2 Land Degradation and Water Productivity in Agricultural Landscapes

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Introduction

Management of land, soil and water are intimately related and complementary to each other. Land degradation, and in particular soil quality degradation, is a major factor limiting agricultural water productivity and is often neglected in water management circles. When degradation of agricultural soil resources results in productivity declines that are more limiting than water, then water productivity declines. The best existing evaluation of the extent of soil degradation worldwide is still the Global Assessment of Land Degradation (GLASOD) by Oldeman (1991). Based on this assessment we can infer that on 50% of arable land worldwide, water productivity is below what could have been expected before degradation occurred (Wood *et al.*, 2000; see also Eswaran *et al.* (2001) for more detailed treatment of yield impacts from land degradation). Soil degradation limits water productivity in cases where absolute quantities of water are not the most limiting factor. This situation is widespread, considering that nutrients can be more limiting than water even in very dry areas, such as the Sahel (Penning de Vries and Djiteye, 1982; Breman, 1998). Addressing these constraints is critical if improvements in water productivity are to be achieved. Increasing awareness of a 'global water crisis' recognizes that the scarcity of clean water does affect food production and conservation of ecosystems. It is predicted that by 2025, most developing countries will face either physical or economic water scarcity, while at the same time global demand for food will increase (Molden, 2007). Because irrigated and rainfed agriculture is by far the largest human consumptive use of fresh water, improving the productivity of water used in agriculture can assist in increasing food production while maintaining water-related ecosystem services. Tackling human-induced degradation of agricultural lands is therefore central to addressing the 'water crisis'.

This chapter reviews a range of studies and concepts regarding options for improving water productivity through improved land management that mitigates soil degradation, and aims to highlight its importance as part of a comprehensive strategy to address global water scarcity. The focus is primarily on crop water productivity at the field scale, but the importance of taking a landscape-scale perspective when evaluating impacts of changes in water use is also discussed.

Land Degradation and Water Productivity

Soil and land degradation can be identified and described in terms of physical, chemical and biological changes from some ideal state brought about by natural or man-made influences. Soil degradation is often assessed as the amount of soil material that has been removed from a landscape by water and wind erosion, since these physical changes are obvious and quantifiable. The effects on fundamental chemical properties, soil nutrient supplies and soil biological activity are, however, often less obvious and more insidious in nature. All of these forms of degradation significantly influence water productivity in both rainfed and irrigated production systems (Table 2.1). The degree of impact will depend on the type and level of degradation.

Chemical degradation

The impact of soil chemical degradation on water productivity is predominantly direct. By reducing yields, chemical degradation reduces water productivity. One form and cause of chemical degradation is the loss of soil organic matter, which is a ubiquitous and underappreciated form of degradation. Soil organic matter (SOM) both acts as a substrate upon which the macro- and micro-flora and fauna depend, and also mediates the cycling of nutrients within ecosystems and imparts important chemical attributes to soils, such as cation exchange capacity (CEC) and buffer capacity. When ecosystems are disturbed through changed land use and continuous cultivation, the productivity of most agricultural soils declines rapidly, particularly under humid climatic conditions, due to a loss in SOM (Kang and Juo, 1986; Aweto *et al.*, 1992; Noble *et al.*, 2000, 2001), accelerated acidification (Gillman *et al.*, 1985; Noble *et al.*, 2000) and a reduction in CEC, thereby limiting the ability of the soil to hold important nutrients.

Chemical degradation, including loss of soil organic matter and nutrient depletion, is a form of degradation that has been underappreciated for decades in high-input systems, as inputs can be increased to offset the yield impacts of degradation. For example, yield declines in rice–rice systems in the Indo-Ganges plain were only recently revealed through long-term yield data analysis. These analyses showed a yield decline of 37 kg/ha/year over 20 years (Padre and Ladha, 2004). This represents a 15% decline over the study period, undetected in shorter-term studies. The decline could be reversed through the application of NPK fertilizer and farmyard manure, thus indicating that soil chemical degradation through organic matter and nutrient depletion was the primary cause of observed yield declines (see Penning de Vries, Chapter 5, this volume).

The impacts of salinization and waterlogging in irrigated systems are better appreciated. In the irrigation systems of arid and semi-arid zones, one of the largest threats to sustained agricultural production and water productivity is secondary salinization. Although data are poor, estimates indicate that 20% of irrigated land worldwide suffers from secondary saliniza-

Table 2.1. Types of soil degradation, their extent and the mechanisms for impact on water productivity.

Degradation type	Extent[a] (M of ha)	Mechanisms for impact on water productivity
Water	1093.7	Loss of topsoil reduces water-holding capacity and nutrient-holding capacity, limiting yield
Wind	548.3	Loss of topsoil reduces water-holding capacity and nutrient-holding capacity, limiting yield
Chemical	239.1	Loss of nutrients, salinization, pollution and acidification create soil conditions in many areas that are more limiting for plant growth than water
Physical	83.3	Compaction and crusting alters water cycling, and increases overland flow, erosion and unproductive evaporative losses of water

[a]Based on GLASOD (Oldeman, 1991).

tion and waterlogging (Wood *et al.*, 2000), induced by the build-up of salts introduced in irrigation water or mobilized within the soil profile. Currently, the FAO estimates that 29% of the irrigated land in six countries of the Near East had salinity problems between 1990 and 1994 (Martinez-Beltran and Manzur, 2005). In Cuba, Argentina, Mexico and Peru, 2.3 million ha were salinized between 1992 and 1998. The salinization of the irrigated areas of central Asia varies between 5.6% in the Kyrgyz Republic and 50% in Uzbekistan. In Pakistan and India 13 and 19% of the irrigated area is affected by salinity, respectively. Local estimates of yield impacts indicate a 15% reduction in wheat yields on 'green revolution' lands affected by secondary salinization in an irrigation command in northern India (Sakthivadivel *et al.*, 1999). Although it is relatively easy to link salinity to poverty, limited information is available that places a monetary value on the social and economic impacts (Ali *et al.*, 2001). Available information addresses mainly crop yield losses on salt-affected soils, revealing estimates of an annual global income loss in excess of US$12 billion (Ghassemi *et al.*, 1995).

Physical degradation

The impact of physical degradation on water productivity is mainly indirect. By interfering with the soil water balance and the ability of plants to access soil water, physical degradation reduces water productivity. Physical degradation includes soil erosion, crust formation, structural decline, compaction and waterlogging, all of which have a negative impact on yields and hence water productivity. As with chemical degradation, loss of soil organic matter is one of the primary causes of physical degradation because it is vital to the maintenance of soil structure.

Soil erosion is one of the most severe forms of soil physical degradation and results in the irreversible removal of fertile surface layers. A decrease in soil depth due to erosion will result in a loss of clay and organic matter, and thereby reduces the water-holding capacity of the soil and soil depth (Stocking, 1994). Both of these impacts will significantly reduce the productivity potential of soils and the physical attributes of the solum. Likewise, the formation of surface crusts will result in a dramatic decline in the saturated hydraulic conductivity of the soil surface, thereby impeding the intake of water into the soil profile and reducing its recharge (Nishimura *et al.*, 1990; Miller and Radcliffe, 1992). Moreover, crusts are known to inhibit the seedling emergence of crops as the crust dries out and develops its hardness (Nabi *et al.*, 2001).

As a result of compaction, the total porosity and the proportion of large pores (macropores) diminishes while the proportion of smaller pores increases (Cruse and Gupta, 1991). A decrease in porosity, with an associated increase in soil bulk density, induces an increase in the mechanical impedance of the soil, thereby limiting root proliferation (Oussible *et al.*, 1992; Dunker *et al.*, 1995). Based on field experiments using upland rice, Hasegawa and Kasubuchi (1993) illustrated the water extraction patterns of plants. When a soil profile is thoroughly wet, plants extract most soil water from shallow, densely rooted layers. With a decrease in surface-layer water content, water retained in deeper layers begins to make a larger contribution to transpiration. If a crop has a sparse root system in these deeper layers, the crop ceases to extract soil water, even though there may be sufficient soil moisture at depth. Thus, crops with a poor root distribution system are more susceptible to drought when compared with crops that do not have this limitation.

Water Scarcity

Global water scarcity analyses generally agree that a large share of the world population – up to two-thirds – will be affected by water scarcity over the next few decades (cf. Shiklomanov, 1991; Alcamo *et al.*, 1997, 2000; Raskin *et al.*, 1997; Seckler *et al.*, 1998; Vorosmarty *et al.*, 2000; Wallace, 2000; Wallace and Gregory, 2002). While views diverge as to whether or not this constitutes a 'crisis', it is clear and inescapable that as the global population grows, there will be proportionally less water available per capita, given that the resource base is more or less constant. It is often assumed that such water scarcity means that people will have insufficient water for their domestic use, but this is not necessarily the case. At a minimum water requirement per capita of 50 l/day, the annual domestic requirement is less than 20 m^3 per capita. In fact, the total amount of water required for domestic purposes is small compared with the water required for other basic needs, such as to produce their food (Rijsberman, 2006).

People require thousands of litres of water per day to produce their food, depending on their dietary and lifestyle preferences. On average, it takes roughly 70 times more water to grow food for people than people use directly for domestic purposes (cf. SIWI and IWMI, 2004). In addition, the large majority (up to 90%) of the water provided to people for domestic purposes is returned after use as wastewater and can be recycled, while most of the water (40–90%) provided to agriculture is consumed (evapotranspired) and cannot be re-used, until it falls again as precipitation.

There is broad agreement that future increases in water scarcity will turn water into a key, or the key, limiting factor in food production and livelihood generation for poor people throughout much of rural Asia and most of Africa, with particularly severe scarcity in the breadbaskets of north-west India and northern China. Competition for water is cause for considerable political tension and concern already, for example on the Euphrates and Jordan, and these tensions have little to do with domestic water demand but are driven by water demands for the agricultural sector (Phillips *et al.*, 2006). The Millennium Development Goal (MDG) target to halve the proportion of poor and hungry by 2015 will require feeding 900 million more people and improving the dietary composition of 400 million others. It is estimated that this will require a 50% increase in freshwater use in agriculture by 2015, and a doubling of freshwater consumption by 2050, if production is to keep pace with population growth (Rockström *et al.*, 2005). Analysis of future water requirements also suggests that a large proportion of this increased food production will have to be met in the rainfed agricultural sector (Rockström *et al.*, 2005), due to limitations to the continued development of irrigated agriculture. In Asia especially, new irrigation development faces increasing competition from other sectors of the economy, including industry, urban centres and the environment.

Agricultural Water Productivity

Given increasing conflicts over fresh water, and considering that the production of food is the largest consumptive user of fresh water, it is now appreciated that efforts to improve the productivity of water in agriculture can result in significant savings in water diverted or used to produce food. Agricultural water productivity can be a very broad concept, expressing the beneficial *output* per unit of water *input*, and encompassing biophysical and social aspects of the relationship between production and water use (Molden *et al.*, 2007). This concept would then have various values at different spatial scales (plant, field, farm, irrigation network, river basin and agroecological zone) and different stakeholders (farmers, system managers, policy makers). Here, we will focus on agricultural water productivity at the plant and field level, where the primary stakeholder is the farmer. Thus, we will concentrate on crop water productivity (CWP), defined as the agronomic yield per unit of water used in transpiration, evapotranspiration (ET), or applied (including precipitated) water. This concept is equally valid for irrigated and rainfed systems and thus also provides a vehicle for exploring water-use options at the basin scale, where a variety of systems and options for development exist.

Increasing agricultural water productivity can significantly reduce the total amount of water we will need in the future to produce food. Thus, agricultural water productivity estimates are an important component in scenarios that have been explored to try to estimate future water requirements. For example, under a base scenario that included optimistic assumptions on yield increases and efficiency, Seckler *et al.* (1998) estimated a 29% increase in irrigated land would be required by the year 2025 to produce enough food to feed the population. But because of gains in water productivity, the increase in water diversions to agriculture would only need to be 17%. FAO (2002a, 2003a,b) and Shiklomanov (1998) had comparable results. FAO (2002b) estimated a 34% increase in irrigated area and a

12% increase in irrigation diversions, and similarly Shiklomanov (1998) projected a 27% increase in irrigated diversions. More recently, scenarios taking into account both irrigated and rainfed agriculture projected that 30–40% more water will be used in agriculture by 2050 than is used today (De Fraiture *et al.*, 2007). This optimistic scenario was based on the assumption of balanced investments in water management in rainfed and irrigated areas, and increased water productivity. Without improved water management the overall increase is projected to be 70–90%. Because of the importance of rainfed agricultural production now and in the future, we are interested in water productivity in both irrigated and rainfed systems.

A fundamental but somewhat technical discussion is required to understand how CWP can be improved. For a given crop variety, there is a near linear relationship between plant biomass (leaves, stems, roots, grain, etc.) and transpiration (Tanner and Sinclair, 1983), depending on plant variety and climate (Steduto and Albrizio, 2005). Since the mid-1960s, breeding strategies that increase the harvest index (the proportion of grain to total biomass) have resulted in larger increases in water productivity than any other agronomic practice. These gains, however, are not based on a decrease in transpiration per unit of biomass produced, but instead on an increase in the proportion of biomass that is marketable or consumable produce (usually grain). Thus, the amount of biomass per unit transpiration has not changed through breeding strategies that increase harvest index. This illustrates the perceived 'biological imperative' that to produce more biomass, more water is required for transpiration. Given that it is now thought that the scope for further increases in harvest index seems small, even with biotechnology (Bennett, 2003), where might we identify opportunities to continue to increase water productivity in agriculture?

Understanding Land Management and Water Productivity

The difference between actual water productivity and this limit represented by plant physiology demonstrates the enormous opportunities to increase water productivity. Taking wheat as an example, Fig. 2.1 shows the significant variation that exists in CWP (Sadras and Angus, 2006). The solid line in Fig. 2.1 may represent the biological limits along which increased biomass production requires increases in water use, while most systems surveyed achieved much lower water productivity. The mechanisms to achieve improvement are related to reducing evaporative losses of water or increasing transpiration efficiency, both of which can decrease ET per unit of biomass produced, thus increasing water productivity. Both of these factors can be strongly affected by land management and soil quality. In particular, increased infiltration rates and soil water-holding capacity can reduce evaporative losses, and soil fertility improvement can increase transpiration efficiency.

Understanding a simple water balance of a typical farm helps guide an analysis of where opportunities lie to increase water productivity. Water which either falls as precipitation or is applied to any particular field can have several fates: transpiration, evaporation, storage or drainage (Fig. 2.2). Storage and drainage water can still be used productively either on-site or downstream, and is not 'lost' unless its quality declines (through, for example, being drained off into a saline aquifer). Evaporation, however, is a significant by-product of agricultural practices, and does not contribute to biomass production. Evaporation depends on climate (thus CWP is generally higher at northern latitudes with lower temperatures) and soil shading (by leaves of the crop canopy), and can thus be high in rainfed systems in the tropics, with high temperatures and low plant densities. In degraded tropical systems, evaporation is even higher, as infiltration into the soil and soil water-holding capacity are reduced, runoff is rapid and plant densities are very low. Transpired water can also be wasted if crop failure occurs after significant biomass growth. Thus, practices that reduce evaporation and prevent crop failure, such as mulching and fertilizer to increase soil water retention, plant vigour and leaf expansion can significantly increase CWP. Losses due to pests also limit harvestable yields, and hence managing these limitations can also increase water productivity.

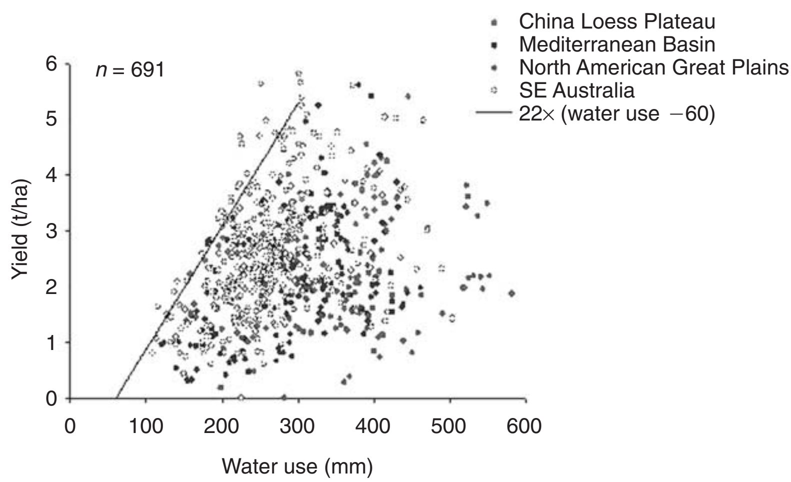

Fig. 2.1. There is a large variation between yield and evapotranspiration for wheat in different regions of the world. The solid line represents the reputed linear relationship between transpiration and yield (Sadras and Angus, 2006).

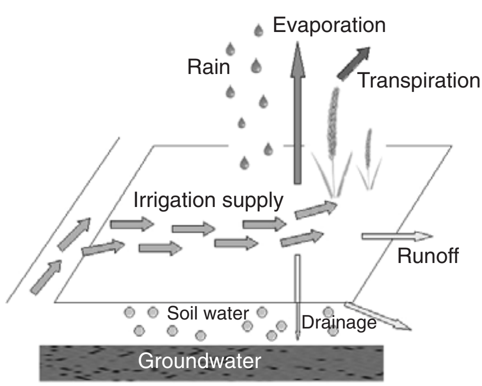

Fig. 2.2. Simple water balance of a farm (adapted from Molden *et al.*, 2007).

Transpiration efficiency – the biomass produced per unit of water transpired – is also highly dependent on soil nutrient availability. In fact, it has only recently been appreciated that the linear relationship between transpiration and biomass production only holds at a constant level of nutrient availability. Soil degradation therefore, particularly poor soil fertility, is a primary cause of low water productivity. A recent modelling study by one of us (Nangia), undertaken to understand the role of nitrogen fertilizer in enhancing water productivity, particularly highlights the role of soil nutrient availability as a determinant of water productivity. While a lot of agronomic studies have been conducted investigating crop response to nutrients and water, they were primarily aimed at understanding land productivity and not water productivity. This work, aimed at bridging this gap, concluded that more biomass and harvestable products can be produced per unit of transpired water given adequate nitrogen availability (Fig. 2.3), and that maximizing water productivity was not equivalent to maximizing land productivity. The improvement is most successful when trying to raise productivity from very low levels, such as are common in many degraded rainfed farming systems.

The Impact of Land Management on Water Productivity

The basis for understanding how much CWP can still be improved in practice is provided by a few recent reviews that have quantified CWP variability in irrigated and rainfed systems. These reviews indicate that significant improvement to CWP can be achieved. On irrigated land, Zwart and Bastiaanssen (2004) estimated the variability in WP for major crops based on measurements of actual ET on fields across five continents (Table 2.2) from 84 published studies conducted since the early 1980s. This variability, often up to threefold differences between low and high water productivity, is

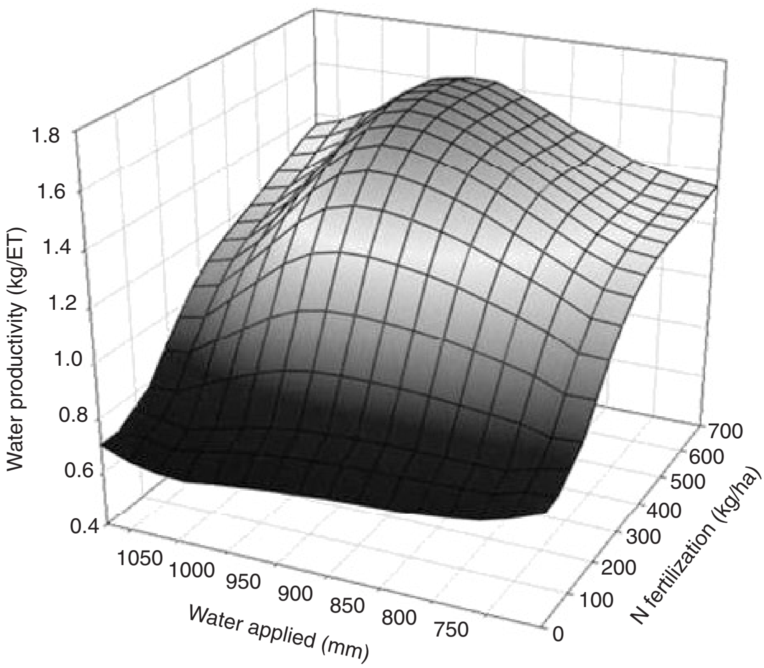

Fig. 2.3. Relationship between water productivity, water applied and N fertilization for maize crop grown at an experimental site in Gainesville, Florida.

Table 2.2. Variability in water productivity for major crops based on measurements of actual ET in fields on five continents (Zwart and Bastiaanssen, 2004).

Crop	Range in water productivity (kg/m^3)
Wheat	0.6–1.7
Rice	0.6–1.6
Cotton seed	0.41–0.95
Cotton lint	0.14–0.33
Maize	1.1–2.7

encouraging since it gives an idea of the tremendous potential that exists to increase CWP. These authors concluded that, if constraints were removed, increases of 20–40% in CWP could easily be achieved. The variation was primarily attributed to climate, irrigation water management and soil management. Similarly, Fig. 2.1 demonstrates the significant variation in CWP for wheat (Sadras and Angus, 2006). In semi-arid zones of sub-Saharan Africa Falkenmark and Rockström (2004) found CWP for maize, sorghum and millet to range from about 2.5 to 15 kg/mm water per/ha. As with Zwart and Bastiaanssen (2004), improving soil management was one of several factors identified that affect CWP.

This gap between actual water productivity and potential is largest in rainfed farming systems in semi-arid areas. Falkenmark and Rockström (2004) review the theory and data supporting the significant opportunities that exist to improve water productivity in these rainfed systems. They highlight the tremendous potential to shift from unproductive evaporative losses to productive transpiration. Figure 2.4 shows the relationship between actual CWP as measured by ET and grain produced across a large range of sites in sub-Saharan Africa. Hatfield *et al.* (2001) support this conclusion, based on an extensive review of studies that examined the potential of soil management practices alone to improve water-use efficiency. Hatfield *et al.* (2001) estimated that CWP could be increased by 25–40% through soil management practices, such as 'no till', to improve infiltration and soil water storage, and between 15 and 25% with nutrient management. Figure 2.5

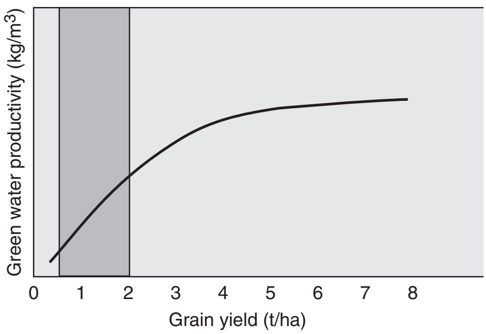

Fig. 2.4. Schematic representation of the relationship between water productivity and grain yield in rainfed farming systems in semi-arid savannahs in sub-Saharan Africa (based on Falkenmark and Rockström, 2004).

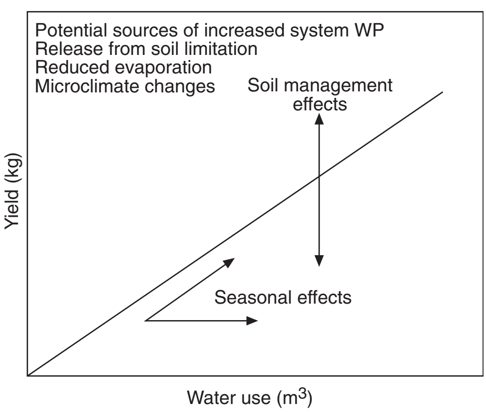

Fig. 2.5. Soil management can improve WP (adapted from Hatfield *et al.*, 2001).

summarizes the idea that, although the biological relationship between water use and biomass may be linear, soil management could significantly push the line towards increased production at the same level of water use, such as illustrated in detail for wheat (Fig. 2.1). Likewise, poor soil management and soil limitations move the line down, limiting water productivity.

In another recent review of case studies of resource-conserving agriculture projects (Pretty *et al.*, 2006), it was estimated that improvement in water productivity ranged from 70 to 100% in rainfed systems, and 15 to 30% in irrigated systems (Table 2.3). These estimates were made based on reported crop yields and average potential evapotranspiration (ETp) for each project location during the relevant growing season. Actual evapotranspiration (ETa) was assumed to equal 80% of ETp, and ETa to remain a constant at different levels of productivity. Impacts are attributed primarily to land management changes such as removing limitations on productivity by enhancing soil fertility, and reducing soil evaporation through conservation tillage. The variability was high due to the wide variety of practices represented in the dataset, but do demonstrate gains in WP are possible through the adoption of sustainable farming technologies in a variety of crops and farm systems (Bossio *et al.*, forthcoming).

A few detailed field studies from Australia, Africa and Asia serve to highlight these potential impacts. Smith *et al.*'s (2000) careful study demonstrated this shift from evaporation to transpiration as influenced by soil fertility in a

Table 2.3. Summary of changes in water productivity (WP) by major crop type arising from adoption of sustainable agricultural technologies and practices in 144 projects (adapted from Pretty *et al.*, 2006).

	kg of produce/m^3 water ETa[a]			
Crop	WP before intervention	WP after intervention	WP gain	Increase in WP (%)
Irrigated				
Rice (n = 18)	1.03 (± 0.52)	1.19 (± 0.49)	0.16 (± 0.16)	15.5
Cotton (n = 8)	0.17 (± 0.10)	0.22 (± 0.13)	0.05 (± 0.05)	29.4
Rainfed				
Cereals (n = 80)	0.47 (± 0.51)	0.80 (± 0.81)	0.33 (± 0.45)	70.2
Legumes (n = 19)	0.43 (± 0.29)	0.87 (± 0.68)	0.44 (± 0.47)	102.3
Roots and tubers (n = 14)	2.79 (± 2.72)	5.79 (± 4.04)	3.00 (± 2.43)	107.5

Standard errors in parentheses. [a] ETa, actual evapotranspiration.

rainfed wheat/lucerne production system in New South Wales, Australia. By increasing fertilizer (i.e. nitrogen) inputs, they were able to demonstrate increases in water productivity of wheat grain as measured by crop evapotranspiration from 8.4 to 14.6 kg/mm of water (Table 2.4). Some interesting trends can be gleaned from these results on improving the CWP of rainfed production systems when limited by the fertility status of the soil. In annual cropping systems, evaporation decreases and transpiration increases with increasing leaf area. As a consequence, the total amount of water consumed through the sum of evaporation and transpiration (ET) in a crop with low leaf area may be similar to that consumed in a crop with high leaf area. In this case, ET of 404 and 439 mm, respectively, was measured between these two contrasting crops. This study therefore clearly demonstrates that it is erroneous to assume that the water use of a high biomass crop will be proportionately greater than that of a low biomass crop, when leaf areas are very different (Smith *et al.*, 2000). In this case, a doubling of grain yield only required a further 35 mm of ET (less than 10% increase) (Table 2.4).

Field results from a low-yielding rainfed system in Africa (Barron and Okwach, 2005) demonstrated that water productivity could be dramatically increased and also highlighted the importance of synergistic water and nutrient management to achieve this impact on farmers' fields. Water productivity in a smallholder maize production system in semi-arid Africa was increased from 2.1 to 4.1 kg grain/mm/ha, almost a 100% increase, by using supplemental irrigation to mitigate dry spells. But this increase was only achieved when supplemental irrigation was applied in combination with nitrogen fertilizer (Barron and Okwach, 2005).

In cases where soil chemical and physical degradation is extreme, rehabilitation of degraded soils can have an even greater impact, as demonstrated in recent studies on rainfed production systems in north-east Thailand (Noble *et al.*, 2004). Sandy soils in NE Thailand have severe nutrient and carbon depletion after 40 or more years of agricultural production. Low nutrient-supplying capacity, poor water-holding capacity and the presence of a compacted layer at 20–30 cm are the dominant constraints to ensuring yield stability under rainfed conditions. Crop failure is now the norm owing to the extremely low availability of both nutrients and water. Annual precipitation is about 1100 mm, and sufficient for rainfed farming. Adding fertilizers or supplemental irrigation cannot stabilize yields, owing to the soil's very low capacity to retain water and nutrients. A novel approach of adding clay materials to these soils has ensured yield stability, as well as significantly enhancing crop yields (Noble *et al.*, 2004; Noble and Suzuki, 2005). A measure of water productivity in these studies was estimated from the biomass produced per unit of rainfall over the growing season. Water productivity increased from a mere 0.32 kg/mm under the degraded situation to 14.74 kg/mm where constraints such as low nutrient supplies and water-holding capacity were addressed through the application of clay-based materials. These dramatic results are partly attributed to a 28% increase in soil water-holding capacity (Noble and Suzuki, 2005).

Conclusion

The primary focus of this chapter has been CWP at field level and the opportunities that exist to improve CWP by mitigating soil degradation through improved land management. We have demonstrated that the potential gain in water productivity through land management interventions, particularly to improve soil

Table 2.4. Evapotanspiration (ET) for wheat in high-yielding and low-yielding agricultural systems (adapted from Smith *et al.*, 2000).

Treatment	Total biomass (t/ha)	Grain yield (t/ha)	ET (mm)	Biomass/ET (kg/mm)	Grain/ET (kg/mm)
Low-input wheat	10.8	3.4	404	26.7	8.4
High-input wheat	15.8	6.4	439	35.9	14.6

quality, is large and, we suggest, generally underappreciated. Various studies estimate that water productivity in irrigated systems could be improved by between 20 and 40%, primarily through land management approaches. In rainfed systems in developing countries, where average crop production is very low and many soils suffer from nutrient depletion, erosion and other degradation problems, potential improvement in water productivity is even higher, and may be as high as 100% in many systems. This is particularly important given that a large share of the needed increases in food production will have to come from rainfed systems.

We have emphasized the importance of reducing real losses in the water balance, such as evaporation, by improving soil physical properties, and increasing transpiration efficiency through improved nutrient management as the key entry points through which desired improvements in water productivity can be achieved. This point is particularly important in the watershed or landscape context. If increases in biomass production on site are achieved simply by using more water, without reducing unproductive losses or increasing transpiration efficiency (i.e. water productivity remains constant), this would then simply represent an increased diversion of water from runoff or deep percolation to biomass production on site. This type of diversion would be a reallocation of water that may have been valuable downstream either to maintain aquatic ecosystems or for other productive purposes in a different location. It is not necessarily an increase in water productivity at the landscape or basin scale if water is simply used in a different location. The important entry point for water productivity improvement at larger scales is to reduce real losses of water that occur through evaporation, losses to saline sinks, ineffective transpiration, or useless transpiration resulting from crop failure.

The diverse set of studies discussed above clearly demonstrate that improved land management is a very promising way to increase water productivity, particularly in low-yielding rainfed systems. To put this in perspective, the recent *Comprehensive Assessment on Water Management in Agriculture* reviewed the opportunities to improve agricultural water productivity and found that alternatives such as genetic improvements can be expected to yield only moderate water productivity improvements, although genetic improvements may play an important role in reducing the risk of crop failure (Molden *et al.*, 2007). Synergistic interventions, including improved water management and maintenance of soil quality, have the greatest potential to improve water productivity. There is every indication, therefore, that investing in the rehabilitation of degraded agricultural lands should be taken up as a priority in efforts to mitigate the 'water crisis'. There are additional gains to be had in such an intervention, including maintenance of terrestrial ecosystems, and also the preservation of aquatic ecosystems and their accompanying services, all of which are linked directly to how agricultural land is managed and maintained.

References

Alcamo, J., Doll, P., Kaspar, F. and Siebert, S. (1997) Global change and global scenarios of water use and availability: an application of WaterGAP 1.0. Center for Environmental Systems Research, University of Kassel, Kassel, Germany.

Alcamo, J., Henrichs, T. and Rosch, T. (2000) World water in 2025: global modeling and scenario analysis for the world commission on water for the 21st century. Kassel World Water Series Report No. 2. Center for Environmental Systems Research, University of Kassel, Kassel, Germany.

Ali, A.M., van Leeuwen, H.H. and Koopmans, R.K. (2001) Benefits of draining agricultural land in Egypt: results of five years monitoring of drainage effects and impacts. *Water Resources Development* 17, 633–646.

Aweto, A.O., Obe, O. and Ayanniyi, O.O. (1992) Effects of shifting and continuous cultivation of cassava (*Manihot esculenta*) intercropped with maize (*Zea mays*) on a forest alfisol in south-western Nigeria. *Journal of Agricultural Science* 118, 195–198.

Barron, J. and Okwach, G. (2005) Run-off water harvesting for dry spell mitigation in maize (*Zea mays* L.): results from on-farm research in semi-arid Kenya. *Agricultural Water Management* 74, 1–21.

Bennett, J. (2003) Opportunities for increasing water productivity of CGIAR crops through plant breeding and molecular biology. In: Kijne, J.W., Barker, R. and Molden, D. (eds) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CAB International, Wallingford, UK and International Water Management Institute, Colombo, Sri Lanka, pp. 103–126.

Bossio, D., Geheb, K. and Critchley, W. (In press) Managing water by managing land: addressing land degradation to improve water productivity and rural livelihoods. *Agricultural Water Management*.

Breman, H. (1998) Soil fertility improvement in Africa: a tool for or a by-product of sustainable production? *African Fertilizer Market* 11, 2–10.

Cruse, R.M. and Gupta, S.C. (1991) Soil compaction mechanisms and their control. In: Lal, R. and Pierce, F.J. (eds) *Soil Management for Sustainability*. Soil and Water Conservation Society, Iowa, pp. 19–24.

De Fraiture, C., Wichelns, D., Roskström, J. and Kemp-Benedict, E. (2007) Looking ahead to 2050: scenarios of alternative investment approaches. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture.* Earthscan, London and International Water Management Institute, Colombo, Sri Lanka, pp. 91–145.

Dunker, R.E., Hooks, C.L., Vance, S.L. and Darmody, R.G. (1995) Deep tillage effects on compacted surface-mined land. *Soil Science Society of America Journal* 59, 192–199.

Eswaran, H., Lal, R. and Reich, P.F. (2001) Land degradation: an overview. In: Bridges, M.E., Hannam, I.D., Oldeman, L.R., de Vries, F.W.T.P., Scherr, S.J. and Sombatpanit, S. (eds) *Response to Land Degradation*. Proceedings of the 2nd. International Conference on Land Degradation and Desertification, Khon Kaen, Thailand. Oxford Press, New Delhi, pp. 20–35.

Falkenmark, M. and Rockström, J. (2004) *Balancing Water for Humans and Nature*. Earthscan, London.

FAO (Food and Agriculture Organization) (2002a) Crops and drops: making the best use of water for agriculture. FAO, Rome.

FAO (Food and Agriculture Organization) (2002b) World agriculture: towards 2015/2030. FAO, Rome.

FAO (Food and Agriculture Organization) (2003a) Agriculture, food and water: a contribution to the World Water Development Report. FAO, Rome.

FAO (Food and Agriculture Organization) (2003b) Unlocking the water potential of agriculture. FAO, Rome.

Ghassemi, F., Jakeman, A.J., and Nix, H.A. (1995) *Salinisation of Land and Water Resources: Human Causes, Extent, Management and Case Studies*. CAB International, Wallingford, UK.

Gillman, G.P., Sinclair, D.F., Knowlton, R. and Keys, M.D. (1985) The effect on some soil chemical properties of the selective logging of a north Queensland rainforest. *Forest Ecology and Management* 12, 195–214.

Hasegawa, S. and Kasubuchi, T. (1993) Water regimes in fields with vegetation. In: Miyazaki, T. (ed.) *Water Flow in Soil*s. Marcel Dekker Inc., New York, pp. 221–253.

Hatfield, J.L., Sauer, T.J. and Prueger, J.H. (2001) Managing soils to achieve greater water use efficiency: a review. *Agronomy Journal* 93, 271–280.

Kang, B.T. and Juo, A.S.R. (1986) Effect of forest clearing on soil chemical properties and crop performance. In: Lal, R., Sanchez, P.A. and Cummings, R.W. (eds) *Land Clearing and Development in the Tropics*. A.A. Balkema, Rotterdam, the Netherlands, pp. 383–394.

Martinez-Beltran, J. and Manzur, C.L. (2005) Overview of salinity problems in the world and FAO strategies to address the problem. Proceedings of the International Salinity Forum, Riverside, California, April 2005, pp. 311–313.

Miller, W.P. and Radcliffe, D.E. (1992) Soil crusting in the southeastern U.S. In: Summer, M.E. and Stewart, B.A. (eds) *Soil Crusting: Chemical and Physical Process*. Lewis Publishers, Boca Raton, Florida, pp. 233–266.

Molden, D. (ed.) (2007) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture.* Earthscan, London and International Water Management Institute, Colombo, Sri Lanka.

Molden, D.J., Oweis, T.Y., Steduto, P., Kijne, J.W., Hanjra, A.H. and Bindraban, P.S. (2007) Pathways for increasing agricultural water productivity. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture.* Earthscan, London and International Water Management Institute, Colombo, Sri Lanka, pp. 279–310.

Nabi, G., Mullins, C.E., Montemayor, M.B. and Akhtar, M.S. (2001) Germination and emergence of irrigated cotton in Pakistan in relation to sowing depth and physical properties of the seedbed. *Soil Tillage Research* 59, 33–44.

Nishimura, T., Nakano, M. and Miyazaki, T. (1990) Effects of crust formation on soil erodibility. *Trans. JSIDRE* 146, 101–107 (in Japanese with English abstract).

Noble, A.D. and Suzuki, S. (2005) Improving the productivity of degraded cropping systems in northeast Thailand: improving farmer practices with innovative approaches. Proceedings of the Joint Meeting on Environmental Engineering in Agriculture. International Conference, Kyoto, Japan, September 2005.

Noble, A.D., Gillman, G.P. and Ruaysoongnern, S. (2000) A cation exchange index for assessing degradation of acid soil by further acidification under permanent agriculture in the tropics. *European Journal of Soil Science* 51, 233–243.

Noble, A.D., Gillman, G.P., Nath, S. and Srivastava, R.J. (2001) Changes in the surface charge characteristics of degraded soils in the tropics through the addition of beneficiated bentonite. *Australian Journal of Soil Research* 39, 991–1001.

Noble, A.D., Ruaysoongern, S., Penning de Vries, F.W.T., Hartmann, C. and Webb, M.J. (2004) Enhancing the agronomic productivity of degraded soils in northeast Thailand through clay-based interventions. In: Seng, V., Craswell, E., Fukai, S. and Fischer, K. (eds) *Water and Agriculture*. ACIAR Proceedings No. 116. Australian Centre for International Agricultural Research, Canberra, pp. 147–160.

Oldeman, L.R. (1991) (ed.). Guidelines for general assessment of the status of human-induced soil degradation. Global Assessment of Soil Degradation (GLASOD), Working Paper and Reprint No. 88/4. International Soil Reference and Information Centre, Wageningen, the Netherlands.

Oussible, M., Crookston, P.K. and Larson, W.E. (1992) Subsurface compaction reduces the root and shoot growth and grain yield of wheat. *Agronomy Journal* 84, 34–38.

Padre, A.T. and Ladha, J.K. (2004) Integrating yield trends of rice–wheat systems using the linear mixed effects model and meta-analysis. Rice–wheat Information Sheet. Issue 48. CGIAR Rice–Wheat Consortium, New Delhi.

Penning de Vries, F.W. and Djiteye, M.A. (1982) La productivité des paturages sahéliens: une étude des sols, des végétations et de l'exploitation de cette resource naturelle. Agricultural Research Report 918. Center for Agricultural Publishing and Documentation (PUDOC), Wageningen, the Netherlands.

Phillips, D., Daoudy, M., McCaffrey, S., Öyendal, J. and Turton, A. (2006) Transboundary water co-operation as a tool for conflict prevention and broader benefit sharing. Ministry for Foreign Affairs, Stockholm, Sweden.

Pretty, J., Noble, A., Bossio, D., Dixon, J., Hine, R., Penning de Vries, F. and Morison, J. (2006) Resource-conserving agriculture increases yields in developing countries. *Environmental Science and Technology* 40, 1114–1119.

Raskin, P., Gleick, P., Kirshen, P., Pontius, G. and Strzepek, K. (1997) *Water Futures: Assessment of Long-range Patterns and Prospects*. Stockholm Environment Institute, Stockholm, Sweden.

Rijsberman, F.R. (2006) Water scarcity: fact or fiction? *Agricultural Water Management* 80, 5–22.

Rockström, J., Axberg, G.N., Falkenmark, M., Lannerstad, M., Rosemarin, A., Cladwell, I., Arvidson, A. and Nordström, M. (2005) *Sustainable Pathways to Attain the Millennium Development Goals: Assessing the Key Role of Water, Energy and Sanitation*. Stockholm Environment Institute, Stockholm, Sweden.

Sadras, V.O. and Angus, J.F. (2006) Benchmarking water use efficiency of rainfed wheat in dry environments. *Australian Journal of Agricultural Research* 57, 847–856.

Sakthivadivel, R., Thiruvengadachari, S., Amerasinghe, U., Bastiaanssen W.G.M. and Molden, D. (1999) *Performance Evaluation of the Bhakra Irrigation System, India, Using Remote Sensing and GIS Techniques.* IWMI Research Report 28. International Water Management Institute, Colombo, Sri Lanka.

Seckler, D., Amarasinghe, U., Molden, D.J., de Silva, R. and Barker, R. (1998) *World Water Demand and Supply, 1990 to 2025: Scenarios and Issues.* IWMI Research Report 19. International Water Management Institute, Colombo, Sri Lanka.

Shiklomanov, I.A. (1991) The world's water resources. In: The Proceedings of an International Symposium to Commemorate 25 Years of the IHP. United Nations Educational, Scientific and Cultural Organization/International Hydrological Program, Paris.

Shiklomanov, I.A. (1998) World water resources: an appraisal for the 21st century. IHP Report. International Hydrological Program, United Nations Educational, Scientific and Cultural Organization, Paris.

SIWI (Stockholm International Water Institute) and IWMI (International Water Management Institute) (2004) *Water – More Nutrition per Drop: Towards Sustainable Food Production and Consumption Patterns in a Rapidly Changing World.* Background report for CSD12, New York, April 2004. SIWI, Stockholm, Sweden.

Smith, C.J., Dunin, F.X., Poss, R. and Angus, J.F. (2000) Nitrogen budget on wheat growing on a riverine clay soil. *Australian Journal of Agricultural Research* 51, 867–876.

Steduto, P. and Albrizio. R. (2005) Resource-use Efficiency of field-grown sunflower, sorghum, wheat and chickpea. II. Water use efficiency and comparison with radiation use efficiency. *Agricultural and Forest Meteorology* 130, 269–281.

Stocking, M. (1994) Soil erosion and conservation: a place for soil science? In: Syers, J.K. and Rimmer, D.L. (eds) *Soil Science and Sustainable Land Management in the Tropics*. CAB International, Wallingford, UK, pp. 40–58.

Tanner, C.B. and Sinclair, T.R. (1983) Efficient water use in crop production: research or re-search? In: Taylor, H.M., Jordan, W.A. and Sinclair, T.R. (eds) *Limitations to Efficient Water Use in Crop Production.* American Society of Agronomy, Madison, Wisconsin.

Vorosmarty, C.J., Green, P., Salisbury, J. and Lammers, R.B. (2000) Global water resources: vulnerability from climate change and population growth. *Science* 289, 284–288.

Wallace, J.S. (2000) Increasing agricultural water efficiency to meet future food production. *Agriculture, Ecosystems and Environment* 82, 105–119.

Wallace, J.S. and Gregory, P.J. (2002) Water resources and their use in food production. *Aquatic Sciences* 64, 363–375.

Wood, S., Sebastian, K. and Scherr, S.J. (2000) *Pilot Analysis of Global Ecosystems (PAGE): Soil Resource Condition*. IFPRI and World Resources Institute, Washington, DC, pp. 45–54.

Zwart, S.J. and Bastiaanssen, W.G.M. (2004) Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management* 69, 115–133.