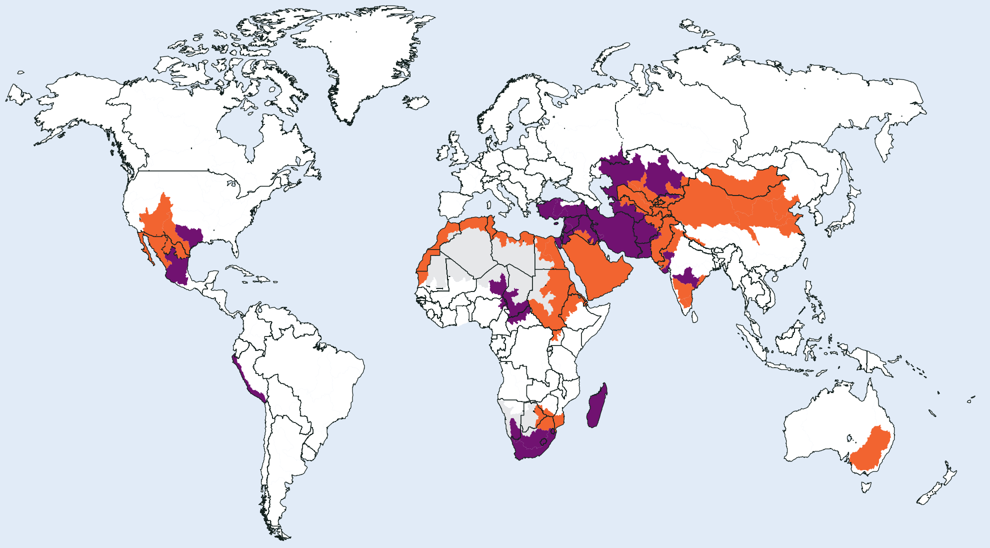
Region	Additional equipped area (millions of hectares) (1)	New irrigation costs (US dollars per hectare) (2)	Total area costs (billions of US dollars) (3 = 1 × 2)	Additional storage (cubic kilometers) (4)	Storage costs (billions of US dollars) (5)	Total costs (billions of US dollars) (6 = 3 + 5)
Sub-Saharan Africa	6.2	5,600	35	89	10	45
Middle East & North Africa	3.1	6,000	19	71	8	26
Central Asia & Eastern Europe	4.5	3,500	16	61	7	22
South Asia	25.1	2,600	65	630	69	135
East Asia	30.4	2,900	88	459	50	139
Latin America	6.9	3,700	26	142	16	41
OECD countries	0.1	3,500	0.4	52	6	6
World	76.3	3,255	248	1,504	165	414

Note: Values may not sum to totals due to rounding.

Source: New irrigation cost estimates are from chapter 9 on irrigation; storage cost estimates are derived using the low estimate in Keller, Sakthivadivel, and Seckler (2000) of $0.11 per cubic meter.

map 3.1 Irrigated area expansion leads to 2.6 billion people living in water-scarce basins by 2050

🟧 Water-scarce basins in 2000 and 2050 🟪 Water-scarce basins in 2050 but not in 2000



Source: International Water Management Institute analysis done for the Comprehensive Assessment of Water Management in Agriculture using the Watersim model.

Improving irrigation performance. Many irrigation schemes, particularly in South Asia, perform below potential (see chapter 9 on irrigation), and the scope for improving water productivity is high (Molden and de Fraiture 2004; Kijne, Barker, and Molden 2003). Here we explore the potential contribution to global food production of improving irrigation performance by formulating an irrigated yield growth scenario that assumes bridging 75%–80% of the exploitable yield gaps in coming decades (table 3.9). This simulates a rather optimistic—though not unrealistic—scenario of implementing institutional reforms (see chapter 5 on policies and institutions), resolving competition among headenders and tailenders, improving water allocation mechanisms (see chapter 16 on river basins), and motivating farmers and water managers to improve the productivity of land and water (Wang and others 2006; Luquet and others 2005). In addition to better water management, this entails higher soil fertility, better pest management, and improved seeds and other agronomic measures (see chapters 7 on water productivity and 15 on land).

This scenario shows the large potential for improving productivity in irrigated areas, particularly where yields are low.

- South Asia can become self-sufficient in all grains, vegetables, and roots and tubers by improving irrigated yields and slightly expanding the harvested area (10% increase in irrigated area, 12% increase in rainfed area). India can meet all additional cereal demands by improving irrigated yields. The near doubling of yields depicted in this scenario is by no means easy but can be achieved with appropriate investments.
- In East Asia, where yields are relatively high, the scope for improving productivity is smaller, yet the demand for agricultural commodities increases rapidly. Improving irrigation can meet 75% of the additional cereal requirements while the remainder is imported.
- In the Middle East and North Africa, where opportunities to improve irrigation performance and expand irrigated area are limited, one-third of additional cereal requirements can be met by improving productivity, while the remainder is imported from OECD countries, Latin America, and Eastern Europe. Globally, agricultural commodity trade declines slightly.
- In Sub-Saharan Africa, where more than 90% of production originates from rainfed areas, improving productivity on existing irrigated areas has only a small impact on food supply.

This scenario foresees a modest 9% expansion of irrigated area globally, while irrigation diversions increase by 32% (see figure 3.5). To achieve the improvements in irrigated yields depicted in this scenario, water supplies must be increased in existing irrigated areas. In India, for example, farmers install additional tubewells in command areas to supplement unreliable surface water supply (see chapter 10 on groundwater). In some areas yield improvements are achieved by augmenting water supplies in tailend areas, partly (but not entirely) at the expense of headend areas (see Hussain and others 2004 for a win-win case in Pakistan). Better timing of water deliveries also is helpful in improving crop yields. All of these measures lead to more water evaporated by crops, a precondition for increasing yields. As a result, water consumption and irrigation diversions increase substantially in this scenario.

Part of the increase in water consumption is offset by improvements in water use efficiency[8] and water productivity. Improving efficiency implies that a larger portion of diverted water is used beneficially by crops, livestock, or other productive processes. This might be achieved, for example, by recycling drainage water or improving on-farm water management (Molden, Sakthivadivel, and Habib 2000; Seckler and others 2000). Improving water productivity implies that more output is obtained per unit of water consumed, perhaps by achieving a higher harvest index or reducing evaporation losses from soils. In the high-yield scenario the global consumptive fraction increases from 59% to 66%. Some authors suggest it is neither feasible nor desirable to increase this fraction further. Seckler and others (2000) explain that increases beyond the range of 70% often are associated with salinization and pollution problems, particularly if leaching requirements are ignored.

Investment costs in this scenario are about $300 billion (table 3.10).

Conclusion: both more irrigation and better irrigation are needed. Comparing both strategies in irrigation investments, the scenario analysis shows that the potential gains from enhancing productivity in irrigated areas are larger than the gains from area expansion. Improving irrigated cereal yields by 77% contributes 550 million metric tons of grains, or 50% of global additional demand by 2050. Expanding irrigated area by 33% contributes only 260 million metric tons of grains.

The potential gains from enhancing productivity in irrigated areas are larger than the gains from area expansion. Improving irrigated cereal yields by 77% meets 50% of global additional demand by 2050, while expanding irrigated areas meets just 23%

Arguably, the largest gains in water productivity in value per unit of water are achieved by diversification and by using water for many productive purposes—such as fisheries, livestock, home gardens, and other small enterprises (van Koppen, Moriarty, and Boelee 2006 and chapter 4 on poverty).[9] This may require changes in irrigation design to incorporate small dams, fisheries, and flood protection.

The analysis also demonstrates large regional differences. In South Asia there is substantial scope for improving productivity in irrigated areas while possibilities to expand areas are more limited or involve large infrastructure investments, such as the Linking of Rivers project in India. In East Asia there is some scope for area expansion, but most of the increase in production must come from productivity improvements. In Sub-Saharan Africa the scope for irrigated area expansion is sizable, but development costs are relatively high and historical success rates are relatively low. In water-scarce Middle East and North Africa area expansion is infeasible, and the scope for improving productivity is comparatively small. With rapid population growth, this region will depend increasingly on imports. In Latin America, OECD countries, Eastern Europe, and Central Asia there is potential to improve productivity in irrigated areas, but improving and expanding rainfed agriculture will be less expensive and might generate greater output gains.

Can trade offset water scarcity?

In the 1950s and 1960s agricultural policy in many developing countries favored import substitution, with food security equated with national food self-sufficiency. Farm lobbies were strong, and protecting agriculture was considered necessary for ensuring national food security. Subsidized water and irrigation infrastructure, marketing boards, tariffs, and input subsidies were viewed as necessary measures to promote food self-sufficiency

table **3.9** Yield scenarios for irrigated agriculture

Crop and region	Yield (metric tons per hectare)			
	Actual 2000	Maximum potential[a]	Simulated 2050	Cumulative growth (%) 2000–50
Wheat				
Sub-Saharan Africa	3.0	5.8	5.3	77
Middle East & North Africa	3.4	6.8	6.3	85
Central Asia & Eastern Europe	3.0	7.7	6.6	117
South Asia	2.8	4.5	4.5	61
East Asia	4.1	7.5	6.8	67
Latin America	4.8	6.3	5.9	23
OECD countries	4.4	7.9	7.7	72
World	3.4	7.1	5.7	70
Rice				
Sub-Saharan Africa	1.8	7.2	4.1	130
Middle East & North Africa	4.2	9.9	7.6	80
Central Asia & Eastern Europe	2.3	7.4	6.0	163
South Asia	2.6	8.2	6.3	138
East Asia	3.7	7.3	6.0	61
Latin America	3.4	6.7	6.1	81
OECD countries	4.6	8.4	7.6	64
World	3.4	7.4	6.1	83
Maize				
Sub-Saharan Africa	2.8	10.5	7.9	180
Middle East & North Africa	6.1	13.2	9.3	51
Central Asia & Eastern Europe	5.0	10.2	9.8	96
South Asia	2.6	10.8	7.3	176
East Asia	5.6	10.3	9.5	68
Latin America	4.9	10.9	9.1	87
OECD countries	9.9	11.3	10.8	10
World	6.1	10.9	9.6	57

a. Maximum attainable irrigated yields derived from GAEZ country-level data.

b. Historical growth rates from 1961–63 to 2001–03 of average yields, FAOSTAT (2006). Time series data disaggregated into rainfed and irrigated yields are not available.

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Annual growth rate (%)		Water productivity (kilograms per cubic meter of evapotranspiration)		
Simulated 2000–50	Historical, irrigated plus rainfed[b]	2000	Simulated 2050	Cumulative growth (%) 2000–50
1.1	2.6	0.37	0.53	45
1.2	4.4	0.43	0.60	37
1.6	2.8	0.44	0.71	61
1.0	1.1	0.46	0.63	36
1.0	1.4	0.63	0.88	40
0.4	2.4	0.69	0.74	8
1.1	1.6	0.70	0.96	37
1.1	2.2	0.54	0.74	38
2.2	0.4	0.18	0.31	72
1.2	2.0	0.37	0.48	30
2.0	1.7	0.26	0.46	78
1.8	0.2	0.27	0.50	86
1.0	2.0	0.54	0.78	46
1.2	1.4	0.40	0.61	52
1.0	0.8	0.53	0.72	36
1.2	1.7	0.46	0.75	65
2.1	0.8	0.36	0.70	96
0.8	3.2	0.77	0.95	23
1.4	1.4	0.81	1.16	43
2.1	1.9	0.30	0.55	83
1.0	2.5	0.84	1.14	36
1.3	3.0	0.44	0.63	42
0.2	2.0	1.33	1.40	5
0.9	2.0	0.87	1.13	31

Source: Derived from GAEZ country data, weighted averages over different land suitability classes. Based on data from Fischer and others (2002), provided by FAO.

table **3.10** **Capital investment cost of the improved irrigation performance scenario**

Region	**Rehabilitated area** (millions of hectares) **(1)**	**Costs of rehabilitation** (US dollars per hectare) **(2)**	**Total costs of rehabilitated areas** (billions of US dollars) **(3 = 1 × 2)**	**Additional storage** (cubic kilometers) **(4)**	**Storage costs** (billions of US dollars) **(5)**	**Total costs** (billions of US dollars) **(6 = 3 + 5)**
Sub-Saharan Africa	6	2,000	12	37	4	16
Middle East & North Africa	17	2,000	34	87	10	44
Central Asia & Eastern Europe	20	1,000	20	85	9	29
South Asia	81	900	73	322	35	108
East Asia	75	700	53	141	16	68
Latin America	18	1,300	23	78	9	32
OECD countries	5	1,000	5	16	2	7
World	222	990	220	766	84	304

Note: Values may not sum to totals because of rounding.

Source: Rehabilitation cost estimates are from chapter 9 on irrigation; storage cost estimates are derived using the low estimate in Keller, Sakthivadivel, and Seckler (2000) of $0.11 per cubic meter.

and minimize the risk of famines (Molden, Amarasinghe, and Hussain 2001; Kikuchi, Maruyama, and Hayami 2001; Barker and Molle 2004). The role of trade in domestic food supply was—and for most developing countries still is—modest.

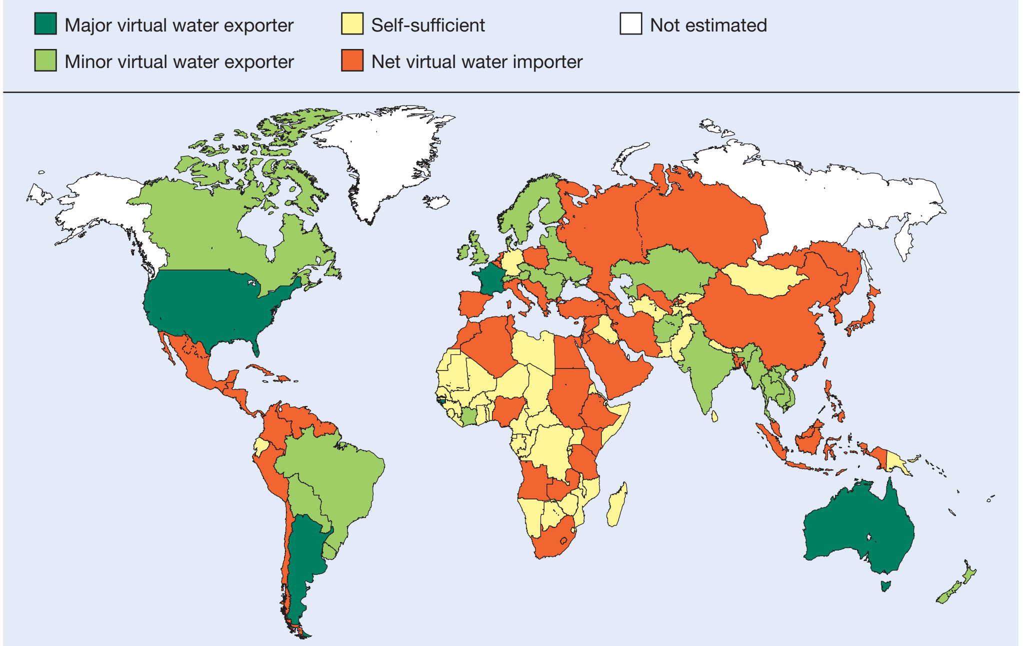
Expanded international food trade can have significant impacts on national water demands. Allan (1998) coined the term "virtual water" to denote the water used to produce imported crops. By importing agricultural commodities, a country "saves" the amount of water it would have required to produce those commodities domestically. For example, Egypt, a highly water-stressed country, imported 8 million metric tons of grain from the United States in 2000. Producing that grain in Egypt would have required about 8.5 billion cubic meters of irrigation water—about one-sixth of Egypt's annual releases from Lake Nasser. Japan, a land-scarce country and the world's largest grain importer, would require an additional 30 billion cubic meters of irrigation water and rainfall to produce its food imports (de Fraiture and others 2004).

Globally, cereal trade has a moderating impact on the demand for irrigation water, as four of the five major grain exporters (United States, Canada, France, and Argentina) produce grain in highly productive rainfed conditions. Without cereal trade global demand for irrigation water in 1995 would have been 11% higher (de Fraiture and others 2004; Oki and others 2003).

Some authors have proposed increasing trade to mitigate water scarcity and reduce environmental degradation (Allan 2001; Hoekstra and Hung 2005; Chapagain 2006; Zimmer and Renault 2003). They suggest that instead of striving for food self-sufficiency, water-short countries should import food from water-abundant countries. Much of that analysis does not account for several key considerations that determine international trade patterns, such as domestic macroeconomic policies, socioeconomic goals, exchange rate policies, and political relationships. Nor does it consider the potential environmental impacts of increasing agricultural trade, such as extending agricultural areas and building new processing and packaging facilities in exporting countries. In addition, there may be substantial costs in shipping large volumes of food between countries and within importing countries. And with rising energy prices the per-unit costs of processing, storing, and shipping food will increase.

Trade scenario. In this scenario production occurs in North America, Europe, and Latin America, while in the rainfed scenarios Sub-Saharan Africa, South Asia, and East Asia increase their production to maintain a desired level of self-sufficiency in staple foods. Thus countries with abundant water resources and production capacities increase their agricultural production and export to water-short countries. North America, Latin America (mainly Brazil and Argentina), Northwestern Europe, and Eastern Europe (Russia and Ukraine) export to the Middle East and North Africa and to India, Pakistan, and China (map 3.2). Sub-Saharan Africa improves its rainfed agriculture but remains a minor importer. In the importing countries crop yields improve at a modest pace (25%) while irrigated and rainfed areas remain constant. China, India, and the Middle East and North Africa reduce their irrigated areas for cereals, shifting toward labor-intensive, higher valued

map **3.2** **Virtual water embedded in agricultural trade**



Source: De Fraiture and others 2004.

crops such as vegetables. Appropriate water pricing schemes and incentives such as credit and subsidies induce farmers to shift to crops with higher value output per unit of irrigation water. Water scarcity problems are lessened through better on-farm management and microirrigation in greenhouses. In exporting countries rainfed yields of staple crops—such as cereals, soybeans (oil crops), and roots and tubers—improve by 60% on average. Rainfed areas in exporting countries increase by 260 million ha, primarily in Latin America, where the scope for area expansion is still large.

Conclusion: high potential for water but many socioeconomic and political issues. The scenario analysis reveals, in theory, that world food demands can be satisfied through international trade, without worsening water scarcity or requiring additional irrigation infrastructure (table 3.11). However, the analysis does not account for the political, social, and economic issues that countries consider when choosing trade strategies. It is not likely that a majority of water-short countries will greatly increase their food imports in the near term.

Food imports already are essential in countries where production is limited by water scarcity or other constraints, as in many countries of the Middle East and Sub-Saharan Africa. This is also true for some countries in Southeast Asia, like Japan and Malaysia, where the expanding industrial service sectors are creating severe labor resource constraints in agriculture. In some countries in Sub-Saharan Africa the costs of inland transportation motivate countries to feed coastal cities with imports rather than to rely on domestic production—at least in the near term, until rural infrastructure can be improved (Seckler and others 2000). Food trade (or aid) also buffers fluctuations in production due to climate variability. In other countries land, not water, is the binding constraint (Kumar and Singh 2005).

table **3.11** **Demand and net trade flows of cereals under different scenarios**

	Demand (millions of metric tons)		**Rainfed scenarios 2050**		**Rainfed scenarios 2050**	
			Low yield		**High yield**	
Region	**2000**	**2050**	**Net trade flows** (millions of metric tons)	**Share of demand** (%)	**Net trade flows** (millions of metric tons)	**Share of demand** (%)
Sub-Saharan Africa	98	213	–32	15	–14	7
Middle East & North Africa	99	208	–149	72	–141	68
Eastern Europe & Central Asia	234	295	151	51	56	19
South Asia	241	476	–88	19	–5	1
East Asia	505	807	–148	18	–57	7
Latin America	149	290	76	26	17	6
OECD countries	508	586	167	29	157	27

Note: Negative values indicate imports, and positive values indicate exports.

Source: International Water Management Institute analysis done for the Comprehensive Assessment of Water Management in Agriculture using the Watersim model.

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Overall, most international food trade occurs for reasons not related to water resources. In 1995 less than one-quarter of global cereal trade was related to water scarcity (de Fraiture and others 2004; Yang and others 2002). This might change as water becomes more scarce and the prices of water-intensive crops increase. International trade provides water-short countries an option for responding to increasing water scarcity. The importance of this option in the future will depend on many factors, including international trade agreements, the costs of engaging in trade, and the nature of domestic economic objectives and political considerations.

The cost of increasing international trade can be substantial for developing countries. Food imports must be paid for with foreign exchange, earned by selling exports or obtained through grants and loans. This fact is somewhat hidden by large amounts of donor assistance in hard currency and historically heavily subsidized exports from Europe and the United States (Seckler and others 2000). Many poor countries, particularly in Sub-Saharan Africa, do not have sufficient exports to pay for imports. Oil-producing countries might face this problem in future, if high prices accelerate their shift to an end-of-oil era (Margat 2006). Further, poor countries relying on one or a few export products are vulnerable to fluctuations in the terms of trade and therefore in purchasing power. Finally, trade requires substantial amounts of energy for transporting goods, adding to the environmental costs of trade.

Poor countries struggling with issues of food security remain wary of depending on imports to satisfy basic food needs. They view such a strategy as increasing their vulnerability to fluctuations in world prices and geopolitics. A certain degree of food self-sufficiency is still an important policy goal, and despite emerging water problems, many countries view the development of water resources as a more secure option for achieving food supply goals and promoting income growth, particularly in poor rural communities. It is debatable

Irrigated scenarios 2050				**Trade scenario 2050**	
Area expansion		**Yield improvement**			
Net trade flows (millions of metric tons)	**Share of demand** (%)	**Net trade flows** (millions of metric tons)	**Share of demand** (%)	**Net trade flows** (millions of metric tons)	**Share of demand** (%)
–44	21	–22	10	–51	24
–131	63	–83	40	–156	75
49	17	3	1	181	61
–32	7	20	4	–119	25
–18	2	–34	4	–191	24
44	15	29	10	178	61
112	19	99	17	136	23

whether poor, water-scarce countries with limited investments in water infrastructure can afford to import large amounts of agricultural commodities. In addition, as recent discussions in the World Trade Organization illustrate, the economic and political interests associated with agricultural trade are substantial. Those interests might dominate water scarcity and environmental concerns in some countries (see Mehta and Madsen 2005). In sum, it is unlikely that food trade alone will solve problems of water scarcity in the near term.

International trade provides water-short countries an option for responding to increasing water scarcity. The importance of this option depends on many factors

Understanding tradeoffs

In the extreme case of no future productivity improvements, 13,050 cubic kilometers of crop water consumption and 2.4 billion ha of cropland would be required to produce the food and feed demanded in 2050. Though none of the scenarios depicts an increase of this magnitude, some scenarios involve more strain on available resources than others. In addition, some scenarios offer better prospects for poverty alleviation, environmental protection, and food security.

We examine linkages and tradeoffs involving terrestrial and aquatic ecosystems, poverty alleviation, and food security (figure 3.7). Our discussion is based on results presented above and discussion presented in other chapters.

Aquatic ecosystems

In all scenarios the demand for freshwater increases to meet future food demands. Water consumption increases substantially in irrigated and rainfed areas (figure 3.8).

Ecosystems provide a range of services such as food production, fisheries, flood protection, water filtration, and groundwater recharge (see chapter 6 on ecosystems). Many authors describe the adverse impacts of irrigation on ecosystem services other than food production (Pimentel and others 2004; Khan and others 2006; chapters 2 on trends and 6 on ecosystems). Extracting water from rivers and aquifers reduces the amount available to aquatic ecosystems and can affect groundwater tables. The infrastructure needed to divert water for irrigation (and other purposes) can alter hydrology, leading to river fragmentation, with negative consequences for aquatic habitats (see chapter 12 on inland fisheries). Reductions in ecosystem services often have severe consequences for poor people, who depend heavily on ecosystems for their livelihoods.

In the irrigated area expansion scenario withdrawals increase by 57%, with potentially large impacts on aquatic ecosystems and coastal zones. More dams and other water storage facilities are needed, which may alter the timing and variability of flows—important for sustaining ecosystem services (Poff and others 1997).

Innovative techniques and management methods are available for mitigating the effects, and the impacts of irrigation development on ecosystem services will vary. In some systems it has been possible to find synergies between fisheries and irrigation, especially in small and medium-scale irrigation schemes. For example, dams can provide fishing opportunities in reservoirs (Nguyen-Khoa and Smith 2004; Nguyen-Khoa and others 2005). Negative environmental impacts can also be limited by adhering to environmental flow regulations (see chapter 6 on ecosystems).

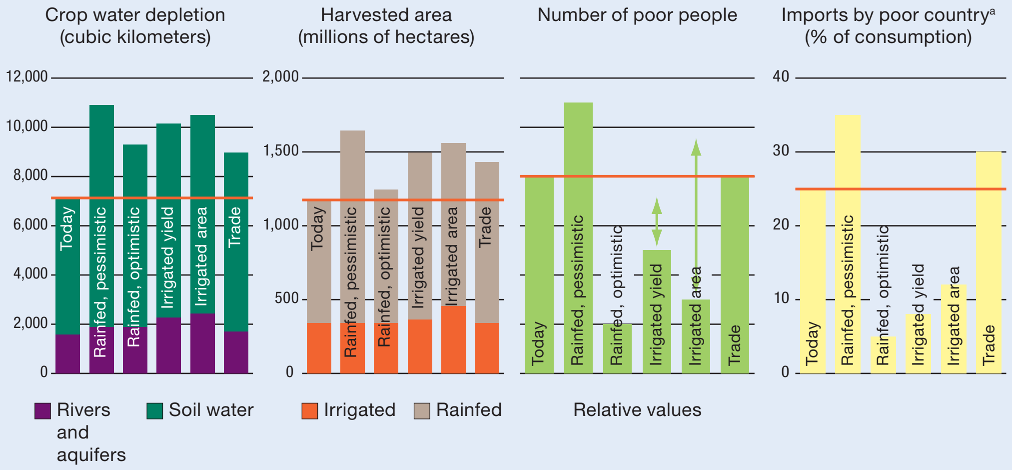
figure **3.7** **Possible quantitative indicators to illustrate tradeoffs**

Aquatic ecosystems
In all scenarios demand for freshwater increases to meet food demand. While some positive impacts can come from investment strategies that include a system perspective, adverse impacts on aquatic systems dominate, particularly in the irrigated area expansion scenario. The effects on aquatic systems of intensifying rainfed agriculture are less known.

Terrestrial ecosystems
Food production affects terrestrial ecosystems through changes in land cover (for example, conversion of forests and savannahs into agricultural land). In the optimistic rainfed yield scenario additional land requirements are lowest, but the rainfed strategy is risky. In a scenario where yields remain below expectations, land requirements are highest.

Poverty alleviation
The impact of different strategies on poverty alleviation is difficult to assess. Much depends on the type of irrigation intervention and how it is implemented. Expansion of smallholder irrigation techniques (both surface water and groundwater) has high potential for poverty alleviation. Improving rainfed agriculture has high potential but carries risks.

Food security
In semiarid areas expanding irrigated areas and improving yields in irrigated and rainfed agriculture offer good prospects for secure food supply. Reaching those whose productivity did not rise significantly and who experienced a net loss in food security because of falling commodity prices is the greatest challenge of coming decades.

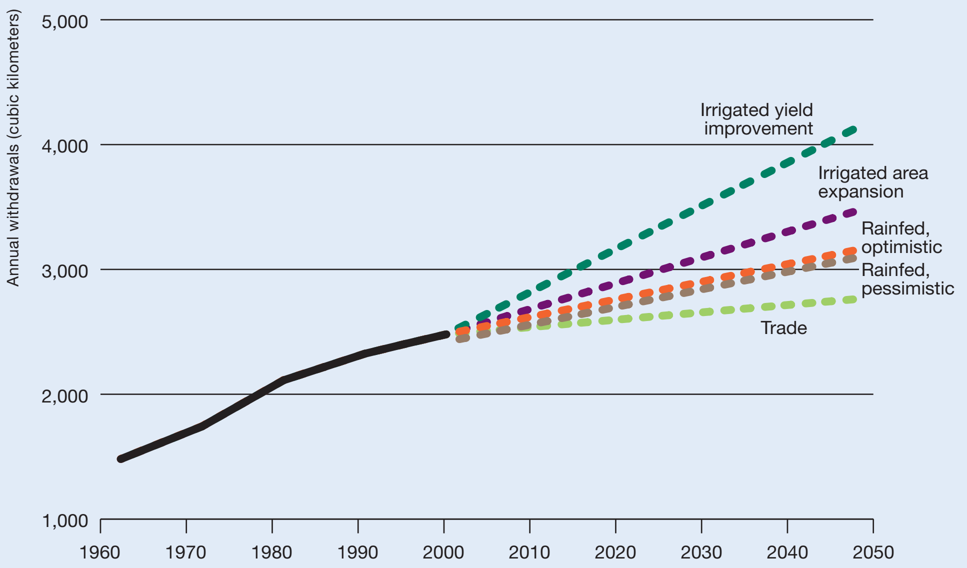


a. Poor countries are those with annual per capita incomes below $2,500. Imports include food aid. Note that the indicators here are used to illustrate tradeoffs rather than to quantitatively analyze the full range of issues.

Source: Results presented in the text and qualitative discussion presented in other chapters.

Examples of positive impacts of irrigation on ecosystem services include groundwater recharge, reduction of soil erosion through terracing, biodiversity in paddy fields and small tanks, and multiple use of irrigation water for domestic and productive purposes (Hussain and Hanjra 2003, 2004; Smith 2004). Studies show that about 80% of groundwater recharge occurs through canal systems in India and Pakistan (Ambast and others 2006; Ahmad, Bastiaanssen, and Feddes 2005). Groundwater recharge is not always positive, however, as it can lead to waterlogging in areas where deep percolation is restricted and drainage systems are inadequate (Scott and Shah 2004; Ambast, Tyagi, and Raul 2006).

Intensive irrigation has larger impacts on water volumes and quality than do low-input systems. Many of the improvements in water-use efficiency arise from greater use of external inputs, increased mechanization, and intensification of production. For example, figure **3.8** **Global water withdrawals increase substantially to 2050**



Source: For 1960–95, Shiklomanov 2000; 1995–2050, modeling results scenarios done for the Comprehensive Assessment of Water Management in Agriculture.

human activities have already doubled the amount of nitrogen sequestered globally, and tripled the phosphorous use (Vitousek and others 1997; Bennett, Carpenter, and Caraco 2001). This has led to eutrophication of lakes and coastal zones, damaging fisheries, reducing recreation values, and increasing the occurrence of toxic algae blooms. Pesticide levels in water can constitute a health threat.

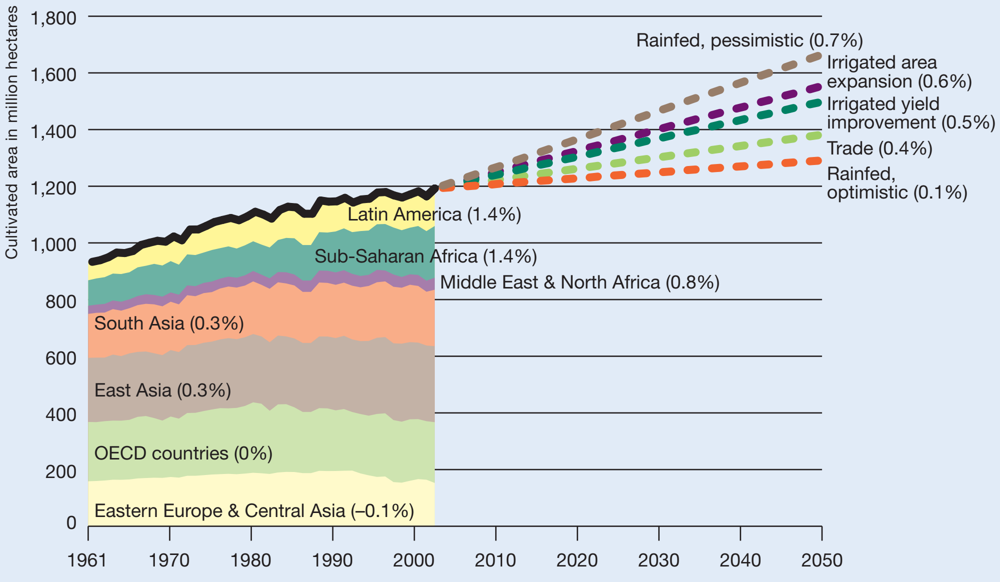
The need for new irrigation investments can be reduced by improving agricultural production in rainfed areas. Because of negative impacts on aquatic systems associated with irrigation development, investments in rainfed agriculture seem compelling from an environmental perspective (see chapter 6 on ecosystems). However, there is ample evidence that land-use decisions alter hydrological flows, which can cause cascading effects to other systems. The impacts on subsurface and surface runoff can vary substantially. Proper land and water management is required to achieve the potential of rainfed agriculture. Intercepting rainwater increases the water consumed by crops, so less water is available for runoff and groundwater recharge. Improving rainfed production through supplemental irrigation requires infrastructure, though smaller and more distributed than in intensive irrigation. Impacts on downstream water resources are more dispersed and difficult to assess. Further intensification of rainfed agriculture is often associated with increased fertilizer and pesticide use, which can have adverse impacts on water quality.

Terrestrial ecosystems

Food production affects terrestrial ecosystems when forests and savannahs are converted to agricultural land. The Millennium Ecosystem Assessment scenarios predict that land-use change will continue to put major pressure on ecosystem services (Alcamo and others 2005). In our scenarios land requirements increase a total of 6%–38% (0.1%–0.7% annual growth) between 2000 and 2050 (figure 3.9). This can have substantial impact on ecosystem services that depend on those habitats. The risks include biodiversity loss, loss of pollinator species, and increases in invasive species (Dudgeon 2000; Thrupp 2000; chapter 6 on ecosystems). Expansion of rainfed agriculture and the conversion of forests into cropland can alter biogeochemical cycles, including carbon sequestration capacity and hydrology (Foley and others 2005). It has been estimated that deforestation has reduced global evaporation by as much as irrigation has increased it (Gordon and others 2005). The changes in water vapor flows may have impacts on climate in some regions and locales (see chapter 6).

Investments in existing irrigated and rainfed areas will reduce the need to expand the area in agriculture, preventing further conversion of forests and natural lands. Improving crop yields will also reduce the need for additional land in agriculture. But if yield growth rates remain low, substantial additional land will be required to meet future demand,

figure **3.9** **In the scenarios land requirements increase a total of 6%–38% in different regions from 2000 to 2050**



Note: Numbers in parentheses are annual growth rates.

Source: For 1961–2002, FAOSTAT 2006; for 2000–2050, International Water Management Institute analysis done for the Comprehensive Assessment of Water Management in Agriculture using the Watersim model.

possibly leading to encroachment of marginal areas and terrestrial ecosystems. Rainfed agriculture, under conditions of poorly distributed rainfall or droughts, might lead to shifting cultivation, underinvestment in land conservation, and nonsustainable land use. Increased yields and intensification of rainfed and irrigated agriculture are often associated with monoculture and greater agrochemical use, which can lead to soil pollution, salinization, and waterlogging.

Many agricultural investments generate benefits within and outside the agricultural sector (Pretty and others 2006; chapter 15 on land). For example, investments in land and water management often are helpful in reducing soil erosion. Investments that enhance the retention of soil organic matter reduce the rate at which carbon is released into the atmosphere. This impact, known also as carbon sequestration, is a globally important ecosystem service. In general, investments that generate ecological benefits can be viewed as helpful in offsetting some of the negative impacts of agricultural expansion and intensification (see chapter 6).

> Managing agricultural systems to generate more than one ecosystem service has been suggested as a method to reduce ecosystem service tradeoffs from agricultural expansion and intensification

Food security

In semiarid areas, expanding irrigated area and improving irrigated yields offer better prospects for achieving secure food supplies than rainfed agriculture. Yields in irrigated areas are higher than in rainfed areas, and year-to-year fluctuations due to weather variability are smaller. With a secure water supply farmers are willing to invest in improved inputs to boost production further. Upgrading rainfed agriculture will offset these risks to a certain extent, but additional risk management strategies (such as cereal banks and crop insurance systems) may be necessary.

In many rainfed areas there is substantial scope for increasing yields, which can increase food security, particularly in poor countries with little ability to build and maintain irrigation infrastructure. But past efforts to improve rainfed agriculture have generated mixed results. In the pessimistic yield scenario, production declines and food prices rise. Countries with limited opportunities for expanding rainfed area increase imports, while facing higher food prices and larger trade deficits, which might adversely affect national food supply. Greater variability in annual weather patterns, due to climate change, might worsen this situation in rainfed areas. Brown and Lall (2006) find a statistically significant relationship between greater interannual rainfall variability and lower per capita GDP, particularly in poor countries. But there are ways to mitigate these risks (see chapter 8 on rainfed agriculture).

International trade provides opportunities to enhance national food security, but some developing countries lack sufficient foreign exchange and the political will required to sustain increased imports. International trade in food and other goods is driven more by politics and economics than by water management decisions.

Poverty alleviation

With increasing globalization, many poor farmers are affected by developments in international markets. Thus, productivity improvements alone might not be sufficient to ensure household food security if market prices decline when aggregate productivity increases. The challenge is to increase food production while not depressing prices below levels that enable farmers to earn sufficient revenue to achieve food security. Improving productivity at a pace that exceeds the rate of decline in market prices requires broader access to water (Evenson and Gollin 2003; chapter 4 on poverty). At the same time, the urban poor and the landless rural poor benefit from lower food prices. The landless rural poor also benefit from labor opportunities provided by large-scale irrigation development (chapter 4 on poverty).

Irrigation development creates the possibility for multiple uses of irrigation water, such as fish and livestock production and other income-generating activities that directly benefit the poor. Irrigation can also stabilize food prices, to the benefit of risk-averse poor farmers and poor urban consumers. Irrigation can also enhance human capital by attracting investments in such social services as education (Foster and Rosenzweig 2004).

The impact of irrigation development on poverty is strongly linked to the type of irrigation. In the past, particularly during the green revolution, large-scale irrigation development contributed to poverty alleviation directly and through multiplier effects (Bhattarai, Sakthivadivel, and Hussain 2002). However, with increasing financial and environmental concerns, the era of large-scale irrigation expansion seems over (see chapter 9 on irrigation).

Small-scale irrigation—such as treadle pumps and drip irrigation kits for home vegetable gardens—targeted directly to the poor can be a cost-effective alternative for reducing poverty

Small-scale irrigation—such as treadle pumps and drip irrigation kits for home vegetable gardens—targeted directly to the poor can be a cost-effective alternative for reducing poverty (Polak 2005). But the successes observed with small-scale systems in South Asia might not be achievable in Sub-Saharan Africa, where aquifers are less suitable, population is less concentrated, and physical infrastructure and institutions are less developed (Goldman and Smith 1995; Mosley 2002). Livelihoods might be enhanced more effectively in Sub-Saharan Africa by improving rainfed agriculture, particularly where small investment costs per hectare enable improvements over a larger area than is possible with similar investments targeted to large-scale irrigation.

Comparing South Asia and Sub-Saharan Africa, homes to most of the world's poor

Optimal investment strategies will differ considerably by region. In the Middle East and North Africa water scarcity constrains further irrigation expansion, and the scope for improving rainfed agriculture is limited. In South Asia the lack of suitable land is becoming a constraint, and water resources are stressed in many basins. China has sufficient water in the south but not in the north. Land and water are sufficient in Latin America and most of Sub-Saharan Africa, but investment funds are limited, institutions are weak, and much of the infrastructure needed to support economic development is not yet in place.

In both Sub-Saharan Africa and South Asia the discussion of investments in water management is highly relevant and debated. The Commission for Africa (2005) and the New Partnership for Africa's Development propose doubling the area under irrigation to boost food production and enhance rural development. India is planning a multibillion-dollar Linking of Rivers project, and Pakistan plans to modernize its aging infrastructure in the Indus Basin. Proponents see investments in new irrigation and hydropower as needed to meet rapidly increasing demand for food and energy. Opponents of large-scale irrigation projects suggest improving rainfed areas where the poor will benefit the most. They claim it is cheaper—in financial, environmental, and social terms—to upgrade underperforming infrastructure, increase rainfed production, and import food. In both Sub-Saharan Africa and South Asia improvements in agricultural water management are needed to increase agricultural productivity and reduce the high rates of rural poverty (Hussain and Hanjra 2003, 2004).

Sub-Saharan Africa: upgrade rainfed agriculture by adding irrigation and investing in transport and governance

Sub-Saharan Africa is largely self-sufficient in major staple crops such as cassava, sweet potatoes, other roots and tubers, maize, and coarse grains (millet, sorghum), but food production and its distribution are highly skewed. Except in rice and wheat, the roles of irrigation and trade in food supply are negligible, with 91% of the supply coming from rainfed agriculture and just under 4% imported from outside the region. Less than 4% of the harvested area is irrigated, and more than 60% of the irrigated area is in just three countries: South Africa, Sudan, and Madagascar (figure 3.10). Water-use approaches potential use in just a few river basins, such as the Limpopo, Orange, and South Madagascar. In most basins water scarcity is caused by inadequate water infrastructure, rather than lack of water resources. Of the potential irrigated area of 40 million ha, 7 million ha are developed (Frenken 2005).

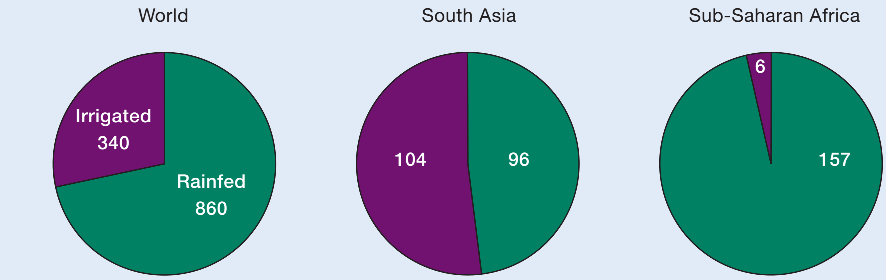
> In an optimistic yield scenario for rainfed agriculture in Sub-Saharan Africa additional food demand can be met from the same harvested area without expansion. But low adoption rates of water harvesting techniques indicate that achieving success will be challenging

Food demand in Sub-Saharan Africa will roughly triple in the coming 50 years. Increases in production likely will come from rainfed agriculture. Despite ample physical potential, irrigation will play a limited role in near-term food supply. Even if the area irrigated in Sub-Saharan Africa is doubled, as suggested by the Commission for Africa (2005), the impact of irrigation on staple food supply will remain small (7%–11% of total food production). The importance of international trade in providing Sub-Saharan Africa's food supply also might be limited in the short term because of a shortage of foreign exchange earnings in many countries. Food aid, which is vital to individual countries and groups in times of emergencies, contributes little to the overall food supply.

The investment cost of doubling the irrigated area is high (see table 3.10), and it is not clear that irrigated cereal production in Sub-Saharan Africa, plagued by high marketing and transportation costs, can compete with subsidized food imports from Europe and the United States. In addition, the institutional infrastructure and experience required for operation, maintenance, and management are lacking. Surface water irrigation schemes have had mixed results in Sub-Saharan Africa, and a groundwater revolution (as in South Asia) has not yet occurred in the region (Giordano 2006).

Without substantial improvements in the productivity of rainfed agriculture, food production will fall short of demand. Water harvesting and small-scale supplemental irrigation methods in rainfed areas—combined with increased input use—can boost productivity by a factor of two or three in Sub-Saharan Africa (Rockström and others 2004; Mati 2006; chapter 8 on rainfed agriculture).

In an optimistic yield scenario for rainfed agriculture additional food demand can be met from the same harvested area without expansion. But low adoption rates of figure **3.10** **The proportion of harvested area that is irrigated is largest in South Asia and smallest in Sub-Saharan Africa** (millions of hectares, 2000)



Source: Based on FAO (2002).

water-harvesting techniques indicate that the extension of local successes throughout the region will be challenging. In a low-yield scenario for rainfed agriculture the cropped area expands by 70%. Where land suitable for agriculture is available, area expansion on such a scale will occur, at least to an extent, at the expense of natural lands and forests, increasing the likelihood of land degradation (Alexandratos 2005; chapter 15 on land).

Low profits and high risks discourage farmers from investing in land and water resources. Major limitations include the lack of domestic market infrastructure, barriers to international markets, and high marketing costs caused by poor roads (Rosegrant and others 2005, 2006). Other barriers include poor governance, institutional disincentives to profitable agriculture (taxes, corruption, lack of formal land titles), and high levels of risk discouraging farmers from investing in labor and other inputs (Hanjra, Ferede, and Gutta forthcoming).

South Asia: improving irrigation and rainfed performance

There is little scope for expanding the agricultural area in South Asia, where 94% of the suitable area already is cultivated (FAO 2002). In addition, more than half the harvested area is irrigated. South Asia has an established system of land and water rights, water institutions, trained manpower, and extensive experience in working with international donors to implement large-scale irrigation projects.

With current yields much lower than potential, output can be increased substantially by increasing productivity in the irrigated sector. In a high-productivity scenario all additional food demand can be met by improving land and water productivity in irrigated areas, without expanding irrigated areas.

The challenge in improving the performance of irrigated agriculture is more institutional than technical, but reforming irrigation bureaucracies is a daunting task (see chapter 5 on policies and institutions), and reducing the subsidies that distort the use of water and energy is politically difficult (Shah and others 2004). These institutional issues must be addressed to enhance the likelihood of achieving higher levels of land and water productivity.

The scope for improving rainfed agriculture in South Asia also is considerable. In a high-yield scenario all additional land and water for food can be met by improving land and water productivity. But if yields remain below expectation, due to low adoption of water-harvesting techniques or climate variability, imports will be needed. Supportive institutions and a supportive economic environment are vital to achieving the potential gains in this scenario.

For many years the Indian government has focused on achieving national food self-sufficiency in staple crops. More recently, as the imminent danger of famines has decreased and nonagricultural sectors have expanded, the national perspective on production and trade has changed. Food trade might become more important in the future, particularly as the relative contribution of nonfarm sectors to the Indian economy increases (Dasgupta and Singh 2005; Rigg 2005, 2006).

> In a high-productivity scenario in South Asia all additional food demand can be met by improving land and water productivity in irrigated areas without expanding irrigated areas

The Comprehensive Assessment scenario

Each of the scenarios described above has emphasized one strategy, such as improving rainfed agriculture through better rainwater management, improving yields and water productivity on existing irrigated areas, or expanding irrigated areas and trade. In reality, a combination of strategies will be implemented, building on regional strengths and limitations (table 3.12). Here we present an additional scenario, the Comprehensive Assessment's optimistic but plausible scenario emphasizing strategies that vary among regions.

In this scenario considerable investments are made in South Asia to improve irrigation performance and, to a smaller extent, improve water productivity in rainfed areas. Local fisheries and livestock are integrated as part of modernizing irrigation systems. The irrigated area expands by 18 million ha (18%). The area irrigated by groundwater is limited to avoid further aggravation of groundwater overdraft. New irrigation development is targeted mostly to small landholdings, with an emphasis on poverty reduction.

In Sub-Saharan Africa investments are targeted toward improving rainfed smallholder agriculture, again with an emphasis on poverty alleviation. The area under irrigation

table **3.12** **Scope for productivity improvement and area expansion**

Region	Scope for improved productivity in rainfed areas	Scope for improved productivity in irrigated areas	Scope for expansion of irrigated area
Sub-Saharan Africa	High	Some	High
Middle East & North Africa	Some	Some	Very limited
Central Asia & Eastern Europe	Some	Good	Some
South Asia	Good	High	Some
East Asia	Good	High	Some
Latin America	Good	Some	Some
OECD countries	Some	Some	Some

increases by 80%,[10] mainly through small-scale, informal irrigation, geared to producing high-value cash crops (sugar, cotton, fruits). Smallholders produce labor-intensive crops for local markets, such that Sub-Saharan Africa becomes largely self-sufficient in all food commodities including fruits and vegetables. To ensure economic feasibility and profitability for individual farmers, due attention is given to supporting physical and institutional infrastructure, such as favorable policies, credit, subsidies, education, and healthcare, capable government institutions, and water user associations. Investments in smallholder agriculture are seen as a necessary first step to promote rural growth and poverty alleviation. In the longer run, however, with more urbanization and diversification of economic activities, the number of people in farming decreases and farm sizes and incomes increase.

Under the Comprehensive Assessment scenario crop water consumption increases by 20%, while withdrawals by agriculture increase by 13%. The challenge is to manage this increase in water use with minimal adverse impacts on environmental services

In the Middle East and North Africa water withdrawals for irrigation and groundwater overdrafts are reduced, and institutional reforms are implemented. Environmental flow regulations are strictly adhered to, even if the area under irrigation is reduced. The area under irrigated cereals is further reduced in favor of higher value crops (fruits and vegetables), which are exported to Europe. Cereal imports increase rapidly.

East Asia consolidates its position as a rice exporter, mainly by improving and intensifying existing irrigated production systems. The integration of fisheries in paddy production is promoted, and aquaculture production increases. China introduces environmental flow regulations to avoid overdrafts, and because of rapid economic growth and the associated demand for agricultural products, China becomes a major grain importer.

Eastern Europe and Central Asia and Latin America expand cultivated areas, primarily under rainfed conditions. Efforts are made to restore degraded river basins in Central Asia by imposing and enforcing stricter rules on environmental flows. Latin America increases its exports of sugar, soybeans, and biofuels. OECD countries emphasize restoring aquatic ecosystem services and reducing groundwater overdrafts. Agricultural exports decline in response to the reform of subsidies.

The global average rainfed cereal yield increases by 58%, while rainfed crop water productivity improves by 31% (table 3.13). Global irrigated yield increases by 55%, while crop water productivity improves by 38%. In monetary terms the output per unit of water increases more rapidly, as multiple uses of water are encouraged and fisheries and livestock production are integrated. Globally, harvested areas increase by 14%. Adverse impacts on terrestrial ecosystems are minimized by zoning regulations where rainfed area expands. Irrigated area increases by 16%, and much of the increase in harvested area comes from higher cropping intensity rather than from expansion of irrigated area.

Crop water consumption increases by 20%, while withdrawals by agriculture increase by 13% (345 cubic kilometers) to 2,975 cubic kilometers by 2050. Water use increases in response to higher food demands. Some of the increase is offset by improvements in crop water productivity and gains in water-use efficiency, although the latter is rather limited. Even in this optimistic scenario, withdrawals by agriculture increase. The challenge is to manage this water with minimal adverse impacts on ecosystem services, while providing the necessary gains in food production.

table **3.13** **The Comprehensive Assessment scenario projections to 2050**

	Irrigated area		Rainfed area		Rainfed cereal yield		Irrigated cereal yield	
Region	**Millions of hectares**	**Cumulative change** (%)	**Millions of hectares**	**Cumulative change** (%)	**Metric tons per hectare**	**Cumulative change** (%)	**Metric tons per hectare**	**Cumulative change** (%)
Sub-Saharan Africa	11.3	80	174.2	10	2.34	98	4.37	99
Middle East & North Africa	21.5	5	16.1	–12	1.19	59	5.58	58
Central Asia & Eastern Europe	34.7	6	120.7	–5	3.00	47	6.06	78
South Asia	122.7	18	83.9	–12	2.54	91	4.84	89
East Asia	135.6	16	182.2	17	3.96	51	5.97	49
Latin America	19.5	18	147.9	46	3.90	58	6.77	68
OECD countries	47.3	4	179.0	4	6.35	33	8.03	22
World	394	16	920.0	10	3.88	58	5.74	55

Source: International Water Management Institute analysis done for the Comprehensive Assessment of Water Management in Agriculture using the Watersim model.

(continues on facing page)

Emerging issues

Water resources planning and management are increasingly affected by a range of emerging issues:

- *Energy.* Rising energy prices affect water use in agriculture in different ways. For example, biofuels production is a new competitor with food for water and land (box 3.4).
- *Climate change.* Climate change adds to the complexity of water resources planning and management. Uncertainty remains regarding how, when, and to what extent this will affect agricultural production and water demand and supply, and what adaptive management strategies may be required (box 3.5).
- *Globalization and trade policies.* Increasingly, decisions taken outside the water sector, such as those on domestic agricultural subsidies and international trade and politics, will influence the water-food-environment equation.
- *The changing role of state and local actors.* Many of the current concerns within the water sector (such as sustainability, efficiency in management, cost recovery, and water rights) will continue to be poorly addressed by top-down interventions mediated by the state and promoted by external development banks or agencies. Success in addressing these issues will reside in the adequate evolution of the roles of states, markets, communities, and civil society (see chapter 5 on policies and institutions).
- *Gender and the feminization of agriculture.* Women play a central role as producers of food, managers of natural resources, income earners, and caretakers of the household's food, water, and nutrition security. While the extent is debated, in many parts of the world women increasingly are involved in agriculture, as men

Rainfed water productivity		Irrigated water productivity		Crop water consumption		Irrigation water diversions		Trade	
Kilograms per cubic meter	**Cumulative change** (%)	**Kilograms per cubic meter**	**Cumulative change** (%)	**Cubic kilometers**	**Cumulative change** (%)	**Cubic kilometers**	**Cumulative change** (%)	**Millions of metric tons**	**Share of consumption** (%)
0.28	75	0.50	58	1,379	29	100	46	–25	12
0.25	47	0.82	41	272	7	228	8	–127	61
0.69	47	1.05	43	773	0	271	11	66	22
0.46	82	0.79	62	1,700	15	1,195	9	2	0
0.57	36	1.06	45	1,990	19	601	16	–97	12
0.63	50	0.91	52	1,361	52	196	12	18	6
1.30	25	1.42	18	1,021	4	238	2	151	26
0.64	31	0.93	38	8,515	20	2,975	13	490	15

box 3.4 **Rising energy prices**

Crude oil prices have risen sharply in the past few years, and fluctuated around $60 a barrel in the first half of 2006. Higher energy prices affect agricultural water use in four ways:

- The demand for alternative energy sources, such as hydropower and bioenergy, increases, with potential impacts on water resource allocation.
- The cost of pumping groundwater increases.
- The viability of desalinization as a source of irrigation water declines (Younos 2005; Semiat 2000).
- Fertilizer prices and the unit costs of other oil-based inputs increase. Some farmers choose to expand irrigated area rather than improving yields, possibly leading to higher aggregate water demand.

Hydropower and bioenergy require substantial water, although hydropower production does not consume water. Multipurpose dams can produce energy, sustain irrigation and fisheries, enhance river regulation, and increase storage. However, dams often have adverse impacts on river ecosystems.

Bioenergy production is a consumptive use of water that might compete with food crop production for water and land resources (Berndes 2002). For example, one of the Millennium Ecosystem Assessment scenarios foresees that by 2050 one-quarter of the global energy supply will be met by energy from biomass (Alcamo and others 2005). Producing the necessary 8 billion tons of biomass requires 5,500 cubic kilometers of crop water consumption, roughly 75% of what is needed for the production of global food today (Kemp-Benedict 2006a, 2006c).

With rising energy prices the cost of groundwater pumping will increase. If India and other countries discontinue energy price subsidies, irrigation might become unaffordable for millions of smallholder farmers.

box **3.5** Changing climate and water resources

The impacts of climate change on agricultural production and water resources are uncertain, with potentially great spatial variation. Semiarid and subtropical areas in Asia, Sub-Saharan Africa, Latin America, and the Middle East and North Africa will likely be affected the most through higher temperatures, greater rainfall variability, and greater frequency of extreme events (Bruinsma 2003; IPPC 2001; Dinar and others 1998; Kurukulasuriya and others 2006).

The Third Assessment report by the International Panel on Climate Change (IPCC 2001) foresees a temperature rise in the range of 2°–6° Celsius by 2100. Temperature increases in the Millennium Ecosystem Assessment scenarios are in the lower range of 1.5°–2.0° Celsius above pre-industrial revolution temperatures in 2050, and 2.0°–3.5° Celsius higher in 2100 (Alcamo and others 2005). Such temperature increases might lead to reductions in crop yields. But these losses might be offset by increases in yields because atmospheric carbon dioxide might act as a “fertilizer.”

The combined effect of temperature rises and carbon dioxide enhancement varies among crops (Parry and others 1999; Alcamo and others 2005). Farmers might be able to adapt to temperature increases by changing planting dates, using different varieties, or switching to different crops (Droogers and Aerts 2005; Droogers 2004). Adaptations might generate substantial transaction costs (Pannell and others 2006).

While future regional temperatures are uncertain, still more uncertain are future precipitation patterns within regions. Most climate models agree on a global average precipitation increase in the 21st century, but they do not agree on the spatial patterns of changes in precipitation (Alcamo and others 2005), though some describe a trend of declining soil moisture (Dai, Qian, and Trenberth 2005).

Most climate change models indicate a strengthening of the summer monsoon. In Asia this might increase rainfall by 10%–20%. Even more important, it might generate a dramatic increase in interyear variability (WWF 2005). For paddy farmers this might imply less water scarcity but more damage from flooding and greater fluctuations in crop production. Some arid areas might become even drier, including the Middle East, parts of China, southern Europe, northeastern Brazil, and west of the Andes in Latin America. According to most climate models, the absolute amount of rainfall in Africa will decline as variability increases. In semiarid areas where rainfall already is unreliable, this might have severe impacts on crop production (Kurukulasuriya and others 2006) and the economy (Brown and Lall 2006). Irrigation might help smooth out variability, but is only useful if the total amount of rainfall remains sufficient to meet crop water demands.

Climate change might also affect agriculture if it causes substantial melting of glaciers that feed major rivers that are used for irrigation. Such melting could affect millions of hectares of irrigated land on the Indo-Gangetic plain. Millions of cubic meters of water are stored during the winter months in the form of ice and gradually released as melting water in spring. The warmer spring weather coincides with the start of the growing season. The disappearance of ice caps may change this flow, leading to greater summer runoff. Without additional storage to capture increased summer runoff, much water will flow unused to the ocean, leading to water scarcity in the drier months (Barnett, Adam, and Lettenmaier 2005; Wescoat 1991; Rees and Collins 2004; Dinar and others 1998).

migrate to cities and abroad in search of employment outside agriculture (see chapter 4 on poverty).

- *Genetically modified crops.* The pros and cons and the potential role of genetically modified crops in improving water productivity and reducing poverty are subject to debate. Box 7.2 in chapter 7 on water productivity gives an overview of the issues.

Summary statement

The path to success in enhancing agricultural production and ensuring food security is not a single, neatly formed vector from the current situation to a well defined target. Instead, the aggregate, global path will include many smaller paths representing the efforts of developing and industrialized countries seeking to ensure domestic food security and enhance public welfare. The smaller paths will become intertwined through international trade and the transfer of technology through the efforts of national and international research centers. We offer the Comprehensive Assessment scenario as one example of a strategy that might achieve the world's goals for food security, poverty reduction, and environmental sustainability.

Reviewers

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Notes

1. In rainfed areas 100% of crop water consumption is provided by precipitation. But in irrigated areas, too, part of the water is provided by rain falling in the command area. Irrigation professionals refer to this as "effective precipitation." This estimate is derived from International Water Management Institute analysis done for the Comprehensive Assessment of Water Management in Agriculture using the Watersim model; the FAO estimates 11%.

2. Our estimate of 2,630 cubic kilometers includes recycling within river basins. Seckler and others (1998, 2000) refer to this as "primary water." Summing all withdrawals from individual water users will lead to a higher estimate because of reuse of drainage flows by downstream users (Perry 1999; Molden, Sakthivaldivel, and Habib 2000). The interpretation of these numbers at such large scales is not always straightforward (Lankford 2006b). According to the FAO's estimate, 1,030 cubic kilometers of crop water evapotranspiration is provided by irrigation water, close to our estimate of 1,130 cubic kilometers.

3. Also refer to a recent web discussion among water experts on this topic (Winrock Water, www.winrockwater.org/forum.cfm).

4. Most literature related to rainfed agriculture describes soil conservation, fertility, pest management, and the like. Very little attention has been given to the need for rainwater management.

5. www.nepadst.org/platforms/foodloss.shtml.

6. The concept of minimum amounts of water has been superseded by the concept of the natural flow regime—flow quantities, temporal patterns, and overall flow variability (Arthington and others 2006). Smakthin, Revenga, and Döll (2004) is one of the few attempts at quantification.

7. This is similar to assumptions underlying the FAO's study *World Agriculture: Towards 2015/2030* (FAO 2002). Note that the expansion of irrigated harvested areas comes from expanding the area equipped and increasing the intensity of cropping (number of crops per year).

8. Efficiency of water use can be expressed by many indicators. In the Watersim model we use effective efficiency, defined as the amount of water beneficially used by plants or animals divided by total water consumption (Keller and Keller 1998), and depleted or consumptive fraction, defined as the ratio of water consumed to water withdrawn (Seckler and others 2000).

9. Frameworks for evaluating water productivity incorporating multiple uses of water exist (see chapters 12 on inland fisheries and 13 on livestock), but empirical observations and data are limited. Therefore, increases in water productivity by integrating fisheries and livestock could not be quantified in the scenario analysis.

10. This is comparable to the doubling envisaged by the Commission for Africa (2005), though its timeframe is shorter. Lankford (2006a) warns that doubling the irrigated area is not feasible without some large-scale irrigation. He recommends a slower rate of growth than foreseen by the Commission for Africa.

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