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Increasing the efficiency of water use in crop production

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Abstract: Agriculture is by far the largest user of water. Increasing the use efficiency of water is essential to sustainably provide food for humans and water for maintaining natural ecosystems. The production ecological approach presented in this chapter allows us to identify constraining factors in crop production that depress use efficiency of water and to determine intervention measures. Much of the additional water needed for world food production in 2050 can be obtained by improving agronomic practices, though expansion of agricultural land to capture rainwater will be inevitable.

Key words: production ecology; water for food and nature; agriculture; water scarcity; world food

2.1 Introduction

Global dialogues about the looming water crisis have placed water scarcity problems high on the political and research agendas, because assessments of current water-related problems depict a depressing view and estimates of future demands for water suggest that billions of people will live under water-stressed conditions. Agriculture is by far the largest user of water, ranging from over 90% in various developing countries in the semi-arid regions, to some 50% in highly industrialized nations. On average, 70% of water withdrawal from natural systems is used for agriculture, 20% for industry and 10% for municipalities. Water withdrawn is not necessarily 'lost', but may be available for reuse, though generally of degraded quality. Any diversion of water from its natural course will affect ecosystems. Some rivers, for instance, do not even reach the sea anymore as their water, apart from evaporation and natural discharge to the subsurface, is completely withdrawn for human activities, creating ecological and environmental problems. Salt intrusion, water pollution, erosion, declining levels of groundwater and the drying up of lakes are phenomena that have become worse in recent decades due to the fierce competition for water. Water withdrawals remain necessary, however, for economic growth and food production in particular. It is essential, therefore, to make the most efficient use of water.

With agriculture being by far the largest user, largest gains are likely to come from this sector. The use efficiency in agriculture of water is relatively low, as a small fraction only of both irrigated water and rain water is ultimately used for transpiration, i.e. the actual physiological process in crop growth in which water is used for cooling the canopy that is heated by the incoming radiation. Large amounts of water could be saved as a means of resolving water scarcity problems, by raising the use-efficiency of water in agriculture in quantitative terms. However, gains in water use efficiency are not easy to achieve.

In this chapter, we first present and analyse the global balance of available fresh water for the production of food crops. Apart from food crops, most diets comprise animal products, which come from secondary production systems that rely on available plant products. We will simplify our analysis to plant production by integrating required plant production for animal products, such as meat. In this way we are able to assess current and future water use requirements. Then we introduce basic production ecological concepts that are essential for identifying realistic options for improving water productivity and concurrently water use efficiency. Subsequently, ways and means to enhance productivity will be elaborated, and finally, institutional arrangements to implement these options on various scales will be outlined.

2.2 Water scarcity – the global dimension

Estimates of future demands for water suggest that billions of people will live under water-stressed conditions. Many projections developed before 1980 showed near exponential increases in water requirement, but actual water withdrawals have been much lower, as has been analysed by Brown (2002). Projection studies made after 1980 have been adjusted to account for possible improvements in water productivity and forecast lower increases (Gleick, 2003). However, demands will still result in increased water withdrawal from natural systems. Current freshwater withdrawal from blue water sources approximate 4000 $km^3 y^{-1}$, which is used for irrigation, industry and domestic purposes (Gleick, 2003), with 70% or an equivalent of about 2800 $km^3 y^{-1}$ for food production. Oki and Kanae (2006) estimate 2660 $km^3 y^{-1}$ of water to be withdrawn from fresh water sources for irrigation, whereas Shiklomanov (2000) estimates 1800 $km^3 y^{-1}$. Rockström (2003) estimates 5000 $km^3 y^{-1}$ of water is needed for rain-fed agriculture, and an additional 1800 $km^3 y^{-1}$

for irrigation to meet food demand based on the current amount of caloric intake. This distinction in water supply for food production through irrigation or rainfall is essential for further considerations in search for improvement of water use efficiency.

The total amount of precipitation on terrestrial land equals 111 000 km^3 y^{-1} (Postel *et al*., 1996), which is equivalent to an average of 8536 m^3 ha^{-1} or 854 mm and is in line with the 834 mm y^{-1} estimated by Rockström and colleagues (1999). The current arable land of 1402 million hectare therefore receives approximately 11 970 km^3 of rainfall, which is similar to the value of 11 600 km^3 y^{-1} stated by Oki and Kanae (2006).

We have developed an approach to estimate current and future water use in agriculture, based on food production statistics. Goudriaan and colleagues (2001) show cereal crops to account for 60% of global carbon fixation in agriculture, followed at a far distance by oil crops (including nuts) and sugar crops, with 9% each. Combined with a productivity rate, i.e. carbon fixation per area unit per year, which is at 87% of the global average fixation rate, cereals are a good representation of global food production. For assessing global food and water requirement and for calculation of global food production we therefore follow the grain-equivalent approach, which converts non-cereal food items into grain equivalents (WRR, 1995). Diets composed of various food items can then be converted to grain equivalents, which facilitates analyses of production and consumption of food.

Current annual global cereal production (2005) is 2239 million tons which, under the above assumptions, converts to a total food production of 3732 million tons per year. The global arable acreage derived from cereals can be estimated by correction for 60% (the proportion of food produced) and 87% (the relative carbon fixation rate relative to the global average) which reaches 685.6 million hectares (current area for cereals)/0.6/0.87 = 1313 million hectares. This estimated acreage is close to the current arable land of 1402 million hectares. For the 6.4 billion people on earth in 2005, a total amount of 1600 g cereals is available per day, equivalent to 584 kg y^{-1}. This amount converts to a diet in between a vegetarian and moderate diet (see WRR, 1995).

Rockström (2003) derived an empirical relation between water productivity and yield of cereals which reveals a natural logarithmic relation. The water requirements per ton of cereals produced decreases drastically with yields increasing from 0.5 to some 2 t ha^{-1}, to gradually decline to stable equivalents of approximately 800 L per kg grain at yield levels exceeding 6–7 t ha^{-1}. By using this relationship, Rockström (2003; Fig. 2.1) estimates global water productivity for cereal crops at 1800 L kg^{-1} at a global average yield level of 2 t ha^{-1} for rainfed cereals.

Due to the non-linear nature of the relation, however, a distinction in yield classes is justified. Using the more-or-less socio-economically homogenous regions as distinguished by the United Nations and further disaggregating Europe because of large differences in cereal yield between different agro-

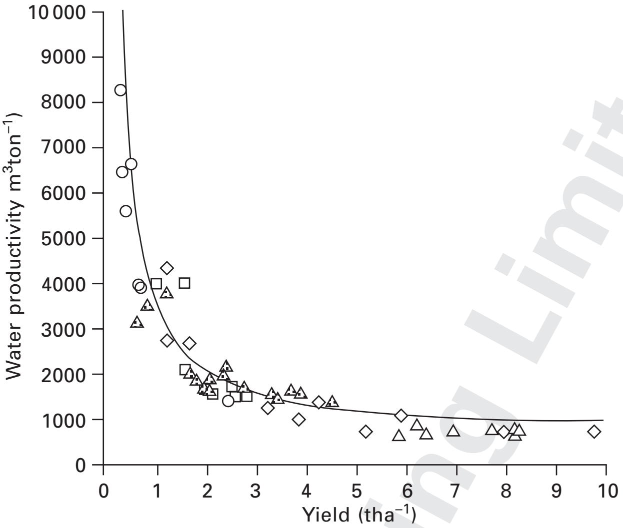

Fig. 2.1 Water productivity (m^3 ton^{-1}) in relation to yield. Data points are derived from several crops and several publications. Solid line represents WP = $WP_{(800)}$ / (1-$e^{[-bY]}$), with $WP_{(800)}$ = 800 m^3 ton^{-1} and b = –0.3 (From: Rockström, 2003).

ecological zones, water productivity is more accurately calculated for each region (Table 2.1). Current actual cereal yields are used without distinction between rainfed or irrigated cultivation (FAOstat, 2006). The highest productivity of some 900 L kg^{-1} cereal is obtained in Western Europe at yield levels of 7 t ha^{-1}, and lowest values of 3500 L kg^{-1} at yields of 0.8 t ha^{-1} in Central Africa. Based on these disaggregated values, the global weighted average water productivity is estimated at 1300 L kg^{-1}, which is much lower than the estimate of Rockström *et al.* (1999, 2003).

Water needed for the total cereal production of 3732 million tons totals 4831 km^3, which is lower than other estimates that forecast water use to reach some 7000 km^3 (Rockström, 2003; Comprehensive Assessment of Water Management in Agriculture, 2007). As we have based our estimate of water requirements using actual yield data and water productivity at field level, we assume the required amount of 4831 to 7000 km^3 y^{-1} to be composed of both irrigation and precipitation volumes. With 1800 to some 2800 km^3 y^{-1} provided by irrigation water, some 3000 to 4000 km^3 y^{-1} of water for crop growth is obtained from rainwater. When we assume that the irrigation water has been collected on non-arable land areas, an estimated 25–33% of the total precipitation falling on arable land of 11 970 km^3 y^{-1} is used by crops. The remainder of the rainwater on cropland therefore does not contribute to crop production and is 'lost' for the crop through drainage, evaporation, leaching, run-off and off-season rains. These water related-components of agricultural production systems need to be looked into for improving water-use efficiency.

Table 2.1 Water requirements for the major global regions at 2005 levels of cereal production (acreage and cereal yield data from FAOstat-agriculture, 2006)

	Actual cereal acreage (10^6 ha)	Actual cereal yield (t ha^{-1})	Cereal Volume (10^6 t)	Water productivity (L $kg^{-1} = m^3\ t^{-1}$)	Water Total (km^3)
South America	36.5	3.3	120.7	1271	153.3
Central America	13.2	2.7	35.4	1448	51.3
Caribbean	0.9	2.1	2.0	1687	3.4
Northern America	73.4	5.7	416.9	978	407.7
Northern Africa	23.8	1.6	38.1	2097	80.0
Western Africa	41.9	1.0	41.0	3142	128.8
Central Africa	6.6	0.8	5.5	3579	19.9
Eastern Africa	24.0	1.3	30.6	2518	77.1
Southern Africa	5.1	3.0	15.2	1349	20.5
Oceania	19.7	2.1	40.8	1729	70.5
Southeast Asia	52.4	3.7	192.3	1199	230.6
Eastern Asia	87.5	5.2	451.4	1016	458.6
Southern Asia	139.6	2.5	347.0	1522	528.1
Western Asia	22.2	2.2	47.9	1676	80.4
Former USSR	77.9	2.0	156.1	1771	276.5
Former DDR	21.2	3.7	78.2	1197	93.6
Southern Europe	14.8	3.8	57.0	1169	66.6
Western Europe	17.6	6.9	120.4	917	110.4
Northern Europe	7.2	5.9	42.7	964	41.2
World	685.6	3.3	2239.2	1295	2898.7

2.3 Future demand for water and food

An equivalent production of 3732 million tons of cereals for 6.4 billion people in 2005 suggests a global average diet of 1600 g grain-equivalents per person per day, which requires 760 m^3 of water per person per year at an efficiency of 1300 L water kg^{-1} grain. Gleick (2003) estimated as high as 1700–1800 m^3 water for food production per person per year for North American diets exceeding 3200 kcal p^{-1} d^{-1}, and 600–900 m^3 for African and Asian diets of 2700 kcal p^{-1} y^{-1}. Rockström *et al.* (1999) arrived at 1200 m^3 p^{-1} y^{-1} based on water productivity and agricultural production, using lower water productivity values of 1800 L water kg^{-1} grain. He estimated a water requirement of 1300 m^3 p^{-1} y^{-1} for a desired diet of 3000 kcal p^{-1} d^{-1}.

Estimating future water demand using a global average food intake that assumes a decrease in intake in wealthier nations and an increase in poorer regions may lead to regional underestimates. As current caloric intake in wealthier nations is not likely to decrease, while the intake in developing nations should reach desired healthy amounts, global average is likely to reach higher values, assumed at 3100 kcal here.

Assuming an increase in the consumption of grain equivalents to 2000 g p^{-1} d^{-1} a total of 945 m^3 p^{-1} y^{-1} water would be required without improvement in water productivity or yield (Table 2.2). The requirement would decrease to 752 m^3 at an average cereal yield level of 5 t ha^{-1}. With 9 billion people on earth, likely to be reached in 2040/2050, total water for cereal production would reach 8500 km^3 without yield improvement and 6800 km^3 at yields of 5 t ha^{-1}. When we assume the amounts of water withdrawal for irrigation to remain within the range of 1800 km^3 y^{-1} (Shiklomanov, 2000) and 2660 km^3 y^{-1} (Oki and Kanae, 2006), a total of 4000–5500 km^3 should be provided by rainwater. Also, assuming the food to be grown on the same land area of 1.4 billion hectares, in order to refrain from further clearing of natural lands, some 33–45% of the rainwater on those lands should be used as evapotranspiration. When correcting for the seasonal effect, i.e. assuming that 60% of annual precipitation is received during the growing season, the efficiency of rainwater would have to increase to 55–77%. Alternatively, expansion of agricultural land will be needed when yields cannot be raised to the required levels on the current land areas and, equally important, to collect the rainwater.

Crops may have multiple cropping seasons depending on variety, thermal conditions and water availability. Under rainfed conditions in Europe, single cropping systems cover 93.0% of the arable area, limited double cropping systems cover 6.4%, and 0.6% for double cropping systems, resulting in 1.04 crop seasons in equivalent all over Europe. In sub-Saharan Africa, 42% of arable areas are used for single cropping systems, 48% for double cropping systems, and 10% for triple cropping systems (FAO and IIASA, 2000), which is equivalent to 1.56 cropping seasons all over Sub-Saharan Africa. Using multiple cropping systems is one of the agronomic measures to increase the effective length of the growing season and thereby the amount of rainwater that can be used for crop production. This does not necessarily mean that the water use efficiency is increased.

2.4 Improving water use efficiency in agriculture

Efficiency gains in the agricultural sector are essential to meet expected demand for water. The main question is whether these efficiency gains can be attained and realized in agriculture. The relations (Fig. 2.1) described by Rockström (2003) show that efficiency gains are possible through an empirical relation that reflects actual water to yield ratios. However, this relation does not reveal the underlying mechanisms, and cannot disclose opportunities as to how efficiency gains could be achieved, except through yield increase. For a sensible assessment of the potential gains in efficiency that can be achieved in agriculture, production ecological concepts have to be used that account for eco-physiological processes in crop growth (e.g. De Wit, 1992). Often, studies that analyse how use efficiencies in agriculture can be enhanced, consider production factors in isolation (e.g. Tilman *et al.*, 2002), while the

Table 2.2 Estimated water use for different diets at three population scenarios

Diet	Current WUE	Current WUE	WUE at $Y = 5\ t\ ha^{-1}$	WUE at $Y = 5\ t\ ha^{-1}$	Population 7.5 billion	Population 9.0 billion	Population 10.0 billion
Grain Equivalents ($g\ p^{-1}\ d^{-1}$)	Water req. ($m^3\ p^{-1}\ d^{-1}$)	Water req. ($m^3\ p^{-1}\ y^{-1}$)	Water req. ($m^3\ p^{-1}\ d^{-1}$)	Water req. ($m^3\ p^{-1}\ y^{-1}$)	Water req. at WUE for $Y = 5\ t\ ha^{-1}$ ($km^3\ y^{-1}$)	Water req. at WUE for $Y = 5\ t\ ha^{-1}$ ($km^3\ y^{-1}$)	Water req. at WUE for $Y = 5\ t\ ha^{-1}$ ($km^3\ y^{-1}$)
1600	2.07	756	1.65	601	4510	5412	6014
1700	2.20	803	1.75	639	4792	5751	6390
1800	2.33	850	1.85	677	5074	6089	6766
1900	2.46	898	1.96	714	5356	6427	7141
2000	2.59	945	2.06	752	5638	6766	7517
2100	2.72	992	2.16	789	5920	7104	7893
2200	2.85	1 039	2.27	827	6202	7442	8269

combined use of resources has been shown to generate many synergistic effects in raising agricultural productivity.

To systematically search for options to enhance the water use efficiency at crop level, we apply the production ecological approach (Fig. 2.2). It provides a systematic approach that relates the physiological and agronomic dimensions of plant growth. Crops realize their potential growth as is determined by their genetic characteristics and by climatic conditions (primarily temperature, radiation, CO_2 concentration and day length), when other production factors are optimally supplied, i.e. sufficient water and nutrient are available and crops are protected against pests and diseases. Crop growth is limited under insufficient availability of water or nutrients to meet their requirements, resulting in lower yields than optimal. Crop growth is further reduced because of pest, disease and weed infestation. In the following sections of this chapter we systematically describe essential plant and field processes.

2.4.1 Plant water use

Eco-physiological processes form the fundamentals to identify whether it is technically feasible to improve water use efficiencies. There is an almost linear relation between the rate of crop photosynthesis and transpiration because of the exchange of both CO_2 and H_2O through stomata (Fig. 2.3). The physiology of this gas exchange leads to a linear relation between crop photosynthesis and transpiration. However, over 99% of the water required by plants is used for cooling by transpiration. Consequently, with stomata wide open under favourable growth conditions, much water transpires and much carbon dioxide enters the leaves, favouring the photosynthetic process

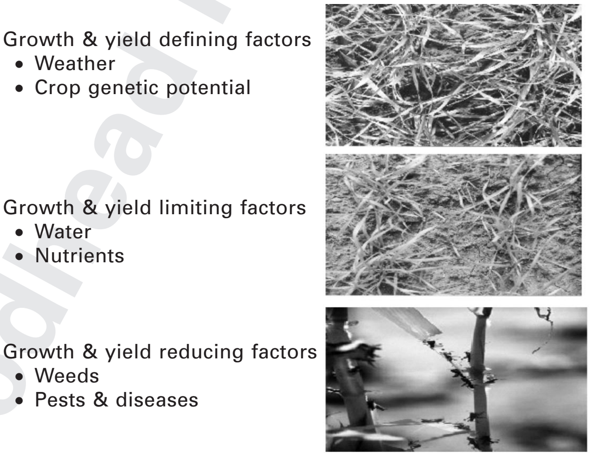

Fig. 2.2 The production ecological approach to systematically arrange production factors that affect plant growth and production (based on Rabbinge, 1993; Van Ittersum and Rabbinge, 1997).

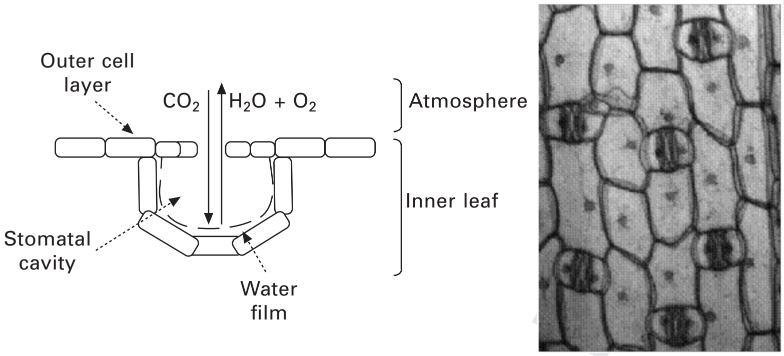

Fig. 2.3 The inflow of CO_2 and outflow of H_2O (schematically represented at the left) is controlled by stomata (right).

and plant production. At optimal rates, plants require approximately 250–300 litres of water for transpiration to produce 1 kg of organic material (Tanner and Sinclair, 1983). This linear relation is affected under extreme conditions, such as drought and low nitrogen contents of plant tissue. The leaf osmotic potential collapses during drought, suppressing photosynthetic capacity (Shimsi, 1970; Chapin III *et al.*, 1988) and because of the resulting closure of stomata (Brodribb and Holbrook, 2003). Associated high temperatures also reduce the rate of photosynthesis under these water stress conditions (Lösch, 1979; Bindraban, 1999). Under nitrogen limitation, the low leaf-chlorophyll content depresses photosynthetic capacity (Shimsi, 1970; Evans, 1983; Bindraban, 1999) while transpiration may remain unchanged, leading to an increased transpiration to photosynthesis ratio. Low nitrogen contents of plant tissue lead to an increase of abscisic acid which, in turn, induces stomatal closure (Chapin III *et al.*, 1988). Schematically, the relation between transpiration and photosynthesis appears as depicted in Fig. 2.4.

2.4.2 Water use at field scale

Cultivated lands lose water not only through transpiration by crops (Fig. 2.5), water evaporates from the bare soil because of heating by solar radiation. The larger the fraction of bare soil in a cultivation crop, the larger the loss of this ’unproductive‘ water will be. Also, water runs off the field or percolates below the rooting zone (drainage) and is lost to the crop. The consequence of the plant physiological processes and the processes at the field scale is that the efficiency of water use can be improved by optimizing agronomic measures such as ensuring the availability of sufficient nutrients and water whenever the plant needs it, and gives the incentive to look in more detail at the physiology and agronomy of plant growth for identifying options to enhance the ratio between water use and growth.

The Production Ecological Approach as developed by De Wit (1992)

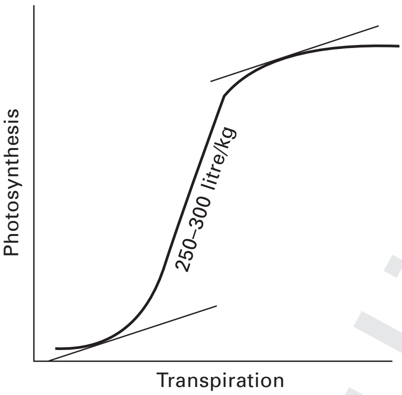

Fig. 2.4 The linear relation between transpiration and photosynthesis resulting in a constant transpiration efficiency over a wide range of growth conditions of 250–300 liters of water for the production of one kilogram of plant dry matter. Deviations occur under extreme conditions (see text).

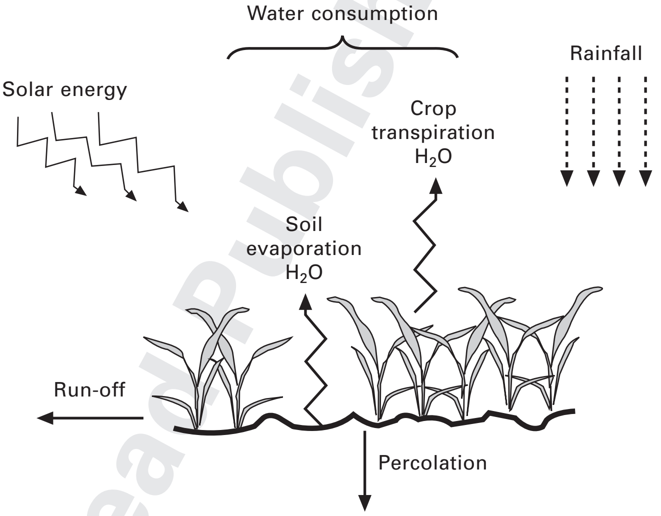

Fig. 2.5 Schematic representation of a water balance at field scale.

and colleagues (Van Ittersum and Rabbinge, 1997; Bindraban *et al.*, 2000) provides a systematic approach that relates the physiological and agronomical dimensions of plant growth (see also Fig. 2.2). The use efficiency of water under optimal growth conditions will be maximal. With insufficient water available to optimally transpire in order to cool its organs, plant growth will be limited and will decrease below the potential. Further growth limitation will occur with inadequate nutrient availability and when the crop experiences competition by weeds or it is attacked by pests and diseases. These production levels are schematically presented in Fig. 2.6, which reveals the decreasing use efficiency of water with worsening growth conditions.

In the field, the soil is exposed to radiation and the heat accelerates the evaporation process, thereby depleting soil water that is actually lost for productive crop transpiration. A range of agronomic measures can be taken to reduce this unproductive loss, such as mulching (providing an isolation layer of organic material that prevents the direct heating of the soil), zero tillage (which prevents direct opening and drying of wet soil surfaces and retains a resistant boundary layer with less favourable evaporation characteristics), and fast ground coverage by rapid closure of the crop canopy. Also, water management practices can be adjusted so as to limit evaporation loss, e.g. the timely delivery of (irrigation) water to crop or spatially more precise allocation methods, such as drip irrigation.

Water that could be available to the crop, especially rainwater, can leave the field beyond the reach of plant roots through run-off, deep infiltration (drainage) and seepage (horizontal underground soil water movement). Water engineering measures such as contour ridges or other constructions to prevent run-off and increase water storage (on various scales), lining of canals, and installation of pipes are feasible options to increase water availability to the crop.

As a result of other limiting or reducing factors, crop yields can dramatically vary at similar rainwater levels, such as has been expounded by the findings of French and Schultz (1984a,b) for Mediterranean-type climates. Figure 2.7 reveals clear maximum yield levels at a certain level of rainfall, while most observations are scattered in a vertical line below this maximum level, due to limiting factors such as nitrogen and phosphorus availability and reducing factors such as diseases that limit yield more than water availability. In addition, yield reductions occur due to delayed time of sowing, weed infestation, and waterlogging.

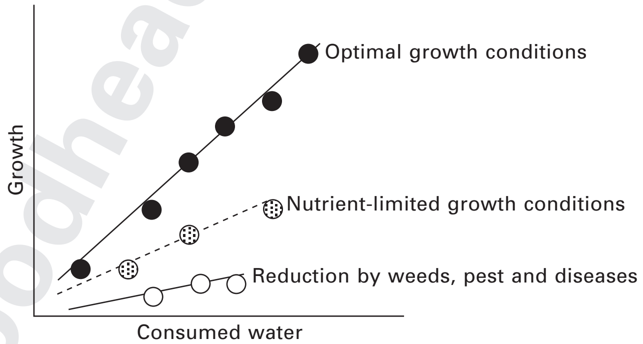

Fig. 2.6 The relation between water consumed by the plant and the amount of carbon dioxide fixed under different production conditions, revealing the decreasing use efficiency of water.

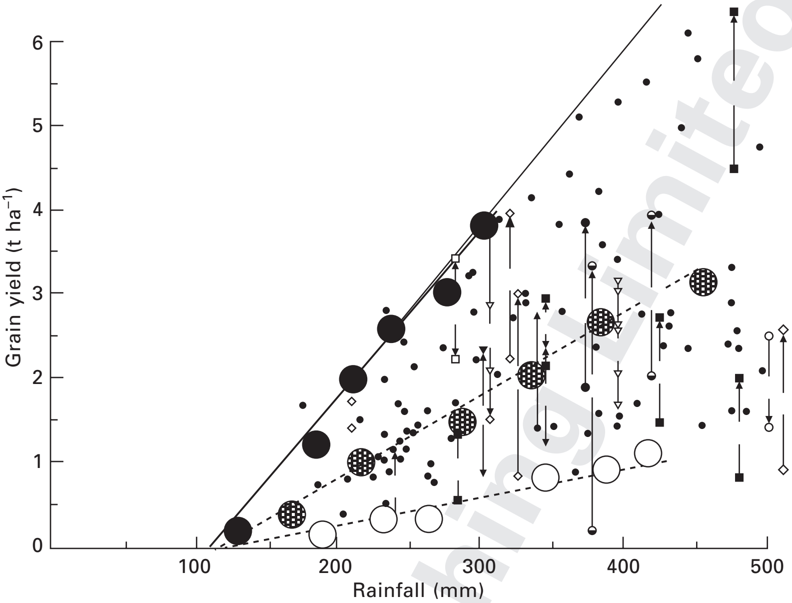

Fig. 2.7 The relation between wheat grain yield and seasonal rainfall for experimental sites and farmers' fields (From French and Schultz, 1984a). The lines and circles are an overlay of Fig. 2.6 to illustrate the applicability of the production ecological concept in explaining variation in yield.

Rockström and colleagues (2003) indeed present strong linear relations between water productivity and yield for field experiments. The largest improvement in water productivity and yield was obtained when combining supplementary irrigation with nitrogen fertilization, underlining the strong synergy between production factors. Fertilization application alone gave better improvements of water productivity than irrigation when dry spells were mild. However, crops would completely fail under heavy drought, with or without fertilization. These data indicate that full benefits of water (harvesting) for supplementary irrigation can be met only by simultaneously addressing soil-fertility management. This principle has been illustrated in Fig. 2.8. However, it should be realised that fertilizer application might also increase production risk under poor rainfall conditions, especially if these are severe enough to induce total crop failure. Additionally, plant growth might be too vigorous during the vegetative phase, using up all available water leading to a collapse in yield with failing rainfall during the reproductive phase (e.g. Fig. 2.9).

More recently, Sadras and Angus (2006) made a similar inventory that allows assessing in more detail the factors that cause low efficiencies of water use (Fig. 2.10). The straight line represents the maximum attainable water use efficiency for cereal crops. The intercept at approximately 60 mm represents evaporation. The slope of the line is equivalent to about 500 L

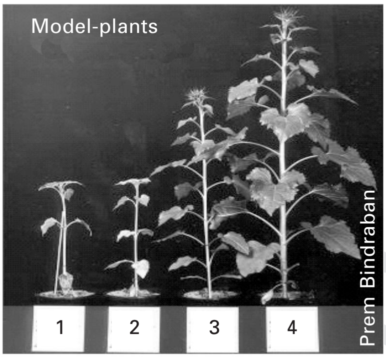

Fig. 2.8 The effect of water and nutrients on plant growth (Own experiments, P.S. Bindraban).

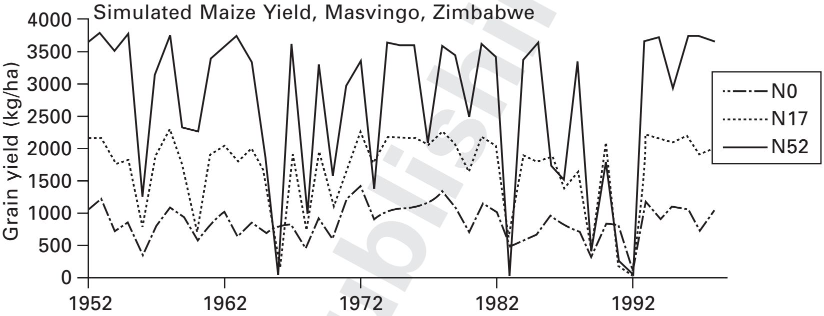

Fig. 2.9 Average yield increases with increasing fertilizer application (0,17,52 kg N ha^{-1}), but so does yield risk. Effective management of the variable rainwater is essential to reduce yield risk. Source: Twomlow *et al.*, 2008.

water per kg of grain is well in agreement with the maximum transpiration efficiency of 250–300 L kg^{-1} biomass of Fig. 2.5, as about half of the total crop biomass ends up in grains, i.e. a harvest index of 50%.

2.5 Future trends and options to increase water use efficiency

The eco-physiological processes described suggest strong interaction between production factors such as for water and nitrogen. Indeed, De Wit (1992) states that 'most production resources are used more efficiently with increasing yield levels'. Many field observations in arid and semi-arid regions indeed reveal that insufficient nutrients limited yield more than water availability, such as for eastern Africa (Smaling *et al.*, 1992; Breman *et al.*, 2001), sub-

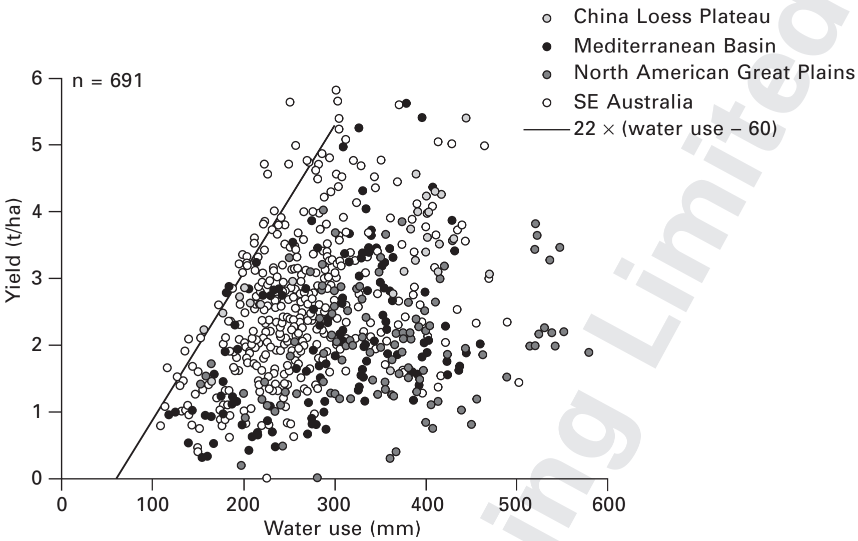

Fig. 2.10 Grain yield related to water use in crop field (Sadras and Angus, 2006). The straight line reflects the maximum attainable yield at the lowest water use and therefore represents the maximum attainable water use efficiency (here about 500 L kg^{-1}).

Saharan Africa (Rockström, 2001), southern India (Ahlawat and Rana, 1998) and western China (Li *et al*., 2001).

The production ecological approach reveals great potential for increasing the use efficiency of water in agriculture. If losses of rainwater can be reduced and the physiological efficiency can be increased through optimized agronomic measures, including fertilization, much of the required increase in efficiency of rainwater use could be attained without expansion of the agricultural area.

Following the production ecological approach, Conijn and colleagues (presented in Bindraban *et al*., 2009) showed that land productivity could be doubled or tripled in sub-Saharan Africa if rainwater was properly managed, soil nutrients precisely applied, weeds effectively controlled, and crops protected from pests and diseases. Yield increase would reduce the need for area expansion, while adverse environmental effects due to intensification could be contained within acceptable limits (Fig. 2.11). However, even such large productivity increases are unlikely to be able to supply the growing population with an adequate diet, making further area expansion of agriculture unavoidable.

Table 2.3 presents a summary of the options for increasing water use efficiencies under different agronomic conditions and which of the components of water use are tackled by these measures.

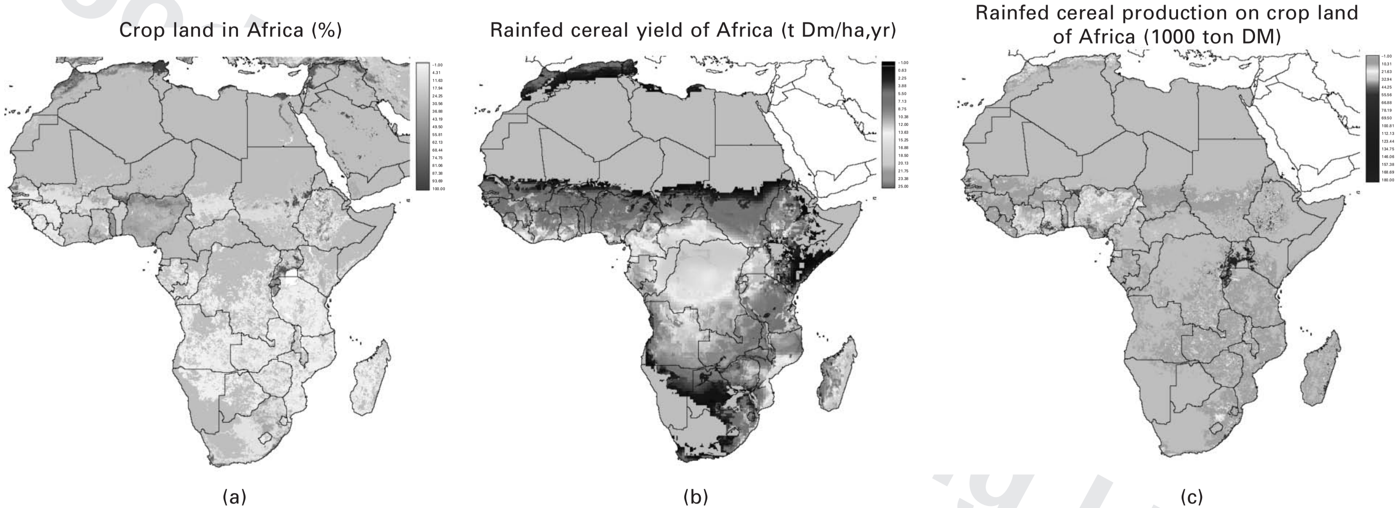

Fig. 2.11 Calculated ecological production potentials based on rainfed agriculture. A. Current distribution of agricultural land (From dark to light – decreasing fraction of grid is agricultural land). B. Maximum attainable biomass production under rainfed conditions on the entire continent. C. Production volumes on current agricultural lands (see Bindraban *et al*., 2009).

Table 2.3 Measures to increase water use efficiencies per water use component(s)

Components of water used	Agronomic conditions	Growth/ Yield	Range in water use (litre/kg biomass)	Measures to improve the efficiency of water use
Transpiration	Optimum growth conditions – no water stress, sufficient nutrients, no competition by weeds or pests and diseases. Highly controlled/closed systems (e.g. greenhouses)	High	250–300	Breeding Improving transpiration/ photosynthesis mechanisms–virtually no gains likely (Tanner and Sinclair, 1983). Improving the proportion of the biomass that is allocated to edible portion (increase Harvest Index) – limited gains (Bindraban, 1997; Bennett, 2003).
Transpiration + Evaporation	Optimum growth conditions – no water stress, sufficient nutrients, no competition by weeds or pests and diseases. Open fields.	High – Medium	300–600	*Agronomic measures* Mulching, zero tillage, fast ground cover, timely delivery to crop, precise allocation methods (drip irrigation), etc. – numerous location-specific measures feasible.
Transpiration + Evaporation + Drainage/ deep infiltration	Good growth conditions – relative excessive water supply, nutrients limitation or competition by weeds or pests and diseases may occur. Open fields.	High – Medium – Low	500–800	*Water engineering and institutional measures* Lining of canals, installation of pipes to prevent water loss – various options available. Timely and adequate supply of water to minimize drainage loss – possible through improved institutional arrangements.
Transpiration + Evaporation + Drainage/ deep infiltration + Seepage, Run-off	Good to moderate growth conditions – excessive water supply, nutrients limitation or competition by weeds or pests and diseases likely to occur. Open fields.	Low (High)*	800–2000 (5000)*	*Agronomic and water measures* In addition to all measures mentioned above, contour ridges to reduce run-off; water storage constructions at various scales are feasible to increase water availability for the crop. Improvement of agronomic measures to ensure timely and adequate supply of

Table 2.3 Continued

Components of water used	Agronomic conditions	Growth/ Yield	Range in water use (litre/kg biomass)	Measures to improve the efficiency of water use
				nutrients, and suppression of weeds and disease infestations will enhance growth.

* For inundated rice cultivation, water use may be as high at 5000 litres per kg of rice, even when growth conditions are optimal.

2.6 Conclusions

The concern for water to limit global food production in the future and to hamper the development of other economic sectors should not be taken lightly. Much emphasis is currently placed on a better distribution of available water. This might indeed alleviate immediate pressures, especially within societies and between social groups because of a fairer distribution between stakeholders. However, these delicate balances may be difficult to sustain, because of the enormous increase in demand for water for food and other amenities to meet human needs. Realizing substantial gains in water use efficiency are the most effective way out.

In general, it is assumed that increase in food production should be achieved with a proportional increase in water demand by the agricultural sector, further depleting water from natural ecosystems. However, we have shown that a substantial gain can be achieved with currently available rainwater and water that is withdrawn from natural systems for irrigation. By enhancing the productivity of agriculture ('more crop per drop') we can diminish the demand for withdrawal of additional water and for converting natural lands into agricultural lands. The resulting increase in crop yield per area unit will also decrease the need for expansion of the agricultural area. However, as the analysis for the African continent shows (Fig. 2.11), it is not likely that all the increase in water and land productivity can be realized on the current agricultural land. Realising the production potential will take decades, during which period the population will steadily increase, as well as the demand for even more food, because of improving income and increasing dietary requirements. Bindraban and colleagues (2008) showed that the rate of increase in yield of crops on the African continent is so low that it would take several decades to reach the production potentials calculated in Fig. 2.11. Therefore, expansion of the agricultural land will remain a necessity to obtain the required increase in production volume and to collect the additional water required. Both additional withdrawal of water from natural systems as well as the expansion of agricultural areas worldwide should be limited as much as possible.

2.7 References

Ahlawat, I.P.S. and Rana, D.S. (1998) Agro-techniques. In: R.L. Yadav, P. Singh, R. Prasad and I.P.S. Ahlawat. *Fifty Years of Agronomic Research in India*. Indian Society of Agronomy. New Delhi, India.

Bindraban, P., Bulte, E., Giller, K., Meinke, H., Mol, A., van Oort, P., Oosterveer, P., van Keulen, H. and Wollni, M. (2009) *Beyond competition – Pathways for Africa's Agricultural Development*, Plant Research International, Wageningen UR, Report 242.

Bindraban, P.S., Löffler, H. and Rabbinge, R. (2008) How to close the ever-widening gap of Africa's agriculture. *Int. J. Technology and Globalisation*, Vol. 4, No. 3, pp. 276–295.

Bindraban, P.S., Stoorvogel, J.J., Jansen, D.M., Vlaming, J. and Groot, J.J.R. (2000) Land quality indicators for sustainable land management: Proposed method for yield gap and soil nutrient balance. *Agriculture, Ecosystems and Environment*, 81, 103–112.

Bindraban, P.S. (1999) Impact of canopy nitrogen profile in wheat on growth. *Field Crops Research*, 63: 63–77.

Breman, H., Groot, J.J.R. and van Keulen, H. (2001) Resource limitations in Sahelian agriculture. *Global Environmental Change*, 11, 59–68.

Brodribb, T.J. and Holbrook, N.M. (2003) Stomatal closure during leaf dehydration, correlation with other leaf physiological traits. *Plant Physiol*. 132, 2166–2173.

Brown, K. (2002) Water scarcity: Forecasting the future with spotty data. *Science*, 297: 926–927.

Chapin III, S.F., Walter, C.H.S. and Clarkson, D.T. (1988) Growth response of barley and tomato to nitrogen stress and its control by abscisic acid, water relations and photosynthesis. *Biomedical and Life Sci*., 173, 352–366.

Comprehensive Assessment of Water Management in Agriculture (2007) Water for food, water for life: A comprehensive assessment of water management in agriculture. London: Earthscan, and Colombo: International Water Management Institute.

De Wit, C.T. (1992) *Resource use Efficiency in Agriculture*. *Agric Syst*., Barking, UK: Elsevier Applied Science Publishers. 1992, 40, 125–151.

Evans, J.R. (1983) Nitrogen and photosynthesis in the flag leaf of wheat. *Plant Physiol*., 72: 297–302.

FAOstat (2006) Data obtained through internet access. http://faostat.fao.org/site/567/default.aspx#ancor

FAO and IIASA (2000) *Global Agro-Ecological Zones (Global-AEZ)*. Food and Agriculture Organization of the United Nations, Rome, Italy; International Institute for Applied Systems Analysis, Laxenburg, Austria. http://www.fao.org/ag/agl/agll/gaez/tab/t39.htm;

French, R.J. and Schultz, J.E. (1984a) Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. *Australian Journal of Agricultural Research*, 35, 743–764.

French, R.J. and Schultz, J.E. (1984b) Water use efficiency of wheat in a Mediterranean-type environment. II. Some limitations to efficiency. *Australian Journal of Agricultural Research*, 35, 765–775.

Gleick, P.H. (2003) Global freshwater resources: Soft-path solutions for the 21st century. *Science*, 302: 1524–1528.

Goudriaan, J., Groot, J.J.R. and Uithol, P.W.J. (2001) Productivity of agro- ecosystems. In: Mooney, H.A. and Saugier, B. (eds.). *Physiological Ecology*. Academic Press, London.

Li, X.Y., Gong, J.D., Gao, Q.Z. and Li, F.R. (2001) Incorporation of ridge and furrow method of rainfall harvesting with mulching for crop production under semiarid conditions. *Agricultural Water Management*, 50, 173–183.

Lösch, R. (1979) Responses of stomata to environmental factors – experiments with isolated epidermal strips of *Polypodium vulgare*. *Oecologia*, 29, 85–97.0

Oki, T. and Kanae, S. (2006) Global hydrological cycles and world water resources. *Science*, 313: 1068–1072.

Postel, S.L., Daily, G.C. and Ehrlich, P.R. (1996) Human appropriation of renewable freshwater. *Science*, 271: 785–788.

Rabbinge, R. (1993) The ecological background in food production. In: *Crop Protection and Sustainable Agriculture*. John Wiley and Sons, Chichester (Ciba Foundation Symposium 177), pp. 2–29.

Rockström, J. (2001) Green water security for the food makers of tomorrow: Windows of opportunity in drought-prone savannahs. *Water Science and Technology*, 43, 71–78.

Rockström, J. (2003) Water for food and nature in drought-prone tropics: Vapour shift in rain-fed agriculture. *Phil. Trans. R. Soc. Lond*. B 358. Published on-line.

Rockström, J., Gordon, L., Folke, C., Falkenmark, M. and Engwall, M. (1999) Linkages among water vapor flows, food production, and terrestrial ecosystem services. *Conservation Ecology*, 3(2): 5. [online] URL: http://www.consecol.org/vol3/iss2/art5/

Rockström, J., Barron, J. and Fox, P. (2003) Water productivity in rain-fed agriculture: Challenges and opportunities for smallholder farmers in drought-prone tropical agroecosystems. In: Kijne, J.W., Barker R. and Molden D. (Eds.). *Water Productivity in Agriculture. Limits and Opportunities for Improvement*. CAB International, Cromwell Press, Trowbridge, U.K. pp. 145–162.

Sadras, V.O. and Angus, J.F. (2006) Benchmarking Water Use Efficiency of Rainfed Wheat in Dry Environments. *Australian Journal of Agricultural Research*, 57: 847–56.

Shiklomanov, I.A. (2000). Appraisal and assessment of world water resources. *Water International* 25: 11–32.

Shimshi, D. (1970) The effect of nitrogen supply on some indices of plant–water relations of beans (*Phaseolus vulgaris* L.). *New Phytol*. 69, 413–424.

Smaling, E.M.A., Nandwa, S.M., Prestele, H., Roetter, R. and Muchena, F.N. (1992) Yield response of maize to fertilizers and manure under different agro-ecological conditions in Kenya. *Agriculture, Ecosystems and Environment*, 41, 241–252.

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., Sinclair, T.R. (eds) *Limitations to Efficient Water Use in Crop Production*. ASA, Madison, Wisconsin, pp 1–27.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R. and Polasky, S. (2002) Agricultural sustainability and intensive production practices. *Nature*, 418, 671–677.

Twomlow, S., Mugabe, F.T., Mwale, M., Delve, R., Nanja, D., Carberry, P. and Howden, M. (2008) Building adaptive capacity to cope with increasing vulnerability due to climate change in Africa – A new approach. *Physics and Chemistry of the Earth* 33: 780–787.

Van Ittersum, M.K. and Rabbinge, R. (1997) Concepts in production ecology for analysis and quantification of agricultural input–output combinations. *Field Crops Research*, 52, 197–208.

WRR (1995) *Sustained risks: A lasting phenomenon*. Netherlands Scientific Council for Government Policy. Reports to the Government 144. The Hague, The Netherlands.