SOLAW TR07

Status of water use efficiency of main crops

SOLAW Background Thematic Report - TR07

Victor O. Sadras[1], Patricio Grassini[2] and Pasquale Steduto[3]

1 South Australian Research & Development Institute, Waite Campus, Australia
2 Department of Agronomy & Horticulture, University of Nebraska – Lincoln, United States
3 Land and Water Division, FAO, Rome, Italy

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Abbreviations and glossary

°C	Degree Celsius
E	Soil evaporation
ET	Evapotranspiration
ETo	Reference evapotranspiration
FAO	The Food and Agriculture Organization of the United Nations
ha	Hectare
ICRISAT	International Crops Research Institute for the Semi-arid Tropics
kg	Kilogram
kPa	Kilopascal (Pascal is a measure of force per unit area)
LAI	Leaf area index
MJ	Mega Joule
mm	Millimeter
N	Nitrogen
NRD	Natural Resource Districts
P	Phosphorus
R&D	Research and Development
T	Transpiration
US	United States
WP	Water productivity

Executive summary

Land and water scarcity are major constraints to food production required for meeting the quantitative and qualitative shifts of the world's demand in the mid-twenty-first century. Whereas land and water availability are constrained on a global scale, there are important regional and crop-specific differences that need to be understood, quantified and managed.

This report assesses the water productivity of the major grain crops in five case studies from environmentally, technologically and culturally diverse regions that cover the whole range from subsistence to high-tech production systems. These include: (i) rainfed wheat in the Mediterranean Basin, North American Great Plains, China Loess Plateau and southeast Australia; (ii) rainfed sunflower in central Argentina; (iii) irrigated and rainfed rice in the lower Mekong River Basin; (iv) irrigated maize in the Western Corn Belt of the United States; and (v) rainfed millet in the Sahel region of Africa. For each case study, we outline biophysical and agronomic features of the cropping system and the approach used to quantify water productivity; we compare actual productivity against relevant benchmarks, and identify opportunities for improvement.

Two complementary approaches were used. First, water productivity was calculated as a ratio, for example between yield and water use, with corresponding units of kilograms of grain per hectare per millimetre water use (kg grain ha^{-1} mm^{-1}). Second, we used the concept of boundary functions whereby yield is plotted against water use, and a line representing the maximum yield that can be achieved for a given water use is fitted. This boundary function provides a benchmark, and the gaps between the boundary function and actual yield at a given water use helps identify environmental and management constraints.

Yield per unit crop water use of wheat was analysed using data from dry environments in southeastern Australia, the North American Great Plains, China Loess Plateau and the Mediterranean Basin. Average yield per unit water use was 9.9 kg grain ha^{-1} mm^{-1} for southeastern Australia, 9.8 kg grain ha^{-1} mm^{-1} for the China Loess Plateau, 8.9 kg grain ha^{-1} mm^{-1} for the northern Great Plains of North America, 7.6 kg grain ha^{-1} mm^{-1} for the Mediterranean Basin, and 5.3 kg grain ha^{-1} mm^{-1} for the southern-central Great Plains. The variation between regions was largely accounted for by evaporative demand around flowering. For the pooled data, a common boundary function was derived with a slope of 22 kg grain ha^{-1} mm^{-1}. Few crops, however, were close to this upper limit. After accounting for the effects of atmospheric demand, the average gap between actual and maximum yield per unit water use was 68 percent for the southern Great Plains of North America, 63 percent for the Mediterranean Basin, 56 percent for China Loess Plateau, Northern Great Plains and southeast Australia. A subset of the data comprising crops in the Mallee region of southeast Australia was used to assess putative causes of under-performing crops. Low availability of phosphorus, late sowing, and subsoil chemical constraints, including sodicity, alkalinity and salinity, all contributed to low water productivity.

Adequate nutrition could improve water productivity, but unproductive soil evaporation could still be large in well-fertilized crops. Reduced row spacing, early vigour, and good supply of nutrients can favour rapid ground cover, reduce soil evaporation and hence increase water productivity. The benefits of these practices that favour rapid use of water early in the season should be weighed against the depletion of soil–water reserves for critical stages of grain set and filling. Likewise, a trade-off needs to be considered for tillage and stubble management to increase water available in the soil and to reduce soil evaporation, as these practices could increase the probability of deep drainage. Early sowing, and a greater proportion of seasonal growth in cold winter months, could enhance water productivity. There are few options for dealing with uncertain rains constraining early sowing, except for good agronomy (e.g. weed control) to allow sowing with the first rain, or genetic improvement (e.g. long coleoptiles) to allow sowing into subsurface moisture before rain. Often there are trade-offs between the yield benefits of early sowing and frost risk.

Yield per unit water supply was compiled for rainfed sunflower in commercial farms of the western Pampas, a region that comprises approximately 4.5 million ha of cropland area in semi-arid central Argentina. This case study was selected as an example of a high-tech, rainfed cropping system. Average on-farm water productivity ranged from 1.1 to 8.0 kg grain ha^{-1} mm^{-1}. A boundary function, with a slope of 9.0 kg grain ha^{-1} mm^{-1}, delimited the maximum yield over the range of water supply. This boundary function was also suitable for analysing the water productivity of rainfed and irrigated sunflower grown in other semi-arid environments including the Mediterranean Basin, the Great Plains of North America and eastern Australia. Although crops were grown under good management practices, there was a common, sizeable gap between actual yield and the boundary function for a given water use. The gaps were associated with high soil evaporation, high vapour pressure deficit and untimely water supply during the growing cycle in relation to critical crop stages. Nutrient availability and its interaction with soil water at sowing is perhaps the most important leverage point for increasing yield and water productivity. Other factors, such as diseases, weeds and lodging also require attention.

Yield per unit water use of rice in the lower Mekong River Basin was analysed at a provincial scale. The Mekong River Basin comprises 795 000 km^2 and 65 million inhabitants across six countries, that is China and Myanmar in the Upper Mekong and Laos, Thailand, Cambodia, and Vietnam in the lower Mekong, the focus of this analysis. Vietnam has two contrasting regions in the Basin, the Central Highlands and the Mekong delta. Agriculture is the most important activity in the lower Mekong and accounts for 80–90 percent of the water extracted from the river. There is a dry cropping season from November to April and a wet season from May to October. While maize, cassava and sugar cane are the main upland crops, rice is the predominant crop in the basin, and lowland rainfed rice grown in the wet season accounts for at least half of total rice production. Between 1993 and 2003, maximum yield per unit water use was 3.0 kg grain ha^{-1} mm^{-1} for Thailand, 3.3 kg grain ha^{-1} mm^{-1} for Cambodia, 5.8 kg grain ha^{-1} mm^{-1} for Laos and 7.7 kg grain ha^{-1} mm^{-1} for Vietnam. These compare with a benchmark of 22 kg grain ha^{-1} mm^{-1}.

Trends of increasing water productivity over this short-time series were observed in Laos and both the Mekong delta and Central Highland regions of Vietnam. Owing to the large share of lowland rice in these cropping systems, increasing the water productivity of rice would increase the water productivity of the whole basin. Main opportunities for improvement include using high-yielding varieties, increasing application of fertilizer, herbicides and pesticides and supplementary irrigation. High-value upland crops such as coffee, vegetables and peanuts outperform rice in terms of economic return per millimetre of water use. Increasing the share of these high-value upland crops may increase farm income per unit of water use.

Yield per unit water supply of irrigated commercial maize crops in the western US Corn Belt was analysed to highlight features of a high-input, irrigated cropping system. The Western US Corn Belt comprises about 7.3 million ha cropped to maize. Irrigated maize represents 43 percent of the total maize area, 70 percent of the total irrigated cropland in the region, and accounts for 58 percent of the total annual maize production of 60 million tonnes in the Western Corn Belt. Surface and sprinkler irrigation systems are in a 1:4 ratio of irrigated land area. Grain yield averaged 13 tonnes ha^{-1} and ranged between 9.5 to 17.2 tonnes $ha^{-1.}$ Total water supply during the growing season comprised available soil water at sowing, sowing-to-maturity rainfall, and applied irrigation in a 25:45:30 ratio. Average applied irrigation ranged from 213 to 347 mm across seasons. Water productivity of irrigated crops ranged from 8.2 to 19.4 kg mm^{-1} ha^{-1} (average: 14 kg mm^{-1} ha^{-1}). Excess irrigation was identified in almost half of the fields where crops exceeded the apparent 900 mm threshold required to maximize yield. Yield per unit irrigation ranged from 44 to 77 kg grain ha^{-1} mm^{-1} under pivot and from 28 to 42 kg grain ha^{-1} mm^{-1} under gravity. Yield per unit water supply of irrigated maize can be improved through changes to the irrigation system, irrigation management or both.

Irrigation schedules based on real-time crop requirements, soil water monitoring, and short-term forecasts appear to be sound options for increasing water productivity in current irrigated maize fields in the Western US Corn Belt. Comparison of actual and attainable yield under current management practices indicated that farmers are operating at 10–20 percent below maximum productivity. While fine-tuning current management practices (e.g. plant population density, hybrid maturity, rotation) may lead to a limited increase in yield and water productivity (< 10 percent), better management of irrigation water appears to be the most feasible way to increase water productivity. Fields under pivot, conservation tillage and maize-soybean rotation have characteristically higher yield per unit irrigation.

Yield per unit water use was compiled for millet in the western Sahel region of Africa as an example of a low-input cropping system. The Sahel is an east-west, 3 million km^2 semi-arid transition belt between the Sahara dessert and the wooded Sudanian savannah. Drought, high temperature and low soil fertility are major constraints to crop production in the region. Annual rainfall varies between 200 and 600 mm, with coefficients of variation between 15 and 30 percent. Millet is commonly grown in low fertility, sandy upland soils, which are often prone to crusting. It is grown on its own or intercropped, and residues provide valuable fodder in systems where crop and animal production are highly integrated. Variable combinations of soil evaporation, runoff and deep drainage comprise a significant unproductive component of the crop water budget.

We collected millet grain yield and water-use data from published sources, mostly from the West African Sahel generally associated with the International Crops Research Institute for the Semi-arid Tropics (ICRISAT). Data from Egypt, a more favourable African environment, and the United States, to represent higher-input cropping systems, were included in the analysis for comparison. For a collection of 58 crops in the Sahel, millet yield per unit water use averaged 3 kg grain ha^{-1} mm^{-1}. A boundary function with a slope of 16.7 kg grain ha^{-1} mm^{-1} captured the upper limit of water productivity for Sahelian millet crops. This boundary function also applied to the more favourable environments of Egypt and North America. Most millet crops under Sahelian conditions were well below this boundary function.

Environmental, management and plant-related factors contributed to the low water productivity of millet in the Sahel. Low soil fertility and sparsely sown crops mean ground cover is typically low, i.e. peak leaf area indices are normally below 1, or below 2 in more intensive systems. This in turn favours unproductive soil evaporation. Sandy soils, which are prone to crusting, favour episodic runoff and deep drainage. Indeed, a series of experimental and modelling studies converge to conclude that production in these environments is not necessarily limited by water but rather by agronomy and inputs, as there is often residual water in the soil at maturity, large unproductive losses of water are common, and nutrient stress is often more severe than water stress.

Improving water productivity of millet in dry, hot environments of Africa would require higher inputs, chiefly large fertilizer doses that need to be considered in the context of risk, trade-offs, and social, economic and infrastructure barriers for the shift to higher input agriculture. Likewise, the low harvest index of millet that contributes to its low water productivity needs to be considered in the context of a trade-off between grain production and valuable crop residues. For example, some popular landrace millet varieties in India are over 3 m tall, and are valued for the large amount of fodder they provide, even though grain yields are relatively low.

Improvement in grain yield and water productivity arise from breeding for superior varieties, better agronomic practices and the important, but often overlooked, synergy between breeding and agronomy. Long-term enhancement of yield potential with no substantial change in crop water uptake has increased the water productivity of most grain crops. Further genetic improvement in water productivity, i.e. 'more crop per drop' can contribute to improvement in yield. More likely gains, however, would derive from management practices that improved the capacity of crops to capture water.

There is an obvious need for agronomic solutions to close the common and often large gap between actual and attainable yield per unit of water use demonstrated for all five case studies in this report. Whereas genetic and agronomic solutions are not mutually exclusive, it has been argued that agronomic practices to narrow the gap between attainable and actual yield per unit water use are a more effective investment of scarce R&D funds, particularly for smallholder farmers. Moreover, the practices required to close this gap are already known for many crops and cropping systems; solutions in these cases involve efforts to provide extension, education and policy development to remove barriers to adoption of such practices.

The particular practices required to close the gap between attainable and actual yield per unit water use are specific for a given crop and cropping system, but some elements seem to be widespread such as timely sowing, effective control of weeds, arthropod pests and diseases and adequate fertilization. As a rule for winter crops, the earliest sowing compatible with frost risk would maximize grain yield and water productivity in association with favourable temperature, radiation and humidity. For crops with broad thermal adaptation such as chickpea and sunflower, massive improvement in water productivity results from shifting the growing season from spring-summer to autumn-winter, provided diseases and weeds are properly managed. Nutrient availability, particularly nitrogen and phosphorus, are critical to high yield and water productivity.

Trade-offs between water productivity and nutrient use efficiency need to be considered because maximizing water productivity in some farming systems may require nitrogen rates that are too costly, too risky or environmentally unsound. This is particularly important with high fertilizer-to-grain price ratio, in environments prone to nitrogen leaching, or where biophysical, social, economic or infrastructure factors constrain the use of fertilizer. Likewise, trade-offs between yield and water productivity, which are mediated by amount and method of water supply are common. All these trade-offs need to be considered, as the aim of improving water productivity on its own is not necessarily the best pathway to sustainability involving specific production, environmental and social targets.

Key messages

I. There is a need to close the common and often large gap between actual and attainable yield per unit water consumption.

1. Land and water scarcity are major constraints to the production of food required to meet the quantitative and qualitative shifts of the world's food demand in the mid-twenty-first century. The scarcity of these resources is further worsened by climate change. Whereas land and water availability are constrained on a global scale, there are important regional and crop-specific differences that need to be investigated, quantified, and managed. Any increase in productivity of one of these two resources will reflect positively on the productivity increase of the other.

2. Improvements in grain yield and crop water productivity arise from breeding for superior varieties, from better agronomic and water management practices and from the important, but often overlooked, synergy between breeding and agronomy. While further genetic enhancement can contribute in the medium- and long-term, on-farm best management practices will provide the most immediate and effective way to increase crop water productivity.

3. Whereas genetic and agronomic solutions are not mutually exclusive, it has been argued that agronomic practices to narrow the gap between attainable and actual yield per unit water use is a more effective investment of scarce financial resources, particularly for smallholder farmers. Moreover, the practices required to close this gap are already known for many crops and cropping systems; solutions in these cases involve efforts to modernize services to farmers (e.g. irrigation delivery systems, extension, etc.) and policy and institutional development to remove the barriers to their adoption.

II. It must be fully recognized and appreciated that beyond water management, non-water related agronomic practices also play important roles in increasing crop water productivity.

4. While the particular practices required to close the gap between attainable and actual yield per unit water use are specific to a given crop and cropping system, some are common to most cases. These are timely sowing, on-farm water management including operation and maintenance of water delivery systems for irrigated agriculture, effective control of weeds, arthropod pests and diseases and adequate fertilization.

5. Trade-offs between water productivity and nutrient requirements need to be considered carefully: maximizing water productivity in some farming systems may require nitrogen rates that are too costly, too risky, or environmentally unsound. This is particularly important with high fertilizer-to-grain price ratio, in environments prone to nitrogen leaching, or where biophysical, social, economic or infrastructure factors constrain the use of fertilizer. Likewise, trade-offs between yield and water productivity that are mediated by amount and method of water supply are common. These, and all other trade-offs need to be considered, as the aim of improving water productivity on its own is not necessarily the best pathway to sustainability as this involves specific production, environment and social targets.

III. Beyond physical crop–water productivity, there is much scope for increasing the ‘value’ per unit of water used in agriculture by designing and managing agricultural water for multiple uses.

6. Strategies for increasing the net value of water consumed in agriculture include: increasing yield, reallocating water from low to higher valued uses, lowering the costs of inputs, increasing health benefits and the value of ecological services of agriculture, decreasing social, health and environmental costs.

IV. The scope for improving crop–water productivity varies between regions, along the value chain from producer to consumer, and has a nexus with trades.

7. There are areas of the world that already exhibit high physical crop water productivity, with limited prospects for improvements using current technology. This is the case in many of the most productive areas of the world, such as the Lower Yellow River Basin, or in most of Europe, North America and Australia. The areas with the highest potential gains are sub-Saharan Africa and parts of South-, Southeast- and Central Asia.

8. There is significant ‘waste’ along the value chain from producer to consumer. The post-harvesting losses (from transport, to conservation, to processing, to packaging, to distribution, etc.) can be relevant insofar as reducing them would already allow a significant increase in water productivity when measured on the basis of production actually reaching consumers. In developing countries, produce waste is close to the beginning of the producer-consumer path, while in developed countries produce waste is close to the end.

9. While trade is driven by economic and political reasons at the global level, gains in water productivity can be achieved by growing crops in places with high water availability and trading them to places with lower water availability.

V. There is a crucial need to create order in the terminology and definitions associated with ‘efficiency’ and ‘productivity’ of water use. As scope, diagnosis and objectives of water ‘accounting’ and expected ‘saving’ may be largely misleading.

10. The term efficiency is widely used by irrigation specialists to express the ratio between water available at different points in the system. Thus ‘conveyance efficiency’ relates water delivered from a channel or system of channels to the water diverted into the channel (the excess going to spills, leakage and evaporation from the water surface). Similarly, ‘field application efficiency’ relates water delivered to the plant root zone to the total water delivered to the field (the excess typically going to runoff, percolation below the root zone, or evaporation from the wetted soil surface). Efficiency is a dimensionless ratio and its theoretical limits are between 0 and 1, or between 0 and 100 if expressed as a percentage.

11. Agronomically, efficiency is usually defined as a ratio of output-to-input. This definition does not scale in the 0-1 range. When evaluating agricultural production systems from the viewpoint of water use, the term water use efficiency refers to production per unit of water used, with units such as kg grain/ha per mm or kg/m^3 or US$/$m^3$. However the literature is full of examples where these ‘efficiency’ terms (especially the latter) are misused, or used without clear definition.

12. Recently, various analysts have proposed revised terminology that entirely avoids the word 'efficiency', thus using (i) hydrologically-based terminology (consumed and unconsumed fraction, recoverable and non-recoverable return flows) for the analysis of resource use, and (ii) productivity terms to describe the effectiveness of the system in using water to produce crops.

13. The proposed revisions in terminology are based on three separate considerations:

- First, the engineering concept of efficiency is entirely appropriate and valid when designing irrigation systems, estimating potentially irrigable areas for a given cropping pattern, and planning releases to meet field-level demands, but is misleading when water competition and scarcity beyond the boundaries of a project are under consideration (and this is increasingly the case as demand for water increases). The engineering concept of efficiency does not distinguish between water that is consumed through transpiration and evaporation and water that simply passes, unconsumed, through the system and may (or may not) be recoverable elsewhere for reuse.

- Second, when water is scarce and interventions are proposed to improve availability, it is critically important to have terminology that is consistent across sectors; so that interventions are evaluated on a common basis. For example, most interventions to improve catchment status will involve increases in consumptive use and reductions in runoff volume (albeit that the rate of runoff may be reduced and spread more usefully over time). Investments in low-flow showers and the like reduce the water used in these activities, but since consumption is close to zero the actual savings in water are minimal. Most observers, when told that irrigation efficiency can be improved from 40 to 80 percent would expect consumption to fall, and more water to be available for other uses, just as would happen if the thermal efficiency of a boiler was dramatically improved. This is not the case for irrigation and terminology based on consumption avoids this confusion. Of course there are situations when improvements in 'efficiency' are highly beneficial – when in-stream flows between offtake and drainage return points are improved; where underlying aquifers are saline, reductions in percolation are real water savings that allow increased consumptive use elsewhere.

- Third, by distinguishing clearly between hydrology and production aspects of water systems, far more clarity is possible in describing the impacts of proposed interventions.

14. Water productivity, in its broader sense, defines the ratio of the net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water consumed to produce those benefits. We can distinguish a physical water productivity, defined as the ratio of mass of product to the amount of water consumed ('more crop per drop'), and economic water productivity, defined as the 'value' derived per unit of water used. In this case the 'value' can refer to economic return or to nutrition, or more broadly to any other economic and social benefit (e.g. jobs, welfare, environment, etc.).

VI. The impact of saving measures must be carefully assessed through the application of proven scientific principles of hydrology, irrigation technology, energy balances and crop physiology that define and constrain the options available.

15. The objectives of any water conservation programme need to be rigorously specified owing to the several implications and trades-off (e.g. water vs energy or vs cost savings).

VII. While society may have the incentive to increase water productivity, agricultural producers may not. The adoption of measures to improve water productivity, either operational, technological or infrastructural, will therefore require an enabling policy and an institutional environment that aligns the incentives of producers, resource managers and society.

1. Introduction

Land and water scarcity are major constraints to the production of food required to meet the quantitative and qualitative shifts of the world's demand in the mid-twenty-first century. Whereas land and water availability are constrained on a global scale, there are important regional and crop-specific differences that need to be understood, quantified, and managed. In this context, the aim of this report is to provide an assessment of water productivity using five case studies that cover major grain crops, and a broad technological range from subsistence to high-tech production systems.

For readers less familiar with crop sciences, this report opens with definitions, and an overview of biophysical and agronomic aspects of water productivity and related concepts. Trade-offs between water productivity and nitrogen use efficiency and between water productivity and grain yield are briefly discussed to highlight the need to consider water productivity in the relevant agronomic, economic and environmental contexts.

Five case studies have been identified to present a broad spectrum of cropping systems with different climate and soils, different crops with different nutritional value and different levels of inputs. These case studies attempt to capture the peculiarities of some of the most relevant food-production regions worldwide, coupled with the availability of high-quality data. They include: (i) wheat in the Mediterranean Basin, North American Great Plains, China Loess Plateau and southeast Australia; (ii) sunflower in central Argentina; (iii) rice in the lower Mekong River Basin; (iv) maize in the Western Corn Belt of the United States; and (v) millet in the Sahel region of Africa. For each case study, we outline biophysical and agronomic features of the cropping system and the approach used to quantify water productivity; we compare actual productivities against relevant benchmarks, and identify opportunities for improvement.

In the closing section of the report, common elements to these five contrasting cropping systems are identified and general opportunities for further improvement of water productivity are proposed. Importantly, trade-offs are emphasized, as the aim of improving water productivity on its own is not necessarily the best pathway to sustainability involving specific production, environmental and social targets.

2. Definitions

In agriculture, efficiency is the relationship between output and input calculated as a ratio (output/input) or as the slope of the functional relationship (Δoutput / Δinput). Relevant outputs include crop production measured as total biomass, grain yield, or particular yield components such as oil, protein or kilocalories. Depending on the application, production can be expressed as mass (kg ha^{-1}), energy (MJ ha^{-1}) or monetary units (US$ ha^{-1}). Inputs include water, nutrients, radiation, fossil energy, labour and capital. Whereas the particular definition of efficiency used depends on the application and data availability, the multitude of possible combinations of outputs and inputs makes explicit definitions highly recommendable.

In the context of water resources, efficiency of water use was originally used from the viewpoint of engineering and irrigation. For example, the ratio between output and input is used to account for conveyance efficiency from the water abstraction point to the scheme or application efficiency in the field. Such expression is dimensionless, as both output and input are water volumes, and ranges from 0 to 1. The Food and Agriculture Organization of the United Nations (FAO) has therefore proposed to reserve 'efficiency' for engineering applications and 'water productivity' for agricultural ratios such as yield per unit evapotranspiration or yield per unit water supply (see Key Messages for further references).

3. Climate and plant factors affecting water productivity

Agronomically, water productivity (WP) is defined in terms of crop grain yield and seasonal evapotranspiration, and is conveniently disaggregated in the following components (1)

$$WP = \frac{WP_{B/T}}{1 + \frac{E}{T}} \times HI \qquad (1)$$

where WPB/T is shoot biomass per unit seasonal crop transpiration, T is crop transpiration, E is evaporation from the soil surface or from the ponded water layer in flooded rice, and HI is harvest index. This expression is useful to understand drivers, constraints and opportunities for improvement of water productivity. With reference to equation (1), here we briefly describe the effects of climate factors with emphasis on evaporative demand of the atmosphere and rainfall patterns, and summarize the main plant factors influencing water productivity.

Evaporative demand of the atmosphere

The evaporative demand of the atmosphere is substantially driven by the vapour pressure deficit and net radiation. The biological roots of the inverse relationship between biomass per unit transpiration and vapour pressure deficit are well established (2). Under isothermal conditions of the atmosphere (i.e. no change in temperature with height above the crop), the evaporative demand of the atmosphere is essentially driven by net radiation, a circumstance indicated as equilibrium evaporation. The variability in space and time of the dominant drivers of evaporative demand have lead to suggest the use of reference evapotranspiration (ETo) as a better normalization factor than vapour pressure deficit (6a and 6b).

An important agronomic corollary considering the space and time variability of the evaporative demand is that early sowing of annual crops, when vapour pressure deficit and evaporative demand are typically lower, favours biomass production per unit transpiration, and this often translates to yield per unit evapotranspiration as illustrated for barley in North America (3) and wheat in Australia (7). Water productivity was increased substantially by shifting from spring to winter sowing of chickpea and sunflower in Mediterranean environments (8, 9). Hence, locations, seasons and sowing dates conducive to low evaporative demand of the atmosphere often enhance yield per unit evapotranspiration.

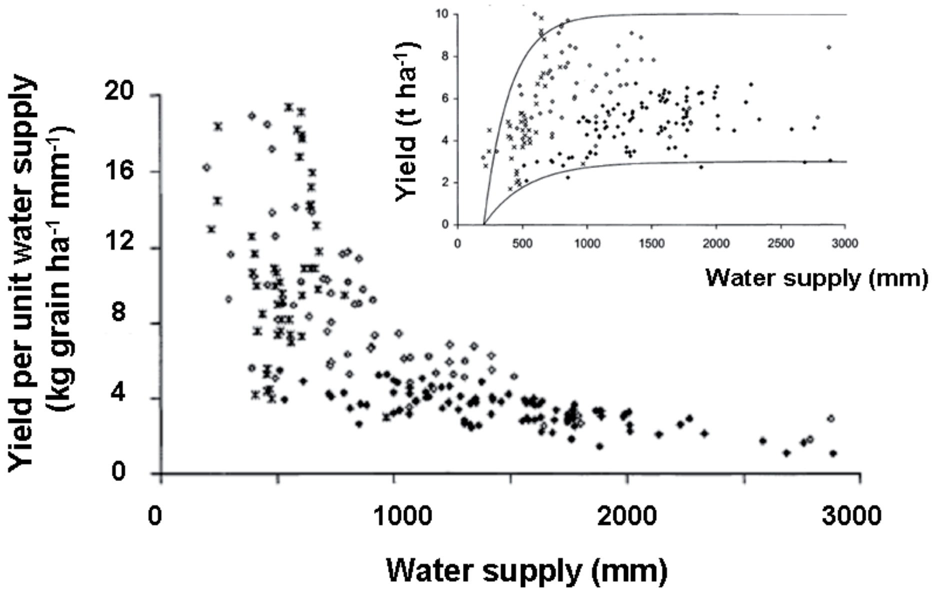
Rainfall pattern

Amount, season, size and timing of rainfall events all affect water productivity. The relationship between yield and water supply typically conforms to the law of diminishing returns, hence the decline in water productivity with increasing water supply, as illustrated in Figure 1. In addition to the inherent decline in water productivity with increasing water supply, excess water can have deleterious effects such as yield and quality reduction associated with waterlogging, favourable conditions for diseases, and leaching of nutrients and agrochemicals.

For a given amount of rainfall, the season has important implications. In general, crops grown on stored soil water have a lower E/T ratio (Equation 1) that favours yield per unit evapotranspiration in comparison with crops that rely on in-season rainfall. For a given amount and seasonality of rainfall, dominance of small events increases unproductive soil evaporation whereas dominance of large events favours unproductive runoff and deep drainage (10). For example, modelled median soil evaporation of wheat in eastern Australia ranges from 172 mm in environments where crops rely on in-season rainfall dominated by small rainfall events to 70 mm for crops that rely on stored soil water and large rainfall events (11).

Timing of rainfall affects water productivity by primarily affecting grain set and size and harvest index. The proportionality between water productivity and harvest index (equation 1) has been demonstrated for rice, maize, sorghum, wheat, sunflower and cotton (12). Critical developmental windows, when crop yield is more sensitive to stress, are broadly from late stem elongation to early post-flowering in wheat, from early stem elongation to flowering in barley, two weeks before full heading in rice, from initial bloom to the beginning of seed filling in soybean, from floral initiation to 20 days after flowering in sunflower, the active period of ear elongation in maize, and from the beginning of flowering to the beginning of seed fill for the last seed-bearing node in field peas. Hence, rainfall or irrigation events at this species-specific critical window of grain yield determination generally improve harvest index, yield and yield per unit evapotranspiration. Exceptions to the positive effect of rain during this critical stage could arise if rainfall is associated with persistent low radiation and conditions favouring diseases.

FIGURE 1: INVERSE RELATIONSHIP BETWEEN YIELD PER UNIT WATER SUPPLY AND WATER SUPPLY IN RICE. WATER SUPPLY IS SEASONAL IRRIGATION PLUS EFFECTIVE RAINFALL. INSET SHOWS THE RELATIONSHIP BETWEEN YIELD AND WATER SUPPLY; LINES ARE FITTED BOUNDARY FUNCTIONS



Adapted from (81).

Other climate factors

Vapour pressure deficit increases exponentially with temperature; hence high temperature, and associated high vapour pressure deficit, would reduce biomass per unit transpiration and yield per unit seasonal evapotranspiration. High temperature accelerates plant development and this effect is particularly important in the species-specific critical window when grain number and potential grain size are determined (13). Grain number of annual crops is indeed proportional to a photothermal quotient defined as the ratio between intercepted radiation and temperature (14, 15). High photothermal quotient favours harvest index and hence higher yield per unit seasonal evapotranspiration. Short, untimely episodes of extreme temperatures, i.e. frost or heat in the window of grain set and potential grain size determination, can reduce harvest index and yield with little impact on water use, hence decreasing yield per unit seasonal evapotranspiration.

Plant factors

The metabolic pathway of photosynthesis (C4 vs C3) and crop-specific seed composition are the two most important plant factors affecting yield per unit seasonal evapotranspiration. The trade-off between leaf photosynthesis and water loss is inherently higher in C4 crops. This difference is reflected in the higher yield per unit seasonal transpiration of maize and sorghum compared with their C3 counterparts (Table 1). Millet, a C4 crop, has biomass per unit transpiration similar to sorghum but its low harvest index leads to yield per unit evapotranspiration closer to that of C3 crops, as discussed in Section 6.5.

The conversion efficiency of sugar into grain ranks cereals > pulses > oilseeds. This reflects the differences in energy content of the seed: 1 g of starch (dominant component of cereal grain) requires 1.2 g of raw sugar, 1 g of protein as in pulses requires 1.62 g of sugar and 1 g of fat as in oilseeds requires 2.7 g of sugar. A plant can therefore produce twice as much starch as fat using the same amount of raw sugar from photosynthesis. This partially explains the large difference in water productivity of cereal, oilseed and pulse crops (Table 1).

TABLE 1: MAXIMUM YIELD PER UNIT SEASONAL TRANSPIRATION AND EXAMPLES OF REPORTED YIELD PER UNIT SEASONAL EVAPOTRANSPIRATION FOR MAJOR ANNUAL CROPS. YIELD PER UNIT SEASONAL TRANSPIRATION IS CALCULATED AS THE RATIO BETWEEN GRAIN YIELD AND SEASONAL TRANSPIRATION OR THE SLOPE OF BOUNDARY FUNCTION RELATING GRAIN YIELD AND SEASONAL EVAPOTRANSPIRATION

Crop	Yield: transpiration (kg grain ha^{-1} mm^{-1})	Yield: evapotranspiration (kg grain ha^{-1} mm^{-1})	
		Irrigated	Dryland
Cereals			
Maize (C4)	30–37	11–32	6–23
Sorghum (C4)	20–30	3–22	5–21
Millet (C4)	17		1–12
Wheat (C3)	20–22	6–17	5–10
Rice (C3)	15–22	7–11	2–8
Oilseeds & pulses			
Soybean	8–9	6–9	6–10
Sunflower	7–9	4–9	3–5
Cotton	9 (seed)	4–9 (seed) 1–3 (lint)	
Winter oilseeds (Brassica spp)	12–15		1–8
Winter pulses (faba bean, chickpea, lentil, lupin)	9–20	3–8	2–16

Source: maize: section 6.4 in this report; grain sorghum (60-65), millet: Section 6.5 in this report; wheat: section 6.1 in this report and (66)], rice: section 6.3 in this report and (66), soybean (67-69), sunflower: section 6.2 in this report, cotton (66), winter oilseeds (70-72), winter pulses (8, 73-78).

4. Effects of nitrogen supply on water productivity

Nitrogen deficit reduces yield per unit evapotranspiration by potentially affecting all three components in equation 1, i.e. biomass per unit transpiration, E/T and HI. Firstly, nitrogen deficiency reduces photosynthesis; hence biomass per unit transpiration is reduced. Brueck (16) compiled the response of biomass per unit transpiration to nitrogen supply for all major crop species. Secondly, nitrogen deficiency reduces canopy size and increases the E/T ratio. Cooper *et al.* (1) demonstrated the improvement in yield per unit evapotranspiration associated with nitrogen and phosphorous fertilization in low-fertility soils of west Asia and north Africa, and emphasized the reduction in E/T. Thirdly, nitrogen deficiency could reduce harvest index.

Ensuring adequate nitrogen supply is therefore critical for high yield per unit evapotranspiration. However, there is a nitrogen-driven trade-off between water productivity and efficiency of nitrogen use that needs to be considered, as outlined in the following section.

5. Improving water productivity: recognizing trade-offs

Breeding and management practices to improve water productivity can involve important trade-offs. For example, breeding to improve short-term leaf carbon assimilation per unit transpiration may lead to selection for traits associated with reduced water uptake, with the net effect of reducing yield under drought (20). The genotype-driven trade-off between leaf carbon assimilation per unit transpiration and tolerance to high temperature is well established in wheat, cotton, rice and grapevine. In this section, we present two examples of trade-offs: between efficiency in the use of water and nitrogen, as related to nitrogen supply, and between water productivity and yield of rice, as related to water regime.

Nitrogen-driven trade-off between water productivity and efficiency of nitrogen use

On the one hand, high water productivity requires adequate nitrogen supply (Section 4). On the other hand, the relationship between yield and nitrogen supply conforms to the law of diminishing returns, and therefore nitrogen use efficiency declines with increasing nitrogen supply. The effect of individual inputs such as water and nitrogen on the carbon, water and nitrogen budgets of crops thus determines a nitrogen-driven trade-off between water productivity and nitrogen use efficiency. This is illustrated for both aerobic and flooded rice in the Philippines (Figure 2ab) and rainfed and irrigated maize in the United States (Figure 2cd). Empirical evidence for the nitrogen-driven trade-off between water productivity and nitrogen use efficiency at leaf and crop levels can also be found for wheat (21), maize (22) and perennial grasses in semi-arid grasslands of China (23).

The rainfall pattern of Mediterranean climates imposes an inherent risk on the use of fertilizer which, associated with low fertility soils, often results in a nitrogen imposed ceiling for water productivity (24, 25). Indeed, water and nitrogen co-limit wheat yield in Mediterranean type environments of eastern Australia (26) and northeastern Spain (27). In Mediterranean climates of West Asia and North Africa, the constraint to using fertilizer is imposed by uncertain rainfall compounded by infrastructure, social and economic factors (28), which are common to many farming systems in temperate and tropical Asia (29).

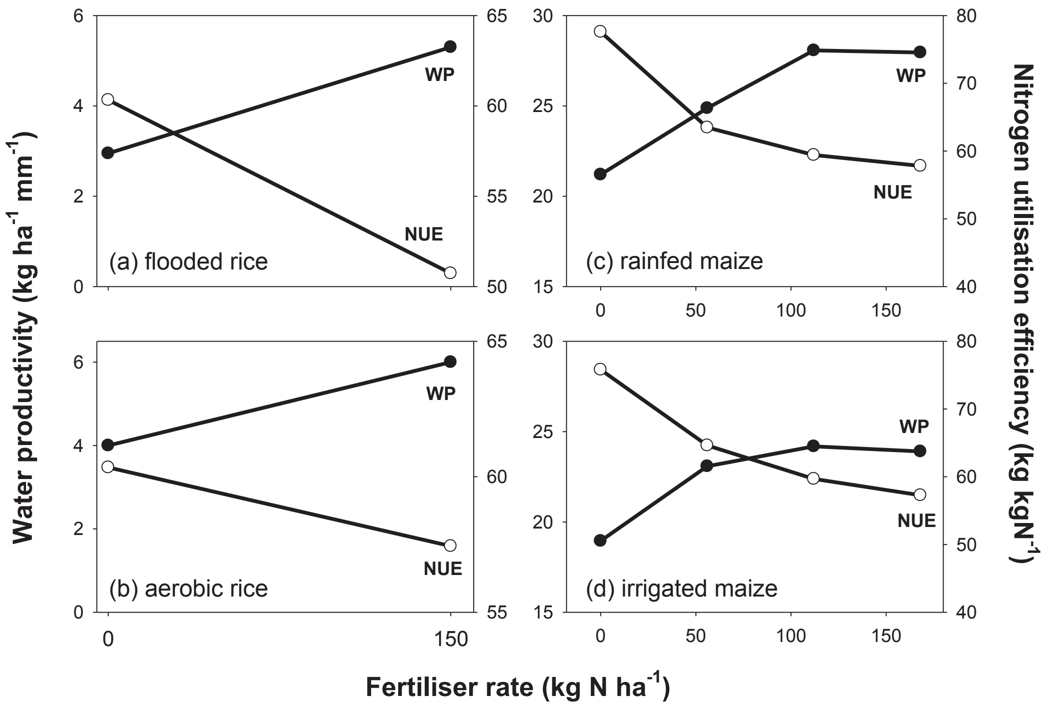
In conclusion, maximizing water productivity in some farming systems may require nitrogen rates that are too costly, too risky or environmentally unsound. This is particularly important with high fertilizer-to-grain price ratio, in environments prone to nitrogen leaching, or where biophysical, social, economic or infrastructure factors limit the use of fertilizer.

Water-regime driven trade-off between rice yield and water productivity

Bouman *et al.* (30) and Farooq *et al.* (31) comprehensively reviewed the water productivity of rice. About 90 percent of the world's rice is produced in irrigated or rainfed lowland fields (paddies). Lowland rice needs to account for land preparation requirements, seepage, percolation, evaporation and transpiration. Combined seepage and percolation, for example, range from 1–5 mm d^{-1} in heavy clay soils to a massive 25–30 mm d^{-1} in sandy and sandy-loam soils (30). In a context of water scarcity, water-saving technologies are being explored to reduce water use and improve water productivity, including aerobic rice and alternate wetting and drying. The principle underlying these techniques is the increase in water productivity associated with reduced water input (Figure 1). However, water-saving techniques can also reduce grain yield.

Comparison of rice crops grown under aerobic (as for sustainable rice intensification) and flooded conditions in tropical environments of the Philippines (14 °N) showed a substantial increase in water productivity (Figure 3a) at the expense of grain yield (Figure 3b). In relation to the flooded regime, aerobic culture increased average water productivity from 5.7 to 7.4 kg grain ha^{-1} mm^{-1} and reduced yield from 6.4 to 5.7 tonnes ha^{-1}. In contrast, aerobic rice crops in temperate environments of Japan (34–35° N) outperformed their flooded

FIGURE 2: NITROGEN DRIVEN TRADE-OFF BETWEEN WATER PRODUCTIVITY AND NITROGEN UTILIZATION EFFICIENCY IN (A) FLOODED AND (B) AEROBIC 'APO' RICE IN THE PHILIPPINES, AND (C) RAINFED AND (D) IRRIGATED MAIZE IN THE UNITED STATES. WATER PRODUCTIVITY IS YIELD PER UNIT IRRIGATION + RAINFALL (A, B) OR YIELD PER UNIT EVAPOTRANSPIRATION (C, D). IN ALL CASES NITROGEN USE EFFICIENCY IS GRAIN YIELD PER UNIT NITROGEN UPTAKE (EXCLUDING ROOT N)



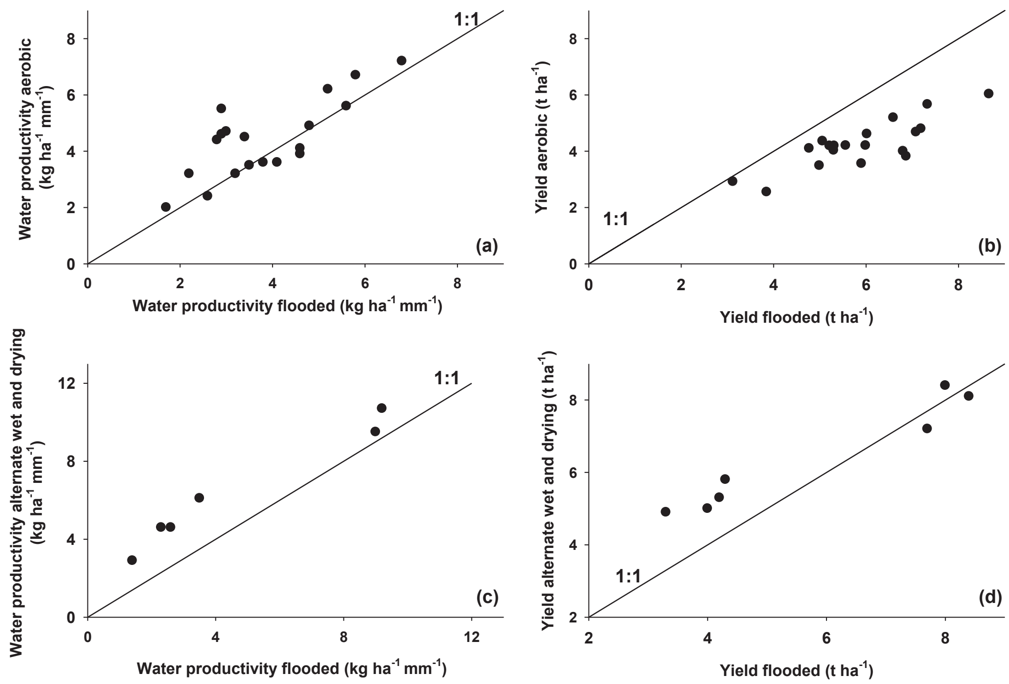
Adapted from (82, 83).

counterparts in terms of water productivity (average 8.3 vs 3.4 kg grain ha^{-1} mm^{-1}) and showed no yield penalty (average 8.6 vs 8.1 tonne ha^{-1}) (32).

For a large number of crops in central-northern India and the Philippines, alternate wetting and drying improved the water productivity of rice in comparison with the flooded checks, but yield penalties up to 70 percent were recorded. Further studies in lowland rice areas with heavy soils and shallow (0.1–0.4 m) groundwater tables in China and the Philippines showed that alternate wetting and drying outperformed their flooded counterparts in terms of water productivity (Figure 3c) with no associated yield penalties (Figure 3d). In all these cases, extremely shallow groundwater tables allowed for ponded water depths that were typically within the root zone during the drying periods (30).

To summarize, cultural practices to improve water productivity are obviously desirable, but need to be seen in the broader context of agronomic, economic and environmental trade-offs. Some trade-offs are inherent in the biophysical features of the cropping system, and cannot be broken. The nitrogen-driven trade-off between water productivity and nitrogen productivity belongs to this category. This type of trade-off may lead to practices that do not necessarily maximize water productivity, but rather account for multiple objectives: lower rates of nitrogen fertilizer and associated low water productivity may be justified in terms of reduced economic and environmental risk. The trade-off between yield and water productivity associated with water-saving techniques can be broken in some instances, as illustrated in Figure 3c, d. Water-saving techniques that improve water productivity at the expense of grain yield can be justified in some cases, but research should be encouraged to identify the conditions where improved water productivity can be achieved with no yield penalties.

FIGURE 3: (A) AEROBIC RICE HAD SIMILAR OR GREATER WATER PRODUCTIVITY AND (B) LOWER YIELD THAN RICE GROWN UNDER A FLOODED REGIME IN THE PHILIPPINES. (C) ALTERNATE WETTING AND DRYING IMPROVED RICE WATER PRODUCTIVITY AND (D) CAUSED NO YIELD PENALTIES IN COMPARISON WITH THE FLOODED CHECKS IN THE PHILIPPINES AND CHINA



Adapted from (30, 84).

6. Case studies

Here we present five case studies from environmentally, technologically and culturally diverse regions covering the whole range from subsistence to high-tech production cropping systems. Case studies are: (i) wheat in the Mediterranean Basin, North American Great Plains, China Loess Plateau and southeast Australia; (ii) sunflower in central Argentina; (iii) rice in the lower Mekong River Basin; (iv) maize in the Western Corn Belt of the United States; and (v) millet in the Sahel region of Africa. For each case study, we outline biophysical and agronomic features of the cropping system and the approach used to quantify water productivity; we compare actual efficiencies against relevant benchmarks, and identify opportunities for improvement.

6.1 Wheat in southeastern Australia, Mediterranean Basin, China Loess Plateau and North American Great Plains

Biophysical and cropping features

This study covered low-rainfall environments in four regions: southeastern Australia, Mediterranean Basin, China Loess Plateau and North American Great Plains. Wheat is the major grain crop in Australia. In the southeastern environments focused on here, soils have poor water-holding capacity that is associated with either coarse texture or chemical constraints to root proliferation. Soils with low water-holding capacity and precipitation concentrated in winter frequently lead to terminal drought. Likewise, a dry, hot summer alternating with a humid and temperate winter is the trademark of cropping systems in the Mediterranean Basin. Stored soil water is usually insufficient to meet atmospheric demand towards maturity, and crops grow under typical conditions of terminal drought. The Loess Plateau in the northwest of China is a vast semi-arid area with annual precipitation from 300 to 600 mm. Rainfed winter wheat, the main crop in the region, is sown in late September and harvested in early July.

Available water is the most important factor limiting grain production, as active growth and the most critical periods of yield determination are out-of-phase with the peak of precipitation between July and September. The Great Plains of North America are recognized for their fertile Mollisol soils and wheat production in typical wheat-fallow rotations, which is currently shifting to more intensive cropping. Uncertain and highly variable precipitation is a major feature of the northern Great Plains. For southeastern Australian and Mediterranean locations, the critical periods of flowering, grain set and grain filling coincide with declining precipitation and increasing reference evapotranspiration. For the plains of North America and the Loess plateau in China, these critical periods occur under increasing precipitation that is, nonetheless, insufficient to match the dramatic increase in reference evapotranspiration.

Approach

Sadras and Angus (33) compiled a data set including grain yield and seasonal evapotranspiration for 679 crops in low-rainfall environments in four regions: southeastern Australia (n = 364), North American Great Plains (n = 129), China Loess Plateau (n = 31), and Mediterranean Basin (n = 155). Evapotranspiration was generally calculated as rainfall plus change in soil–water content between sowing and harvest; drainage and runoff terms in water balances were neglected in most cases. Frequency distributions of yield per unit evapotranspiration were calculated and a scatter plot of yield versus evapotranspiration was compared against a linear model with x-intercept = 60 mm and slope = 22 kg grain ha^{-1} mm^{-1}. Notwithstanding the large variation in soils, climate and farming systems within each region, they provide a sound basis for comparisons.

To analyse the influence of evaporative demand on yield per unit evapotranspiration, however, the North American Great Plains were divided into Northern and Southern and Central regions. Of the 679 crops analysed, 57 percent were grown in well managed experimental plots; the remaining were from growers' fields. The majority of crops at the farm scale (96 percent) were from southern Australia. The conditions in experimental plots are frequently more favourable for high grain yield than those in large growers' fields. This means a relative bias in yield and water productivity whereby Australian crops in this data set reflect commercial crops more closely than the crops for the other environments.

Water productivity of wheat

Owing to the relatively small number of crops, caution is required in analysing the histogram for the China Loess Plateau. Average water productivity (kg grain ha^{-1} mm^{-1}) was 9.9 for southeastern Australia, 9.8 for the China Loess Plateau, 8.9 for the northern Great Plains of North America, 7.6 for the Mediterranean Basin, and 5.3 for the southern-central Great Plains; the variation between regions was largely accounted for by reference evapotranspiration around flowering. For the pooled data, maximum water productivity was 22 kg grain ha^{-1} mm^{-1} but few crops were close to this value. After accounting for the effects of reference evapotranspiration, the gap between average and maximum water productivity was 68 percent for the southern Great Plains of North America, 63 percent for the Mediterranean Basin, and 56 percent for China Loess Plateau, Northern Great Plains, and southeast Australia.

Figure 4 shows grain yield as a function of evapotranspiration for the pooled data. A boundary line with slope 22 kg grain ha^{-1} mm^{-1} and x-intercept = 60 mm provided an upper limit for all the data. This boundary function is similar to that proposed by French and Schultz (34, 35) for southern Australia and it seems to be a sensible reference for other dry environments. Although the slope of the line may seem arbitrary, it is interesting to note that the value of 20 kg grain ha^{-1} mm^{-1} originally proposed by French and Schultz in the 1980s and the value of 22 kg grain ha^{-1} mm^{-1} suggested by Angus and van Herwaarden (36) for crops in the late 1990s reflect the technology status of those years. Cultivar improvement, particularly increase in yield potential associated with greater harvest index (37, 38) and possibly increased atmospheric CO_2 concentration (36).

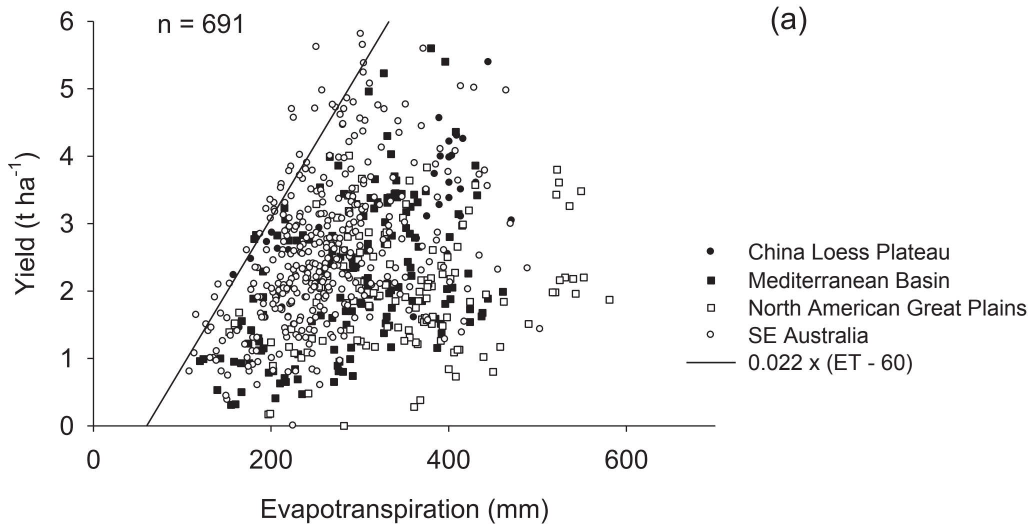
Opportunities for improvement

A subset of the data comprising crops in the Mallee region of southeast Australia was used to assess putative causes of under-performing crops. Low availability of phosphorus, late sowing, and subsoil chemical constraints, including sodicity, alkalinity and salinity, all contributed to the typically low water productivity of wheat in this environment. Adequate nutrition could improve water productivity, but rates of soil evaporation could still be large in well-fertilized crops (1).

Reduced row spacing, early vigour, and good supply of nutrients can favour rapid ground cover and reduce soil evaporation. The benefits of practices that favour rapid use of water early in the season have to be weighed against the depletion of soil water reserves for critical stages of grain set and filling. Likewise, a trade-off needs to be considered for tillage and stubble management aiming at increasing soil available water and reducing soil evaporation, as these practices could increase the probability of deep drainage.

The gap between actual yield measured in growers' fields and the boundary function increased at a rate of 19 kg grain/ha per day delay in sowing from mid-April. The reduction in water productivity associated with late sowing is partially related to (i) a reduction in grain set associated with lower photothermal coefficient and (ii) increase in vapour pressure deficit reducing biomass per unit transpiration. In Mediterranean climates, vapour pressure deficit increases from around 0.3 kPa in winter to 1.2 kPa toward the end of spring

FIGURE 4: RELATIONSHIP BETWEEN WHEAT GRAIN YIELD AND SEASONAL EVAPOTRANSPIRATION IN FOUR MEGA-ENVIRONMENTS. LINE PARAMETERS ARE X-INTERCEPT = 60 MM AND SLOPE = 22 KG GRAIN HA^{-1} MM^{-1}



(adapted from (33).

and summer; hence, greater proportion of seasonal growth in cold winter months could enhance water productivity. There are few options for dealing with uncertain opening rains that constrain early sowing, except for good agronomy (e.g. weed control) to allow sowing with the first rain, or genetic improvement (e.g. long coleoptiles) to allow sowing into subsurface moisture before rain. There are often trade-offs between the yield benefits of early sowing and frost risk.

Chemical subsoil constraints are widespread in Mallee soils, and affect the gap between actual and attainable water productivity. The main effect of subsoil chemical constraints on water productivity is mediated by constraints to canopy expansion and increased soil evaporation, rather than by reduction in biomass per unit transpiration (39-41).

6.2 Rainfed sunflower on the Western Pampas of Argentina

Biophysical and cropping features

The Western Pampas region (33.5 ºS-36.5 ºS; 62 ºW-65 ºW) comprises a rainfed cropland area of ~ 4.5 million ha in semi-arid central Argentina where sunflower production is widespread. The predominant landscape is characterized by flat to gently rolling continental dunes where prevalent agricultural soils are sandy or loamy Entic Haplustolls and Entic Hapludolls with medium-to-low water-holding capacity. The climate is temperate with some continental features.

Annual rainfall is summer-dominant and decreases from east to west. Reference crop evapotranspiration exceeds mean rainfall during the entire growing season except for the 50-day period after sowing. Thus, sunflower crops are exposed to unavoidable water stress in most years. Stress intensity and yield depend on the stored soil water (42), which varies with early-autumn and spring rainfall and with fallow duration. Occasionally, high rainfall causes waterlogging, which coupled with higher incidence of pathogens can reduce sunflower yield in wet years (43).

Approach

We explored the relationship between grain yield and seasonal water supply using a 4-year database (1995-1998) collected on commercial farms on the Western Pampas (n = 169; paddock size range: 21-130 ha). Water productivity for each field-year was calculated as the quotient between grain yield and seasonal water supply, where water supply is initial soil water plus seasonal rainfall. Grain yield and water supply data collected from small-plot (56 m^2) fertilization studies on the Western Pampas during 1996–1998 seasons by Bono *et al.* (44) were also included in the analysis (n = 231). Only crops grown on deep soils with no obvious physical or chemical constraints to rooting were included. Yields are reported at a standard moisture content of 11 percent.

A boundary function was fitted between yield and water supply using data constrained to the range of yield response between 300 and 630 mm of water supply. This boundary function was used to (a) benchmark crops in other environments, including locations in the Mediterranean Basin, the Great Plains of North America and Australia and (b) to identify constraints to crop water productivity on the Western Pampas. To do this, observations were first separated into three categories: (i) crops with apparent water excess (seasonal water supply > 630 mm; category 1); (ii) crops with limiting water supply (≤ 630 mm) and large yield gap (> 10 percent with respect to the attainable yield derived from the boundary function; category 2); (iii) crops with limiting water supply and small yield gap (≤ 10 percent; category 3).

A series of management factors, crop adversities, and physiological attributes were assessed for each crop category, including water content at sowing in the upper 0.6 m of the soil profile, total rainfall in each of three periods ('pre-anthesis' [sowing to 15-days prior to anthesis], 'around anthesis' [±15-days around anthesis], and 'grain filling' [15-days post-anthesis to maturity]), percent of ground cover at anthesis, photo-thermal quotient for the 30-day period centered on anthesis, nitrogen and phosphorous deficiencies, incidence of weeds, diseases and insects, lodging and grain abortion. In a complementary analysis, data reported by Bono *et al.* (44) were used to assess the response of water productivity to N and P fertilization.

On-farm sunflower water productivity on the Western Pampas

The fitted boundary function had a slope of 9.0 kg grain ha^{-1} mm^{-1}, and an x-intercept of 75 mm (Figure 5a). This function delimits the maximum yield over the range of water supply. Salient features of this figure are: (i) water supplies for many crops were greater than the maximum expected cumulative ET_C (630 mm) for the region; (ii) yield varied widely for a given water availability; (iii) on average, farmers' yields were 50 percent below the boundary function; and (iv) maximum on-farm grain yields (4.9 tonnes ha^{-1}) approached those reported for modern hybrids under potential conditions (45). Average on-farm yield per unit water supply ranged from 1.1 to 8.0 kg grain ha^{-1} mm^{-1}.

The boundary function defined for the Western Pampas provided a reasonable upper limit for rainfed and irrigated sunflower crops grown in other semi-arid environments in the Mediterranean Basin (Lebanon, Spain, Turkey), the Great Plains of North America and Australia (Figure 5c). Although crops were grown under good management practices, most of the data points were below the boundary function. The gaps were associated with high soil evaporation, high evaporative demand of the atmosphere, and untimely rainfall during the growing cycle in relation to critical crop stages.

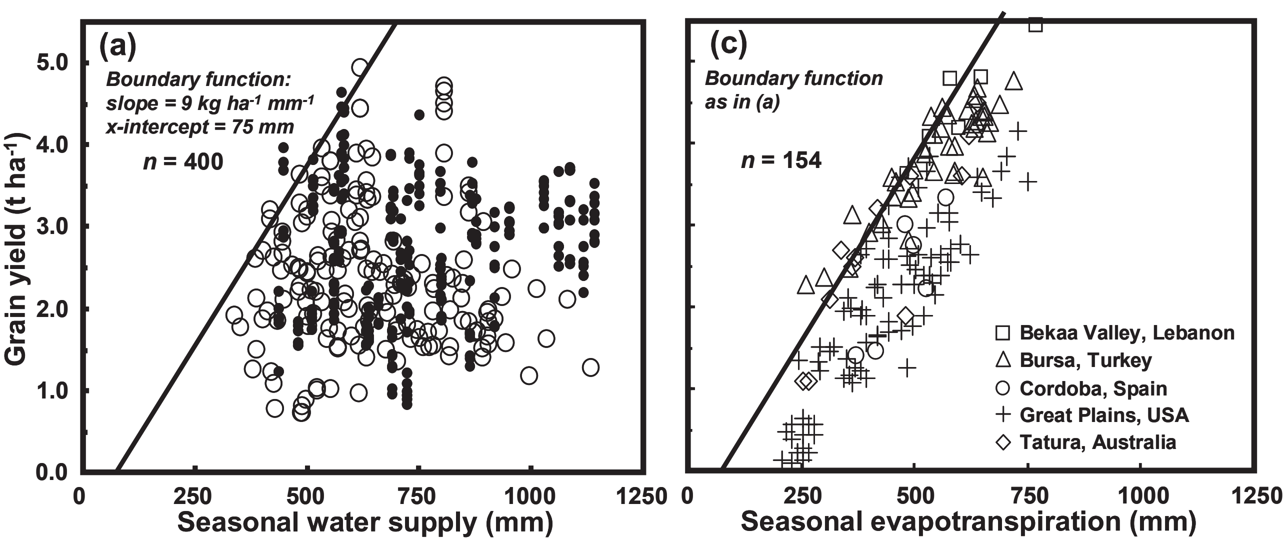
Opportunities for improvement

Table 2 summarizes environmental, management, and physiological variables for commercial sunflower crops on the Western Pampas, grouped according to seasonal water supply and yield gaps with respect to the boundary function. Category 1 crops (seasonal water supply > 630 mm) had greater soil water content at sowing and greater rainfall earlier in the season than crops in the remaining categories. In Category 1, frequencies of low topsoil phosphorus and nitrogen, and of weeds, pests, diseases and lodging were greater than for Category 3 crops (seasonal water supply ≤ 630 mm, small yield gap). Category 3 crops had higher initial soil water storage than Category 2 crops (seasonal water supply ≤ 630 mm, large yield gap), but crops in both categories had similar patterns of seasonal rainfall. In comparison to Category 2, Category 3 crops had much lower frequencies of P and N deficiency in the topsoil, less weed incidence, higher photothermal quotient, less grain abortion and higher ground cover at anthesis.

Further, Category 1 (seasonal water availability > 630 mm) crops were subdivided into two sets: those with yields within 10 percent of the boundary function for a seasonal water availability of 630 mm, and those with yields that departed from the boundary function by more than 10 percent. Interestingly, the contrasts between these two sets produced a pattern of differences between candidate yield-reducing factors that was equivalent to the comparison between Category 2 and Category 3 crops. Thus, to increase the value of the boundary function as a benchmark to guide farming practice on the Western Pampas and to evaluate crop-water productivity, it would be useful to remove the apparent water excess observed in some years by treating any value of water supply > 630 mm as equal to 630 mm.

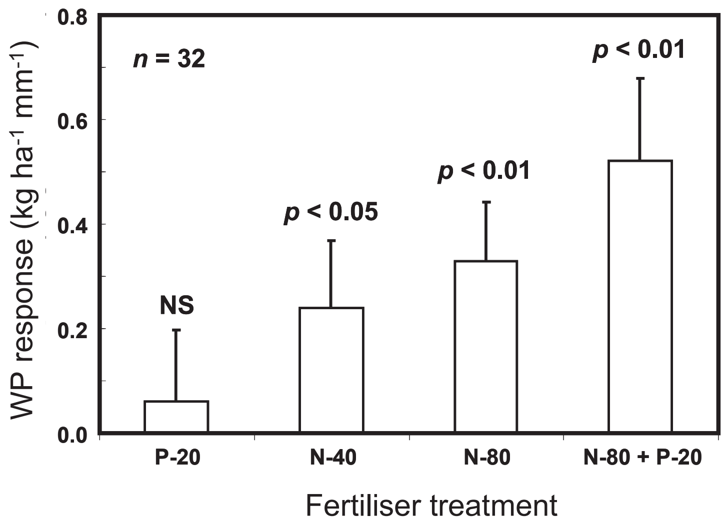
Analysis of the data by Bono *et al.* (44) showed average yield per unit water supply responses of 0.06 (range: -1.32 to 1.16), 0.24 (range: -0.67 to 2.14), 0.33 (range: -0.49 to 1.56) and 0.52 kg grain ha^{-1} mm^{-1} (range: -0.37 to 2.21) to fertilizer applications of 20 kg P ha^{-1}, 40 or 80 kg N ha^{-1}, and 20 kg P ha^{-1} plus 80 kg N ha^{-1} at sowing, respectively (Figure 6). Analysis of yield response to fertilization indicated that 75 percent of the crops were nutrient limited, of which 60 percent were limited by N or P and 40 percent were limited by both nutrients. Negative responses to fertilization in approximately 20 percent of the cases were mainly associated to low available soil water around flowering or very high rainfall during the growing season.

FIGURE 5: (A) RELATIONSHIP BETWEEN GRAIN YIELD AND SEASONAL WATER SUPPLY IN FARMERS' FIELDS ON THE WESTERN PAMPAS (OPEN SYMBOLS; N = 169). DATA FROM SMALL-PLOT (56 M^2) FERTILIZER TRIALS ARE ALSO SHOWN (CLOSED SYMBOLS; N = 231). WATER SUPPLY IS AVAILABLE SOIL WATER AT SOWING PLUS SOWING-TO-MATURITY RAINFALL. (C) RELATIONSHIP BETWEEN YIELD AND EVAPOTRANSPIRATION FOR SUNFLOWER CROPS IN AUSTRALIA, LEBANON, SPAIN, TURKEY, AND UNITED STATES



Adapted from (79) and references cited therein.

FIGURE 6: WATER PRODUCTIVITY OF SUNFLOWER CROPS IN RESPONSE TO FERTILIZER. THE RESPONSE WAS CALCULATED AS THE DIFFERENCE IN YIELD PER UNIT WATER SUPPLY BETWEEN FERTILIZED AND NON-FERTILIZED CROPS. FERTILIZER TREATMENTS WERE 20 KG P HA^{-1} (P-20), 40 KG N HA^{-1} (N-40), 80 KG N HA^{-1} (N-80), AND COMBINED N AND P (N-80 + P-20). MEAN YIELD PER UNIT WATER SUPPLY OF NON-FERTILIZED CROPS WAS 3.5 KG GRAIN HA^{-1} MM^{-1}. SIGNIFICANCE OF PAIRED T-TEST FOR THE COMPARISON BETWEEN FERTILIZED AND NON-FERTILIZED CROPS IS SHOWN FOR EACH TREATMENT.



Data collected from 32 site-years on the Western Pampas by Bono et al. (44).

To summarize, the boundary function derived from this study defined an upper limit for sunflower yield over the range of water supply up to 630 mm. Parameters of this boundary function, i.e. slope = 9 kg grain ha^{-1} mm^{-1} and x-intercept = 75 mm, were suitable for crops in contrasting semi-arid environments worldwide. Identification of the causes of yield gaps and, where possible, their mitigation, should lead to improved sunflower yield and water productivity. Although we cannot assign precise weightings to the factors contributing to these gaps, Figure 6 and Table 2 strongly indicate potential causes. Nutrient availability and its interaction with soil water at sowing is perhaps the most important leverage point to increasing yield and water productivity. Other factors, such as diseases, weeds, and lodging also require attention.

6.3 Rice in the lower Mekong River Basin

Biophysical and cropping features

This section summarizes the study of Mainuddin and Kirby (46). The Mekong River Basin comprises 795 000 km^2 and 65 million inhabitants across six countries, that is China and Myanmar in the Upper Mekong and Laos, Thailand, Cambodia, and Vietnam in the lower Mekong, which is the subject of this study. Vietnam has two contrasting regions in the basin, the Central Highlands and the Mekong Delta. Agriculture is the most important activity in the lower Mekong and accounts for 80-90 percent of the water extracted from the river. There is a dry cropping season from November to April, and a wet season from May to October. Rice is the predominant crop in the basin, and lowland rainfed rice grown in the wet season accounts for at least half of total rice production (Table 4). Maize, cassava and sugar cane are the main upland crops.

TABLE 2: ENVIRONMENTAL AND CROP VARIABLES FOR THE THREE CATEGORIES OF CROPS DERIVED FROM FIGURE 5A. CATEGORY 1: AVAILABLE WATER → 630 MM; CATEGORY 2: WATER SUPPLY ↸ 630 MM AND LARGE YIELD GAP; AND CATEGORY 3: WATER SUPPLY ↸ 630 MM AND SMALL YIELD GAP

Variable	Category 1 (n = 83)	Category 2 (n = 65)	Category 3 (n = 21)
Initial available soil water$_{0\text{-}0.6m}$ (mm)	71±3*	48±3	65±3
Pre-anthesis rainfall (mm)	309±11*	144±7	159±12
Rainfall around anthesis (mm)	135±7*	75±5	54±5
Grain-filling rainfall (mm)	70±5*	44±3	36±5
Ground cover around anthesis (%)	86±1*	79±2	91±2
$Q_{anthesis}$ (MJ°C^{-1}m^{-2})	1.41 ± 0.01*	1.39 ± 0.01	1.45 ± 0.02
Low topsoil P	30/73**	21/57	2/21
Low topsoil N	12/83**	14/63	1/21
Weed incidence	17/71**	15/56	2/14
Pest incidence	7/71**	1/52	0/14
Disease incidence	41/63**	2/50	1/14
Lodging	22/58**	2/51	0/14
Grain abortion	22/54**	11/31	0/12

* mean (±SE) for each variable; ** number of cases, expressed as a fraction of the total number of crops assessed, in which topsoil nutrient content was below to the regional threshold for yield response (N-$NO_{3\text{- }0\text{-}0.6\,m}$= 50 kg ha^{-1}; P-Bray$_{0\text{-}0.2m}$= 12 mg kg^{-1}) or crops were affected by a moderate-to-severe incidence of the adversity.
Adapted from (79).

Approach

Mainuddin and Kirby (46) combined provincial time-series of yield and modelled evapotranspiration to calculate yield per unit evapotranspiration at the regional (provincial) scale. Time series were 1993–2006 or shorter within this time window. Modelled evapotranspiration was derived from monthly rainfall and reference evapotranspiration, crop coefficients, rooting depth, sowing time, growing period, length of growing stages and soil hydraulic properties. A range of soil types was assumed and results were averaged.

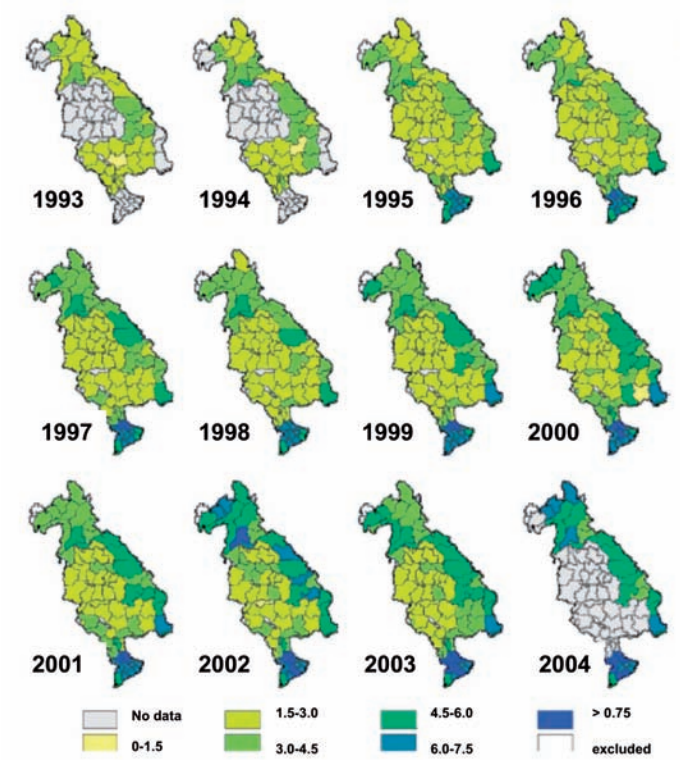
Regional water productivity of rice and short-term trends

Figure 7 maps the water productivity of rice in the lower Mekong River Basin at a provincial level between 1993 and 2003. Maximum yield per unit evapotranspiration was 3.0 kg grain ha^{-1} mm^{-1} for Thailand, 3.3 kg grain ha^{-1} mm^{-1} for Cambodia, 5.8 kg grain ha^{-1} mm^{-1} for Laos and 7.7 kg grain ha^{-1} mm^{-1} for Vietnam (Table 3). These compare to maximum yield per unit transpiration of 22 kg grain ha^{-1} mm^{-1} (30). Trends of increasing efficiency over these short time series were observed in Laos and both the Mekong delta and Central Highland regions of Vietnam.

Opportunities for improvement

Owing to the large share of rice, and particularly lowland rice in these cropping systems (Table 3), increasing water productivity of rice would increase the water productivity of the whole basin. Mainuddin and Kirby (46) outlined the main opportunities for improvement. These include using high-yielding varieties, increasing application of fertilizer, herbicides and pesticides, and supplementary irrigation. Upland crops such as coffee, vegetables and peanuts outperform rice in terms of economic return per millimetre water use. Increasing the share of these high-value upland crops, Mainuddin and Kirby (46) conclude, can increase farm income and reduce poverty with unlikely trade-offs in terms of food security in the basin.

FIGURE 7: MEKONG RIVER BASIN YIELD PER UNIT EVAPOTRANSPIRATION OF RICE AT A REGIONAL SCALE, IN KG GRAIN HA^{-1} MM^{-1}



Adapted from [46].

6.4 Irrigated maize in the Western US Corn Belt

Biophysical and cropping features

The Western US Corn Belt (37 °N-45 °N; 92 °W-105 °W) includes ~ 7.3 million ha cultivated with maize (Figure 11a). The landscape is undulate and predominant agricultural soils are Haplustolls and Argiustolls with medium-to-high water holding capacity. Elevation increases westwards from 309 m in Ames to 1 384 m in Akron, at an equivalent rate of 118 m per degree longitude. The climate is continental and temperate, and

TABLE 3: SHARE OF RICE ACREAGE, CONTRIBUTION OF LOWLAND RICE TO TOTAL RICE PRODUCTION, LOWLAND RICE AVERAGE YIELD (2003), COEFFICIENT OF VARIATION OF RAIN DURING THE LOWLAND RICE SEASON (AMONG PROVINCES WITHIN A COUNTRY), SUPPLEMENTARY IRRIGATION REQUIREMENT FOR LOWLAND RICE, AND MAXIMUM WATER PRODUCTIVITY AT REGIONAL (PROVINCIAL) LEVEL IN THE LOWER MEKONG RIVER BASIN

Country	Rice acreage (fraction of annual harvested area)	Lowland rice production (fraction of total rice production)	Lowland rice yield (t ha^{-1})	CV of rain during the growing season of lowland rice (%)	Supplementary irrigation requirement (fraction)	Maximum yield per unit evapotranspiration (kg grain ha^{-1} mm^{-1})
Cambodia	0.89	0.87	2.1	17-49	0.9	3.3
Laos	0.72	0.77	3.2	21-34	0.9	5.8
Thailand	0.78	0.96	1.9	10-25	1.0	3.0
Vietnam	0.89	0.46	4.4	15-22	0.3	7.7

Adapted from [46].

the frost-free period decreases from the southeast to the northwest along the altitudinal gradient. Spring and summer account for 70-80 percent of the annual precipitation. Reference evapotranspiration increases and rainfall decreases from east to west. Variation in rainfall (CV ~ 80 percent) is large compared to the variation in reference evapotranspiration (CV ~ 23 percent). Except for the first month after sowing, crop ET exceeds rainfall during the growing season especially on the western edge of the longitudinal gradient. Thus, timing, magnitude, duration and probability of water stress episodes depend on stored soil moisture that accumulates from snow melt and spring rains and, when available, irrigation water.

Irrigated maize represents 43 percent of the total maize area, 70 percent of the total irrigated cropland in the region, and accounts for 58 percent of the total annual maize production of 60 million tonnes in the Western Corn Belt (47). Surface gravity and sprinkler irrigation systems are in a 1:4 ratio of irrigated land area.

Approach

Data on maize grain yield, applied irrigation, irrigation system and nitrogen fertilizer rate (n = 777) were collected over three years (2005–2007) from commercial irrigated fields (mean size: 46 ha) inside the Tri-Basin Natural Resources Districts (NRD), one of the 23 NRD in Nebraska. Water productivity for each field-year was calculated as the quotient between grain yield and seasonal water supply, where water supply = available soil water at sowing + sowing-to-maturity rainfall + applied irrigation.

Irrigation water productivity was calculated as the quotient between (i) grain yield and applied irrigation or (ii) between the difference between irrigated and rainfed yield (ΔY) and applied irrigation. Accounting for yield benefits of irrigation through ΔY seeks to remove the effect of rainfall variation across years. Farmers' yields were compared against two benchmarks and variation of grain yield and applied irrigation were investigated using data on crop management collected from a subset of 123 field-years.

The benchmarks relate attainable grain yield and water supply as described in Grassini *et al.* (48, 49). Briefly, modelled yield and water supply in 18 locations across the Western US Corn Belt were used to derive (i) a boundary function (slope = 27.7 kg grain ha^{-1} mm^{-1}, x-intercept = 100 mm) and (ii) a mean function (slope = 19.3 kg grain ha^{-1} mm^{-1}, x-intercept = 100 mm). The boundary function defines the maximum attainable yield over the range of water supply, and the mean function accounts for the variability in attainable yield at a given water supply caused by year-to-year variation in solar radiation, temperature, vapour pressure deficit, and seasonal distribution of water supply.

Maize water productivity in the western corn belt

Farmer's grain yield in the Tri-Basin NRD averaged 13 tonnes ha^{-1} and ranged between 9.5 to 17.2 tonnes ha^{-1}. Total water supply during the growing season comprised available soil water at sowing, sowing-to-maturity rainfall, and applied irrigation in a 25:45:30 ratio. Average applied irrigation ranged from 213 to 347 mm across seasons. Fertilizer rates averaged 183 kg N ha^{-1} and 25 kg P ha^{-1}.

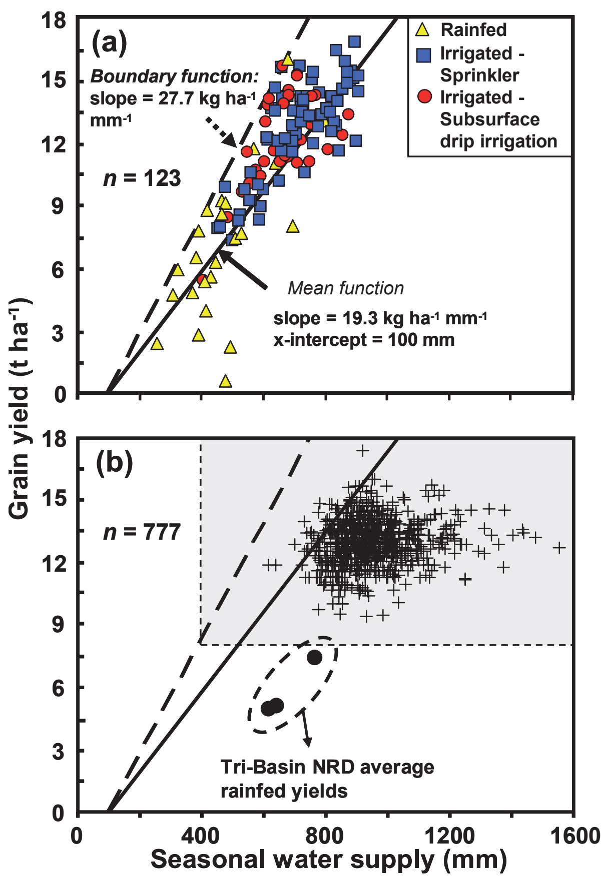
When compared to reported data on grain yield and water supply from maize crops in the Western US Corn Belt under good management, both the boundary and mean functions proved to be robust benchmarks (Figure 8a). On average, farmers' yields were 20 percent below the mean benchmark function although ~ 4 percent of the cases approached or even exceeded this benchmark (Figure 8b). Grain yield was not responsive to water supply over 900 mm; an important fraction of the total fields (55 percent) exceeded the apparent 900 mm threshold required to maximize yield. The apparent water excess was weakly related to available soil water at sowing and sowing-to-maturity rainfall but strongly related to applied irrigation. Water productivity of irrigated crops ranged from 8.2 to 19.4 kg mm^{-1} ha^{-1} across field-years. Average water productivity was higher in irrigated than in rainfed crops (14.0 vs 8.8 kg grain ha^{-1} mm^{-1}).

Fields under pivot had higher water productivity (~13 percent) than their counterparts under gravity irrigation. Yield per unit irrigation averaged 44, 62, and 77 kg grain ha^{-1} mm^{-1} under pivot and 28, 36, and 42 kg grain ha^{-1} mm^{-1} under gravity in 2005, 2006, and 2007, respectively. When these values were corrected by the average rainfed yield on each year (5.1, 5.2, and 7.5 tonnes ha^{-1}), the resulting water productivity became relatively stable across years: 27, 37, and 32 kg grain ha^{-1} mm^{-1} under pivot and 18, 21, and 18 kg grain ha^{-1} mm^{-1} under gravity in 2005, 2006, and 2007, respectively. High ΔY per unit irrigation reflects not only the response to increasing water supply, but also differences in the agronomic management between irrigated and rainfed crops (e.g. plant population, nutrient inputs). Consequently, rainfed crops had lower attainable yield and water productivity than irrigated crops, even when water supply is not limiting, as shown in Figure 8b.

Opportunities for improvement

Trends in the recommended plant population for rainfed maize in the Western US Corn Belt closely follow the east-west gradients of rainfall and reference evapotranspiration, reflecting management adaptation to reduced water supply (Figure 9). Given the high probability of water stress, recommended plant populations decrease with the east-west rainfall gradient to avoid fast depletion of soil moisture during the vegetative

FIGURE 8: (A) RELATIONSHIP BETWEEN GRAIN YIELD AND SEASONAL WATER SUPPLY (AVAILABLE SOIL WATER AT SOWING PLUS SOWING-TO-MATURITY RAINFALL AND APPLIED IRRIGATION) FOR MAIZE CROPS GROWN UNDER NEAR-OPTIMAL MANAGEMENT IN THE WESTERN US CORN BELT. THE DATABASE INCLUDED A WIDE RANGE OF ENVIRONMENTS AND IRRIGATION SCHEDULES; NONE OF THE FIELDS HAD OBVIOUS LIMITATIONS DUE TO NUTRIENT DEFICIENCIES, DISEASES, INSECT, WEEDS, OR HAIL. (B) FARMERS' IRRIGATED YIELDS IN THE TRI-BASIN NRD AS A FUNCTION OF SEASONAL WATER SUPPLY (+). TRI-BASIN COUNTY-LEVEL AVERAGE RAINFED YIELDS ARE ALSO SHOWN FOR COMPARISON (•).



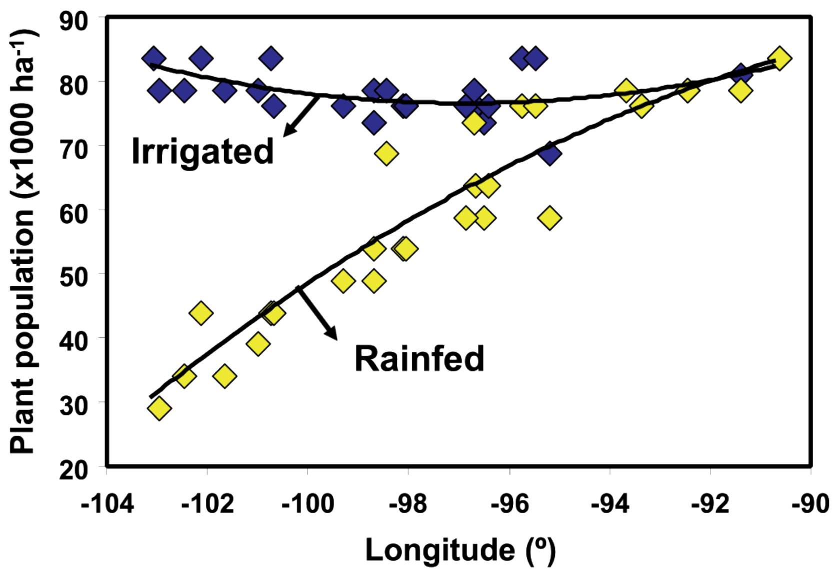
stage, hence reducing the likelihood and intensity of stress at the most critical window of grain yield determination (Section 3.2). Although lower plant populations may limit yield in years with above-to-average rainfall, field and simulation studies in Western Nebraska confirm the long-term benefits of reducing maize plant population as the available water supply decreases (50).

Figure 8a-b indicates that water productivity of irrigated maize can be improved by changes to the irrigation system, irrigation management or both. Whilst sprinkler and subsurface drip irrigation have higher efficiencies than gravity systems, irrigation schedules based on real-time crop requirements, soil water monitoring, and short-term forecasts appear to be sound options to increase efficiency in current irrigated maize fields in the Western US Corn Belt. In comparison with standard farmers' practice, scheduling irrigation on the basis of soil water content and crop requirement could reduce the irrigation rate by 35 percent with no yield penalty in eastern Nebraska (51).

Comparison of actual and attainable yield under current practices indicated that farmers in the Tri-Basin NRD are operating at about 10–20 percent below maximum productivity (52). Fine-tuning current management practices such as plant population density, hybrid maturity, and rotation, may lead to a limited increase in yield and water productivity, in the order of 10 percent. Better management of irrigation water appears to be the most feasible way of achieving larger increases in water productivity. Data from commercial maize fields in the Tri-Basin NRD indicated the effects of irrigation system, previous crop, and tillage on yield, applied irrigation and/or water productivity (Figure 10).

To achieve the same yield, pivot used 36 percent less irrigation water than gravity irrigation, and conservation tillage required 20 percent less irrigation water than conventional tillage. Crop residues under conservation tillage may diminish irrigation requirements by increasing precipitation storage efficiency and by reducing direct soil evaporation and surface runoff. So, fields under pivot and conservation tillage exhibit higher ΔY per unit irrigation than their counterparts under gravity and conventional tillage.

FIGURE 9: ACTUAL RECOMMENDED PLANT POPULATIONS FOR IRRIGATED AND RAINFED MAIZE AS A FUNCTION OF LONGITUDE IN THE WESTERN US CORN BELT. AT SOME EASTERN LOCATIONS, SYMBOLS FOR IRRIGATED AND RAINFED CROPS OVERLAP. DATA PROVIDED BY PIONEER AGRONOMY SCIENCES, PIONEER HI-BRED INTERNATIONAL, INC



Adapted from (49).

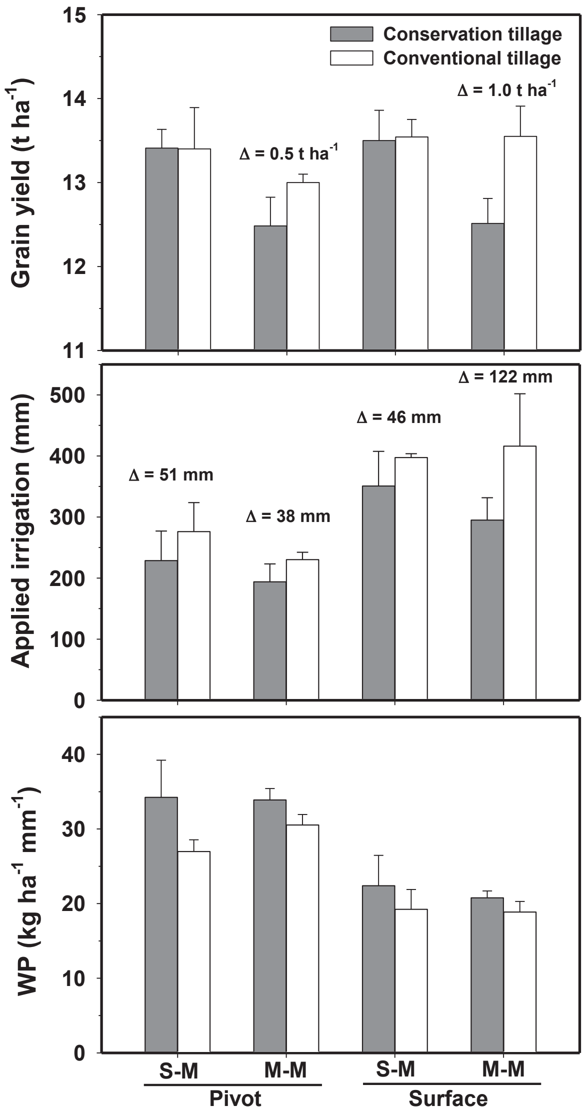
Interestingly, tillage and previous crop interact on their effect on grain yield: while no difference between tillage systems were observed under soybean-maize rotation, yield under conventional tillage was higher than under conservation tillage under continuous maize. Maximum ΔY per unit irrigation (~ 35 kg grain ha^{-1} mm^{-1}) and yield (~ 13.5 tonnes ha^{-1}) were achieved in fields under pivot irrigation, conservation tillage and soybean-maize rotation.

6.5 Millet in the Western Sahel region of Africa

Biophysical and cropping features

The Sahel is an east-west, 3 million km^2 semi-arid transition belt between the Sahara dessert and the wooded Sudanian savannah. Drought, high temperature and low soil fertility are major constraints to crop production in the region. Annual rainfall varies between 200 and 600 mm, with variation coefficients between 15

FIGURE 10: MAIZE YIELD, IRRIGATION, AND WATER PRODUCTIVITY UNDER DIFFERENT COMBINATIONS OF IRRIGATION SYSTEM (SURFACE GRAVITY; PIVOT), ROTATION (SOYBEAN-MAIZE [S-M]; MAIZE-MAIZE [M-M]), AND TILLAGE (CONSERVATION [STRIP-, RIDGE-, OR NO-TILL]; CONVENTIONAL [DISK]). WATER PRODUCTIVITY IS THE RATIO BETWEEN THE DIFFERENCE BETWEEN IRRIGATED AND RAINFED YIELD (ΔY) AND THE AMOUNT OF APPLIED IRRIGATION. ERROR BARS INDICATE ± SE. DIFFERENCES (Δ) FOR SELECTED COMPARISONS BETWEEN TILLAGE SYSTEMS ARE SHOWN



Adapted from (48).

and 30 percent (53). Millet is a C4 cereal that is commonly grown in low fertility, sandy upland soils, which are often prone to crusting. It is grown on its own or intercropped, and residues provide valuable fodder in systems where crop and animal production are highly integrated. Variable combinations of soil evaporation, runoff and deep drainage comprise a significant unproductive component of the crop-water budget.

Approach

We collected millet grain yield and evapotranspiration data from published sources, mostly from the West African Sahel generally associated with ICRISAT. Data from Egypt were compared against the high-input cropping system of United States. We derived frequency distribution of yield per unit evapotranspiration and scatter-plots of yield versus evapotranspiration. A boundary function with slope = 16.7 kg grain ha^{-1} mm^{-1} and x-intercept = 158 mm was derived from studies by Rockström *et al.* (54) in Nigeria.

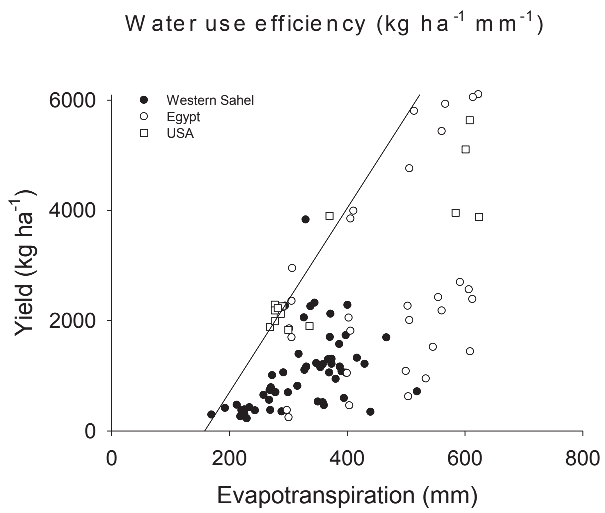
Millet water productivity

For a collection of 58 crops in the Sahel, millet yield per unit evapotranspiration averaged 3 kg grain ha^{-1} mm^{-1}. Although these studies captured the local soils and climates and most of the local practices, e.g. sowing dates and plant population densities, they possibly overestimated the water productivity in farmers' paddocks. For example, 50 percent of crops in the data set yielded more than 1 tonne ha^{-1}, as compared to national averages for Western Sahelian countries typically below 0.7 tonnes ha^{-1}. A boundary function with slope = 16.7 kg grain ha^{-1} mm^{-1} and x-intercept = 158 mm seemed to capture the upper limit of water productivity for Sahelian millet crops (Figure 11). The generality of this boundary function is reinforced by its applicability to the more favourable environments of Egypt and North America (Figure 11). Most millet crops under Sahelian conditions were well below this boundary function.

Opportunities for improvement

Environmental, management and plant-related factors summarized in Table 4 contribute to the low water productivity of millet in the Sahel. Low soil fertility and sparsely sown crops mean ground cover is typically low, i.e. peak leaf area indices below 1, or below 2 in more intensive systems. This in turn favours unproductive soil evaporation. Sandy soils, which are prone to crusting, also favour episodic runoff and deep drainage,

FIGURE 11: RELATIONSHIP BETWEEN GRAIN YIELD AND EVAPOTRANSPIRATION FOR CROPS IN WESTERN SAHEL; DATA FROM EGYPT AND UNITED STATES ARE INCLUDED FOR COMPARISON. THE SOLID LINE HAS A SLOPE = 16.7 KG GRAIN HA-1 MM-1 AND AN X-INTERCEPT = 158 MM, BOTH DERIVED FROM (54)



Data from (54, 58, 85-96).

as demonstrated in detailed water budget studies (Table 4). Indeed, a series of experimental and modelling studies converge to conclude that production in these environments is not necessarily limited by water but rather by agronomy and inputs, as there is often residual water in the soil at maturity (55), large unproductive losses of water, and nutrient stress is often more severe than water stress (56, 57). Yield per unit transpiration of millet is the lowest among C4 crops (Table 1). In a direct comparison of sorghum and millet, Maman *et al.* (58) found both crops had similar water use and biomass production, hence similar biomass per unit evapotranspiration but large differences in yield and hence in yield per unit evapotranspiration. The low harvest index of millet relative to sorghum accounts for this difference (Table 4).

Improving water productivity of millet in dry, hot environments of Africa would require higher inputs, chiefly large fertilizer doses that need to be considered in the context of risk and trade-offs. Likewise, the low harvest index of millet needs to be considered in the context of a trade-off between grain production and valuable crop residues. For example, some popular landrace millet varieties in India are over 3 m tall, and are valued for the large amount of fodder they provide, even though grain yields are relatively low.

TABLE 4: TYPICAL PEAK LEAF AREA INDEX (LAI), MODELLED WATER AND NITROGEN STRESS INDICES, AND MEASURED RANGES OF NON-PRODUCTIVE COMPONENTS OF THE WATER BUDGET OF MILLET CROPS IN THE WESTERN SAHEL REGION. COMPARISON OF SORGHUM AND MILLET HARVEST INDEX IS FROM COMMON LOCATIONS AND GROWING CONDITIONS IN NEBRASKA, UNITED STATES.

Crop feature		Value
Peak LAI	Standard crop	← 1
	Intensively managed crop	← 2
Water stress index	Emergence-end juvenile stage	0
	End juvenile stage-panicle initiation	0.02
	Panicle initiation - end leaf growth	0.27
	End leaf growth -end panicle growth	0
	End panicle growth -maturity	0
Nitrogen stress index	Emergence-end juvenile stage	0.07
	End juvenile stage-panicle initiation	0.04
	Panicle initiation - end leaf growth	0.63
	End leaf growth -end panicle growth	0.16
	End panicle growth -maturity	0.03
Soil evaporation	mm	158-248
	Percentage of rainfall	30-50
Runoff	mm	0-157
	Percentage of rainfall	0-30
Drainage	mm	75-328
	Percentage of rainfall	15-55
Harvest index (%)	Millet	23-37
	Sorghum	34-45

Sources: LAI (80), water and nitrogen stress indices (57), water budget components (54), and harvest index (58). Water and nitrogen stress indices were calculated for Tara, Niger, in a season when seasonal rainfall was 65 percent of normal; indices range from 0 (no stress) to 1 (maximum stress).

7. Conclusions

Improvement in grain yield and water productivity arise from breeding for superior varieties, better agronomic practices and the important, but often overlooked, synergy between breeding and agronomy (59). Long-term enhancement of yield potential with no substantial change in crop water uptake has increased yield per unit transpiration. Table 1 summarizes the current upper limit of yield per unit transpiration of the main grain crops. These upper limits reflect differences between C3 and C4 species, between winter and summer crops with their associated difference in prevailing evaporative demand of the atmosphere, and between species with dominance of starch, protein or oil in the seed. Further genetic improvement in yield per unit transpiration can contribute to improvement in yield and water productivity but more likely gains would derive from improving the capacity of crops to capture more water (20).

There is an obvious need for agronomic solutions to close the common and often large gap between actual and attainable yield per unit evapotranspiration or yield per unit water supply demonstrated for most crops and cropping systems worldwide including wheat (Figure 4), sunflower (Figure 5a), maize (Figure 8b) and pearl millet (Figure 11b). Also for rice, actual yield per unit evapotranspiration is typically well below that attainable (Figure 7, Table 1).

Whereas genetic and agronomic solutions are not mutually exclusive, it has been argued that agronomic practices to narrow the gap between attainable and actual yield per unit evapotranspiration is a more effective investment of scarce R&D funds, particularly for smallholder farmers. Moreover, the practices required to close this gap are already known for many crops and cropping systems; solutions in these cases involve efforts to provide extension, education and policy development to remove barriers to adoption of these practices.

The gap between maximum yield per unit transpiration representing the attainable yield per unit water uptake, and actual yield per unit evapotranspiration can be interpreted in two ways (Figure 4, 5ab, Figure 8b). In the vertical direction, there is a yield gap that might be reduced with better agronomy. In the horizontal direction, the gap indicates wasteful use of water, chiefly soil evaporation but also deep drainage and runoff, depending on rainfall patterns, irrigation system and scheduling and other features of the cropping system. Indeed, this type of analyses led many authors to conclude that water is not necessarily a limiting factor even in very dry environments of Africa and Australia. The particular practices required to close the gap between attainable and actual yield per unit evapotranspiration are specific for a given crop and cropping system, but some elements seem to be widespread: timely sowing, effective control of weeds, pests and diseases, and adequate fertilization.

As a rule for winter crops, the earliest sowing compatible with frost risk would maximize grain yield in association with high photothermal quotient and would improve yield per unit evapotranspiration by placing much of the growing cycle under conditions of lower vapour pressure deficit. For highly plastic crops such as chickpea and sunflower, massive improvement in yield per unit evapotranspiration results from shifting the growing season from spring-summer to autumn-winter, provided diseases and weeds are properly managed.

Nutrient availability, particularly nitrogen and phosphorus, are critical to high yield and water productivity. Trade-offs between water productivity and nutrient use efficiency need to be considered, i.e. maximizing water productivity in some farming systems may require nitrogen fertilization rates that are too costly, too risky or environmentally unsound. Likewise, trade-offs between yield and water productivity that are mediated by amount and method of water supply are common. All these trade-offs need to be considered, as the aim of improving water productivity on its own is not necessarily the best pathway to sustainability involving specific production, environmental and social targets.

8. References and data sources

1. **Cooper, P.J.M., Gregory, P.J., Tully, D. & Harris, H.C.** 1987. Exp. Agr. 23, 113.

2. **Tanner, C.B., Sinclair, T.R.** 1983. In: Limitations to efficient water use in crop production, Taylor, H.M., Jordan, W.R., Sinclair, T.L. (eds). ASA, CSSA, SSSA, Madison, pp. 1-27.

3. **Kemanian, A.R., Stöckle, C.O. & Huggins, D.R.** 2005. *Agric. Forest Meteorol*. 130, 1.

4. **Abbate, P.E.** *et al.***,** 2004. *Crop. Sci*. 44, 474.

5. **Moriana, A., Villalobos, F.J. & Fereres, E.** 2002. *Plant Cell Environ* 25, 395.

6. **Steduto, P. & Albrizio, R.** 2005. *Agric. Forest Meteorol*. 130, 269.

7. **Doyle, A.D. & Fischer, R.A.** 1979. *Aust. J. Agric. Res*. 30, 815.

8. **Oweis, T., Hachum, A. & Pala, M.** 2004. *Agric Water Manag*. 66, 163.

9. **Gimeno, V., Fernández, J. & Fereres, E.** 1989. *Field Crops Res*. 22, 307.

10. **Sadras, V.O.** 2003. *Aust. J. Agric. Res*. 54, 341.

11. **Sadras, V.O. & Rodriguez, D.** 2007. Aust. J. Agric. Res. 58, 657.

12. **Fereres, E. & Gonzalez-Dugo, V.** 2009. In *Crop physiology: applications for genetic improvement and agronomy*. Sadras, V.O., Calderini, D.F. (eds) San Diego, United States, Academic Press, pp. 123–143.

13. **Sadras, V.O. & Denison, R.F.** 2009. *New Phytol*. 183, 565.

14. **Fischer, R.A.** 1985. *J. agric. Sci*. 105, 447.

15. **Cantagallo, J.E., Chimenti, C.A. & Hall, A.J.** 1997. *Crop. Sci*. 37, 1780.

16. **Brueck, H.** 2008. *Journal of Plant Nutrition and Soil Science* 171, 210.

17. **Caviglia, O.P. & Sadras, V.O.** 2001. *Field Crops Res*. 69, 259.

18. **Zhao L.M. *et al.*** July 2009. *Exp. Agr*. 45, 275.

19. **van Herwaarden, A.F., Farquhar, G.D., Angus, J.F., Richards, R.A. & Howe, G.N.** 1998. *Aust. J. Agric. Res*. 49, 1067.

20. **Blum, A.** 2009. *Field Crops Res*. 112, 119.

21. **Brown, P.L.** 1971. *Agron*. J. 63, 43.

22. **Di Paolo, E. & Rinaldi, M.** 2008. *Field Crops Res*. 105, 202.

23. **Chen, S.P., Bai, Y.F., Zhang, L.X. & Han, X.G.** 2005. *Environ. Exp. Bot*. 53, 65.

24. **Sadras, V.O. & Roget, D.K.** 2004. *Agron. J*. 96, 236.

25. **Sadras, V.O.** 2002. *Field Crops Res*. 77, 201.

26. **Sadras, V.O.** 2005. *Aust. J. Agric. Res*. 56, 1151.

27. **Cossani, C.M., Savin, R. & Slafer, G.A.** 2009. In: Sixteenth Nitrogen Workshop. Turin, Italy, 2009).

28. **Ryan, J., Ibrikci, H., Sommer, R. & McNeill, A.** 2009. *Adv. Agron*. 104, 53.

29. **Sharma, R.C.** 2009. In *Crop physiology: applications for genetic improvement and agronomy*, Sadras, V.O., Calderini, D.F. (eds). San Diego, United States, Academic Press, pp. 99-119.

30. **Bouman, B.A.M., Humphreys, E., Tuong, T.P. & Barker, R.** 2006. *Adv. Agron*. 92, 187.

31. **Farooq, M., Kobayashi, N., Wahid, A., Ito, O. & Basra, S.M.A.** 2009. *Adv. Agron*. 101, 351.

32. **Kato, Y., Okami, M. & Katsura, K.** 2009. *Field Crops Res*. 113, 328.

33. **Sadras, V.O. & Angus, J.F.** 2006. *Aust. J. Agric. Res*. 57, 847.

34. **R.J. & Schultz, J.E.** 1984 *Aust. J. Agric. Res*. 35, 765.

35. **R.J. & Schultz, J.E.** 1984. *Aust. J. Agric. Res*. 35, 743.

36. **Angus, J.F. & van Herwaarden, A.F.** 2001. *Agron*. J. 93, 290.

37. **Siddique, K.H.M., Tennant, D., Perry, M.W. & Beldford, R.K.** 1990. *Aust. J. Agric*. Res. 41, 431.

38. **Slafer, G.A., Satorre, E.H. & Andrade, F.H.** 1994. In *Genetic improvement of field crops,* Slafer, G.A. (ed). New York, Marcel Dekker, pp. 1-68.

39. **Holloway, R.E. & Alston, A.M.** 1992. *Aust. J. Agric. Res*. 43, 987.

40. **Halvorson, A.D. & Reule, C.A.** 1976. Regional Saline Seep Control Symposium Proceedings. Bulletin No 1132, Montana State University (Mont.), 115.

41. **Sadras, V.O., Baldock, J., Roget, D.K. & Rodriguez, D.** 2003. *Field Crops Res*. 84, 241 (2003).

42. **Mercau, J.L. *et al.*** February 2001. *Agric. Syst*. 67, 83.

43. **Grassini, P., Indaco, G.V., Pereira, M.L., Hall, A.J. & Trapani, N.** 2007. *Field Crops Res*. 101, 352.

44. **Bono, A. Montoya, J.C. & Babinec, F.** 1999. Publicación Técnica #48, EEA Anguil, INTA, Argentina.

45. **López Pereira, M., Sadras, V.O. & Trápani, N.** 1999. *Field Crops Res*. 65, 157.

46. **M. Mainuddin, M. Kirby**, *Agric Water Manag* 96, 1567 (2009).

47. **USDA.** No date. Crops, US State and county databases. United States Department of Agriculture–National Agricultural Statistics Service, 2000-2009.

48. **Grassini, P., Thorburn, J., Burr, C. & Cassman, K.G.** 2011. Field Crops Res. *Field Crops Res*. 120, 142-150.

49. **Grassini, P., Yang, H.S. & Cassman, K.G. Agric.** 2009. *Forest Meteorol*. 149, 1254.

50. **Lyon, D.J., Hammer, G.L., McLean, G.B., & Blumenthal, J. M.** 2003. *Agron. J*. 95, 884.

51. **M. J. Burgert, University of Nebraska** (2009).

52. **Grassini, P., Yang, H., Irmak, S., Thorburn, J., Burr, C. & Cassman, K.G.** 2011. *Field Crops Res*. 120, 133-141.

53. **Rockström, J., Barron, J., Brouwer, J., Galle, S. & DeRouw, A.** 1999. *Soil. Sci. Am*. J. 63, 1308.

54. **Rockström, J., Jansson, P.E. & Barron, J.** 1998. *Journal of Hydrology* 210, 68.

55. **Payne, W.A. Wendt, C.W. & Lascano, R.J.** 1 July 1990. *Agron. J*. 82, 813.

56. **Bley, J., Van Der Ploeg, R.R., Sivakumar, M.V.K. & Allison, B.E.** 1991. Soil water balance in the Sudano-Sahetian Zone. Proceedings of the Niamey Workshop, February 1991. IAHS Publ. No. 199, 571.

57. **Fechter, J., Allison, B.E., Sivakumar, M.V.K., Van Der Ploeg, R.R. & Bley, J.** 1991. Soil Water Balance in the Sudano-Sahetian Zone. Proceedings of the Niamey Workshop, February 1991. IAHS Publ. No. 199, 505.

58. **Maman, N., Lyon, D.J., Mason, S.C., Galusha,T.D. & Higgins, R.** Nov-Dec, 2003. *Agron. J. 95*, 1618.

59. **Fischer, R.A.** 2009. In *Crop physiology: applications for genetic improvement and agronomy*, Sadras, V.O.,

Calderini, D.F. (eds). San Diego, United States, Academic Press, pp. 23–54.

60. **Farre, I. & Faci, J.M.** May 2006. *Agric Water Manag*. 83, 135.

61. **Mastrorilli, M., Katerji, N. & Rana, G.** 1995. *Agric Water Manag*. 28, 23.

62. **Stewart, B.A., Musick, J.T. & Dusek, D.A.** 1983. *Agron. J*. 75, 629.

63. **Stone, L.R., Goodrum, D.E., Jaafar, M.N. & Khan, A.H.** 2001. *Agron. J*. 93, 1105.

64. **Chaudhuri, U.N., Kanemasu, E.T.** 1985. *Field Crops Res*. 10, 113.

65. **Blum, A.** 1972. *Agron. J*. 64, 775.

66. **Zwart, S.J. & Bastiaanssen, W.G.M.** 2004. *Agric Water Manag*. 69, 115.

67. **Suyker, A.E. & Verma, S.B.** 2009. *Agric. Forest Meteorol*. 149, 443.

68. **Dardanelli, J.L., Suero, E.E., Andrade, F.H. & Andriani, J.** 1991. *Agronomie* 11, 747.

69. **Casa, R. & Lo Cascio, B.** Aug. 2008. *J Agron Crop Sci* 194, 310.

70. **Hocking, P.J., Kirkegaard, J. A., Angus, J.F., Gibson, A.H. & Koetz, E.A.** 1997. *Field Crops Res*. 49, 107.

71. **Gunasekera, C.P., French, R.J., Martin, L.D. &. Siddique, K.H.M.** 2009. *Crop and Pasture Science* 60, 251.

72. **Robertson, M. & Kierkegaard, J.A.** 2005. *Aust. J. Agric. Res*. 56, 1373.

73. **Loss, S.P., Siddique, K.H.M. & Tennant, D.** 1997. *Field Crops Res*. 54, 153.

74. **Siddique, K.H.M. & Sedgley, R.H.** 1986. *Aust. J. Agric. Res*. 37, 599.

75. **Siddique, K.H.M., Regan, K.L., Tennant, D. & Thomson, B.D.** 2001. *Eur. J. Agron*. 15, 267.

76. **Zhang, H., Pala, M., Oweis, T. & Harris, H.** 2000. *Aust. J. Agric. Res*. 51, 295.

77. **Oweis, T.** 2004. *Agric. Water Manag*. 68, 251.

78. **Oweis, T., Hachum, A. & Pala, M.A.W.M.** 2005. 73, 57.

79. **Grassini, P., Hall, A.J. & Mercau, J.L.** 2009. *Field Crops Res*. 110, 251.

80. **Payne, W.A.** 2000. *Agron. J*. 92, 808.

81. **Bouman, B.A.M., Tuong, T.P.** 2001. *Agric Water Manag*. 49, 11.

82. **Belder, P. *et al.*** 2005. *Plant Soil* 273, 167.

83. **Kim, K.I., Clay, D.E., Carlson, C.G., Clay, S.A., Trooien, T.** 2008. *Agron. J*. 100, 551.

84. **Bouman, B.A.M., Peng, S., Castañeda, A.R., Visperas, R.M.** 2005. *Agric Water Manag*. 74, 87.

85. **Anderson, R.L. & Greb, B.W.** 1987. *Crop Prot* 6, 61.

86. **Chaudhuri, U.N. & Kanemasu, E.T.** 1985. *Field Crops Res*. 10, 113.

87. **Akponikpe, P.B.I. Dr.** 2008. Université Catholique de Louvain.

88. **Manyame, C.** 2006. Texas A&M University. (Ph.D. Thesis)

89. **Kassam, A.H. & Kowal, J.M.** 1975. *Agric. Meteorol*. 15, 333.

90. **Nouri, M. & Reddy, K.C.** 1991. Soil Water Balance in the Sudano-Sahetian Zone (Proceedings of the Niamey Workshop, February 1991). IAHS Publ. No. 199, 421.

91. **Gaber, A.M., Gaber, E.I., El-Hassanin, A.S. & El-Boraie, F.M.** 2006. Second International Conference on Water Resources & Arid Environment, 1.

92. **Payne, W.A.** 1997. *Agron. J*. 89, 481.

93. **Payne, W.A.** 1999. *Soil Sci Soc Am J*. 63, 972.

94. **Sivakumar, M.V.K.** 1990. *Agric. Forest Meteorol*. 51, 321.

95. **Grema, A.K. & Hess, T.M.** 1994. *Agric. Water Manag*. 26, 169.

96. **Oluwasemire, K.O., Stigter, C.J., Owonubi, J.J. & Jagtap, S.S.** 2002. *Agric Water Manag*. 56, 207.