Pathways for Increasing Agricultural Water Productivity

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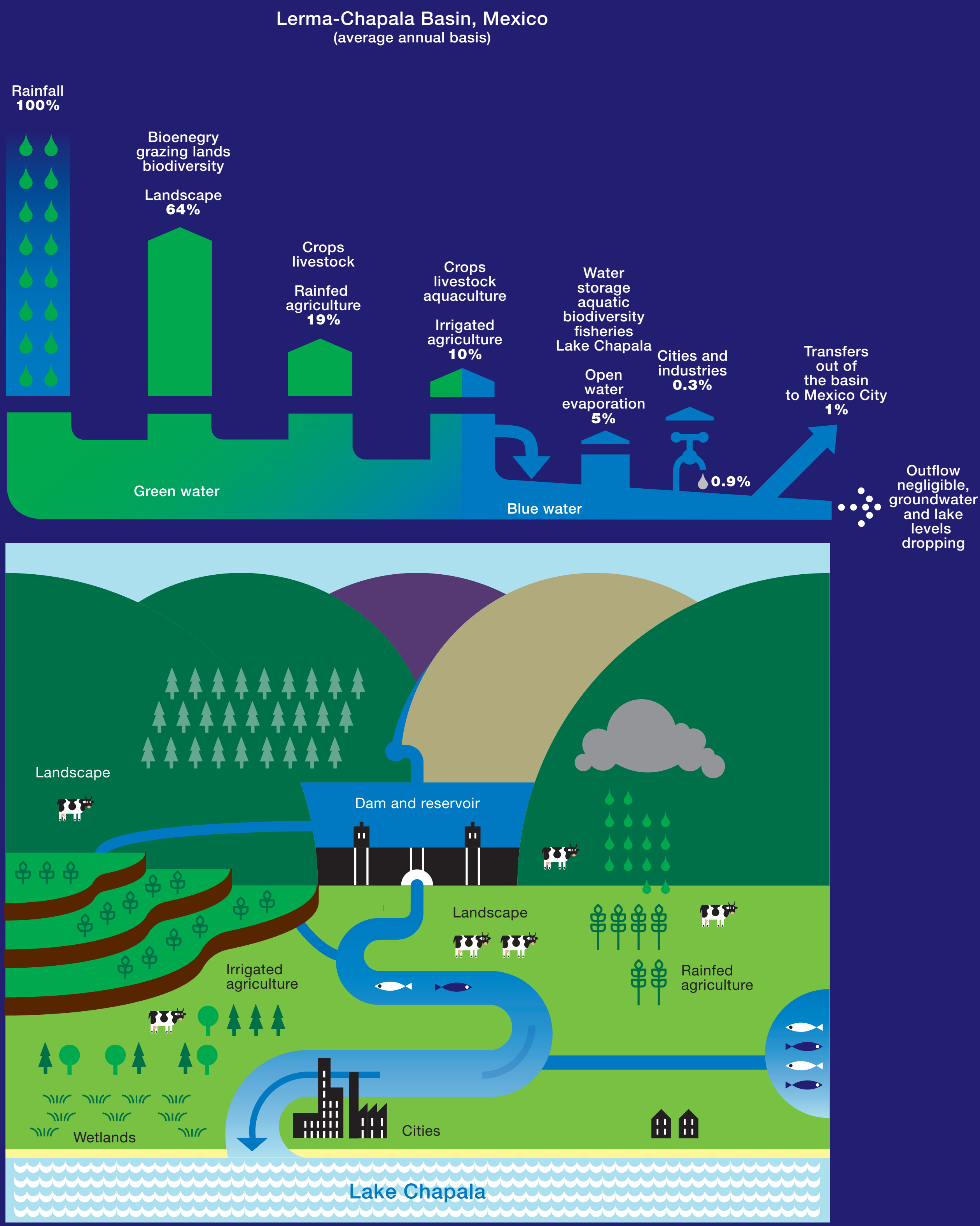
Water use and productivity in a river basin



Source: Wester and others forthcoming.

Grow more food with less water

Artist: Monique Chatigny, Quebec, Canada

7 Pathways for increasing agricultural water productivity

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Overview

Water productivity is defined as the ratio of the net benefits from crop, forestry, fishery, livestock, and mixed agricultural systems to the amount of water required to produce those benefits. In its broadest sense it reflects the objectives of producing more food, income, livelihoods, and ecological benefits at less social and environmental cost per unit of water used, where *water use* means either water delivered to a use or depleted by a use. Put simply, it means growing more food or gaining more benefits with less water. *Physical water productivity* is defined as the ratio of the mass of agricultural output to the amount of water used, and *economic productivity* is defined as the value derived per unit of water used. Water productivity is also sometimes measured specifically for crops *(crop water productivity)* and livestock *(livestock water productivity)*.

To feed a growing and wealthier population with more diversified diets will require more water for agriculture on an average annual basis [well established]. Evapotranspiration from agricultural land is estimated at 7,130 cubic kilometers and without increases in water productivity could increase by 60%–90% by 2050 (see chapter 3 on scenarios). Agricultural water withdrawals from natural systems are estimated at 2,664 cubic kilometers, or about 70% of water withdrawn for human purposes. Additional water for agriculture will strain terrestrial and aquatic ecosystems and intensify competition for water resources. Improving physical water productivity in agriculture reduces the need for additional water and land in irrigated and rainfed systems and is thus a critical response to increasing water scarcity, including the need to leave enough water to sustain ecosystems and to meet the growing demands of cities and industries.

There is considerable scope for improving physical water productivity, but not everywhere [established but incomplete]. In areas of the world that already exhibit high physical water productivity, the scope for improvements is limited. But scope for improvement remains in high potential areas in many rainfed, irrigated, livestock, and fisheries systems in many regions of the world. Many farmers in developing countries could raise water productivity by adopting proven agronomic and water management practices because raising land productivity generally leads to increases in water productivity. Many promising pathways for raising water productivity are available over the continuum from fully rainfed to fully irrigated farming systems. These include supplemental irrigation (some irrigation to supplement rainfall); soil fertility maintenance; deficit irrigation; small-scale affordable management practices for water storage, delivery, and application; modern irrigation technologies (such as pressured systems and drip irrigation); and soil-water conservation through zero or minimum tillage. Breeding and biotechnology can help indirectly by reducing biomass losses through increased resistance to pests and diseases, vigorous early growth for fast ground cover, and reduced susceptibility to drought. But water productivity gains are context dependent and can be properly assessed only by taking an integrated basin perspective.

> Many farmers in developing countries could raise water productivity by adopting proven agronomic and water management practices because raising land productivity generally leads to increases in water productivity

Increasing water productivity, especially the value produced per unit of water, can be an important pathway for poverty reduction [established but incomplete]. Increasing the value derived per unit of water, especially the opportunities for employment, income generation, nutrition, and opportunities for women, is important for poverty reduction. But carefully crafted programs are required to ensure that these gains reach the poor, especially rural women, and are not captured only by wealthier or more powerful users.

There is significant scope to improve physical and economic water productivities in livestock and aquaculture [established but incomplete]. Rising demand for livestock and fish products leads to rising demand for water. Water productivity gains can be made by carefully considering feed sources and feeding strategies, improving the quality of produce, and integrating fisheries and livestock into farm production systems. Because capture fisheries are increasingly threatened by reductions in streamflows *[established but incomplete]*, basin water productivity analysis should consider the social and ecological values generated by fisheries before reducing river flows that support them.

Increasing the value generated by water use and decreasing associated costs require understanding and interventions that look beyond the direct production benefits and investment costs of agricultural water management to the livelihood and ecological benefits and costs. Integrated and multiple-use systems—in which water serves crops, fish, livestock, and domestic purposes—can increase the value derived per unit of water used. Gains in crop production have often come, for instance, at the expense of fisheries. Values generated by fisheries, including ecosystem sustenance values, are routinely underestimated. Understanding values helps us to understand where there are win-win situations and what tradeoffs will have to be made. But these values are poorly understood and rarely enter into decisionmaking.

The adoption of techniques to improve water productivity requires an enabling policy and institutional environment that aligns the incentives of producers, resource managers, and society and provides a mechanism for dealing with tradeoffs. Despite adequate technologies and management practices, achieving net gains in water productivity is difficult for numerous reasons. The price of most agricultural produce is low, and the risks for farmers are high. Productivity gains tend to suppress market prices by increasing supply. Gains achieved by one group often come at the expense of another (crop farmers taking water out of fisheries). Incentive systems do not support the adoption and uptake of existing technologies (who pays for the water-saving practices by farmers that ultimately benefit city users?). The incentives of producers (more water for more income) are often much different than the incentives of broader society (more water for cities and the environment). Gains are often captured by more powerful users, and the poor are left behind (those who can afford drip irrigation tend to gain more). Strategies must recognize these tradeoffs and provide incentives and compensation for greater equity among winners and losers. Many incentives will come from outside the water sector and address issues of vulnerability and risk, markets, and the profitability of the agriculture enterprise. Research should explore ways to limit the magnitude of the tradeoffs, while inclusive processes for involving interest groups should balance the ways in which these tradeoffs are dealt with.

There are four high priority areas for water productivity gains:

- Areas where poverty is high and water productivity is low, where improvements could particularly benefit the poor, as in much of Sub-Saharan Africa and parts of South Asia and Latin America.
- Areas of physical water scarcity where there is intense competition for water, such as the Aral Sea Basin and the Yellow River, especially where gains in economic water productivity are possible.
- Areas with little water resources development where high returns from a little water can make a big difference.
- Areas of water-driven ecosystem degradation, such as falling groundwater tables, river desiccation, and intense competition for water.

Integrated and multiple-use systems—in which water serves crops, fish, livestock, and domestic purposes—can increase the value derived per unit of water used

What is water productivity and why is it important?

In the broadest sense water productivity relates to the net socioeconomic and environmental benefits achieved through the use of water in agriculture, including fisheries, livestock, crops, agroforestry, and mixed systems. The concept reflects the desire to do better using less of scarce water resources.

There are important reasons to improve agricultural water productivity:

- To meet the rising demand for food from a growing, wealthier, and increasingly urbanized population, in light of water scarcity.
- To respond to pressures to reallocate water from agriculture to cities and to ensure that water is available for environmental uses.
- To contribute to poverty reduction and economic growth. For the rural poor more productive use of water can mean better nutrition for families, more income, productive employment, and greater equity. Targeting high water productivity can reduce investment costs by reducing the amount of water that has to be withdrawn.

Globally, the additional amount of water needed to support agriculture directly will depend on the gains in water productivity. With no gains in water productivity current average annual agricultural evapotranspiration of 7,130 cubic kilometers could nearly double in the next 50 years. But with appropriate practices in livestock, aquaculture, rainfed, and irrigated systems the increase could be held down to 20%–30%. Increases in withdrawals for irrigation, now at 2,664 cubic kilometers, could range from zero to 55% depending on investments in increasing water productivity and on how much rainfed and irrigated agriculture expand.

> To understand water productivity, it is essential to follow the flow of water through a basin and to understand how water supports life and livelihoods

Within the broad definition of water productivity there are interrelated and cascading sets of definitions useful for different purposes. Physical water productivity relates the mass of agricultural output to water use—"more crop per drop." Economic water productivity relates the economic benefits obtained per unit of water used and has also been applied to relate water use in agriculture to nutrition, jobs, welfare, and the environment. Water productivity depends on a number of nonwater factors, such as fertilizer use and labor, as well as on water. Increasing water productivity is particularly appropriate where water is scarce compared with other resources involved in production.

This chapter presents a framework for water productivity analysis and highlights how the framework can be used in different situations. Physical water productivity is presented in detail because it underpins many of the broader concepts and has the largest impact on the amount of water required to produce food. The chapter then examines promising pathways to achieving higher water productivity, implications for poverty reduction, and the constraints to achieving high water productivity. The chapter concludes with investment priorities for increasing water productivity.

A framework for water productivity

Water productivity analysis can be applied to crops, livestock, tree plantations, fisheries, and mixed systems at selected scales—crop or animal, field or farm, irrigation system, and basin or landscape, with interacting ecosystems (table 7.1). The objectives of water productivity analysis range from assessing agricultural production (kilograms of grain per unit of water depleted by a crop on a field) to assessing incremental welfare per unit of water used in the agricultural sector. Because expressions for water productivity differ in each context, it is important to be clear about the agriculture output and input terms used.

To understand water productivity, it is essential to follow the flow of water through a basin and to understand how water supports life and livelihoods (see chapter frontispiece). The natural source of basin water is rain. Interbasin transfers, conveying water from one river basin to another, are an increasingly common source of water. As water moves downstream, a drop may be transpired by a plant, be evaporated from the land, or continue to flow downstream to be used and reused by cities, agriculture, and fisheries.

The denominator of the water productivity equation is expressed as water either supplied or depleted. Water is depleted when it is consumed by evapotranspiration, is incorporated into a product, flows to a location where it cannot be readily reused (to saline groundwater, for example), or becomes heavily polluted (Seckler 1996; Molden and others 2003).

table 7.1	Water productivity interests at different scales				
	Crop, plant, or animal	**Field or pond**	**Farm or agricultural enterprise**	**Irrigation system**	**Basin and landscape**
Processes	Energy conversion, nutrient uptake and use, photosynthesis, and the like	Soil, water, nutrient management	Balancing risks and rewards, managing farm inputs including water	Distribution of water to users, operation and maintenance, fees, drainage	Allocation across uses, regulation of pollution
Interests	Agricultural producers, breeders, plant and animal physiologists	Agricultural producers; soil, crop, fish, livestock scientists	Agricultural producers, agriculturalists, agriculture economists	Irrigation engineers, social scientists, water managers	Economists, hydrologists, social scientists, engineers, water managers
Production terms (numerator)	Kilograms of produce	Kilograms of produce	Kilograms, $	Kilograms, $, value, ecosystem services	$, value, ecosystem services
Water terms (denominator)	Transpiration	Transpiration, evaporation, water application	Evapotranspiration, irrigation supply	Irrigation deliveries, depletion, available water	Deliveries, flows, depletion

Note: The $ sign represents marketable financial values, while the word *value* includes other intrinsic values such as the value of livelihood support, ecological benefits, and cultural significance.

This notion of water productivity evolved from two disciplines. Crop physiologists defined *water use efficiency* as carbon assimilated and crop yield per unit of transpiration (Viets 1962), and then later as the amount of produce per unit of evapotranspiration. Irrigation specialists have used the term *water use efficiency* to describe how effectively water is delivered to crops and to indicate the amount of water wasted. But this concept provides only a partial and sometimes misleading view because it does not indicate the benefits produced, and water lost by irrigation is often gained by other uses (Seckler, Molden, and Sakthivadivel 2003).

The current focus of water productivity has evolved to include the benefits and costs of water used for agriculture in terrestrial and aquatic ecosystems (table 7.2). Water productivity analysis can be seen as part of an ecosystem approach to managing water. Rain, natural flows, withdrawals, and evaporation support terrestrial and aquatic ecosystems, which produce numerous services for people. The primary service of agroecosystems is food and fiber production, but other important services are produced as well (see chapter 6 on ecosystems).

Crop water productivity basics

An assessment of the potential for reducing water needs and increasing production and values requires an understanding of basic biological and hydrological crop-water relations. Answering the question of how much more water will be needed for agriculture requires understanding the connections among water, food, and diets. The amount of water that we consume when eating food depends on diet and on the water productivity of the agriculture production system (box 7.1) The amount of water required for field crops and the relation to yield dominates the equation on the need for additional water for food.

table **7.2** **A framework for linking water productivity with ecosystem approaches**

Ecosystems	Agricultural activities	Water source and depletion	Services (provisioning, regulating, cultural, and supporting services)	Ways to increase water productivity
Terrestrial: forests, grasslands	Livestock grazing, forest products	Rain, evaporation, transpiration	Biodiversity, climate and water flow regulation, cultural values	• Increase services • Decrease water depletion • Decrease negative impacts on other ecosystems
Agroecosystems	Crops, agroforestry, livestock, aquaculture	Rain plus water diversion, evaporation, transpiration	Provision of food and fiber plus other services	
Aquatic: wetlands, rivers, lakes	Capture fisheries, aquatic plants	Runoff, return flows, evaporation, transpiration	Biodiversity, water regulation, recreational, and cultural values	

box **7.1** **How much water do we eat?**

It is possible to calculate how much water in terms of evapotranspiration is required to sustain different diets based on knowledge of the relations between evaporation, transpiration, and yield. Depending on climate and management, it takes 400–2,000 liters of evapotranspiration to produce a kilogram of wheat. After taking into consideration the amount of evapotranspiration for grazing or feed and how much of this food livestock consume, it is possible to calculate the water required to produce eggs or meat. The amount is highly variable, depending on the type of animal, feed, and management practices, but it is on the order of 1,000–20,000 liters per kilogram of meat (see chapter 13 on livestock).

Based on these estimates, researchers have reported values of daily water requirements to support diets of 2,000–5,000 liters of water a day (Renault and Wallender 2000), with a rule of thumb of about 3,000 liters per person per day, or 1 calorie per liter of water evapotranspired. High-calorie, protein-rich diets require more water than do vegetarian diets. Where water productivity is quite low, as in much of Sub-Saharan Africa, the amount of water required to sustain a balanced daily diet can be quite high despite low calorie intake and undernutrition.

Estimated daily water consumption from primary dietary components for Ethiopia, Thailand, and Italy

Product	Description	Ethiopia	Thailand	Italy
Cereals[a]	Calories per person per day	1,253	1,180	1,166
	Water use (liters per kilogram)	1,576	3,523	949
	Daily per capita use (liters)	573	1,141	428
	Share of diet (% of total calorie intake)	68	50	32

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box 7.1 **How much water do we eat?** (continued)

Product	Description	Ethiopia	Thailand	Italy
Starchy roots[b]	Calories per person per day	229	47	72
	Water use (liters per kilogram)	375	279	152
	Daily per capita use (liters)	57	12	1
	Share of diet (% of total calorie intake)	12	2	2
Vegetable oil	Calories per person per day	31	151	652
	Water use (liters per kilogram)	17,842	3,764	1,719
	Daily per capita use (liters)	27	305	683
	Share of diet (% of total calorie intake)	2	6	17
Vegetables	Calories per person per day	10	36	93
	Water use (liters per kilogram)	418	264	108
	Daily per capita use (liters)	13	30	44
	Share of diet (% of total calorie intake)	1	1	3
Fruits[c]	Calories per person per day	13	108	172
	Water use (liters per kilogram)	507	851	440
	Daily per capita use (liters)	10	144	239
	Share of diet (% of total calorie intake)	2	5	5
Animal products[d]	Calories per person per day	102	295	950
	Water use from grazing land (liters per kilogram)	23,289	2,486	1,474
	Daily per capita use (liters)	2,238	605	1,611
	Share of diet (% of total calorie intake)	6	12	26
Other[e]	Calories per person per day	200	566	498
	Daily per capita water use (liters)	225	718	230
	Share of diet (% of total calorie intake)	11	24	14
Total	Total calories supplied per person per day	1,838	2,383	3,603
	Total daily water consumption (liters)	3,143	2,955	3,236

Note: Values are based on national averages and include losses from retail to consumer so do not reflect what is actually ingested. Values for share of diet may not sum to 100% because of rounding.

a. Predominant cereal crop is tef in Ethiopia, rice in Thailand, and wheat in Italy.

b. Predominant starchy root is cassava in Thailand, various in Ethiopia, and potatoes in Italy.

c. Predominant fruit is bananas in Ethiopia and Thailand and citrus in Italy.

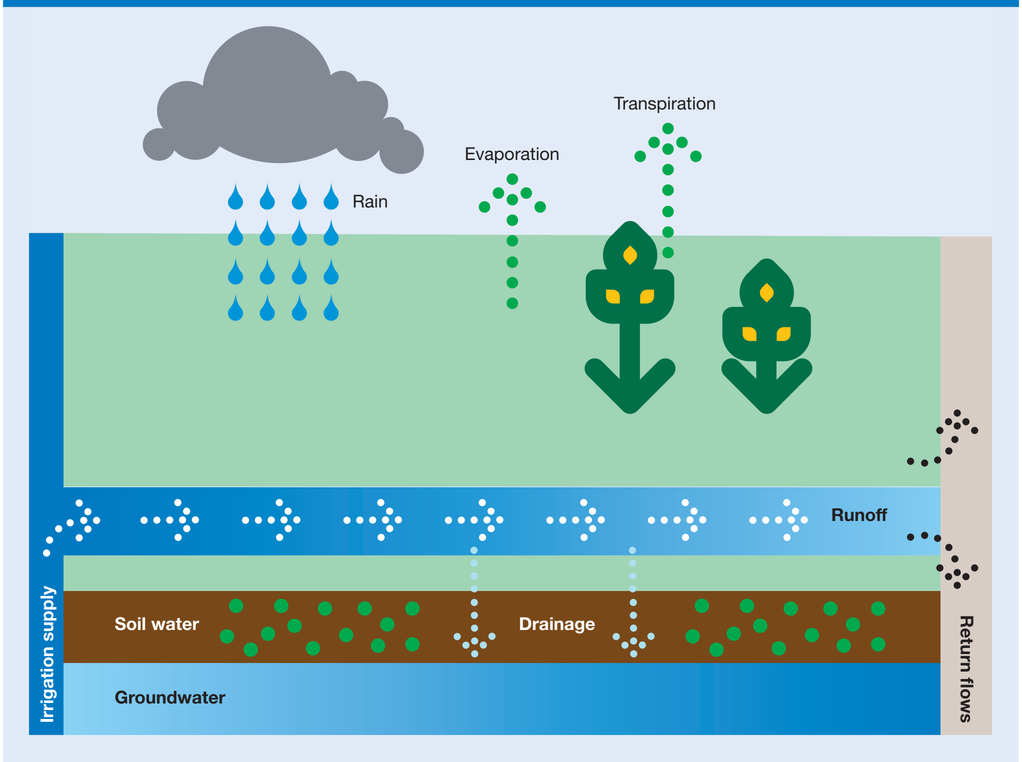
d. Predominant animal products are beef and milk in Ethiopia, pork and fish in Thailand, and milk and pork in Italy.

e. Other includes sugar, oil crops, alcohol, spices, and pulses.

Source: Analysis by Food and Agriculture Organization for the Comprehensive Assessment of Water Management in Agriculture.

Thus this section starts with a fundamental but somewhat technical presentation of the relations among transpiration, evaporation, delivery, drainage, biomass, and yield shown in figure 7.1.

As figure 7.1 shows, the supply of water is from rain and irrigation. Water is depleted by productive transpiration and evaporation—together known as evapotranspiration. Water in excess of evapotranspiration runs off the field (runoff), drains into soil water figure **7.1** **Crop and water balance**



(green water source), or percolates to groundwater. These return flows are not necessarily wastage, as other users downstream may depend on that water.

Transpiration, biomass, and yield

For a given crop variety, fertility level, and climate there is a well established linear relation between plant biomass (leaves, stems, roots, grain) and transpiration (Tanner and Sinclair 1983; Steduto and Albrizio 2005), a process by which plants convert liquid water to water vapor. More biomass production requires more transpiration because when stomata open, carbon dioxide flows into the leaves for photosynthesis and water flows out. Water outflow is essential for cooling and for creating liquid movement in the plant for transporting nutrients. Stomata close during drought, limiting transpiration, photosynthesis, and production. Different kinds of plants are more water efficient in terms of the ratio between biomass and transpiration. The most common crops, C_3 crops such as wheat and barley, are least efficient. C_4 crops such as maize and sugarcane are more efficient, while the most efficient are CAM (crassulacean acid metabolism) crops such as cactus and pineapple.

To boost economic yield, plant breeders have developed varieties with a higher harvest index, or the proportion of economic produce (such as food grains) to total biomass. In doing so, they have also achieved more economic produce per unit of transpiration.

This breeding strategy has probably raised the potential for water productivity gains more than any other agronomic practice over the last 40 years (Keller and Seckler 2004). The harvest index for wheat and maize rose from about 0.35 before the 1960s to 0.5 in the 1980s (Sayre, Rajaram, and Fischer 1997) when green revolution breeders focused their attention on these crops. But the rate of increase has slowed over the last 20 years as physiological limits are being reached. In situations of low yield, however, values for harvest index are less than the maximum achievable because of suboptimal management practices.

This relation between transpiration and crop production has far-reaching consequences for water. Increases in food production are achieved with a near proportionate increase in transpired water. That is why increases in food production have taken water from ecosystems, reducing the amount of water transpired by forests and grass and reducing water flows to the sea, and why future production will continue to do the same. Feeding more people will require more water to be transpired.

Increases in food production are achieved with a near proportionate increase in transpired water

Evaporation and transpiration

Agriculture depletes the water resource base mainly through evapotranspiration, the combination of productive transpiration and collateral evaporation from land and water surfaces (photo 7.1). It is a commonly used concept partly because it is difficult to separately measure evaporation and transpiration. Evapotranspiration is critically important because it is essential for crop production and because raising agricultural evapotranspiration means that less water is available for ecological and other human uses. Ultimately, the extent of agriculture is limited by the available water resources that can be depleted by evapotranspiration.

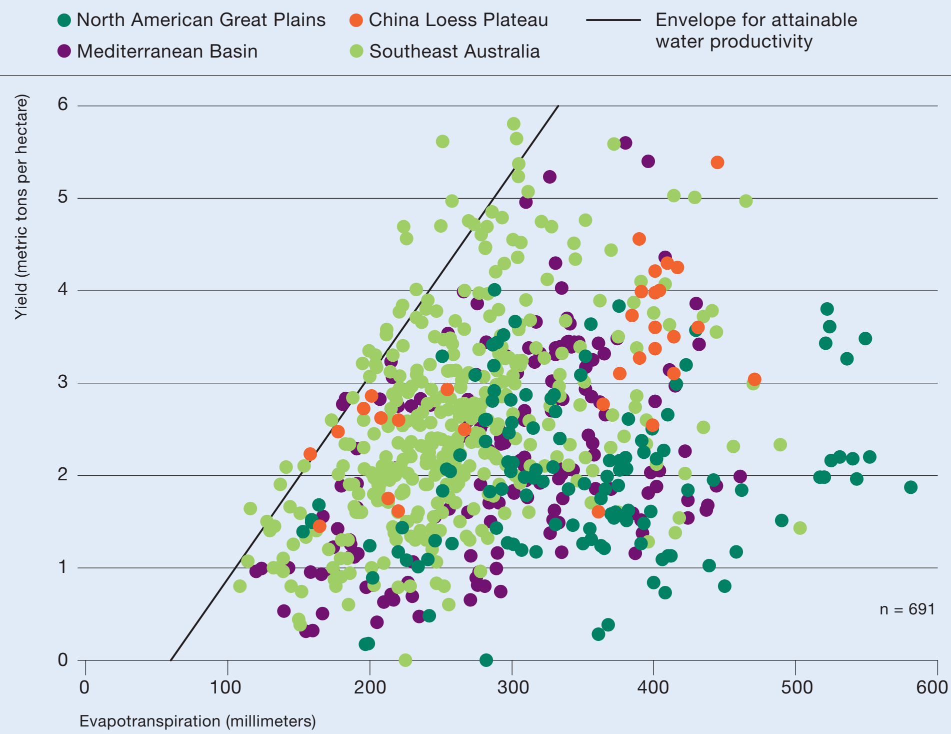
Photo by Mats Lannerstad

Photo 7.1 Crop evapotranspiration: water is transpired through leaves and evaporated from soil surfaces

Climate plays a central role in water productivity per unit of evapotranspiration. Higher productivity is achievable at lower vapor pressure deficits (the difference between the actual and maximum amount of water vapor in the air) (Tanner and Sinclair 1983) *[well established]*, which are common at higher latitudes (Zwart and Bastiaanssen 2004). It has been speculated that the higher carbon dioxide levels associated with climate change will raise water productivity per unit of evapotranspiration because more carbon can enter the plant for more photosynthesis (Droogers and Aerts 2005; IPCC 2001), but more recent evidence that productivity gains will be substantially offset by increased temperature (Long and others 2006) casts doubts on claims that increased carbon dioxide from climate change will enhance yield and water productivity.

While there is a fixed relation between biomass and transpiration, there is substantial variability in yield (here, the marketable produce of a crop) relative to transpiration because of differences in evaporation, harvest index, climate conditions, cultivars, water stress, pest and diseases, nutritional and soil status, and other management and agronomic practices (figure 7.2). Thus there seems to be considerable scope for raising the amount of yield relative to evapotranspiration before reaching the upper limit (the straight line in figure 7.2 that coincides with the reputed linear relationship between transpiration and yield). That much of the variability is due to management practices (French and Schultz 1984) is important because it offers hope of possible improvements in the ratio between marketable produce and evapotranspiration.

figure **7.2** **There are large variations between yield and evapotranspiration for wheat in different regions of the world**

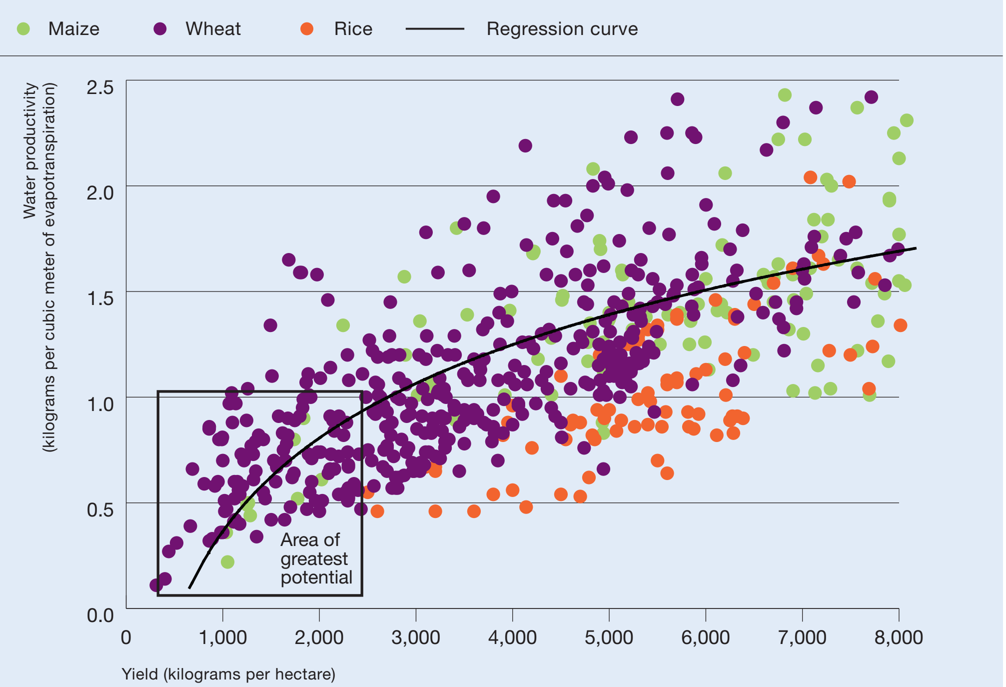


Source: Adapted from Sadras and Angus 2006.

In situations where yield is less than 40%–50% of potential, nonwater factors such as soil fertility limit yield and crop water productivity per unit of evapotranspiration (Tanner and Sinclair 1983). Land degradation and nutrient depletion significantly constrain opportunities to increase water productivity (see chapter 15 on land). In these situations there is a synergistic effect when water practices that increase access to water at the right time or reduce land degradation processes are combined with other agronomic practices such as maintaining soil health and fertility, controlling weeds and disease, and timing planting. Such synergistic interactions between production factors raise water productivity, especially when yield values are low, because most production resources are used more efficiently as yield levels rise (de Wit 1992). When yields are above 40%–50% of their potential, however, yield gains come at a near proportionate increase in the amount of evapotranspiration (figure 7.3).

Deliveries and drainage

Much attention has been given to reducing water deliveries to agriculture (blue water focus), while less has been given to the depletion of water, especially through evapotransfigure **7.3** **Water productivity rises faster at lower yields and levels off at higher yields**



Source: Adapted from Zwart and Bastiaanssen 2004.

piration. Both are important, but both have different implications. A crucial point is that strategies to increase water productivity per unit of water delivered must also consider what happens to drainage flows.

Several farm water management practices such as shorter furrows, alternating wet and dry irrigation, and sprinkler irrigation are intended to convert more of the water input into transpiration to increase yield and consequently to reduce drainage flows. Similarly, concrete lining or pipes in irrigation systems are employed to reduce seepage from canals and so to reduce drainage flows.

To know whether more precise farm and irrigation management practices "save" water that can be used for something else, it is important to know what happens to drainage flows. Drainage flows are undesirable in situations where flows are directed to a saline aquifer, contribute to waterlogging, or are directed away from an important ecosystem. But drainage flows can also be desirable, when they are a source of water for downstream farmers, reach shallow groundwater for home gardens (Bakker and others 1999) and domestic wells (Meijer and others 2006), or support other important ecosystem services. Misguided investments to "save" water in such cases can be detrimental to livelihoods and well-being. What is needed is more analysis in a basin context.

Water productivity as value per unit of water

Increasing net benefits or value per unit of water has key implications for farmer decisions, economic growth, poverty reduction, equity, and the environment. There is much more scope for increasing value per unit of water use in agriculture (economic water productivity) than in physical water productivity, which is becoming increasingly constrained. Strategies for increasing the value of water used in agriculture include:

- Increasing yield per unit of supply or depletion.
- Changing from low- to high-value crops—from wheat to strawberries, for example (photo 7.2)
- Reallocating water from low to higher valued uses (for example, from agriculture to cities).
- Lowering the costs of inputs (labor, water technologies).
- Increasing health benefits and the value of ecological services of agriculture.
- Decreasing social, health, and environmental costs (for example, minimizing degradation of other ecosystems).
- Obtaining multiple benefits per unit of water (for example, using water for drinking and agriculture).
- Achieving more livelihood support per unit of water (more jobs, nutrition, and income for the same amount of water).

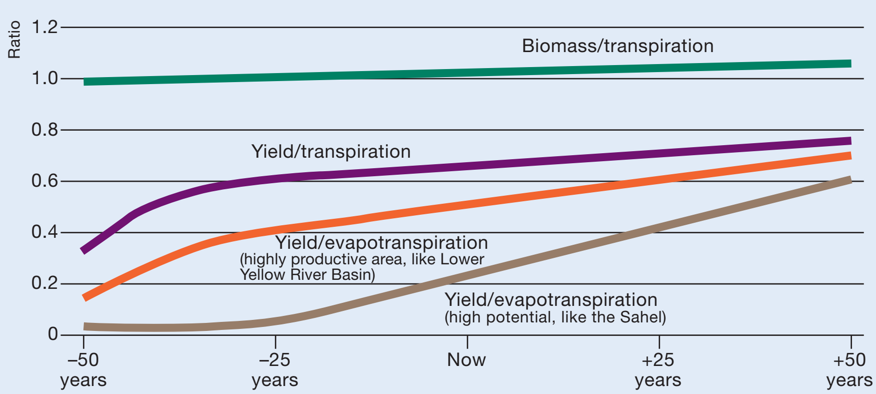
Photo by Mats Lannerstad

Photo 7.2 Growing higher valued crops, such as irrigated bananas and cabbage, improves economic water productivity

Pathways to improving water productivity

Pathways to improving water productivity include improving the productivity of green and blue water; improving the water productivity of livestock and fisheries; applying an integrated approach to increase the value per unit of water; and adopting an integrated basin perspective to understand water productivity tradeoffs.

figure **7.4** **The highest gains in water productivity for common crops such as rice, wheat, and maize are likely in areas where yields are still low**



Source: Schematic developed for the Comprehensive Assessment of Water Management in Agriculture.

Improving water productivity with respect to evapotranspiration

Physical water productivity can be increased for the most common grain crops like rice, wheat, and maize in three fundamental ways (figure 7.4). There is controversy over the potential for future increases in the harvest index (ratio of grain weight to biomass) or the ratio of biomass to transpiration for common crops like wheat and rice, ranging from deep skepticism (Tanner and Sinclair 1983) to slight optimism (Bindraban 1997; Bennett 2003). Much of the potential for increasing the harvest index for common grains such as wheat, maize, and rice was met during the green revolution. But surprises do happen, which could lead to unexpected changes in these relations (box 7.2).[1] There are greater opportunities to improve the harvest index in other crops like sorghum and millet, important crops for many poor people. Breeding, targeting early growth vigor to reduce evaporation, and increasing resistance to drought, disease, or salinity could all improve water productivity per unit of evapotranspiration.

The two lower lines of figure 7.4 indicate that improvements in physical water productivity are possible through improved management that increases the ratio of yield to evapotranspiration. But in many of the most productive areas of the world, such as the lower Yellow River Basin, large improvements have already been made and the remaining scope is small. The implication is that for these areas achieving higher yields will require more evapotranspiration.

The areas with the highest potential gains are those with very low yields, such as Sub-Saharan Africa and South Asia. These are also areas of extreme poverty, with the largest

box 7.2 | Can biotechnology improve water productivity?

Crop breeding has been responsible for tremendous gains in water productivity through interventions that have increased the harvest index. Common grains such as wheat, maize, and rice, which achieved such gains during the 1960s to 1980s, are less likely to make further gains in this area. But there are several indirect means to improve physical water productivity in which biotechnology can play a role:

- Targeting rapid early growth to shade the soil and reduce evaporation.
- Breeding drought-resistant varieties. The gains are clear when crop failure is avoided, but where yield is increased, so is evapotranspiration, and therefore the gain in water productivity is ambiguous.
- Breeding for resistance to disease, pests, and salinity.
- Boosting the harvest index for crops such as millet and sorghum that have not received as much attention as the green revolution grains.

More value per unit of evapotranspiration can be achieved by:

- Improving the nutritional quality of crops.
- Reducing agrochemical inputs by planting disease- and pest-resistant crops.

For this Comprehensive Assessment and a time scale of 15–20 years we therefore conclude that only moderate impacts on crop water productivity should be expected from improvements in plant genetics. But such improvements can reduce the risk of crop failure. This can be achieved slowly through conventional breeding or more quickly using appropriate biotechnological tools. Genetic modification, still highly contentious, is but one possible means championed by some people for its potential benefits. Because the gap between actual practice and biophysical potential is so large, greater gains are possible through better management *[competing explanations]*.

concentration of poor people and high dependence of the poor on agriculture. This is a heartening conclusion because a focus on these areas can both reduce the amount of additional water needed for agriculture globally and help to reduce poverty. Current levels of water productivity show large variation by commodity, implying scope for improvement (table 7.3).

Improving soil fertility. For arid and semiarid regions, in particular for the Sahel, model analysis and field experiments have shown that nutrient limitations set a stronger ceiling on yield than water availability (Breman, Groot, and van Keulen 2001). In much of Africa fertilizer use is low—only 9 kilograms of nutrients per hectare in Sub-Saharan Africa compared with 73 kilograms in Latin America, 100 kilograms in South Asia, and 135 kilograms in East and Southeast Asia (Kelly 2006, p. 1)—and a constraint to water productivity (Twomlow and others 1999). Bindraban and others (1999, 2000) found that the biophysical opportunity to increase yields in semiarid West Africa is high. Extremely low yields in West African rainfed agriculture (map 7.1; top) because of limited availability

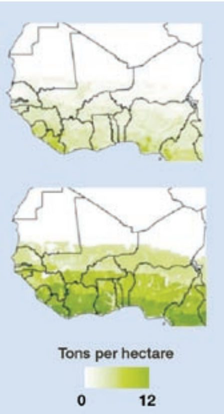
table **7.3** **Value produced from a unit of water for selected commodities**

	Water productivity			
Product	**Kilograms per cubic meter**	**Dollars per cubic meter**	**Protein grams per cubic meter**	**Calories per cubic meter**
Cereal				
Wheat ($0.2 per kilogram)	0.2–1.2	0.04–0.30	50–150	660–4,000
Rice ($0.31 per kilogram)	0.15–1.6	0.05–0.18	12–50	500–2,000
Maize ($0.11 per kilogram)	0.30–2.00	0.03–0.22	30–200	1,000–7,000
Legumes				
Lentils ($0.3 per kilogram)	0.3–1.0	0.09–0.30	90–150	1,060–3,500
Fava beans ($0.3 per kilogram)	0.3–0.8	0.09–0.24	100–150	1,260–3,360
Groundnut ($0.8 per kilogram)	0.1–0.4	0.08–0.32	30–120	800–3,200
Vegetables				
Potatoes ($0.1 per kilogram)	3–7	0.3–0.7	50–120	3,000–7,000
Tomatoes ($0.15 per kilogram)	5–20	0.75–3.0	50–200	1,000–4,000
Onions ($0.1 per kilogram)	3–10	0.3–1.0	20–67	1,200–4,000
Fruits				
Apples ($0.8 per kilogram)	1.0–5.0	0.8–4.0	Negligible	520–2,600
Olives ($1.0 per kilogram)	1.0–3.0	1.0–3.0	10–30	1,150–3,450
Dates ($2.0 per kilogram)	0.4–0.8	0.8–1.6	8–16	1,120–2,240
Others				
Beef ($3.0 per kilogram)	0.03–0.1	0.09–0.3	10–30	60–210
Fish (aquaculture[a])	0.05–1.0	0.07–1.35	17–340	85–1,750

a. Includes extensive systems without additional nutritional inputs to superintensive systems.

Source: Muir 1993; Verdegem, Bosma, and Verreth 2006; Renault and Wallender 2000; Oweis and Hachum 2003, Zwart and Bastiaanssen 2004.

of nutrients could be much higher with soil fertility improvements combined with better management of rainfall (bottom). With improvements in soil fertility and management of rainwater to reduce evaporation and divert more flows to transpiration, yields can double or even quadruple.



Map 7.1 Simulated yields before and after soil fertility and rainfall management improvements in West Africa

Using international trade to increase global water productivity. Global gains in water productivity can be achieved by growing crops in places where climate and management practices enable high water productivity and trading them to places with lower water productivity. In 1995 global trade from high water productivity areas to low water productivity areas resulted in an estimated 6% less evapotranspiration and 11% less depletion of irrigation water to grow the same amount of crops (de Fraiture and others 2004) than would have been required without trade. But trade takes place for other economic and political reasons, and water productivity gains are merely a by-product. A more detailed analysis of trade that considers payment for imports, rural employment, and environmental impacts must be considered (see chapter 3 on scenarios).

Reducing evaporation. Reducing evaporation while increasing productive transpiration can enhance water productivity. Evaporation varies with agricultural practices (Burt and others 2005) and ranges from 4% to 15%–25% in sprinkler irrigation systems (Burt, Howes, and Mutziger 2001) up to 40% and more in rainfed systems (Rockström, Barron, and Fox 2003). The amount of evaporation depends on climate, soils, and the extent of the crop canopy, which shades the soil (photo 7.3). Evaporation can be a very high share of evapotranspiration in rainfed systems with low plant densities. Surprisingly, drip and sprinkler irrigation systems do not necessarily result in less evaporation than good surface irrigation systems (Burt, Howes, and Mutziger 2001). Practices such as mulching,


Photo by David Molden

Photo 7.3 Water left standing after irrigation evaporates quickly. Reducing evaporation saves water.

plowing, or breeding for fast leaf expansion in order to shade the ground as rapidly as possible reduce evaporation and increase productive transpiration.

In some agricultural landscapes there is significant scope for reducing evaporation from water bodies, high water tables, and water-logged areas, taking care that these do not support important wetland functions. Drainage or reduced water applications are key practices. In many areas high water tables are a result of agricultural practices, and drainage could have positive benefits such as reduction of mosquito breeding sites. Using groundwater instead of reservoirs for storage reduces evaporation. In the Mexican Lerma-Chapala Basin an annual average of 1.8 cubic kilometers evaporates from water bodies under current conditions, about 54% of the amount used by irrigated agriculture and 38% of annual runoff from the basin (IMTA 2002).

The water-saving benefits of reducing deliveries are often overestimated because return flows and reuse are not properly brought into the analysis

In arid environments up to 90% of rainfall evaporates back into the atmosphere, leaving just 10% for productive transpiration. Micro- and macro-catchment water-harvesting techniques can capture more of this water for crops and livestock before it evaporates, increasing beneficial rainwater available for transpiration to 20%–50% (Oweis, Hachum, and Kijne 1999).

Improving the water productivity of water deliveries

Reducing or limiting water withdrawals from rivers and groundwater through water-saving practices and demand management remains an important strategy to control water resources, limit damage to aquatic ecosystems, and in some cases release water from agriculture to other uses. Excess water deliveries generate excess drainage that is hard to control, require energy for pumping, reduce the quality of water, and can provide breeding grounds for disease vectors. Moreover, reduced deliveries can mean that more surface water remains in rivers to support ecosystem functions and biodiversity. Using more precise water delivery practices gives water managers more flexibility to deliver water where it is needed, when it is needed. But the water-saving benefits of reducing deliveries are often overestimated because return flows and reuse are not properly brought into the analysis (box 7.3).

Because timing, amount, and reliability of blue water application influence yield and the quality of produce, blue water productivity can be improved through better management. Applying irrigation water at a time when a crop is susceptible to water stress raises yield per unit of water delivered and per unit of evapotranspiration; missing the application has the reverse effect. The quality of some fruits and vegetables is better under conditions of water stress at key times, and farmers fetch a higher market price for them.

Enhanced reliability of deliveries and greater flexibility in the timing and amount of water provided are important factors in farmers' investment decisions. When the supply of water is unpredictable, farmers will not invest in inputs and will tend to cultivate crops that are resilient to water stress and variable irrigation timing and thus that tend to have low yield and low monetary value (Hussain and others 2004).

Supplemental irrigation—the addition of small amounts of water at the right time to supplement rain—is an excellent way to increase the productivity of water supplies and evapotranspiration. Water productivity can also be increased with deficit irrigation—supplying less water than the maximum level of crop evapotranspiration box **7.3** **Are the water savings real?**

Saving water, especially releasing water from irrigated agriculture, can make it available to other, higher value uses in cities, industries, ecosystems, or more agriculture. Investments in improving irrigation efficiency by lining canals, installing drip and sprinkler irrigation, harvesting water, and applying on-farm water management practices are important when they prevent salinization and waterlogging or improve overall water management.

But many people question whether these practices promote real water savings, in which water can be transferred to other users without affecting production levels, or whether they simply "rob Peter to pay Paul" (Seckler 1996; Perry 1999; Seckler, Molden, and Sakthivadivel 2003; Molle, Mamanpoush, and Miranzadeh 2005).

Practices that reduce deliveries typically also reduce drainage outflows. Farmers downstream may be using these drainage flows or the flows may be supporting important ecosystems. What often happens is that the perceived gain is offset by a loss (Gichuki 2004) that is difficult to recognize. In other cases, where the deliveries to farms are not reduced, farmers will have a high incentive to use "saved" water on their own farm, resulting in more evapotranspiration and thus more food but less water available to other users in the basin.

Whether reducing water deliveries results in real water savings depends on what happens to drainage flows. Reducing deliveries and drainage works well in situations where drainage flows damage, pollute, or flow to a saline sink (Molden, Sakthivadivel, and Keller 2001). In other cases a basin perspective is needed to determine whether savings are real.

(Zhang 2003). In western Syria wheat yields increased from 2 to 5 metric tons per hectare with the timely application of 100–200 millimeters of water and water productivity improved from 0.6 kilograms per cubic meter to 1.85 (Oweis and Hachum 2003). Yields of sorghum in Burkina Faso and maize in Kenya were increased from 0.5 metric tons per hectare to 1.5–2.0 metric tons with supplemental irrigation plus soil fertility management (Rockström, Barron, and Fox 2003). These practices work particularly well when water supplies are constrained by the limited supply or high costs of water.

There is substantial scope to reduce water deliveries to irrigation through a range of technical and management practices: drip and sprinkle irrigation, more precise application practices (level basins, surge irrigation), canal lining or delivery through pipes, reduced allocations of water to farmers, or pricing to influence demand. Many of these practices increase yields (table 7.4). Several practices are applicable to rice irrigation, such as alternate wet and dry irrigation (Bouman and others 2003; see chapter 14 on rice). But, again, whether these practices are warranted requires examination from a larger, basin context.

A common misperception is that irrigation is wasteful because of highly inefficient practices (typical irrigation system efficiencies are reported at 40%–50%). But because so much drainage flow is reused downstream, especially in closed basins (see chapter 16 on river basins), there is actually much less scope in saving water in irrigation than is commonly believed *[established, but incomplete]*. In fact, in irrigated regions in dry areas it is common to document ratios of evapotranspiration to irrigation plus rain much greater than 60%, often depleting more water than is renewable and leading to aquifer mining. Such areas include the Gediz Basin in Turkey (Droogers and Kite 1999), Egypt's Nile (Keller and Keller 1995)

table 7.4	**Water productivity gains for various crops from shifting from conventional surface irrigation to drip irrigation in India** (percent)		
Crop	**Increase in yield**	**Decline in water application**	**Gains in water productivity**
Bananas	52	45	173
Cabbage	2	60	150
Cabbage (evapotranspiration)	54	40	157
Cotton	27	53	169
Cotton	25	60	212
Cotton (evapotranspiration)	35	15	55
Cotton	10	15	27
Grapes	23	48	134
Okra (evapotranspiration)	72	40	142
Potatoes	46	~0	46
Sugarcane	6	60	163
Sugarcane	20	30	70
Sugarcane	29	47	143
Sugarcane	33	65	280
Sugarcane	23	44	121
Sweet potatoes	39	60	243
Tomatoes	5	27	44
Tomatoes	50	39	145

Note: Water productivity is measured as crop yield per unit of irrigation water supplied or as the ratio of yield to evapotranspiration where evapotranspiration is indicated in parentheses.

Source: Adapted from Postel and others 2001; Tiwari, Singh, and Mal 2003 for cabbage row 2; Rajak and others 2006 for cotton row 3; Shah and others 2003 for cotton row 4; Tiwari and others 1998 for okra; and Narayanmoorthy 2004 for sugarcane row 5.

and Fayoum (Bos 2004), the Christian subdivision in Pakistan (Molden, Sakthivadivel, and Habib 2000), the Bhakra irrigation system in India (Molden, Sakthivadivel, and Habib 2000), the Liu Yuan Ku irrigation system in China (Hafeez and Khan 2006), the Tunuyuan irrigated area in Argentina (Bos 2004), the Nilo Coelho in Brazil (Bos 2004), and the Rio Grande Basin in Mexico and the United States (Booker, Michelsen, and Ward 2005).

Irrigation systems are under increased pressure to produce more with reduced supplies of water. Frequently, allocations to irrigation are diminishing because of increased demands by cities and the environment, and increases in blue water productivity are often a response to this reduced allocation so that farmers can continue to produce. Reducing water delivered to irrigation requires two actions: a change in agricultural practice combined with a change in water allocation. If farmers increase blue water productivity, they are more likely to use the saved water on their own land than to give it to cities. But if farmers have to adjust to reduced allocations, they may try to achieve at least the same value of production with the reduced supplies.

A complete assessment of irrigation performance requires a view beyond crops that includes other functions of irrigation and their value. Renault, Hemakumara, and Molden (2001) showed that the perennial vegetation at Kirindi Oya system in Sri Lanka evapotranspires about the same amount of water as rice and generates valuable ecosystem services, giving a different picture (65% of inflows beneficially depleted) than if paddy rice were considered alone (22% of inflows depleted by rice). Home gardens at Kirindi Oya, a key source of livelihood for women, depend almost entirely on the seepage flows from the irrigation channels. In these cases the problem is not wastage but high withdrawals and evapotranspiration rates that reduce drainage and tend to dry up rivers and wetlands, leaving little to downstream use. It is important to view each case from a basin perspective, considering the quality and equity dimensions of water and how drainage flows are used downstream.

In addition to producing more food, there are ample opportunities in irrigation to generate more value and incur fewer social and environmental costs (see chapter 6 on ecosystems) in new and established irrigation. Achieving this will require more integrated approaches promoting multiple uses and multiple ecosystem services (Scherr and McNeely forthcoming; Matsuno and others 2006; Groenfeldt 2006).

Increasing the water productivity of livestock

Globally, livestock production accounts for some 20% of agricultural evapotranspiration, and this proportion could grow with the increasing consumption of animal products (see chapter 3 on scenarios). Reducing the amount of water required for livestock production could thus contribute considerably to reducing future agricultural water needs.

The physical water productivity of animal products is derived mainly from the water required for the food that animals consume; the drinking water requirements of livestock are negligible by comparison. Estimates of the amount of evapotranspiration required to produce 1 kilogram of animal products vary widely, depending on management practices, the kind of feed, how crop residues are used, the processing system, and how well the animals convert feed and plants into the animal product. Gains in livestock water productivity can be made by adjusting each of these factors (see chapter 13 on livestock).

The physical water productivity of animal products is derived mainly from the water required for the food that animals consume; the drinking water requirements of livestock are negligible by comparison

The information on diets in the table in box 7.1 is instructive. While only 6% of the average Ethiopian diet consists of animal products, three-quarters of the daily water requirement for food is from animal requirements. One-quarter of the Italian diet consists of meat products, with half the water consumed coming from meat products. While there is considerable uncertainty about these estimates, there is a pattern. Where livestock productivity is low, as in Ethiopia, animal products require a lot of water. Where meat is a high proportion of the diet, dietary water requirements are high, but this can be offset by intensive livestock management practices, as in Italy.

But a focus solely on water requirements for livestock can be misleading. Livestock add value in many ways to production systems and play an important role in livelihood strategies, contributing to overall productivity and welfare gains. A reason that livestock water use is so high in Ethiopia is that livestock are used for transport, plowing, and fertilizer generation (manure). Keeping livestock reduces vulnerability to food shortages and agroclimatic risk (Fafchamps, Udry, and Czukas 1998). Livestock production is a key strategy for livelihood diversification in the smallholder irrigated systems in India and Pakistan, where livestock generate productive employment for the landless, especially women, and income, especially for the poor, important for improving equity (Adams and Alderman 1992).

There is considerable scope for increases in livestock productivity, in both physical and economic water productivity. Water productivity–enhancing strategies include improving feed sourcing of animals; enhancing animal production (milk, meat, eggs), services, and cultural values from livestock; and conserving water resources to lessen the amount of water required for grazing and reduce negative environmental impacts.

Increasing water productivity in fisheries and aquaculture

Fish can often be integrated into water management systems with the addition of little or no water

As with livestock, there is considerable scope for better integrating fisheries and aquaculture with water management systems to improve water productivity and reduce poverty (see chapter 12 on fisheries).

The two major components of water use in aquaculture are the water required for feed and the blue water required for aquaculture. Water productivity is the mass or value of the aquaculture produce divided by the amount of water required for feed plus the amount of evaporation from the pond. On-farm water use in aquaculture can be as low as 500–700 liters in superintensive recirculation systems and as high as 45,000 liters of water (evaporation plus seepage plus feed) per kilogram of produce in extensive ponds (Verdegem, Bosma, and Verreth 2006).

Fish can often be integrated into water management systems with the addition of little or no water (Prein 2002). Renwick (2001) found that the fisheries in irrigation reservoirs at Kirindi Oya, Sri Lanka, contributed income equal to 18% of the rice production in the system. Haylor (1994, 1997) assessed the potential for aquaculture in small and large irrigated farming systems in the Punjab, Pakistan, and noted that aquaculture was almost entirely pond culture of carp fed with tubewell water and that there was economic justification for expanding such aquaculture using local shallow tubewells. The revenue potential for cage aquaculture in irrigation canals was also attractive, but operational conflicts in the use of water for agriculture would need to be resolved. Murray and others (2002) pointed out that traditional power structures may undermine attempts to integrate aquaculture in irrigation systems and that changes in laws and regulations would be required from community to national levels. In coastal areas aquaculture may severely degrade land and water quality and biodiversity, requiring special attention (Gowing, Tuong, and Hoanh 2006).

Fisheries in lakes, rivers, and wetlands present a special case for water productivity assessment because fish are only one of the many ecosystem services provided by aquatic ecosystems (see chapter 12 on fisheries). The values and livelihood benefits of fisheries are high and often ignored or underestimated, but considering only the values of fish produce would grossly underestimate the value of water in these aquatic ecosystems. The water productivity of fisheries systems needs to be considered in terms of the ecosystem services and livelihoods supported per unit of water. Thus maintenance of wetlands and biodiversity should be considered potential benefits of leaving water in these aquatic ecosystems.

Applying integrated approaches to increasing the value per unit of water

Designing and managing agricultural water for multiple uses—drinking water, industries, livestock, fisheries—can raise the social and economic productivity of water in water management systems (Meinzen-Dick 1997; Bhatnagar and others 2004; Nguyen-Khoa, Smith, and Lorenzen 2005; van Koppen, Moriarty, and Boelee 2006; photo 7.4). Irrigation provides water for fruit and shade trees, habitat to sustain biodiversity, and is a source of recharge for groundwater, a common source of rural drinking water supporting the livelihoods of smallholders. Multifunctional farm ponds that store water for crop irrigation and for domestic purposes may be suitable for raising fish to improve household nutrition and provide a ready source of income. Integrated agriculture-aquaculture provides a means of recycling water and nutrients and obtaining more value and income from farm enterprises (Gupta and others 1999). On-farm pounds may serve as nutrient traps for surface runoff (from crops and livestock) that may be recycled by fish, with the residue used as fertilizer for crops grown on pond dikes, helping to upgrade smallholder agriculture.

Agricultural water management practices can provide multiple ecosystem services beyond food production (see chapter 6 on ecosystems). The value of paddy cultivation is underestimated unless its multifunctional roles are taken into consideration (see chapter 14 on rice). Practices that reduce environmental costs and enhance ecosystem services increase the value derived from agricultural water management (Matsuno and others 2006; Scherr and McNeely forthcoming).

Designing and managing agricultural water for multiple uses—drinking water, industries, livestock, fisheries—can raise the social and economic productivity of water in water management systems

Adopting an integrated basin perspective for understanding water productivity tradeoffs

A change in basin water use will result in winners and losers. Putting water into the service of agriculture by expanding rainfed systems or adding irrigation takes water away from other uses—forests, grasslands, rivers (photo 7.5). Expanding agriculture upstream through better rainfall capture and artificial storage can reduce downstream flows supporting other

Photo by Mats Lannerstad

Photo 7.4 Using irrigation water for multiple purpose means more value per unit of water agriculturalists, fishers, and household users. Producing more food means putting more water into production and taking it out of other uses. Water productivity analysis at a basin scale can illuminate these tradeoffs to help decisionmakers develop strategies in which benefits exceed costs (box 7.4).

Instead, most basin-level water use strategies today are guided by individual political, economic, and social factors, with water productivity issues barely considered (see chapter 16 on river basins). Typically, with urbanization, water is reallocated from agriculture to cities (Molle and Berkoff 2006) and from natural uses like rivers and wetlands to agriculture. Rarely are the intrinsic values generated by ecosystems and agriculture considered in these reallocations, and often the transfers are made without negotiation or adequate compensation. Thus changes in farmers' practices are typically a response to reallocation of supplies rather than the driver behind reallocation.

Most basin-level water use strategies today are guided by individual political, economic, and social factors, with water productivity issues barely considered

In sum, basin water productivity can be improved by improving water productivity for crops, irrigation, livestock, and fish per unit of water use; reducing nonproductive evaporation or flows to sinks; tapping into more available water while also addressing tradeoffs with others uses; and generating higher economic benefits through comanagement or reallocation of water to activities with a higher monetary value or increased social and ecological values; or in any of these activities reducing social and environmental costs associated with changes in water use patterns (see table 7.2).

At larger scales water productivity issues become increasingly complex, particularly for multisector systems where competition among water users, recycling of water, resource degradation, and opportunity costs and equity issues of water come into play. Assessing the impact of a change in basin water use requires analysis of the changes in benefits and costs and their distribution among stakeholders. The first part of the analysis requires a hydrological examination to understand the changes in quality, quantity, and timing of water for different uses. This is not always obvious because of complex hydrologic interconnections. People who tap into a stream in the hills may have no idea of the consequences for downstream agriculture or wetlands.

The second part requires a comprehensive valuation exercise to assess marginal water productivity and the nonmarketable values associated with water use—livelihood support


Photo by Karen Conniff

Photo 7.5 Water use within a landscape

box 7.4 Means of increasing productivity of water in a basin context

There are four primary ways to increase the productivity of water in a basin context.

- Increasing the productivity per unit of evapotranspiration:
  - Improving soil and water management and agronomic practices that promote soil fertility, reduce salinity, or improve the environment for fish and livestock.
  - Changing plant varieties to those that can provide increased yields or values for each unit of water consumed or that consume less water.
  - Using deficit, supplemental, or precision irrigation to achieve higher yields per unit of evapotranspiration, especially when combined with other management practices.
  - Improving irrigation water management by providing better timing of supplies to reduce stress at critical crop growth stages or by increasing the reliability of water supply so farmers invest more in other agricultural inputs, leading to higher output per unit of water.
  - Managing water and improving feed sourcing in fish and livestock production.
  - Lessening nonproductive evaporation by mulching, enhancing soil infiltration and storage properties, enhancing canopy cover, subsurface drip irrigation, matching planting dates with periods of less evaporative demand, and reducing evaporation from fallow land and high water tables by decreasing areas of exposed water surface and decreasing vegetation (weed control).
- Minimizing nonproductive depletion of blue water flows (taking care that these are not serving other important purposes like wetlands or other farmers):
  - Reducing water flows to sinks by interventions that reduce irrecoverable deep percolation and surface runoff, such as canal lining, drip irrigation, and alternating wet and dry irrigation of rice.
  - Minimizing salinization and pollution of return flows by minimizing flows through saline or polluted soils, drains, and groundwater, and managing the mixing of saline or polluted water with freshwater (see chapter 11 on marginal-quality water).
  - Shunting polluted water to sinks to avoid the need to dilute with freshwater; saline or polluted water should be shunted directly to sinks.
- Providing additional supplies for human uses by tapping uncommitted outflows, taking care to address possible tradeoff with downstream human and ecological uses:
  - Adding water storage facilities (reservoirs, groundwater aquifers, small tanks, ponds on farmers' fields, and soil moisture storage) so that more water is available when it can be more productively used.
  - Improving management of existing irrigation facilities to reduce drainage flows that contribute to uncommitted outflow. Possible interventions are reducing delivery requirements by improving application efficiency, water pricing, and allocation and distribution practices. Policy, design, management, and institutional interventions may allow for an expansion of irrigated area, increased cropping intensity, or increased yields within service areas.
  - Reusing return flows by controlling, diverting, and storing drainage flows and using them again.
- Reallocating and comanaging water among uses:
  - Reallocating water from lower value to higher value uses within and between sectors, for example by allocating water from agriculture to cities or industries, but taking care of compensation and consequences to other users and uses.
  - Identifying and managing committed outflows for environment and downstream water allocation.
  - Comanaging among multiple uses, recognizing multiple uses, and reaping multiple benefits while mitigating adverse impacts.
  - Incorporating aquaculture, fisheries, and livestock considerations into basin management.

and values derived from ecosystem services (Ward and Michelsen 2002). The concept of marginal water productivity is simple. For example, if a small amount of water is moved from agriculture to higher value industry, it can generate a large net gain because water in support of, say, computer chips generates much more value than water provided to wheat. But industries typically have a very low consumptive water requirement, and after enough water is given for the industrial process, the value of additional water flowing to industry falls to zero—or becomes negative if industry pollutes return flows. Similarly, taking a little water from rivers for agriculture may result in very small changes in ecosystem services delivered by the river but provide a large gain in agricultural value. But when rivers are reduced to minimum levels, the next drop taken out of the river may be at considerable ecosystem cost. Such analysis is not common in part because the integrated hydrological and valuation tools are complex and imprecise (box 7.5), but also because there are too few institutional arrangements where such information enters the decisionmaking process.

> Most water productivity interventions can be tailored to benefit the poor

Nevertheless, it is possible to make much more informed decisions than are being made today. Stakeholders representing each use should be involved in decisions on reallocating water, and the types of information discussed should be available to them. Valuation of nonmarketable functions and services calls for stakeholder processes to decide how to balance the needs of the various groups. Disagreements about actual allocation will always remain because people's values, goals, priorities, and aspirations differ (Warner, Bindraban, and van Keulen 2006). Thus informed multistakeholder decisionmaking processes are needed to address conflicts and find constructive solutions (Emerton and Bos 2004).

Water productivity pathways for reducing poverty

Water productivity improvement can provide two pathways to poverty alleviation. First, targeted water interventions can enable poor and marginalized people to gain access to water and use it more effectively. Second, across-the-board increases in water productivity may benefit poor people through multiplier effects on food security, employment, and income.

Targeting techniques range from a combination of agronomic and water management practices to raise grain yields in high-potential areas, to strategies to increase the value per unit of scarce water, to strategies to reduce vulnerability to drought, polluted water, or loss of water allocations. Most water productivity interventions can be tailored to benefit the poor (see chapter 4 on poverty and photo 7.6). For example, efforts to reduce the cost of drip irrigation have made it affordable for smallholders (Postel and others 2001). Poverty alleviation efforts may drive water productivity gains in areas where access to water is difficult—in economically water-scarce areas. Interventions targeted to the rural poor can help them get the most out of limited water supplies. Examples include treadle pumps providing low-cost access, drip lines reducing the amount of water needed, and water bags for storage. With access to a little water and some precision technologies small-scale farmers can produce high-value crops such as vegetables and fruits. Microcredit and private commercial investments can help people use water. Access to markets is essential.

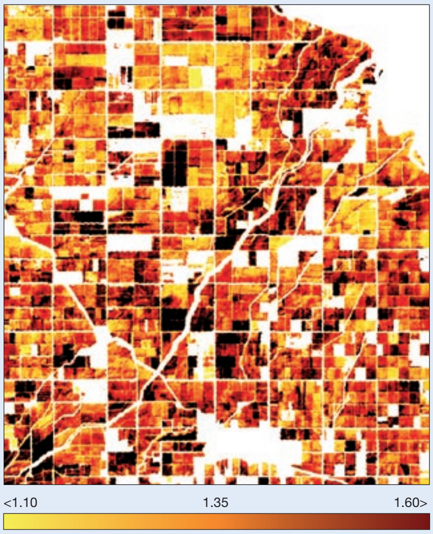
More effort is needed to tailor practices to the requirements of women, who play a large role in agriculture. Adapting water systems for home gardens and domestic needs improves

box 7.5 | Tools for water productivity analysis

Increasing demand for basin analysis and the complexity of interlinked hydrologic, socioeconomic, and ecological systems require new tools for analysis to better inform stakeholder decisions (van Dam and others 2006). These range from economic valuation, modeling, remote sensing, and geographic information system analysis to more participatory approaches. To influence investment and management information these tools needs to be closely integrated into political decisionmaking processes.

For example, remote sensing analysis has proven useful in identifying the range of possible values for crop water productivity and, combined with ground analysis, can help to pinpoint constraints to improvements. At the Yaqui irrigation district in Mexico remote sensing images have captured wide variations in water productivity (see photo).

Remote sensing image displaying variations in crop water productivity in wheat, Yaqui Valley, Sonora State, Mexico



The image shows water productivity per unit of evapotranspiration. Wheat yields and actual evapotranspiration were assessed with the surface energy balance algorithm for land methodology using high-resolution Landstat and low-resolution U.S. National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer satellite images. The map depicts strong variation in water productivity across fields, with water productivity varying from 1.1 kilograms per cubic meter of evapotranspiration (yellow) to 1.6 kilograms per cubic meter (dark red). This variation is attributed to the management decisions of individual farmers, such as choice of seeds, fertilization, and amount and timing of irrigation.

Source: Zwart and others 2006.

nutrition and contributes to better health, improving the productivity of water and greatly helping rural women (Moriarty, Butterworth, and van Koppen 2004). But these interventions can only be pro-poor and sustainable when they really target the poor, are crafted to meet local needs, and are an integral part of a long-term development program and not merely a short-term relief effort (Polak and Yoder 2006; Moyo and others 2006).

There is ample evidence to conclude that women are as efficient producers as men, provided that they have similar access to inputs and markets and that they control the fruits of their labor (van Koppen 2000). It should be possible to reap higher productivity gains by addressing the concerns of women as well as men. Clearly, this is the case in farming systems dominated by women, but also, more subtly, in mixed and male-dominated systems where a focus on women could raise the value per unit of water.

Improvements in water productivity that indirectly increase food security and generate employment opportunities and income through multiplier effects can also reduce poverty. The full range of economic benefits from agricultural production are much greater than the simple measure of the value of local production (Hussain and Hanjra 2004).

Photo by Sharni Jayawardena

Photo 7.6 Irrigation technology made affordable—a low-cost sprinkler

Estimates of economywide farm and nonfarm multipliers vary widely. Estimates for India suggest a multiplier as low as 1.2 for local irrigation schemes to as high as 3 for the country as a whole. Multipliers tend to be higher in Asia than in Africa and higher in developed countries (estimated as high as 6 for Australia and Canada; Hill and Tollefson 1996).

Moreover, pro-poor gains in water productivity also come from outside water management—through better credit and insurance, support for better farm practices, improved links to markets and support services, and basic education and healthcare—thus calling for approaches that look beyond water management alone.

Water productivity itself is unlikely to feature prominently among the many considerations facing agricultural producers

Establishing enabling conditions

While many strategies exist for improving water productivity, adoption rates remain low. There are many reasons why. Reliable, low-cost supplies of sufficient water enable high levels of productivity and reduce risk, so why should producers reduce water inputs? And while incentives for agriculture to deplete less water are high for society and river basin managers trying to allocate limited supplies, they are low for individual agricultural producers (Luquet and others 2005). These complex factors can be organized according to three types of uncertainty.

One type of uncertainty concerns the practical benefits of increasing water productivity relative to other factors that influence decisions. Water productivity itself is unlikely to feature prominently among the many considerations facing agricultural producers. Farmers rarely manage to increase water productivity; rather they manage to make their entire enterprise profitable. Factors that influence the uptake of water productivity–enhancing practices include:

- Cost and affordability—the ability to pay for a management practice or technology is an important determinant of whether farmers will adopt it.
- Price and profitability—will there be a payback on the investment?
- Risk—returns from a particular strategy may vary greatly from year to year, based on market, climate, and availability of water.
- Markets—can a farmer sell the produce and make a profit (photo 7.7)?
- Availability of a reliable supply of water—knowing when water is available may be more important for management decisions than the total quantity.
- Education—knowing about a product and its use may encourage uptake.
- Incentives and institutional structures—support for water productivity–enhancing measures can influence farmers' decisions.

A second type of uncertainty concerns the scale of potential benefits. Until decision-makers are clear about the degree, timing, and cost of the potential improvement, prospects for a concerted effort seem limited. Who stands to gain from improvements? Who are the winners and losers in proposed redistributions? What are the risks of change, for example, through loss of "nonproductive" environmental flows? Surprisingly few detailed measurements exist of current water productivity on which to gauge the scope for improvement. Nor is it clear how *potential* water productivity—which expresses the upper limit of gain—varies spatially. This uncertainty can be removed by continuing measurement and analysis.

Photo by Sanjini de Silva

Photo 7.7 Market access is an enabling condition for improved water productivity

The scale of decision can be critical. Increases in water productivity at the farm level can actually increase basin water depletion, especially where water is scarce compared with land. Farmers may see water productivity–enhancing technologies like drip irrigation as an opportunity to expand areas using the same amount of water, ultimately increasing the amount of water depleted by agriculture and reducing the amount of water available for other users.

A third type of uncertainty concerns how people value water productivity improvement collectively. Water scarcity is a key driver behind water productivity gains, with agriculture under pressures from increased use by cities and a demand for more allocations for the environment. Because this driver does not directly influence the decisions of individuals who have water access, economic instruments have been considered to reflect physical scarcity values. Some people argue that because the price of agricultural water is so low, farmers do not feel the scarcity and that therefore raising the price would lower the demand for water by farmers, releasing some water for cities. Others argue that there is little evidence that pricing is an effective means of controlling demand within irrigation because the price increase would have to be so substantial, because of a lack of water rights and monitoring systems, and because there is typically strong political opposition within agrarian societies (Hellegers and Perry 2006; Molle and Berkhoff 2006; Berbel and Gómez-Limón 2000). Administrative allocation has been shown to be an effective option. Farmers adopt water productivity practices in response to less supply.

Adoption of water-productivity enhancements requires understanding potential tradeoffs, identifying winners and losers, and aligning the incentives of all actors

There are a variety of actors with different incentives, all with an interest in water productivity gains and reallocation. Society has an incentive to allocate water to various uses. Cities in search of more water may set their sights on cheap agricultural water. Farmers have an incentive to retain their supply for more production relative to costs. Raising prices for water can be seen as a further penalty for producers who are already struggling to make a living. Understanding incentives, the tradeoffs of different management options, and the proper alignment of incentives across various actors is a key to adoption. One strategy for bringing farmers into alignment with urban and broader social concerns is to compensate them for releasing water out of agriculture and to invest in water saving and profitability-enhancing farming technologies.

Thus adoption of water-productivity enhancements requires understanding potential tradeoffs, identifying winners and losers, and aligning the incentives of all actors. Many incentives will come from outside the water sector and address issues of the vulnerability and risk and markets and profitability of the agriculture enterprise and the equity and welfare of stakeholders.

Investment priorities

Water productivity hotspots that need special attention are:

- Areas where poverty is high and water productivity is low, where attention could particularly benefit the poor, as in much of Sub-Saharan Africa and parts of South Asia and Latin America.

- Areas of physical water scarcity where there is intense competition for water, such as the Aral Sea Basin and the Yellow River Basin, especially where gains in economic water productivity are possible.
- Areas with little water resources development, where high returns from a little water can make a big difference.
- Areas of water-driven ecosystem degradation, such as falling groundwater tables, river desiccation, and intense competition for water.

Some actions can be taken up immediately, while others will require more time and persistence:

- Diagnosing reasons for high or low water productivity, and setting standards through benchmarking (fast).
- Concentrating on major factors limiting production (fertilizers, pests and diseases, water) and perpetuating poverty (fast).
- Building infrastructure and institutional capacity for better governance (slow).
- Strengthening producers' skills in managing systems (slow).
- Improving water resources management skills at different levels to deal with the diversity of competing water uses (slow).

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Note

1. For example, putting the characteristics of more water-efficient C_4 or CAM crops into less efficient C_3 crops would be a breakthrough.

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