8 Increasing Water Productivity in Agriculture

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Abstract

Increasing water productivity is an important element in improved water management for sustainable agriculture, food security and healthy ecosystem functioning. Water productivity is defined as the amount of agricultural output per unit of water depleted, and can be assessed for crops, trees, livestock and fish. This chapter reviews challenges in and opportunities for improving water productivity in socially equitable and sustainable ways by thinking beyond technologies, and fostering enabling institutions and policies. Both in irrigated and rainfed cropping systems, water productivity can be improved by choosing well-adapted crop types, reducing unproductive water losses and maintaining healthy, vigorously growing crops through optimized water, nutrient and agronomic management. Livestock water productivity can be increased through improved feed management and animal husbandry, reduced animal mortality, appropriate livestock watering and sustainable grazing management. In agroforestry systems, the key to success is choosing the right combination of trees and crops to exploit spatial and temporal complementarities in resource use. In aquaculture systems, most water is depleted indirectly for feed production, via seepage and evaporation from water bodies, and through polluted water discharge, and efforts to improve water productivity should be directed at minimizing those losses. Identifying the most promising options is complex and has to take into account environmental, financial, social and health-related considerations. In general, improving agricultural water productivity, thus freeing up water for ecosystem functions, can be achieved by creating synergies across scales and between various agricultural sectors and the environment, and by enabling multiple uses of water and equitable access to water resources for different groups in society.

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Background

As water resources around the world are threatened by scarcity, degradation and overuse, and food demands are projected to increase, it is important to improve our ability to produce food with less water. There are only a few basic methods of using the earth's water resources to meet the growing food demands: continuing to expand rainfed and irrigated lands; increasing production per unit of water; trade in food commodities; and changes in consumption practices. Land expansion is no longer a viable solution (Godfray *et al*., 2010). Therefore, improving agricultural productivity on existing lands using the same amount of water will be essential. Increasing water productivity means using less water to complete a particular task, or using the same amount of water, but producing more. Increased water productivity has been associated with improved food security and livelihoods (Cook *et al*., 2009b; Cai *et al*., 2011). Additionally, it leads to savings in fresh water, making it available for other uses, such as healthy ecosystem functioning. Increased water productivity is therefore an important element in improved management of water and ecosystems for sustainable agriculture and food security.

Water productivity is the amount of beneficial output per unit of water depleted. In its broadest sense, it reflects the objectives of producing more food, and the associated income, livelihood and ecological benefits, at a lower social and environmental cost per unit of water used (Molden *et al*., 2007). Usually, water productivity is defined as a mass (kg), monetary ($) or energy (calorific) value of produce per unit of water evapotranspired (Kijne *et al*., 2003; Molden *et al*., 2010), and, as such, it is a measure of the ability of agricultural systems to convert water into food. Water use efficiency and water productivity are often used in the same context of increasing agricultural outputs while using or degrading fewer resources. Although definitions vary, water use efficiency usually takes into account the water input, whereas water productivity uses the water consumption in its calculation. In this chapter, both terms are used interchangeably, reflecting the most common use in a specific field.

Improving agricultural water productivity is about increasing the production of rainfed or irrigated crops, but also about maximizing the products and services from livestock, trees and fish per unit of water use. Crop water productivity has been the subject of many years of research, and its assessment and means for improvement are well documented (Kijne *et al*., 2003; Bouman, 2007; Molden, 2007; Rockström and Barron, 2007). However, for other agricultural outputs and systems, such as livestock, agroforestry, fisheries and aquaculture, research on improving water productivity is still in its infancy. In recent years though, a growing body of evidence is creating a clearer picture on the potential solutions and ways forward (Cai *et al*., 2011). Besides going beyond crops, this chapter also emphasizes the need for careful targeting of technologies and enabling policies and institutions for successful adoption in farmer communities. Other cross-sectoral approaches for improved water productivity, such as multiple use of water, reducing postharvest losses and basin studies will be discussed briefly.

Increasing Crop Water Productivity

Opportunities for improving crop water productivity mainly lie in choosing adapted, water-efficient crops, reducing unproductive water losses and ensuring ideal agronomic conditions for crop production (see, for example, Kijne *et al*., 2003; Bouman, 2007; Rockström and Barron, 2007). In general, agronomic measures directed at healthy, vigorously growing crops favour transpirational and productive water losses over unproductive losses. An important principle for crop water productivity is that taking away water stress will only improve water productivity if other stresses (nutrient deficiencies, weeds and diseases) are also alleviated or removed (Bouman, 2007), i.e. water management should go hand in hand with nutrient management, soil management and pest management (Bindraban *et al*., 1999; Rockström and Barron, 2007). Since the Comprehensive Assessment of Water Management in Agriculture, of which the main ouput was the report *Water for Food, Water for Life* (Molden, 2007), research on the performance of various interventions for crop water productivity improvement has included, among others, supplemental irrigation, precision irrigation and drainage, soil fertility management, reduced tillage operations, soil moisture conservation, and the use of drought- and disease-resistant crop varieties (Fischer *et al*., 2009; Geerts and Raes, 2009; Gowda *et al*., 2009; Oweis and Hachum, 2009a,b; Stuyt *et al*., 2009; de Vries *et al*., 2010; Arora *et al*., 2011; Balwinder *et al*., 2011; Mzezewa *et al*., 2011).

There is great variation in water productivity across cropping systems, under both irrigated and rainfed conditions. It has been estimated that three quarters of the additional food we need for our growing population could be met by increasing the productivity of low-yield farming systems, probably to 80% of the productivity that high-yield farming systems obtain from comparable land (Molden, 2007). Especially where yield gaps are large, there is large scope for improvement (de Fraiture and Wichelns, 2010; Cai *et al*., 2011). In that respect, the highest potential water productivity gains can be achieved in low-yielding rainfed areas in pockets of poverty across much of sub-Saharan Africa and South Asia (Rockström *et al*. 2010). As many of the world's poorest people live in currently low-yielding rainfed areas, improving the productivity of water and land in these areas would result in multiple benefits. Thus, by getting more value out of currently underutilized rainwater, agricultural land expansion would be limited, and the livelihoods of these poor men and women would be improved, without threatening other ecosystem services (WRI *et al*., 2008).

A recent global analysis on closing yield gaps indicated that appropriate nutrient and water management are essential and have to go hand in hand (Mueller *et al*., 2012). Comparing bright spots (examples of high water productivity) with hot spots (examples of low water productivity) across ten different basins showed that yield increases through tailored interventions are possible at many locations and would lead to major gains in water productivity (Cai *et al*., 2011). Gaps in crop water productivity are often linked to access to water, but also to access to other inputs such as seeds and fertilizers, which illustrates the importance of markets and infrastructure (Ahmad and Giordano, 2010). However, in highly productive areas, caution on the scope for gains in crop water productivity is warranted (Molden *et al*., 2010). There is a crop-dependent biophysical limit to the biomass production per unit of transpiration (Seckler *et al*., 2003; Steduto *et al*., 2007; Gowda *et al*., 2009), and whereas plant breeders have managed to increase the harvest index of crops (the ratio of marketable produce to total biomass), gains in this index appear to have peaked (Molden *et al*., 2010). The canopy development that is associated with increasing yields limits the scope for reducing water losses, because doubling the yield also requires almost twice the amount of transpiration.

Increasing Water Productivity in Agroforestry Systems

The area under agroforestry worldwide was estimated at 1023 million ha in 2009, but it has been suggested that substantial additional areas of unproductive crop, grass and forest lands, as well as degraded lands, could be brought under agroforestry (Nair *et al*., 2009). The concept of agroforestry is based on the premise that structurally and functionally more complex land use systems capture resources more efficiently than monocultures (Schroth and Sinclair, 2003). Agroforestry enhances resource utilization by improving temporal and/or spatial complementarity in resource capture (Ong *et al*., 2007). Trees enhance below-ground diversity and this supports local ecosystem stability and resilience (Barrios *et al*., 2012); trees also provide connectivity with forests and other features at the landscape and watershed levels (Harvey *et al*., 2006). Agroforestry provides numerous benefits, ranging from diversification of production to improved exploitation of natural resources and provision of environmental functions, such as soil conservation (protection against erosion), improvement or maintenance of soil fertility, water conservation and more productive use of water (Cooper *et al*., 1996).

Trees outside forests, or trees on farms, are an important component of man-made landscapes. With 10% tree cover on nearly half of the world's agricultural land, agroforestry is a common reality (Zomer *et al*., 2009). Trees are important landscape elements that help regulate water flows. Even a small change in tree cover can have a large impact on reducing runoff and enhancing infiltration and transpiration (Carroll *et al*., 2004; Hansson, 2006), through the use of the trees to provide fuelwood, fodder, fruit and timber (Ong and Swallow, 2003). 'Hydraulic lift' is an interesting phenomenon in agroforestry systems, whereby the tree root system lifts water from moist deep soil layers to the upper soil layers, where it is accessible to crops (Roupsard, 1997; Ong and Leakey, 1999; Bayala *et al*., 2008). Agroforestry belts have also been proposed as riparian buffers to combat non-point source water pollution from agricultural fields and help to clean runoff water by reducing runoff velocity, thereby promoting infiltration, sediment deposition and nutrient retention (Jose, 2009). The management of riparian vegetation can improve the quality of water in the river and hence, via its outflow, help to protect valuable coastal ecosystems, such as the Great Barrier Reef (Pert *et al*., 2010). In degraded areas of the Abay Basin in Ethiopia, integrating multi-purpose trees into farms helped to fight land degradation while increasing the productive use of water (Merrey and Gebreselassie, 2011).

A key challenge for agroforestry is to identify which combination of tree and crop species optimizes the capture and use of scarce environmental resources such as light, water and nutrients, at the same time as fulfilling farmers' needs for timber, fuel, mulch, fodder and staple food (Sanchez, 1995; Muthuri *et al*., 2009). The complementary aspects of trees in relation to crops can be enhanced by selecting and managing trees to minimize competition (Schroth, 1999) by means of root and shoot pruning (Siriri *et al*., 2010), increasing tree spacing within the crops (Singh *et al*. 1989), and matching the trees and crops to appropriate niches within the farm (van Noordwijk and Ong, 1996).

Increasing Livestock Water Productivity

Livestock products provide one third of the human protein intake, but also consume almost one third of the water used in agriculture globally (Herrero *et al*., 2009). Most of the world's animal production comes from rainfed mixed crop–livestock systems in developing countries and from intensive industrialized production in developed countries (Herrero *et al*., 2010). Livestock production systems are rapidly changing in response to various drivers, which calls for the constant adaptation of policy, investment and technology options (Chapter 2). With increasing demands for animal products, along with increasing global water scarcity and competition for water, improving livestock water productivity (LWP) has become essential (Descheemaeker *et al*., 2010a).

LWP was first defined by Peden *et al*. (2007) as the ratio of livestock products and services to the water depleted and degraded in producing these; it can also include water depleted in slaughterhouses and milk-processing facilities. Since the launch of the LWP concept, several studies have investigated the livestock–water nexus and dealt with LWP at various scales (Amede *et al*., 2009a,b; Cook *et al*., 2009a; Gebreselassie *et al*., 2009; Haileslassie *et al*., 2009a,b; van Breugel *et al*., 2010; Descheemaeker *et al*., 2011; Mekonnen *et al*., 2011). While offering good insights into how LWP can be increased, these studies have also advanced the methodologies for LWP assessment. A remaining question is how to account for the value of the water consumed (Peden *et al*., 2009b). For example, livestock grazed on arid and semi-arid pastures utilize water that cannot be used for crops and would be depleted through evapotranspiration before it could enter groundwater and surface water bodies (Bindraban *et al*., 2010). Such water would be valued less than water in an irrigation scheme that can be used for growing high-value vegetable crops. A consideration of the value of water could lead to demand-side management that would foster a rebalancing of water use among agricultural sectors. Especially for livestock production in areas of low potential and in smallholder systems, such considerations would show that livestock are very efficient in making productive use of water that is of low value for other sectors.

Global environmental evidence suggests that the livestock sector has a strong negative impact on water depletion and pollution (Steinfeld *et al*., 2006). However, caution is needed with respect to such pronouncements, because big differences exist between various livestock systems and agroecologies. For example, in industrial livestock systems, soil and water contamination from manure and wastewater mismanagement and the use of chemicals is a common problem, whereas in smallholder low-input systems this is not (yet) the case. In these smallholder systems, livestock often provide multiple services, including farm power for cultivation and transport, and manure for soil fertility management (Tarawali *et al*., 2011). Valuing manure as a beneficial output of livestock systems would result in a much higher figure for LWP than when only meat and milk are taken into account. This illustrates the importance of the context in which livestock productivity assessments are made (Cai *et al*., 2011).

Calculations of LWP have shown that servicing and drinking, though at first sight the most obvious water uses of livestock, in reality constitute only a minor part of the total water consumption in livestock-based agroecosystems (Peden *et al*., 2007, 2009a). The major water depletion in relation to livestock production is the evapotranspiration of water for feed production (Peden *et al*., 2007; Gebreselassie *et al*., 2009). The large global variations in feed water productivity (see Table 8.1) are not only a sign of divergent methodologies, but also illustrate that LWP depends on the type, the growing conditions and the management of forage production. Hence, the large variation in LWP in the Nile Basin (Box 8.1) is not surprising, and illustrates that there is ample scope for improvement.

Innovative interventions for improved LWP can be grouped in three categories (Peden *et al*., 2009b; Descheemaeker *et al*., 2010a; Herrero *et al*., 2010):

- Feed-related strategies for improving LWP comprise: the careful selection of feed types, including crop residues and other waste products; improving the nutritional quality of the feed; optimizing the use of multi-purpose food–feed–timber crops; increasing feed water productivity by appropriate crop and cultivar selection and improved agronomic management; and implementing more sustainable grazing management practices.
- Water management strategies for higher LWP consist of water conservation and water harvesting, strategic placement and monitoring of watering points, and the integration of livestock production into irrigation schemes.

Table 8.1. Global ranges of feed water productivity for different feed types, derived from the literature.[a]

Feed type	Feed water productivity (kg/m^3)
Cereal grains	0.35–1.10
Cereal forages	0.33–2.16
Food–feed crops (total biomass)	1.20–4.02
Irrigated lucerne	0.80–2.30
Pastures	0.34–2.25
(Semi)-arid rangelands	0.15–0.60

[a]Ferraris and Sinclair, 1980; Sala *et al.*, 1988; Bonachela *et al.*, 1995; Saeed and El-Nadi, 1997, 1998; Renault and Wallender, 2000; Chapagain and Hoekstra, 2003; Oweis *et al.*, 2004; Singh *et al.*, 2004; Smeal *et al.*, 2005; Nielsen *et al.*, 2006; Gebreselassie *et al.*, 2009; Haileslassie *et al.*, 2009a,b; van Breugel *et al.*, 2010.

Box 8.1. Livestock water productivity (LWP) in the Nile Basin

A basin-wide assessment of livestock water use and productivity showed that the total water need for feed production in the Nile Basin was roughly 94 billion m^3, which amounts to approximately 5% of the total annual rainfall (68 billion m^3, or 3.6% of total annual rainfall when excluding water for crop residues) (van Breugel *et al.*, 2010). In most areas of the basin, LWP is less than 0.1 US$/m^3, with only a few areas showing an LWP of 0.5 US$/m^3 and higher (Fig. 8.1). Livestock water productivity is on average low, but large differences exist across the basin, both within and between livestock production systems. These differences suggest that there is scope for improvement of LWP (see main text for an overview of options), which could lead to significant reduction of water use at the basin level while maintaining current levels of production. In line with the large-scale (basin-wide) analysis, community and household level analyses indicated that in the Ethiopian highlands, LWP ranges from 0.09 to 0.69 US$/m^3 (Haileslassie *et al.*, 2009b; Descheemaeker *et al.*, 2010b), whereas in animal feeding trials LWP ranged from 0.27 to 0.64 US$/m^3 (Gebreselassie *et al.*, 2009).

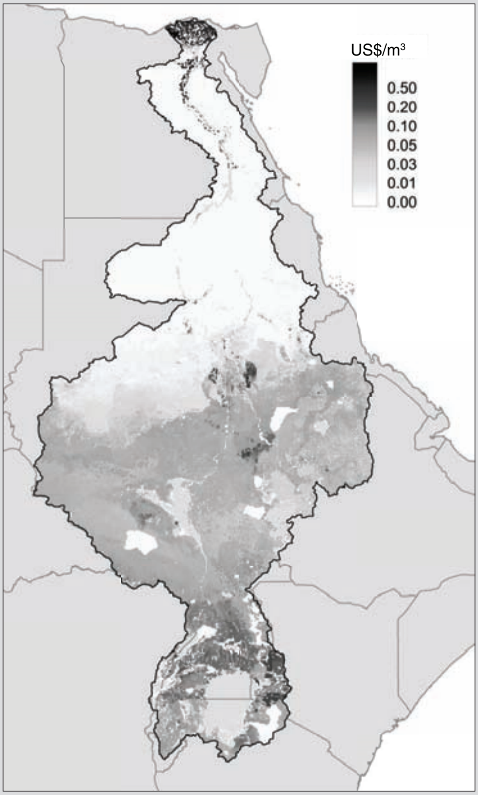

Fig. 8.1. Livestock water productivity of the Nile Basin (outlined area) expressed as the ratio of the summed value of meat and milk and the water depleted to produce the required livestock feed. Water for residues was not included in the calculation of depleted water (Map by P. van Breugel, based on van Breugel *et al.*, 2010).

When considering just milk production, smallholder production systems in the Ethiopian highlands are characterized by very low water productivity, ranging between 0.03 and 0.08 l milk/m^3 (Descheemaeker *et al.*, 2010b; van Breugel *et al.*, 2010). In other words, the virtual water content of milk in these systems ranges from 12.5 to 33 m^3 water/l milk, which is very high considering the global average of 0.77 m^3 water/l milk (Chapagain and Hoekstra, 2003). However, the difference from the highly specialized and efficient industrial systems is that in smallholder systems, milk production is often viewed as a by-product of livestock keeping. Livestock are kept for multiple purposes and services (Thornton and Herrero, 2001; Moll *et al.*, 2007; Cecchi *et al.*, 2010), of which manure and draft power are usually more important than milk and meat production. The LWP concept and framework developed by the International Water Management Institute (IWMI) and International Livestock Research Institute (ILRI) (Peden *et al.*, 2007; Descheemaeker *et al.*, 2010a) allow the taking into account of these multiple livestock products and services in water productivity assessments.

- Animal management strategies include improving breeds, disease prevention and control, and appropriate animal husbandry, supported by raising awareness among livestock keepers that the same benefit can be obtained from smaller and fewer, but more productive, herds.

Designing LWP interventions that benefit the poor requires an understanding of the differentiated access to livestock-related capitals and livelihood strategies of men and women and of different socio-economic groups within local communities (Clement *et al*., 2011). Livestock often provide an important source of income for women, particularly in mixed crop–livestock systems. Furthermore, in order to facilitate their adoption, technological interventions need to be supported by appropriate policies and institutions (Amede *et al*., 2009b). For example, establishing institutions such as water users' associations, together with policies such as cost recovery for water use, can contribute to improving the efficiency of feed crop irrigation.

The important role of informal arrangements in LWP should not be underestimated as these can provide socially acceptable ways for different groups in society to access water (Adams *et al*., 1997). In communal grazing lands, for example, it is not only vegetation but also water resources that bind herders together, and arrangements are needed to ensure equitable access and sustainable use. Opportunities for the sustainable management of livestock grazing systems in a way that maintains ecosystem services include institutions that enable the management of climate variability – such as early warning and response systems, improved markets, livestock loss insurance schemes and fodder reserves (World Bank, 2009). Other approaches deal with changing the incentive system for keeping large herds, such as payment for environmental services and increasing the level of cost recovery in the use of natural resources, and veterinary services (World Bank, 2009). Such incentive systems require great attention to issues of equity and legitimacy, as they might increase existing or create new social inequities.

Increasing Water Productivity in Aquaculture

Benefits from aquaculture include the production of food, improved livelihoods, nutrition and health (Dugan *et al*., 2007). The abstraction and discharge of water for aquaculture may, however, affect ecological processes and compromise ecosystem services that support other livelihoods. Appropriation of water for aquaculture may lead to competition with other resource users, including other aquaculture operators. Water requirements for aquaculture are both qualitative and quantitative in nature, but the definition of the water quantities 'used' presents difficulties (Nguyen-Khoa *et al*., 2008). Consumptive use of water for the accumulation of aquatic resources biomass is negligible in aquaculture. The water is mainly consumed indirectly in the production of aquaculture feed or via percolation, seepage, and evaporation from ponds and stocked reservoirs. Water productivity can thus be defined as the mass or value of the aquaculture produce divided by the amount of water required for feed plus the amount of evaporation and seepage from the pond or reservoir.

Water productivity assessment in cage or pen aquaculture presents yet another challenge. Cages allow natural water exchange and, like capture fisheries, do not induce significant water losses to the system. The disadvantage is that cage aquaculture discharges large quantities of nutrients and metabolites directly to its aquatic environment. Hence, the relative environmental impact per ton of product of cage and pen aquaculture in inland waters is much higher than that of any other aquatic production system (Hall *et al*., 2011). Water use efficiency varies markedly between different aquaculture production systems (Table 8.2), although fish and crustaceans are more efficient than terrestrial animals in terms of feed-associated water use. However, on-farm use of non-feed associated water in aquaculture can be very high, attaining up to 45m^3 per kg produced in ponds.

Pressures to enhance water productivity in aquaculture (Box 8.2) derive from global changes and domain-specific challenges such as production efficiency, risk management,

Table 8.2. Water use efficiency (in m^3 water/kg fresh weight) in aquaculture systems (adapted from Bunting, 2013).

Aquaculture system	Water use efficiency	Water management characteristics
Traditional extensive fish pond culture	45[a]	Rainwater and drainage water are routinely channelled into fish ponds to compensate for seepage and evaporation losses; excessive water exchange is detrimental as it is desirable to retain nutrients within the pond
Flow-through ponds	30.1[a]	Water exchange of 20% of the pond volume/day removes waste and replenishes oxygen levels; annual production of 30 t/ha is attainable, but seepage and evaporation contribute to water loss in the system
Semi-intensive fish ponds	11.5[a]	Fish ponds fed with formulated pellet feed can yield 6 t/ha, while producing two crops annually, and with complete drainage to facilitate harvest; one fifth of water consumption is associated with feed inputs
Wastewater-fed aquaculture	11.4[b]	Wastewater is routinely fed into fish ponds in the East Kolkata Wetlands (West Bengal, India) to make up the water to a desirable level; estimates suggest 550,000 m^3/day of wastewater is used to produce 18,000 t/year of fish in 3900 ha of ponds
Intensively managed ponds	2.7[a]	Lined ponds provide an annual production of 100 t/ha, while intensive mixing results in evaporation of 2000 mm/year
Super-intensive recirculation systems	0.5–1.4[a]	Process water is recirculated with pumps and treated with mechanical filters, biofilters and disinfection technology; stocked animals are entirely dependent on high-protein formulated feed inputs

[a]Based on Verdegem *et al.*, 2006; [b]from Bunting, 2007.

conflict avoidance, legislation and controls, consumer demand and public perception (Verdegem *et al*., 2006; Chapter 2). The water productivity of aquaculture can be increased through improving system design, good management, good water quality, good brood stock, or using a combination of non-competing species that fill different niches in the aquatic ecosystem. Practices and policies that include construction, systems design and operation, optimization of production efficiency, water management practices, horizontally integrated aquaculture systems (Box 7.1, Chapter 7), water rates and pollution taxes, and policy and planning have been identified as potential areas where water use efficiency in aquaculture could be improved. The integration of aquaculture with other agricultural and water uses has potential for enhancing the productivity of appropriated freshwater resources in a wider systems context. Reservoir storage water, for example, is usually committed to uses other than fish production, but fish can be stocked in these for complementary production, while making non-depletive use of water (Chapter 7).

Aquaculture producers have an interest in reducing the financial as well as the environmental costs of managing (regulating, moving and conditioning) water resources. Consequently, aquaculture farmers are generally active in trying to make more efficient use of appropriate water resources, and work hard to comply with discharge standards, whether statutory or imposed by the community. Moreover, on-farm water movement and wastewater discharge may increase the likelihood of stock escaping, resulting in

Box 8.2. Pressures inducing enhanced water use efficiency in aquaculture.

Pressures to enhance water productivity in aquaculture come from internal drives for production efficiency and management optimization, efforts to reduce risks and avoid conflict, obligations to comply with legislation and standards, and endeavours to assure consumers and bolster public perception (see Bunting, 2013).

Producers wish to limit the costs of appropriating, handling, conditioning and treating water, reduce production-enhancing resources lost from culture systems and avoid the liabilities and negative perceptions associated with discharging wastewater. Operators are conscious of the risks from disease, pests, predators and pollution that may be entrained in water appropriated for aquaculture. Water transfers and discharges increase the risk of stock escaping and causing negative environmental impacts and financial losses. Rising costs for fuel and feed, and new and emerging hazards, are prompting producers to become less reliant on externalizing technology and to adopt more extensive and diversified production strategies. Abstraction and wastewater discharges can cause negative environmental impacts and disrupt ecosystem services that sustain the livelihoods of others, thus giving rise to grievances and, potentially, to conflict. Failure to comply with legislation and standards concerning wastewater discharge standards may result in financial penalties for producers, while the imposition of charges for water use and effluent releases may prove prohibitive. Unfavourable commentary and media coverage on water use for aquaculture can result in local opposition, and negative perceptions among consumers may adversely affect demand for aquaculture products.

revenue loss and negative environmental impacts. Farmers also have an interest in reducing water intake, as this will lessen competition between various aquaculture producers, and help to avoid conflict with other water (and land) users.

In order to have marketable products, aquaculture producers must also manage animal health risks associated with their own water intake, which may be polluted, and also with the ingress of entrained aquatic organisms that may harbour pests and pathogens. Control measures adopted by farmers include screening inflows to prevent predators and other aquatic animals from entering, and restricting the abstraction of water as far as possible, depending instead on reducing stocking densities and promoting ecological processes to condition culture water for continued use.

Transition by producers to more intensive water management through mechanical pumping and aeration can further reduce dependence on the appropriation of natural water resources, but may exacerbate environmental problems associated with fuel extraction or electricity generation and greenhouse gas emissions. The comprehensive life cycle assessment (LCA) of aquaculture systems permits the identification of the least environmentally damaging production strategies. Further research and development are needed to develop practical approaches to evaluating, in concert, the environmental and social (including gender) impacts, livelihoods outcomes, financial viability, and economic and ethical implications of aquaculture developments. In the short term, these assessments could make life harder for poor aquaculture farmers, with new costs for licences, rents and taxes. In the longer term, they may benefit as stricter controls can protect the ecological status of receiving water bodies and thereby secure water resources for other and future users. This would also maintain and enhance the stocks and flows of ecosystem services. Product and livelihood diversification should be looked at as well so as to reduce dependence on aquaculture and generate more regular cash flows and higher revenues.

Water Productivity and Fisheries

Capture fisheries in lakes, rivers and wetlands present a special case for water productivity assessment, and the use of the concept is relatively new in this area. The values and livelihood benefits are high, but often ignored or underestimated (Béné *et al*., 2010). Lemoalle (2008) and Brummett *et al*. (2010) argue that the concept of water productivity cannot be extended from managed systems, including aquaculture, to natural systems, including fisheries, for the purposes of attributing relative value and prioritizing water allocation. This is because: (i) fisheries do not induce any water losses to the system other than water incorporated in the harvested product; (ii) there is a difficulty in fully parameterizing fisheries ecology models; and (iii) the water productivity concept does not sufficiently capture inherent trade-offs between different uses of water (Nguyen-Khoa *et al*., 2008). The term 'marginal water productivity', which represents the economic, social and other values lost when fisheries are affected by other developments in a watershed, is proposed as a more appropriate measure of water productivity in this system. However, the differences in benefits accrued from fisheries and agriculture, and the difficulties in determining ecosystem flows, make inter-sectoral comparisons difficult. If the objective of such a comparison is to support water allocation decisions, it needs to be acknowledged that both the water productivity and the marginal water productivity of fisheries compare poorly with the water productivity of cultivated crops (Brummett *et al*., 2010).

An additional focus needs to be put on fisheries management, which is often difficult (Andrew *et al*., 2007). Badly managed fisheries can compromise the physical integrity of aquatic environments through destructive gear use – a problem associated with the use of dredges and bottom trawls in marine environments – and through overfishing, which, ultimately, can reduce the economic value of provisioning (i.e. fish catches) and other ecosystem services.

The Role of Technologies, Policies and Institutions

Agriculture is done by people in communities and landscapes that host a variety of agroecological and socio-economic conditions. With such complexity, it is not surprising that prescribed technologies, for instance to increase water productivity, do not always work, or are abandoned by farmers who do not benefit from them (see also Chapter 9). Commonly, this is caused by inappropriate targeting of technologies (e.g. Merrey and Gebreselassie, 2011). This can be improved by considering development domains (e.g. Kruseman *et al*., 2006), which combine agricultural biophysical potential with economic and demographic factors. In addition, technological innovations are not gender neutral, and the neglect of gender and caste, class, or ethnic or religious differentiation within communities can reinforce existing inequities in access to and control over water. This can result in high environmental, health and social costs, such as chronic undernutrition, decreased yields or loss of livelihood opportunities (Zwarteveen, 1995). A bad example of such neglect comes in the case where women are the main users of water, e.g. for vegetable production, but only men are trained for the operation and maintenance of technologies – which fall under the perceived 'male domain' (Berejena *et al*., 1999).

In addition, many new technologies aimed at making water more accessible or cheaper, lead to higher water consumption and negative environmental consequences (Molden, 2007). There are many examples of upstream water users improving local productivity but utilizing so much water that little is left for downstream users (Molle *et al*., 2010). In many areas, the large growth in the use of water pumps has led to water overuse and the decline of environmental flows and groundwater tables (Shah, 2009). This problem is worse where the use of agrochemicals has resulted in poor water quality (Falkenmark and Molden, 2008; UNEP, 2010). These challenges related to improved water access illustrate the importance of the co-implementation of water resource development on the one hand and of supporting regulations and policies on the other hand, in order to preserve both the quantity and quality of water resources.

The development of water infrastructure has been identified as a key strategy towards poverty reduction (World Bank, 2008; Kandiero, 2009). Such water infrastructure developments would include water supply and sanitation systems, and dam construction, as well as investments in irrigation (World Bank, 2008). Stakeholders may need guidance on how to develop appropriate infrastructure with a view to maximizing ecosystem services and reaching an equitable share of benefits between men and women, and among different social groups. The choice that stakeholders face is not only one of whether to build or not, but also how to build and how to integrate the multiple needs, interests and perceptions of local communities. Some of the older existing infrastructure needs rehabilitation and this could be done in such a way that it not only helps to reduce poverty by providing wider and more equitable access to water, but also reduces water losses in current distribution networks, improves the overall efficiency of water use networks, and caters for the wider agroecosystem and its various functions and services. Infrastructure projects, combined with new technological advancements, can create more efficient irrigation systems that lose less water to evapotranspiration. New technology for improving water efficiency, such as drip irrigation, biotechnology advances, improved pump technology and better water practices, is already in place in many areas of high productivity, and could be implemented in areas of lower productivity too.

The economic aspects of water management interventions need to be considered as well. If the initial investment cost, the return on investment and the effect on production risk and labour inputs are unfavourable, farmers are unlikely to adopt the intervention. Many studies have investigated the economic aspects of different irrigation and drainage options (Al-Jamal *et al.*, 2001; Mintesinot *et al.*, 2004; Nistor and Lowenberg-DeBoer, 2007; Capra *et al.*, 2008; Hagos *et al.*, 2009; Amarasinghe *et al.*, 2012) and rainwater management options (Goel and Kumar, 2005; Merrey and Gebreselassie, 2011). However, generalized conclusions on the economic performance of different options are impeded by its case- and situation-specific nature.

Some solutions for improving water productivity lie outside the water sector, such as in markets, prices and subsidies, but these are hard to influence, as trade is conducted for many economic and strategic reasons, with water often last on the long list of reasons for trade (Wichelns, 2010). There are also serious questions about whether trade or food aid is a viable pathway to food security for places like sub-Saharan Africa. Some countries would rather invest their resources in utilizing their water resources better, in order to produce their own food, and aim for greater food self-sufficiency and a reduction in trade. Countries can also focus on producing crops that do not require a lot of water, such as the small grains produced in sub-Saharan Africa. The implication is that we will probably have to rely on better agricultural practices, as suggested in this chapter. Nevertheless, trade will grow in importance, both in terms of rural–urban connections and internationally, as its impact on ecosystem services at production points and at consumption locations also grows (Chapter 2). Though the negative impacts of depleted water are likely to be disconnected from consumers, pricing changes, brought about by depleted water, might eventually influence consumption patterns.

Finally, the failure of technical interventions is usually related to the neglect of the necessary underpinning policies and institutions (Merrey and Gebreselassie, 2011). For example, the root cause of the poor performance of irrigation systems is often poor governance and management, inappropriate policies and availability of inputs, and subsidies of fertilizer or output prices (Mukherji *et al.*, 2009). Simultaneously, technology development and related investments in other sectors may have far-reaching impacts on the water sector (Box 8.3; see also Chapter 2).

Bridging Scales and Water Management Concepts

A shift in thinking about water resource development and management is imperative, including bridging the strict division between rainfed and irrigated agriculture (Rockström *et al.*, 2010). It would help to think of rain as the ultimate source of water for all agro-ecosystems, and consider agricultural water management options across a wide spectrum that includes large-scale gravity irrigation, small-scale irrigation systems, provision of supplemental irrigation, use of groundwater, demand management, water harvesting techniques, soil moisture storage, and conservation and drainage. Water storage options along the continuum from soil and groundwater to

Box 8.3. The link of the water sector with renewable energy developments.

Renewable energy developments show promise for reducing both the carbon and water footprints of energy production. However, the push for renewable energy can have significant impacts on water availability through, for example, the disruption of water flows by hydropower dams and higher water consumption in the production of biofuels (UNEP, 2007). In closed basins, such as in the western USA or in much of Europe, the hydropower potential has been exhausted (WWAP, 2009), but in the developing world, more large dams are likely to be constructed. Dams change the hydrological cycle and often have negative environmental effects, including the disruption of migratory fish production (e.g. Dugan *et al.*, 2010). Conversely, renewable technologies, such as biogas and solar power, may reduce the use of water for power generation: coal uses about 2 m^3 water/MW h of electricity produced, nuclear power 2.5 m^3 and petroleum 4 m^3 (WWAP, 2009). Extracting oil also uses lots of water – up to 45 m^3/MW h from tar sands, one of the largest 'new' sources of oil (WWAP, 2009). In contrast, the increased applications for biofuel have led to high demand, with significant impacts on and trade-offs for water use, food security and agroecosystems (e.g. Berndes, 2002; de Fraiture *et al.*, 2008; FAO, 2008, 2009; Hellegers *et al.*, 2008; Bindraban *et al.*, 2009).

natural wetlands and dams can make water more accessible at different spatial and temporal scales (McCartney and Smakhtin, 2010). These scales range from field and farm to the level of large dams serving various communities, and from year-round accessibility to bridging shorter or longer dry spells (Johnston and McCartney, 2010; Merrey and Gebreselassie *et al*., 2011).

When moving between scales, the concept of water wastage can change. For example, when considering irrigation efficiencies, which usually turn out to be disappointingly low (e.g. Calzadilla *et al*., 2008, revealed a range in irrigation efficiency from 40 to 70%), one may conclude that a lot of water is wasted. However, this conclusion overlooks the fact that farmers living in or near irrigation systems in water-scarce environments make ample reuse of drainage water. Much of the 'wasted' water can be important for home gardens (Molle and Renwick, 2005), livestock (Peden *et al*., 2005), fish (Nguyen-Khoa *et al*., 2005), domestic uses leading to improved health (Boelee *et al*., 2007), or recharging aquifers. This is in line with the finding that multiple use of water by both men and women can greatly increase the total value of beneficial outputs per water unit used and hence increase productivity (Meinzen-Dick, 1997; Bouma *et al*., 2011). Multiple use of water can be considered at landscape and basin level, where water is used for various purposes, including non-provisioning ecosystem services, and either in parallel or in succession (reuse) (Gordon *et al*., 2010).

Recent basin-scale studies have demonstrated that by contrasting bright spots and hot spots, integrated water productivity assessments – bringing together crops, livestock, trees and fish – are useful means to identify tailored interventions (Ahmad and Giordano, 2010; van Breugel *et al*., 2010; Cai *et al*., 2011). At field level, crops with high water consumption such as rice can still be part of water-productive systems if their multiple agricultural (e.g. crop residues for feed), ecosystem (e.g. water flow regulation) and health (e.g. nutrition) services are taken into consideration (Matsuno *et al*., 2002; Boisvert and Chang, 2006; Nguyen-Khoa and Smith, 2008). Hence, agricultural water management needs to focus on strategies that reduce costs, while at the same time aiming for greater integration between food production systems (such as crops, trees, livestock, aquaculture and fisheries), as well as safeguarding ecosystem services (Gordon *et al*., 2010) (see Chapters 5 and 9). More water productivity gains could be made if not only food production systems, but the entire value chain, including postharvest losses, is considered (see Box 8.4).

Conclusions

Increasing the water productivity of crop, livestock and aquatic food production, while reducing social inequities and preserving the functioning of water bodies in a context of

Box 8.4. Reducing postharvest losses.

Approximately 1.3 billion t of food are lost or wasted annually, which is roughly one third of the human food produced (Gustavsson *et al.*, 2011). These losses occur mostly at the postharvest and processing levels in developing countries, and at the retail and consumer levels in industrialized countries (Gustavsson *et al.*, 2011). However, the per capita food losses in developing and industrialized countries are remarkably comparable. In sub-Saharan Africa, postharvest grain losses can amount to 10–20% of the production (World Bank *et al.*, 2011), which means that 10–20% of the inputs, including water, are wasted (Lundqvist *et al.*, 2008) as well. Therefore, reducing postharvest losses could be an effective way of achieving higher productivity (including water productivity) in agriculture (Clarke, 2004; INP*h*O, 2007). Many promising practices and technologies are available for reducing postharvest losses, including improved handling, storage and pest control (World Bank *et al.*, 2011). Incentives and public programmes are also needed to raise awareness and promote societal change in behaviour towards both a healthy diet and food waste.

increased demand for food and energy, is a real challenge. Consideration of the various ecosystem functions of irrigated and rainfed agroecosystems is essential, as is effective water governance at different scales, and attention to gender issues to help ensure sustainable and equitable use of water resources. In this chapter, the various options and solutions that are available for increasing agricultural water productivity have been reviewed. It has been demonstrated that going beyond crops, and including livestock, trees and fish in water productivity assessments, is crucial, and that many potential solutions are available. Greater awareness of these options among producers and policy makers can encourage more cost-effective water management strategies that can free up water for other uses, including ecosystem functioning.

An analysis of the effects of different options on future water demands from agriculture can be done through scenario analysis (e.g. de Fraiture and Wichelns, 2010). The inclusion of other sectors, such as livestock, fisheries, aquaculture and trees – as well as non-provisioning ecosystem services, makes it possible for such scenario analyses to contribute to a better understanding of the trade-offs between food, environment and the equitable distribution of gains (Cai *et al.*, 2011). Advances in modelling capabilities also enable impact assessments of climate change on the various components of agricultural water productivity. In addition, further research is needed on the implications of various (integrated) interventions and of improved agricultural water productivity on poverty, food security, economic growth and landscape functioning.

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