Agricultural Water Management 97 (2010) 528–535

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Improving agricultural water productivity: Between optimism and caution

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ARTICLE INFO

Article history:
Available online 10 June 2009

Keywords:
Water use efficiency
Poverty
Environment
Livestock
Fisheries
River basins
Agronomy
Crop breeding
Socioeconomics

ABSTRACT

In its broadest sense, water productivity (WP) is the net return for a unit of water used. Improvement of water productivity aims at producing more food, income, better livelihoods and ecosystem services with less water. There is considerable scope for improving water productivity of crop, livestock and fisheries at field through to basin scale. Practices used to achieve this include water harvesting, supplemental irrigation, deficit irrigation, precision irrigation techniques and soil–water conservation practices. Practices not directly related to water management impact water productivity because of interactive effects such as those derived from improvements in soil fertility, pest and disease control, crop selection or access to better markets.

However, there are several reasons to be cautious about the scope and ease of achieving water productivity gains. Crop water productivity is already quite high in highly productive regions, and gains in yield (per unit of land area) do not necessarily translate into gains in water productivity. Reuse of water that takes place within an irrigated area or a basin can compensate for the perceived losses at the field-scale in terms of water quantity, though the water quality is likely to be affected. While crop breeding has played an important role in increasing water productivity in the past, especially by improving the harvest index, such large gains are not easily foreseen in the future. More importantly, enabling conditions for farmers and water managers are not in place to enhance water productivity. Improving water productivity will thus require an understanding of the biophysical as well as the socioeconomic environments crossing scales between field, farm and basin.

Priority areas where substantive increases in water productivity are possible include: (i) areas where poverty is high and water productivity is low, (ii) areas of physical water scarcity where competition for water is high, (iii) areas with little water resources development where high returns from a little extra water use can make a big difference, and (iv) areas of water-driven ecosystem degradation, such as falling groundwater tables, and river desiccation. However, achieving these gains will be challenging at least, and will require strategies that consider complex biophysical and socioeconomic factors.

1. Introduction

Water productivity is the ratio of the net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water used to produce those benefits. In its broadest sense, it reflects the objectives of producing more food, income, livelihood and ecological benefits at less social and environmental cost per unit of water consumed. *Physical water productivity* is defined as the ratio of agricultural output to the amount of water consumed – "more crop per drop" –, and *economic water productivity* is defined as the value derived per unit of water used and this has also been used to relate water use in agriculture to nutrition, jobs, welfare and the environment. The denominator of the water productivity equation is expressed in terms of either water supply or water depletion. Water is depleted when it is consumed by evapotranspiration (ET), is incorporated into a product, flows to a location where it cannot be readily reused, or if it becomes heavily polluted (Seckler, 1996; Molden et al., 2003).

The water productivity concept evolved from separate fields. Crop physiologists originally defined *water use efficiency* as carbon assimilated and crop yield per unit of transpiration (Viets, 1962), and then later as the amount of produce (biomass or marketable yield) per unit of ET. Irrigation specialists have used the term *water use efficiency* to describe how effectively water is delivered to crops

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doi:10.1016/j.agwat.2009.03.023

and to indicate the amount of water wasted. But this concept provides only a partial view because it does not indicate the benefits produced, nor does it specify that water lost by irrigation is often reused by other uses (Seckler et al., 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.

Increasing WP is particularly appropriate where water is scarce compared with other resources involved in production. Reasons to improve agricultural water productivity include: (i) to meet rising demands for food from a growing, wealthier, and increasingly urbanized population in light of water scarcity, (ii) to respond to pressures to re-allocate water from agriculture to cities and ensure that water is available for environmental uses, and (iii) 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 and productive employment. Targeting high water productivity can reduce investment costs by reducing the amount of water that has to be withdrawn. Higher water productivity reduces the need for additional water and land resources in irrigated and rainfed systems. Enhancing water productivity is thus a critical response to growing water scarcity, including the need to leave enough water in rivers to sustain ecosystems to meet the growing demands of cities and industries (e.g., Hengsdijk et al., 2006).

Globally, the additional amount of water needed to support agriculture directly depends on gains in water productivity. With no gains, average annual agricultural ET could double in the next 50 years (de Fraiture et al., 2007). But with enough investments in improving water productivity the increase in global ET could be held down to 20–30%. Irrigation systems are already under pressure to produce more with reduced supplies of water. Allocations for irrigation are diminishing in many river basins because of increased demands from cities and the environment, and in response, efforts need to be aimed at increasing water productivity so that farmers can continue to produce.

In spite of the need for increasing, and the opportunities to increase, water productivity, gains are elusive due to a number of complex interacting factors. The objective of this paper is to present a comprehensive analysis of the water productivity concept, to identify promising approaches for its improvement and to identify key constraints that must be overcome.

2. Improving agricultural water productivity

2.1. Biophysical background of WP at the plant scale

Assessing the scope for gains in water productivity requires an understanding of basic biological and hydrological crop–water relations. How much more water will be needed for agriculture in the future is governed, to a large extent, by links between water, food and changes in diets. The amount of water that we consume when eating food depends on diet and also on the water productivity of the agriculture production system. The amount of water required for field crops and its relation to yield dominates the equation on the need for additional water for food.

For a given crop variety and climate there is a well-established linear relationship between plant biomass and transpiration (de Wit, 1958; Tanner and Sinclair, 1983; Steduto et al., 2007). Different kinds of plants are more water efficient in terms of the ratio between biomass and transpiration. 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, thereby limiting transpiration, photosynthesis and production. The most common crops, C3 crops such as wheat and barley, are less water-efficient than C4 crops such as maize and sugarcane. The most water-efficient crops are the CAM (crassulacean acid metabolism) crops such as cactus and pineapple.

These different plant types (C3, C4 and CAM) have evolved according to their different environments, and are classified primarily based on how they fix carbon dioxide in the photosynthetic process (Steduto, 1996).

To boost economic yield, plant breeders have developed varieties with a higher harvest index (the ratio of marketable grain yield to total crop biomass), achieving more economic produce per unit of transpiration. This breeding strategy has probably raised the potential for gains in water productivity 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 et al., 1997), when plant breeders of the green revolution focused their attention on these crops. But the rate of increase in the harvest index has slowed over the last 20 years as physiological limits are being reached, and, thus, there has been a slowdown in the rate of gains in water productivity that are achieved through this method.

In situations where yield is less than 40–50% of the potential, non-water factors such as soil fertility limit yield and crop water productivity per unit of ET (Tanner and Sinclair, 1983). Land degradation and nutrient depletion significantly constrain opportunities to increase water productivity. 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 the timing of 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 ET (Fig. 1), thus incremental gains in water productivity become smaller as yields become higher. Raising yields from 1 to 2 tons per hectare (ha) will lead to much more gains in water productivity than doubling the yield from 4 to 8 tons per ha.

This relationship between transpiration and crop production has far-reaching consequences for water. Increases in food production in productive areas are achieved with near proportionate increases in transpired water. This is the reason why

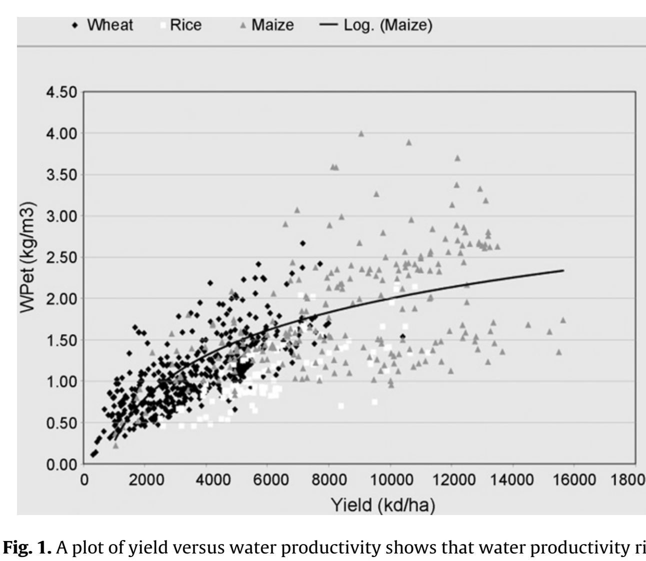

Fig. 1. A plot of yield versus water productivity shows that water productivity rises faster at lower yields and levels off at higher yields. *Source*: Adapted from Zwart and Bastiaanssen (2004).

increases in food production have taken water from ecosystems, thereby reducing the amount of water transpired by forests and grass and reducing water flows to the sea, and is also the reason why future production will continue to do the same. Feeding more people will require more water to be transpired. The amount of additional transpiration depends on the changes made in water productivity.

3. Reasons for optimism

3.1. Reaching the biophysical potential

While there is a fixed relationship between biomass and transpiration, there is substantial variability in yield 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. Thus, there appears to be considerable scope for raising the amount of yield relative to ET before reaching the upper limit (the straight line in Fig. 2 that coincides with the reputed linear relationship between transpiration and yield). That much of variability is due to management practices (French and Schultz, 1984) and is important because it offers hope for possible improvements in the ratio between marketable produce and ET.

Reducing evaporation while increasing productive transpiration can enhance water productivity at the field level. Evaporation varies with agricultural practices (Burt et al., 2005) and ranges from 4% to 25% in sprinkler irrigation systems (Burt et al., 2001), and up to 40% and more in rainfed systems (Rockström et al., 2003). The amount of evaporation depends on climate, soils and the extent of the crop canopy. Practices such as mulching, plowing or crop breeding for fast leaf expansion – in order to shade the ground as rapidly as possible – reduce evaporation and increase productive transpiration.

In arid environments, up to 90% of rainfall evaporates back into the atmosphere. Water harvesting can increase the beneficial rainwater available for transpiration from 20% to 50% (Oweis et al., 1999). Supplemental irrigation (adding a little irrigation in critical stages to supplement rainfall) and deficit irrigation (irrigating but less than the full amount) can increase the productivity of water. In Northern Syria, water productivity of wheat improved from 0.06 kilograms (kg) of grain per cubic meter of ET to 1.85 with the addition of small amounts of irrigation water at the right time (Oweis and Hachum, 2003; Zhang and Oweis, 1999). Grain yields of sorghum in Burkina Faso and maize in Kenya were increased from 0.5 metric tons per hectare to 1.5–2.0 tons with supplemental irrigation plus soil fertility management (Rockström et al., 2003). These practices are particularly effective when water supplies are constrained by the limited supply or the high costs of water. In arid and semi-arid regions, nutrient limitations set a stronger ceiling on yield than water availability (Breman et al., 2001; Bindraban et al., 1999). Fertilizer use is low in many parts of Africa and this constrains water productivity (Twomlow et al., 1999). In sub-Saharan Africa, only 9 kg of nutrients are used per hectare as compared to 73 kg used in Latin America, 100 kg in South Asia and 135 kg in East and Southeast Asia (Kelly, 2006, p. 1). With the currently available amounts of rainfall, improvements in soil fertility could double productivity. Current levels of water productivity show a large variation by commodity (Table 1). Differences within a commodity reflect the effects of management, thereby implying that there is scope for improvement. Differences between commodities arise from differences in economic value, water content of the product and water requirement. A better water management environment can, in some cases, allow users to switch readily between commodities.

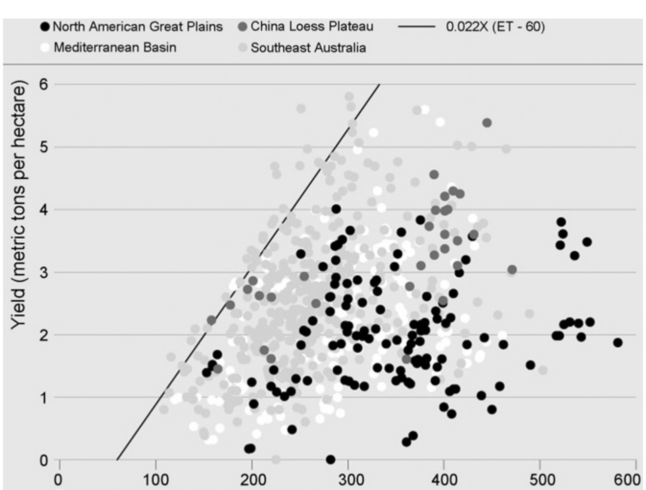

Fig. 2. Variations between yield and evapotranspiration for wheat in different regions of the world. *Source*: Adapted from Sadras and Angus (2006).

3.2. Looking beyond crops

There is much more scope for increasing the value per unit of water used in agriculture (economic water productivity) rather than increasing physical water productivity, which is becoming

Table 1
Range of water productivities in biological, economical and nutritional terms for selected commodities (Molden et al., 2007a,b).

Product	Water productivity			
	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	660–4000
Rice ($0.31 per kilogram)	0.15–1.6	0.05–0.18	12–50	500–2000
Maize ($0.11 per kilogram)	0.30–2.00	0.03–0.22	30–200	1000–7000
Legumes				
Lentils ($0.3 per kilogram)	0.3–1.0	0.09–0.30	90–150	1060–3500
Fava beans ($0.3 per kilogram)	0.3–0.8	0.09–0.24	100–150	1260–3360
Groundnut ($0.8 per kilogram)	0.1–0.4	0.08–0.32	30–120	800–3200
Vegetables				
Potato ($0.1 per kilogram)	3–7	0.3–0.7	50–120	3000–7000
Tomato ($0.15 per kilogram)	5–20	0.75–3.0	50–200	1000–4000
Onion ($0.1 per kilogram)	3–10	0.3–1.0	20–67	1200–4000
Fruits				
Apples ($0.8 per kilogram)	1.0–5.0	0.8–4.0	Negligible	520–2600
Olives ($1.0 per kilogram)	1.0–3.0	1.0–3.0	10–30	1150–3450
Dates ($2.0 per kilogram)	0.4–0.8	0.8–1.6	8–16	1120–2240
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	85–1750

Source: Adapted from Muir (1993), Verdegem et al. (2006), Renault and Wallender (2000), Oweis and Hachum (2003) and Zwart and Bastiaanssen (2004).

[a] Includes extensive systems without additional nutritional inputs to super-intensive systems.

increasingly constrained. Strategies for increasing the net value of water used in agriculture include: increasing yield, changing from low to high value crops, re-allocating water from low to higher valued uses, lowering the costs of inputs, increasing health benefits and the value of ecological services of agriculture, decreasing social, health, and environmental costs, obtaining multiple benefits per unit of water, and achieving more welfare per unit of water. 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.

3.2.1. Livestock water productivity

Globally, livestock production accounts for some 20% of agricultural ET (de Fraiture et al., 2007), and this proportion is projected to grow substantially with the increasing consumption of animal products. 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. Estimates of the amount of ET required to produce 1 kg of animal products vary widely between 3000 and 15,000 l (Molden et al., 2007a,b) 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.

There is considerable scope for increases in livestock productivity, in both physical and economic water productivity (Peden et al., 2007). Strategies to enhance water productivity include improving feed sourcing of animals, enhancing animal production (milk, meat, eggs), improving health through veterinary services, grazing practices that avoid land degradation to lessen the amount of water required for grazing and reduce negative environmental impacts such as erosion (Peden et al., 2007). Livestock generate numerous values beyond food production that should be taken into account, including transport, plowing, support of cultural values and a means of buffering against drought.

3.2.2. Fisheries and aquaculture

As with livestock, there is considerable scope for better integration of fisheries and aquaculture with water management systems to improve water productivity. The two major components of water use in aquaculture are the water required to produce 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 l in super-intensive re-circulation systems and as high as 45,000 l of water per kilogram of produce in extensive ponds (Verdegem et al., 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. Fisheries in lakes, rivers and wetlands are only one of the many ecosystem services provided by aquatic ecosystems. The values and livelihood benefits of fisheries are high and often ignored or underestimated, but considering only the values of fish produced per unit of water would grossly underestimate the value of water in these aquatic ecosystems. Thus, maintenance of wetlands and biodiversity and their livelihood values should be considered, in addition to fish production, as potential benefits of leaving water in these aquatic ecosystems.

3.2.3. Applying integrated approaches

Designing and managing agricultural water for multiple uses – drinking water, industries, livestock, fisheries – raises the economic productivity of water in water management systems (Meinzen-Dick, 1997; Bhatnagar et al., 2004; Nguyen-Khoa et al., 2005; van Koppen et al., 2006). Irrigation provides water for fruit and shade trees, habitat to sustain biodiversity and is a source of recharge for groundwater, which is a common source of rural drinking water supporting the livelihoods of smallholders. Integrated agriculture-aquaculture provides a means of recycling water and nutrients and obtaining more value and income from farm enterprises (Gupta et al., 1999). Multi-functional farm ponds, storing water for crop irrigation and domestic purposes, may be suitable for raising fish to improve household nutrition and provide a ready source of income. Agricultural water management practices provide multiple ecosystem services beyond food production. Practices that reduce environmental costs and enhance ecosystem services increase the value derived from agricultural water management (Matsuno et al., 2006; Scherr and McNeely, 2007).

3.3. Opening opportunities within river basins and beyond

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

(a) increasing the productivity per unit of ET at the plant-, field- and farm-scale, as indicated above;
(b) minimizing nonproductive depletion of water flows by reducing water flows to sinks, minimizing salinization and pollution of return flows and discharging polluted water to sinks;
(c) improving management of existing irrigation facilities and reusing return flows by controlling, diverting and storing drainage flows; and
(d) re-allocating and co-managing water among uses by re-allocating water from lower value to higher value uses within and between sectors, identifying and managing committed outflows for the environment and for downstream water allocation, co-managing among multiple uses, recognizing multiple uses, and reaping multiple benefits while mitigating adverse impacts and incorporating aquaculture, fisheries, and livestock considerations into basin management.

At larger scales with more users, and more interaction between users, water productivity issues become increasingly complex. The intersectoral nature of water, competition for water use, resource degradation and issues of equity 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 such as the those derived from ecosystem services (Ward and Michelsen, 2002). For example, if a small amount of water is moved from agriculture to a 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 produce 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 this may provide a large gain in agricultural value. However, when rivers are reduced to minimum levels, the next drop taken out of the river may be at a considerable ecosystem cost. Such analysis is not common in part because the integrated hydrological and valuation tools are complex and imprecise, but also because there are too few institutional arrangements where such information enters the decision-making process.

Nevertheless, it is possible to make much more informed decisions than those that are being made today. Stakeholders representing each use should be involved in decisions on re-allocating 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 of the differences in the values, goals, priorities and aspirations of people (Warner et al., 2006). Thus, informed multi-stakeholder decision-making processes are needed to address conflicts and find constructive solutions (Emerton and Bos, 2004).

3.3.1. Increasing WP at the global level

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 7% less ET and 15% less depletion of irrigation water than would have been required to grow the same amount of crops (de Fraiture et al., 2004) without trade. But trade takes place for other economic and political reasons, and gains in water productivity are merely a by-product. A more detailed analysis of trade that considers payment for imports, rural employment and environmental impacts must be considered. This is even more important in view of the current high commodity prices which have led some countries to raise export tariffs on grains.

4. Reasons for caution

4.1. Limits in the scope for increasing crop water productivity

Does crop breeding and biotechnology hold the key to gains in water productivity? There is controversy about the potential for future increases in the harvest index for common crops like wheat and rice (Keller and Seckler, 2004). Some argue that much of the potential for increasing the harvest index for common grains such as wheat, maize and rice was met during the green revolution (Tanner and Sinclair, 1983; Richards et al., 1993), and others see some scope, especially in crops such as sorghum and millet, that have not received so much intensive research (Bindraban, 1997; Bennett, 2003). Crop breeding that targets early growth vigor to reduce evaporation and increase resistance to droughts, disease or salinity could all improve water productivity per unit of ET.

Moderate impacts on crop water productivity from improvements in plant genetics should be expected in the medium-term. Because the gap between the actual practice and the biophysical potential is so large, greater and easier gains are possible through better management. Improvements in plant genetics, however, can play an important role in reducing the risk of crop failure. More value per unit of ET can be achieved by improving the nutritional quality of crops and reducing pesticides and other agrochemical inputs through disease- and pest-resistant crops. This can be achieved slowly through conventional breeding, or more quickly using appropriate biotechnological tools (Bindraban et al., 2006).

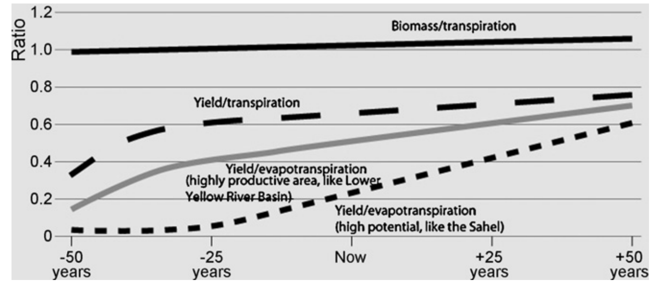

Fig. 3. Generalization of past water productivity gains and forecast of gains to made in the future. The highest gains in water productivity for common crops such as rice, wheat and maize are likely in areas where yields are still low (Molden et al., 2007a).

How much scope is there to increase the grain yield relative to ET? Because of the biophysical relation between biomass and transpiration, there is possibly little gain to be made in this area (top curve in Fig. 3). The yield versus transpiration index has already improved substantially because of changes in the harvest index in many places. The lower two lines in Fig. 3 indicate that improvements in physical water productivity are possible through improved management that increases the ratio of yield to ET. But in many of the most productive areas of the world, such as the Lower Yellow River Basin, or in most of Europe, North America and Australia, large improvements have already been made and there is little scope for further improvements. The implication is that more ET will be required to achieve higher yields in these highly productive areas.

4.2. Water saving potential

Saving water, especially to release water from irrigated agriculture, can make it available to other, higher value uses in cities, industries, ecosystems or more agriculture. A common (mis)perception, however, is that irrigation is wasteful because of highly inefficient practices. Investments in improving water management are important in increasing WP, but many people question whether these practices promote real water savings (Seckler, 1996; Perry, 1999; Seckler et al., 2003; Molle et al., 2004).

Several conditions exist where there is actually less scope for saving water in irrigation than commonly perceived, especially in cases where drainage water from fields is reused. It is well accepted that there is substantial scope to reduce irrigation water deliveries through a range of technical and management practices: drip and sprinkler irrigation, more precise application practices, canal lining or delivery through pipes, reduced allocations of water to farmers or pricing to influence demand. Many of these practices increase yields, and are important for water quality management and the overall control of water. Several practices, such as alternate wet and dry irrigation, are applicable to rice irrigation (Bouman et al., 2007). But, we need to be cautious about the expectations of water saving because practices that reduce deliveries typically also reduce drainage outflows. First, as a way to cope with water stress, farmers commonly reuse these drainage flows by pumping water from groundwater or withdrawing water from open drains if possible. Second, those farmers who follow water saving practices may use that "saved" water to expand their irrigation. Often the perceived gain is offset by a loss (Gichuki, 2004) that is difficult to recognize. Reducing deliveries and drainage works well in situations where flows cause damage, polluted water, or go to a saline sink (Molden et al., 2001). A basin perspective is required to determine if on-farm water management practices lead to "real" water savings that can be made available for other uses, or whether on-farm practices result in a redistribution of water within agriculture.

4.3. Winners and losers in the river basin

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. Expanding agriculture upstream through better rainfall capture and artificial storage systems reduces downstream flows supporting other 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 highlight these tradeoffs to help decision makers to develop strategies where the desired benefits exceed the undesired costs.

Typically, with urbanization, water is re-allocated 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 re-allocations, and often the transfers are made without negotiation or adequate compensation. Thus, changes in the practices of farmers are typically in response to the re-allocation of supplies rather than the being the driver behind the re-allocation.

4.4. The need to establish enabling conditions

While many strategies exist for improving water productivity, adoption rates remain low for many reasons. 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 et al., 2005). There are several reasons for this. First, water productivity itself is unlikely to feature prominently among the many considerations facing resource managers. Farmers rarely manage to increase water productivity; rather, they manage to make their entire enterprise profitable or to enhance household food security. Factors that influence the uptake of practices that that enhance water productivity include costs, profitability, risks, access to markets, water availability, education, incentives and institutional structures.

Second, increases in water productivity at the farm level can actually increase basin water depletion, especially where water is scarce compared with land resources. Farmers may see technologies that enhance water productivity 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 available for other uses (Molle et al., 2004).

Third, incentives for increasing water productivity are rarely in place. Water scarcity is a key driver behind gains in water productivity, with agriculture under pressure from the increased use of water by cities and a demand for more allocations for the environment. In areas where this driver does not directly influence the decisions of individuals who have water access, economic instruments have been considered to reflect the values of physical scarcity. Some argue that, in areas where water is scarce, but the price of agricultural water is low, farmers are not aware of the scarcity condition. Hence, raising the price would reduce agricultural water demand, thus increasing the supply available for cities. Others argue that, there is little evidence that pricing is effective in reducing irrigation demand because the responsiveness to higher water prices is limited by existing systems of water rights, inadequate measurement and monitoring of water deliveries, and strong opposition to higher water prices in agrarian societies (Hellegers and Perry, 2006; Molle and Berkoff, 2006; Berbel and Gómez-Limón, 2000). Administrative allocation has been shown to be an effective option when farmers must adopt water productivity practices in response to less supply.

Fourth, there are a variety of actors with different incentives, all influencing water productivity and re-allocation (Molden et al., 2007a,b). 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 trade-offs of different management options and the proper alignment of incentives across various actors is a key to adoption. Thus, adoption and uptake of practices that enhance water productivity require understanding potential trade-offs, identifying winners and losers and aligning the incentives of all actors.

4.5. The impact of climate change and other emerging drivers of change

Because climate is central to physical crop water productivity, climate change brings about a further uncertainty to the scope for increasing water productivity. Higher biomass production per unit of transpiration is achievable at a lower vapor pressure deficit (Tanner and Sinclair, 1983), 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 ET because more carbon can enter the plant for more photosynthesis (Droogers and Aerts, 2005; IPCC, 2001). More recent evidence shows that gains in water productivity will be substantially offset by increased temperature (Long et al., 2006). In fact, the Intergovernmental Panel on Climate Change (IPCC) points to a reduction in potential yields in sub-Saharan Africa, also implying a reduction in potential rates of water productivity, but this has yet to be analyzed.

Many factors outside the water sector must also be considered in efforts to improve water productivity. These include changing prices for agricultural commodities, increasing demand for biofuels, urbanization and changing diets with a rising population (de Fraiture et al., 2008; Molden et al., 2007a,b). Policies influencing these drivers will also influence water use, and thereby influence the scope for gains in water productivity. While some factors, such as the recent increase in commodity prices may make investments in water productivity attractive, there is a high degree of uncertainty as to how these will impact water productivity in the future (World Bank, 2008).

5. Discussion and conclusions

Optimists see many possibilities for large gains in water productivity, while pessimists see many difficulties in reaching those gains. Rather than try and judge who is right, it is more important to understand key messages that both optimists and pessimists bring forward. We know that we cannot afford the environmental and livelihood costs of not achieving gains in water productivity, and we have to recognize that reaching those gains will be a difficult task. We conclude that there are gains to be made in water productivity, but these will require policies and actions that recognize the complex nature of achieving those gains.

There is considerable scope for improving water productivity, but not everywhere. The scope for improvement remains 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. Many promising pathways for raising water productivity are available over the continuum from fully rainfed to fully irrigated farming systems.

There are areas of the world that already exhibit high physical water productivity, with limited scope for improvements. There are much smaller gains to be made in physical water productivity when yields increase from 7 to 8 tons per hectare, than when yields increase from 1 to 2 tons per hectare. Thus, increasing yields in these highly productive areas will require more ET. Also, while many crop breeding strategies were successful in increasing water productivity for common crops like wheat, rice and maize, their future potential may be limited because gains from these strategies have already been made. However, for less common crops, breeding may play an important role.

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 concentration of poor people with a high dependence on agriculture. This is an important 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 a large variation by commodity, implying that there is scope for improvement.

Optimistic estimations in the scope for saving water in irrigation, an important strategy to free up water for cities and the environment, are commonly overstated. While there is scope for reducing water applied to fields, and there are good reasons to do this, the scope for water savings at a river basin scale is often limited because of the prevalence of situations where water is reused. Moreover, water saving measures that do not adequately take into consideration how other users of water are impacted may result in a gain for one user and a loss for another user.

There is great scope for increasing economic water productivity by increasing the value generated by water use and decreasing associated costs. But to achieve these gains will require an 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. These interventions need to be framed within a river basin perspective to understand the complex web of impacts on numerous users. In fact, a number of key drivers including climate change, urbanization, changes in population and diets, and changing commodity prices will require that systems need to rapidly respond to take advantage of potential gains in water productivity.

Where we know there is potential to increase physical and economic water productivity, adoption of practices that enhance water productivity is slow. While society may have the incentives to increase water productivity, agricultural producers may not. Producers manage labor and other inputs to get better economic gains, and the incentive for increasing water productivity is, typically, not high on their agenda. The adoption of techniques to improve water productivity will, therefore, require an enabling policy and an institutional environment that aligns the incentives of producers, resource managers and society, and provides a mechanism for dealing with trade-offs.

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