Benchmarking water productivity in agriculture and the scope for improvement

remote sensing modelling from field to global scale

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Summary

Due to the rapid growth in world population, the pressure on water resources is increasing. In the future less water will be available for agricultural production due to competition with the industrial and domestic sectors, while at the same time food production must be increased to feed the growing population. It is inevitable that the production per unit water consumed, the water productivity, must be increased to meet this challenge. Till start of this research, little was known on the current levels of water productivity in agriculture. Information is outdated or measured values are made in small experimental plots that are not representative for the situation in farmer's fields.

This research will therefore focus on the benchmarking of physical water productivity and gaining a better understanding of the spatial variations and the scope for improvement. The major goal of this research was to benchmark water productivity values globally and at various scales (field level, system level and global level). A review of the literature sources that provide measurements of water productivity was conducted to assess plausible ranges of water productivity levels for wheat, maize, cotton and rice. Remote sensing and modelling were the major tools applied for this work to assess the spatial variation of water productivity of wheat at system and global level, and to provide a first explanation for the differences that are found.

The first step was to establish a water productivity database for the four major crops in the world, namely wheat, rice, cotton and maize. Results form field experiments that were reported in international literature in the recent 25 years were synthesized in a data base to provide up-to-date ranges of feasible water productivity values. The ranges found were higher than those reported some 25 years earlier in the FAO33 publication by Doorenbos and Kassam (1979). For example, this research provides a plausible range of 0.6 - 1.7 kg m^{-3} for the water productivity of wheat (with an average of 1.1 kg m^{-3}), whereas a much lower range of 0.8 - 1.0 was provided by FAO33 in the 1970's. Also for the other three researched crops it was found that the water productivity values in FAO33 are on the conservative side. This might partially be related to the development of crops that are able to produce higher yields and to improved soil fertility and water management.

Spatial information on water use, crop production and water productivity will play a vital role for water managers to assess where scarce water resources are wasted and where in a given region the water productivity can be improved. A methodology has been developed to quantify spatial variation of crop yield, evapotranspiration and water productivity using the SEBAL algorithm and high and low resolution satellite images. SEBAL-based actual evapotranspiration estimates were validated over an irrigated, wheat dominated area in the Yaqui Valley, Mexico and proved to be accurate (8.8% difference for 110 days). Estimated average wheat yields in Yaqui Valley of 5.5 ton ha^{-1} were well within the range of measured yields reported in the literature. Area average water productivity in the Yaqui Valley was 1.37 kg m^{-3} and could be considered to be high as compared to other irrigated systems around the world where the same methodology was applied. A

higher average value was found in Egypt's Nile Delta (1.52 kg m^{-3}), Kings County (CA), USA (1.44 kg m^{-3}) and in Oldambt, The Netherlands (1.39 kg m^{-3}). The spatial variability of water productivity within low productivity systems (CV=0.33) is higher than in high productivity systems (CV=0.05) because water supply in the former case is uncertain and farming conditions are sub-optimal. The high CV found in areas with low water productivity indicates that there is considerable scope for improvement. The average scope for improvement in eight systems was 14%, indicating that 14% reduction in water cinsumption can be achieved while maintaining the same yield.

The WATer PROductivity (WATPRO) model was developed to assess water productivity of wheat on a global scale. WATPRO is based on remote sensing-derived input data sets and can be applied at local to global scales. The model is a combination of Monteith's theoretical framework for dry matter production in plants and an energy balance model to assess actual evapotranspiration. It is shown that by combining both approaches, the evaporative fraction and the atmospheric transmissivity, two parameters which are usually difficult to estimate spatially, can be omitted. Water productivity can then be assessed from four spatial variables: broadband surface albedo, the vegetation index *NDVI*, the extraterrestrial radiation and air temperature.

The WATPRO model was applied at 39 locations where water productivity was measured under experimental conditions. The correlation between measured and modelled water productivity was low, and this can be mainly attributed to differences in scales and in the experimental and modelling periods. A comparison with measurements from farmer's fields in areas surrounded by other wheat fields located in Sirsa District, NW India, showed an improved correlation. Although not a validation, a comparison with SEBAL-derived water productivity in the same region in India proved that WATPRO can spatially predict water productivity with the same spatial variation.

WATPRO was applied with global data sets of the *NDVI* and surface albedo to benchmark water productivity of wheat for the beginning of this millennium. Time profiles of the *NDVI* were used to determine the growing season from crop emergence to harvest on a pixel basis. The WATPRO results were compared with modelling information by Liu et al. (2007) who applied the GEPIC model at a global scale to map water productivity, and by Chapagain and Hoekstra (2004) who used FAO statistics to determine water productivity per country. A comparison with Liu et al. showed a good correlation for most countries, but the correlation with the results by Chapagain and Hoekstra was less obvious. It was found that water productivity varies from approximately 0.2 to 1.8 kg of harvestable wheat per cubic metre of water consumed. From the 10 largest producers of wheat, France and Germany score the highest country average water productivity of 1.42 and 1.35 kg m^{-3} respectively.

The global patterns of the water productivity map were compared with global data sets of precipitation and reference evapotranspiration to determine the impact of climate and of water availability reflected by precipitation. It appeared that the highest levels of water productivity are to be expected in temperate climates with high precipitation. Due to its non-linear relationship with precipitation, it is expected that large gains in water productivity can be made with rain water harvesting or supplemental irrigation in dry areas with low seasonal precipitation. Investing in rain water harvesting techniques and/or systems for supplemental irrigation, in combination with improved agronomic management and the use of fertilizers, may give a significant boost to the productive use of water resources within a basin. A full understanding of the spatial patterns by country or river basin will support decisions on where to invest and what measures to take to make agriculture more water productive.

List of symbols

$APAR$	absorbed photosynthetical active radiation (MJ m^{-2})
DM	above ground dry mater production (g m^{-2})
ET_{act}	actual evapotranspiration (mm day^{-1})
ET_{max}	maximum evapotranspiration (mm day^{-1})
f	APAR/PAR fraction (-)
G_0	soil heat flux (W m^{-2})
H	sensible heat flux (W m^{-2})
H_i	harvest index (-)
I	applied irrigation water (mm)
k_y	crop yield response factors (-)
$NDVI$	normalized difference vegetation index (-)
PAR	photosynthetical active radiation (MJ m^{-2})
r_{av}	aerodynamic resistance to water vapour transport (s m^{-1})
r_s	bulk surface resistance (s m^{-1})
$r_{s,min}$	minimum bulk surface resistance (s m^{-1})
R_n	net radiation (W m^{-2})
s_a	slope of the saturated vapour pressure curve (mbar K^{-1})
$S^{\downarrow}_{EXO}$	extraterrestrial radiation (W m^{-2})
$S^{\downarrow}_{IN}$	incoming shortwave radiation (W m^{-2})
T_{act}	actual transpiration (mm day^{-1})
T_{max}	maximum transpiration (mm day^{-1})
T_{mon}	monthly average air temperature (^{o}C)
T_{opt}	T_{mon} for period with maximum leaf area index (^{o}C)
W	water scalar (-)
WP_{ET}	water productivity (kg m^{-3})
Y_{act}	harvestable/marketable yield (kg m^{-2})
Y_{max}	maximum harvestable/marketable yield (kg m^{-2})
α	broadband surface albedo (-)
ε	light use efficiency (g MJ^{-1})
$\varepsilon_{\max}$	maximum light use efficiency (g MJ^{-1})
θ_{grain}	grain water content fraction (-)
λE	latent heat flux (W m^{-2})
Λ	evaporative fraction (-)
τ_{SW}	atmospheric transmissivity (-)
φ	psychometric constant (mbar K^{-1})
Φh	stomatal response to ambient temperature (-)
χ	PAR / $S^{\downarrow}_{EXO}$ fraction (-)

Contents

1 Introduction

1.1 Food and water in a changing world

In recent decades the world's human population has shown tremendous growth from an estimated 2.5 billion in the 1950's to approximately 6.7 billion to date. The continents where the majority of this growth has taken place include Asia, Africa and Latin America. This growth is expected to continue: it is predicted that the global population may even reach 9.1 billion by 2050 (United Nations Population Division, 2009). Although the growth rates have diminished in many countries, strong growth will continue in developing countries located in sub-Saharan Africa,. A major challenge for the coming years is to provide a secure food supply to all newcomers. It is believed that currently around 850 million people are already undernourished, and the demand for food is growing. Due to increased welfare, people are changing to more nutritious diets, and therefore the demand for food is growing even faster than the growth in population. Food security is at stake and international organisation such as the Food and Agriculture Organization (FAO), the World Bank and the United Nations are calling for action. Recently the FAO argued that global food production will have to increase 70 percent for an additional 2.3 billion people by 2050 (FAO, 2009). Moreover, the effects of climate change, such as rising temperatures and more erratic rainfall patterns, and the recent focus on biofuel production both represent major risks for long-term food security and water availability (De Fraiture *et al*., 2008). The latter issue emerged, for example, in 2008 when food prices sharply increased by 50%, partially as a result of the competing demands for agricultural lands for biofuels, resulting in protests and riots throughout the world.

By 1798, it was already predicted by British economist Malthus that the world would face a food crisis. In his theory on hunger, Malthus predicted an exponential growth of the population, whereas the food supply would only grow arithmetically (Malthus, 1798). At a certain point in history, population growth would outpace food production, and the world would be swept by hunger and stricken by wars. Malthus' theory has, however, yet to come true. So far, on a global scale, the world's population has increased at a tremendous rate as predicted by Malthus, but technological advances have likewise increased food production. These technological advances have included the widespread use of artificial fertilizers, breeding efforts to develop high yielding hybrid crop varieties, large scale development of irrigation systems, and the increasing use of machines in the production of food. This so called "Green Revolution", which started in the 1950s in Mexico and rolled out around the globe in the decades thereafter, was a massive, coordinated effort to transfer these latest advances in agricultural technology from developed countries to the developing world. It resulted in a strong increase in food production. Today this process continues in the genetic modification of crops to reduce the risk of failure, though it is not believed that this development will impact water productivity significantly. The success of the Green Revolution in the past decades depended on ample amounts of fresh water and arable land, both of which are now in short supply. Agricultural lands are degrading due to salinization and erosion, and urbanization also claims fertile lands. Most mega-cities are located on alluvial plains with highly fertile soils which are considered best suited to agricultural production.

That fresh water resources are not infinite is clearly demonstrated in river basins where, through increased water withdrawals for the expansion of irrigated agricultural areas, rivers fail to reach the sea, i.e. closed basins. Typical issues in such closed basins are environmental degradation (water quality reduction, loss of biodiversity), declining ground water tables, intrusion of seawater in estuaries and aquifers, and deterioration of the ecological state of wetlands (Molle *et al*., 2010). River discharges have dropped significantly in many basins, and insufficient water is available to meet the competing demands from various other users. Industries and the tourist sector are demanding more water, and growing populations require more water for domestic use. The production of food in agricultural systems, whether in rainfed or irrigated areas, takes water from the system that is not available for later reuse. Water disappears into the air through evaporation from the surface and transpiration from plants. It is estimated that approximately 80% of the global evapotranspiration budget comes from rainfed areas, whereas the remaining 20% comes from irrigated agriculture (De Fraiture and Wichelns, 2010). To supply water to agricultural fields for the evapotranspiration process, water is diverted from rivers, pumped from groundwater reservoirs, or harvested from the rain. Excess water infiltrates the soil and returns to the system where it may be available for reuse (Perry, 2007). It is estimated that globally agriculture accounts for approximately 70% of total water diversions (Comprehensive Assessment of Water Management in Agriculture, 2007).

In the context of a changing climate, a growing population, an affected ecology and increasing competition for water, it is therefore unlikely that agriculture can secure a larger share of the already highly exploited fresh water resources. With the limits of the Green Revolution being reached, and the fresh water resources unsustainably exploited, international research and development organizations are opting to increase the productivity of water in agriculture to sustain and improve food security for the coming generations. This strategy is more popularly stated: *to produce more crop per drop* (Kijne *et al*., 2003). In a broader sense, increasing the productivity of water means getting more value from each drop of water. Water may be used for growing crops, but also for cultivating fish, keeping livestock or for forestry. With agriculture being the largest consumer of water, the largest gains in water production are expected to be made in this sector. Questions that are raised are whether we can save water for other users while maintaining food production, or whether we can increase food production from the same amount of water (Postel, 1998).

1.2 The scientific approach on food and water

The relationship between agricultural production and water consumption through evapotranspiration is complex. It is affected by numerous growing conditions, such as climate, agronomic practices, soil type and fertility, and crosses scales varying from individual plants to farmer fields, river basins, nations and the global level. Since the 1900's the food production-water consumption relationship has been investigated by scientists from different backgrounds and with different interests. As a result of these different points of views by scientists or engineers, and the different scales of application, many definitions of water productivity exist in scientific publications. The water consumption and the production parts of the water productivity function are therefore defined in several ways (Molden *et al*., 2003).

Plant physiologists and breeders have analysed photosynthesis or dry matter production in relation to the plant's transpiration, which can be considered the true water consumption for production. However, at field level it is inevitable that water is also lost though the evaporation process from soil. Soil and crop scientists therefore commonly define evapotranspiration as water consumption, and express crop production as harvestable yields of grains or fruits, for example. At farm level, farmers aim at maximizing or optimizing the agricultural output, defined as total harvestable yield or economic profit. Agricultural engineers and economists define water productivity at farm level in terms of economic benefit in relation to evapotranspiration or irrigation water supply. Similarly irrigation engineers consider water deliveries, or water depletion and the available water at the irrigation system level to evaluate the economic benefit of water diversions. Numerous irrigation indicators are available to evaluate the system's conveyance, distribution and applications of water to fields. These relate the total crop water use or the beneficial crop water use to water availability from irrigation water diversions and/or from (effective) precipitation (Bos *et al*., 2005).

In the beginning of the 20th century agricultural scientists from the United States started to look at the relationship between water use and dry matter production. Calculation of evapotranspiration in field experiments proved to be quite unreliable since certain components of the water balance could not be determined at all, or could only be estimated roughly. Most experiments at that time were conducted in pots, and by covering the soil surface, transpiration could be determined with greater certainty. Pioneering work was conducted by Briggs and Shantz (1913) who determined for lucerne a transpiration ratio, defined as the amount of water required to grow a certain dry weight of crop. One of the conclusions drawn by many and summarized by De Wit (1958), based on a synthesis of experimental results, was that solar radiation played a dominant role in determining the levels of both yield and transpiration, especially when water is non-limiting. Similar conclusions were drawn by Stanhill (1960) who plotted linear relations between cumulative dry matter production and cumulative evapotranspiration of grass grown at different latitudes. The highest slopes, and thus the highest water use efficiencies, were found in locations at higher latitudes (Denmark, Netherlands, England), and the lowest ones in Israel and Trinidad.

With the development of new and better equipment, such as climate-controlled glass houses and electronic equipment, more accurate measurements could be carried out. Bierhuizen and Slatyer (1965) conducted experiments on cotton leaves where airstreams with fixed temperature, humidity and CO_2 concentrations were passed through a leaf chamber. Photosynthesis and transpiration were measured as the difference in CO_2 and water vapour concentrations of air before and after passing through the leaf chamber. Using this experimental setup, the transpiration efficiency under different levels of air temperature, wind speed, CO_2 concentration and light intensities could be determined with higher accuracy. They were the first to claim and prove that transpiration and photosynthesis (and thus the transpiration efficiency) were more controlled by evaporative demand from the air, expressed as the vapour pressure deficit, than by radiation regimes or by latitude as claimed by De Wit (1958) or Stanhill (1960). This conclusion was later confirmed in a thorough review by Tanner and Sinclair (1983) who defined the water productivity relation as the transpiration efficiency which is the reciprocal of the transpiration ratio.

With the Green Revolution at its peak, numerous programmes were set up at universities and national research organizations to determine the optimal growing conditions for maximizing crop yields in farmer's fields. Whereas most experimental results from the first half of the 20th century originated from the western countries, the focus shifted to the developing countries in the later decades. International research organizations were established with large campuses to develop new crop varieties, make them available to the local farmers, and to provide optimal irrigation and fertilizer application strategies applicable to local conditions. Examples are the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India, and the International Rice Research Institute (IRRI) in the Philippines.

With water resources being abundantly available in most new or expanding irrigation systems, research focussed on maximizing crop yields for farmers by meeting the maximum crop water demands. Several models were developed that describe the relation between crop production and water use, with the purpose of determining the effect of crop water stress on yields. For example Hanks (1974) linearly relates yields (Y_{act}) to transpiration (T_{act}), with the maximum attainable yields (Y_{max}) under maximum transpiration (T_{max}):

$$\left(\frac{Y_{act}}{Y_{\max}}\right)=\left(\frac{T_{act}}{T_{\max}}\right) \qquad 1.1$$

FAO research paper 33 on yield response to water (Doorenbos and Kassam, 1979) provided a simple method to assess the impact of crop water stress on yield reduction for more than 25 crops. Water stress is determined as the difference between the actual evapotranspiration (ET_{act}) and the evapotranspiration when crop requirements are met (ET_{max}). These are linearly related to crop yield (Y_{act}) under certain conditions, and maximum yields (Y_{max}) under optimal conditions (Stewart *et al.*, 1977):

$$\left(1-\frac{Y_{act}}{Y_{\max}}\right)=k_y\left(1-\frac{ET_{act}}{ET_{\max}}\right) \qquad 1.2$$

where k_y is the crop-dependent empirical yield response factor. A major drawback of both frameworks is the need to estimate ET_{max}, T_{max} and Y_{max}. *These* are difficult to estimate under actual field conditions and agronomic management conditions. In many publications, ET_{max} is considered equal to the potential evapotranspiration (ET_{pot}), whereas Y_{max} is usually considered as the maximum yield obtained in an experimental set-up. This FAO33 method, which assumes a linear relationship between ET_{act} and Y_{act}, is, however, still commonly applied in irrigation design and operation, and referred to in scientific literature (see e.g Istanbulluoglu, 2009; Abou Kheira, 2009; Payero *et al*., 2009). The FAO33 publication was, however, the first to provide average water productivity values, defined as 'water utilization efficiency for harvested yield' or Y_{act} divided by ET_{act} , for more than 25 different crops.

In recent decades water productivity (or water use efficiency) has shifted from being a by-product of the developed strategies for maximizing crop yields per unit land, to a means to express the efficiency of plants or farmers to use scarce water resources for food production. Growing pressure on fresh water resources gave a new direction to the water productivity concept. Purposely reducing irrigation water applications and stressing crops to achieve higher water productivity (deficit irrigation) was introduced as a means of saving water (Fereres and Soriano, 2007). During particular growth periods, crop water stress is induced, thereby reducing final crop yields, but also reducing evapotranspiration and increasing water productivity. This is an entirely different approach to earlier high intensity irrigation strategies based on entirely meeting crop water demands and keeping the root zone wet. Other agronomic management options are also adopted to increase water productivity, such as using plastic or mulch soil covers, optimizing planting distance, adjusting planting date and growing season, soil tillage, and optimal fertilization rates.

As a response to these changing strategies, the FAO introduced the AquaCrop toolbox[1] in 2009 as a revision of the previously mentioned FAO33 publication. AquaCrop is a crop water productivity model that simulates the yield response to water and that is particularly suited to function under water scarce conditions (Steduto *et al*., 2009). The model simulates biomass production, which is converted into fresh crop yields using a harvest index that is adjusted for water and heat stress during the growing season. As shown by Steduto *et al*. (2007), biomass production shows a remarkable linear relation with crop transpiration when normalised for the climatic demand quantified by the reference evapotranspiration (preferred to the vapour pressure deficit). This theory is used to assess climate adjusted water productivities. Moreover, in line with the recent focus on beneficial and non-beneficial water use, this model allows separation of beneficial transpiration from non-beneficial evaporation.

Recent attention by scientists to water shortages and improving water productivity has increasingly focussed on river basins, rather than on fields, farms or irrigation districts. By considering river basins, policies, measures and interventions for water savings at more local level can be placed in a wider context that accounts for impacts on downstream water users, such as wetlands, irrigation systems or industries A saving in diverted irrigation water at field level may not necessarily lead to more water being available at basin level, since excess applied water usually returns to the system for reuse. Exceptions occur when water quality deteriorates, or when water flows to the sea or to evaporation ponds. These are called the sinks in a system (Seckler, 1996). Measures for

[1] http://www.fao.org/nr/water/aquacrop.html

saving water in agriculture should therefore focus on reducing the real losses in a basin, such as evapotranspiration from agricultural lands, rather than on saving water diverted from rivers that can be later reused. This is described by Keller and Keller (1995) as dry and wet water savings, where the latter is a real water saving where more water becomes available to other users. At basin level, water can thus be saved by reducing water losses to sinks or by reducing the pollution of water. Measures are advocated where the output of agriculture per unit of water evapotranspired is promoted, or in other words where the water productivity is increased (Comprehensive Assessment of Water Management in Agriculture, 2007).

1.3 The contribution of this research

The importance of the water productivity concept for food security in a world where water resources are rapidly being exhausted, has been outlined in the previous two paragraphs. An uncountable number of publications has been published in which experimental results on yields, water consumption and/or water productivity are reported. These studies are conducted in small fields representing local conditions in specific years under varying seasonal weather conditions. The impact of weather conditions on water productivity levels, in particular the evaporative demand defined by either the vapour pressure deficit or the reference evapotranspiration, is stressed by many authors. However, the plausible ranges of water productivity on a global level are poorly understood. The latest overview for various crop was presented in the FAO33 publication, but it is realised that in recent decades crops have been improved, and it is likely that the reported ranges have altered in a positive way. Moreover the question can be raised whether a system is performing well with respect to water productivity or whether improvements can still be achieved. This is particularly of interest to governments, donors and water managers, who would like to know whether a system is performing well, and whether there is scope for improvement. Farmers also realize that lower water use in crops contributes to their own sustainability.

Measurements within a system are location dependent and may not represent the overall system performance. Remote sensing, the use of satellite images and spatial modelling have been tested and applied over the last thirty years to assess evapotranspiration and yields. Time series analysis of satellite images allows accurate spatial estimation of yields and evapotranspiration over large areas and at high spatial detail. This information will be used to assess and benchmark water productivity and the scope for improvement in various systems. On a global level such spatial information is not available, but relevant to understanding where crops can be grown most efficiently with regards to their climate, and where improvements are still feasible.

This research will therefore focus on the benchmarking of physical water productivity, i.e. the amount of agricultural production (harvestable yield) that can be attained per unit of water evapotranspired, rather than on the economic water productivity where the production term is replaced by a revenue or profit. The major goal of this research is to benchmark water productivity values globally and at various scales (field level, system level and global level), which at the start of this thesis was unavailable. Remote sensing and modelling are the major tools applied for this work to assess the spatial variation of water productivity of wheat at system and global level, and to provide a first explanation for the differences that are found. A review of the literature sources that provide measurements of water productivity is conducted to assess plausible ranges of water productivity levels for wheat, maize, cotton and rice.

1.4 Thesis outline

The research in this thesis follows the steps in scale that were described before. The next chapter provides a literature review of experiments where water productivity of wheat, rice, cotton and maize, the major staple crops, were measured. These results were consolidated in a database, and current benchmark levels of water productivity for the four crops were established. An initial explanation of the large variation found in the experimental results was provided by linking water productivity to climate conditions and to variations in the applied amounts of irrigation water and fertilizers. The large variation also underlines the necessity of mapping water productivity at a regional scale, but at high resolution. The third chapter provides a methodology that allows mapping of water productivity using the SEBAL algorithm applied to low and high resolution satellite imagery. This methodology was tested and validated in the wheat dominated Yaqui Valley region in north-western Mexico, and thereafter applied in seven other wheat regions in the Netherlands, Pakistan, India, China, Egypt and the United States. A statistical method based on the coefficient of variation was used to determine the scope for improvement in water productivity with the purpose of quantifying the potential for water savings. Finally, the thesis moves up to the global level in chapters 4 and 5 with the purpose of benchmarking the water productivity of wheat globally at a high spatial resolution with the use of remote sensing data sets. The WATer PROductivity (WATPRO) model is developed, based on the same principles underlying the evapotranspiration and biomass production modules in SEBAL. The development of the model, the inherent simplifications and assumption that were required, and the validation are outlined in chapter 4. Chapter 5 describes the application of the WATPRO model at a global scale to benchmark wheat water productivity. The resulting map was compared with earlier water productivity modelling efforts from two different sources. Variations in water productivity were attributed to variations in seasonal precipitation from standard TRMM products, and to differences in seasonal reference evapotranspiration. This thesis ends with conclusions on water productivity benchmark values at different scales synthesized from the previous chapters.

2 Review of measured water productivity values for irrigated wheat, rice, cotton and maize*

2.1 Introduction

With a rapidly growing world population, the pressure on limited fresh water resources increases. Irrigated agriculture is the largest water-consuming sector and it faces competing demands from other sectors, such as the industrial and the domestic sectors. With an increasing population and less water available for agricultural production, the food security for future generations is at stake. The agricultural sector faces the challenge to produce more food with less water by increasing crop water productivity (see Kijne *et al*., 2003a for a review). A higher water productivity results in either the same production from less water resources, or a higher production from the same water resources, so this is of direct benefit for other water users. In this study water productivity (WP_{ET} in kg m^{-3}), which is originally referred to in literature as 'water use efficiency', is defined as the marketable crop yield over actual evapotranspiration:

$$WP_{ET} = \frac{Y_{act}}{ET_{act}} \text{ (kg m}^{-3}\text{)} \qquad (2.1)$$

where Y_{act} is the actual marketable crop yield (kg ha^{-1}) and ET_{act} is the seasonal crop water consumption by actual evapotranspiration (m^3 ha^{-1}). When considering this relation from a physical point of view, one should consider transpiration only. The portioning of evapotranspiration in evaporation and transpiration in field experiments is, however, difficult and therefore not a practical solution. Moreover, evaporation is always a component related to crop specific growth, tillage and water management practices, and this water is no longer available for other usage or reuse in the basin. Since evapotranspiration is based on root water uptake, supplies from rainfall, irrigation and capillary rise are integrated.

Despite that water productivity is a key element in longer-term and strategic water resources planning, the actual and practically feasible values are hardly understood. The most complete international work so far is compiled by Doorenbos and Kassam (1979), who used crop yield response factors (k_y) for relating ET_{act} to Y_{act}. The problem with the standard 'FAO33-approach' is that the maximum yield ought to be known, which differs for given cultural practices. This implies that $Y_{act} = f(k_y, Y_{pot}, ET_{act}, ET_{max})$ is not straightforward, although it is often applied in absence of alternative expressions.

Kijne *et al*. (2003b) provide several strategies for enhancement of water productivity by integrating varietal improvement and better resources management at plant level, field level and agro-climatic level. Examples of options and practices that can be taken are: increasing the harvest index, improving drought tolerance and salinity tolerance (plant

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level), applying deficit irrigation, adjusting the planting dates and tillage to reduce evaporation and to increase infiltration (field level), water reuse and spatial analysis for maximum production and minimum ET_{act} (agro-ecological level), to mention a few.

Due to agronomical research (e.g. plant breeding) and improved land and water management practices, water productivity has increased during the years. For example Grismer (2002) conducted a study on water productivity values for irrigated cotton in Arizona and California and concluded that water productivity values exceed the range given by Doorenbos and Kassam (1979) in many cases. In rice production water productivity increased due to shorter growing periods (Tuong, 1999) and due to increase in the ratio of photosynthesis to transpiration (Peng *et al*., 1998). It is likely that water productivity for other crops has changed significantly as well.

Various studies have researched water use and yield relationship of specific crops, on specific locations, with specific cultural and water management practices. The current investigation summarizes the results of field experiments that have been conducted over the last 25 years and tries to find a range of plausible values for four major staple crops: wheat (*Triticum aestivum L.*), rice (*Oryza sativa L.*), cotton (*Gossypium spp.*) and maize (*Zea mays L.*). The second objective of this paper is to find some first order explanatory variables for the global scale water productivity differences found.

Database and terminology

A database is established with water productivity data collected from field experiments that were reported in the international literature, conference proceedings and technical reports. The majority of field experiments was conducted at experimental stations under varying growing conditions, including variations in climate, irrigation, fertilization, soils, cultural practices, etc. As the purpose of this research is to find plausible water productivity ranges under farm management conditions, all measured water productivity values of an experiment are included in the database.

To be included in the database, the results of the experiments should provide minimally the total seasonal measured actual evapotranspiration (ET_{act}), the method applied to determine ET_{act} and the crop yield, Y_{act}. Most studies do not measure ET_{act} and use the potential evapotranspiration (ET_{pot}) instead. These studies are not incorporated into the database and, hence, not used and discussed in this paper. Results from greenhouse experiments, pot experiments and water balance simulation models were excluded. Also, experiments based on the reference evapotranspiration method (Allen *et al.*, 1998) has not been regarded as being suitable for the current review; evapotranspiration is not measured, but estimated.

Lysimeters are a common instrument for determining ET_{act}. The soil water balance methods that monitor soil water content during the growing season by measurements of gravimetric soil moisture, or by neutron scattering equipment (neutron probes) or by Time-Domain-Reflectometry (TDR), is also often used. Micro-meteorological *in situ* flux measurement techniques, such as the Bowen ratio and eddy-correlation methods are not common for agronomical studies (they are mainly used for micro-meteorological and climate studies in which yield is not reported).

Yield is defined as the marketable part of the total above ground biomass production; for wheat, maize and rice total grain yield is considered, and for cotton the total lint yield and/or total seed yield. Unfortunately, very few sources give the moisture content at which the yield was measured, which inevitably means an error exists in the final results. Siddique *et al*. (1990) investigated water productivity of old and new wheat cultivars and found that older cultivars have lower water productivity values due to lower harvest index. No significant difference in total biomass production between the old and new cultivars was found. For example in rice production water productivity increased throughout the years due to developments in the new plants types with a higher ratio of photosynthesis to transpiration and due to a decrease in growth period (Peng *et al*., 1998; Tuong, 1999). Thus, experiments with results older than approximately 25 years are excluded to minimize the influence of older varieties with lower harvest index and longer growth period.

The results of experiments were first re-organized into a crop-wise database, that includes latitude/longitude, country, location, ET_{act}, Y_{act}, biomass production, harvest index, experimental year(s) and reference. Some of the references cited provide the results of each field experiments, while others give averages for e.g. each experimental year or each management strategy applied. Each value, whether it is reported as an average of more experiments or a unique value for one experiment, is considered as one value in the database.

2.2 Results

Database

An overview of the contents of the database is given in Table 2-1, while appendix 1 depicts all results by crop and by source. A total of 84 publications was included. For wheat, 28 data sources across 13 countries on 5 continents were analysed. Data on rice is with 13 sources across 8 countries remarkably less. Many studies on rice production and water use were found to focus on irrigation water inputs, while few consider actual evapotranspiration (ET_{act}). For cotton, 16 experiments conducted in 9 different countries were found, while maize had 27 sources in 10 different countries on 4 continents. Research on water productivity of maize is concentrated mainly in the USA (9 sources) and China (7 sources). Although the literature search was conducted in the Spanish and French language as well, few publications that meet the minimal data demands for all four crops could be found for the African, Latin American and European continents. Unfortunately many publications focus on either determination of crop water use or crop yields, whereas others only consider irrigation water applied.

Table 2-1: Summary of the database.

Crop	# publications	# continents	# countries*
Wheat	28	5	13
Rice	13	4	8
Cotton	16	5	9
Maize	27	4	10

Water productivity

Figure 2-1a-d depict the frequency distribution histograms of wheat, rice, cotton and maize. For the purpose to exclude extreme values, the water productivity range is determined by taking the 5 and 95 percentiles of the cumulative frequency distribution. The results are presented in Table 2-2.

Wheat has the largest number of experimental points (n = 412) and the WP_{ET} range is between 0.6 and 1.7 kg m^{-3}. Doorenbos and Kassam (1979) give a lower range of 0.8 – 1.0 kg m^{-3} (see Table 2-2). The maximum values are found by Jin *et al*. (1999) in China: application of manure led to higher production and straw mulching improved soil water and soil temperature conditions. WP_{ET} for the experiment with straw mulching was 2.67 kg m^{-3} and 2.41 kg m^{-3} for a combination of straw mulching and manure. ET_{act} in the winter season was tempered to 268 and 236 mm respectively, while yields were relatively high with 7,150 and 5,707 kg ha^{-1} (see Figure 2-2a).

WP_{ET} of rice ranges between 0.6 and 1.6 kg m^{-3} (Figure 2-1b). Tuong and Bouman (2003) give a very similar range of 0.4 –1.6 kg m^{-3} for lowland rice conditions. The maximum WP_{ET} value of 1.1 kg m^{-3} for rice given by Doorenbos and Kassam (1979) (Table 2-2) is exceeded in six out of thirteen data sources. The WP_{ET} range of rice is similar to wheat ; the shape of the frequency distribution of rice is not as smooth as for wheat because less points are available. The maximum values go up to 2.20 kg m^{-3} and were measured in China on alternate wetting and drying rice plots (Dong *et al*., 2001). Rice grain yields of over ten tons per hectare were amongst the highest measured, whereas ET_{act} was on the lower side with 465 mm (Figure 2-2b).

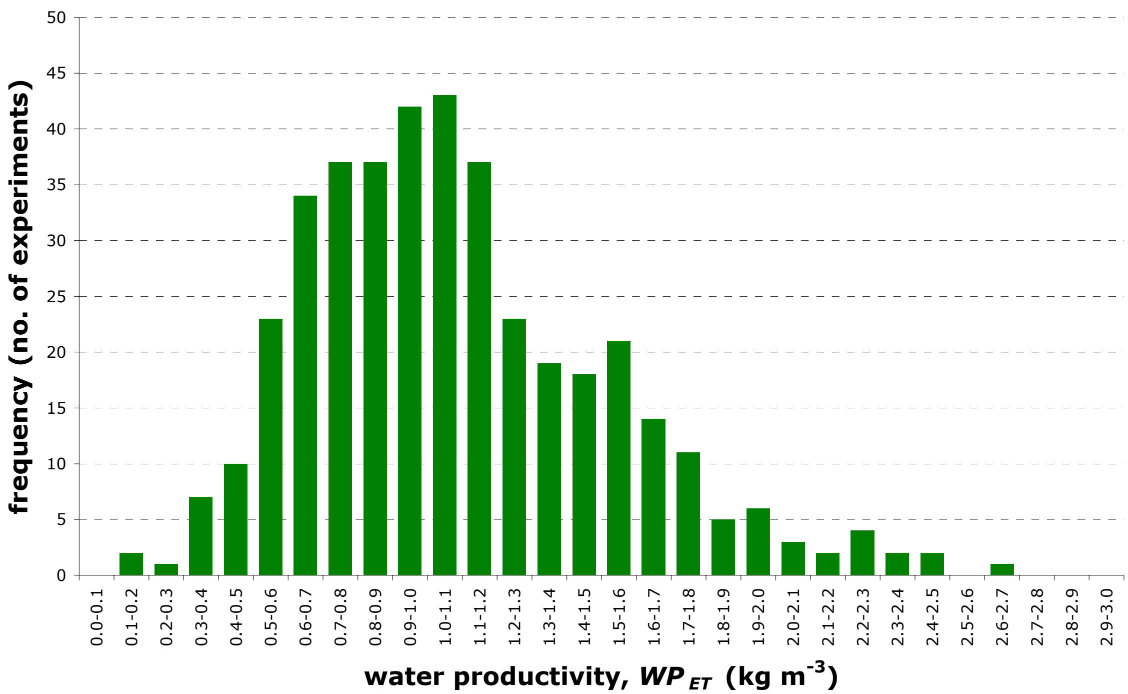
WP_{ET} values of cotton lint yield range from 0.14 to 0.33 kg m^{-3}. The maximum values exceed 0.35 kg m^{-3} and are found by Jin *et al*. (1999) and Saranga *et al.* (1998) in China and Israel, respectively. Jin *et al*. (1999) conducted experiments in which cotton was planted in furrows and the soil covered with plastic leaving holes for infiltration near the plants, thus reducing soil evaporation and improving soil water status of the root zone. Saranga *et al*. (1998) measured average lint yield values of 1,300 kg ha^{-1} in a field trial with deficit irrigation, while seasonal ET_{act} was very low with 390 mm (see Figure 2-2c). Howell *et al*. (1984) measured similar values (0.33 kg m^{-3}) in an experiment with high frequency trickle irrigation and reduced water deficits management for narrow row cotton in California (USA). Lint yield was more than 2,000 kg m^{-3}, while seasonal ET_{act} was relatively low (617 mm). The range for cotton seed yield is with 0.41-0.95 kg m^{-3} higher than the range given in FAO33 (0.4-0.6 kg m^{-3}). In Argentina maximum values were measured exceeding 1.0 kg m^{-3} in experiments where water was applied during critical periods such as pre-seeding and flowering (Prieto and Angueira, 1999). Cotton seed yields did not differ compared to other treatments, though ET_{act} was lower (447-495 mm – see also Figure 2-2c).

Finally, maize WP_{ET} values were measured ranging from 0.22 up to a maximum of 3.99 kg m^{-3} (Figure 2-1d) which exhibits a large range of variation (CV=0.38). In 67 per cent of the publications the maximum value of the source exceeds the value of 1.6 kg m^{-3} provided by FAO33. The WP_{ET} range of 1.1-2.7 kg m^{-3} for maize, a C4-crop, is significantly higher than wheat, rice and cotton, which are C3-crops. The maximum values were measured by Kang *et al*. (2000b) in a combination of alternate furrow irrigation and deficit irrigation experiments under Chinese conditions: low amounts of irrigation water were alternately applied to one of the two neighbouring furrows. ET_{act} was with 226 mm very low, whereas grain yield was still 9,058 kg ha^{-1} (Figure 2-2d).

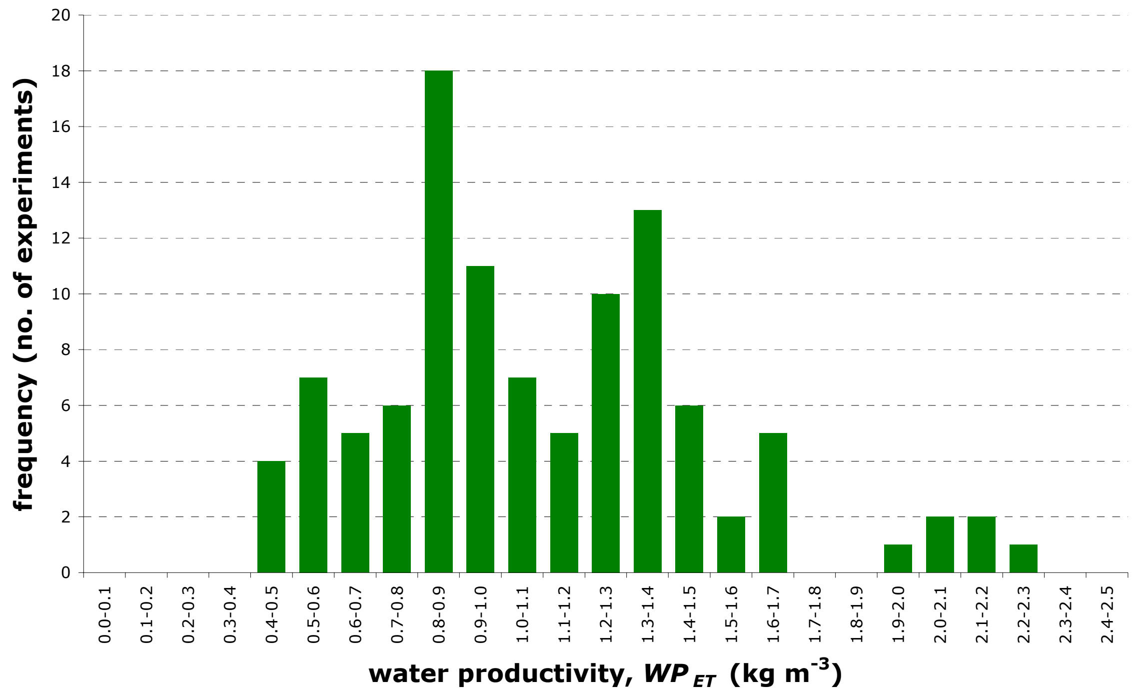
Table 2-2: Water productivity (WP_{ET}) benchmark values per unit of water depletion according to "FAO33" (Doorenbos and Kassam, 1979), WP_{ET} ranges according to this study, the maximum, minimum, mean and median WP_{ET} values and the standard deviation (SD) and coefficient of variation (CV) of the data sets by crop.

crop	WP_{ET} -range ("FAO33")	WP_{ET} -range* (this research)	n	min	max	mean	median	SD	CV
	(kg m^{-3})	(kg m^{-3})							
Wheat	0.8 – 1.0	0.6 – 1.7	412	0.11	2.67	1.09	1.02	0.44	0.40
Rice	0.7 – 1.1	0.6 – 1.6	105	0.46	2.20	1.09	1.02	0.40	0.36
Cotton (seed yield)	0.4 – 0.6	0.41 – 0.95	126	0.38	1.70	0.65	0.58	0.23	0.35
Cotton (lint yield)	not given	0.14 – 0.33	66	0.10	0.37	0.23	0.23	0.064	0.28
Maize	0.8 – 1.6	1.1 – 2.7	233	0.22	3.99	1.80	1.60	0.69	0.39

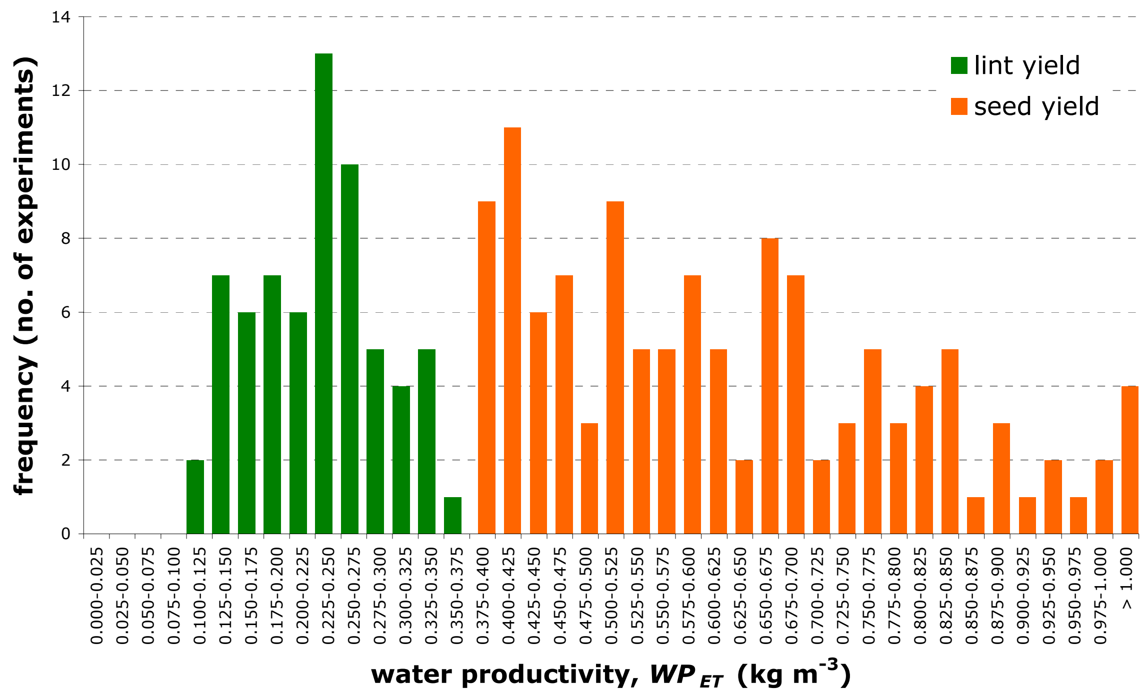
* defined as the 5 and 95 percentiles of the entire range



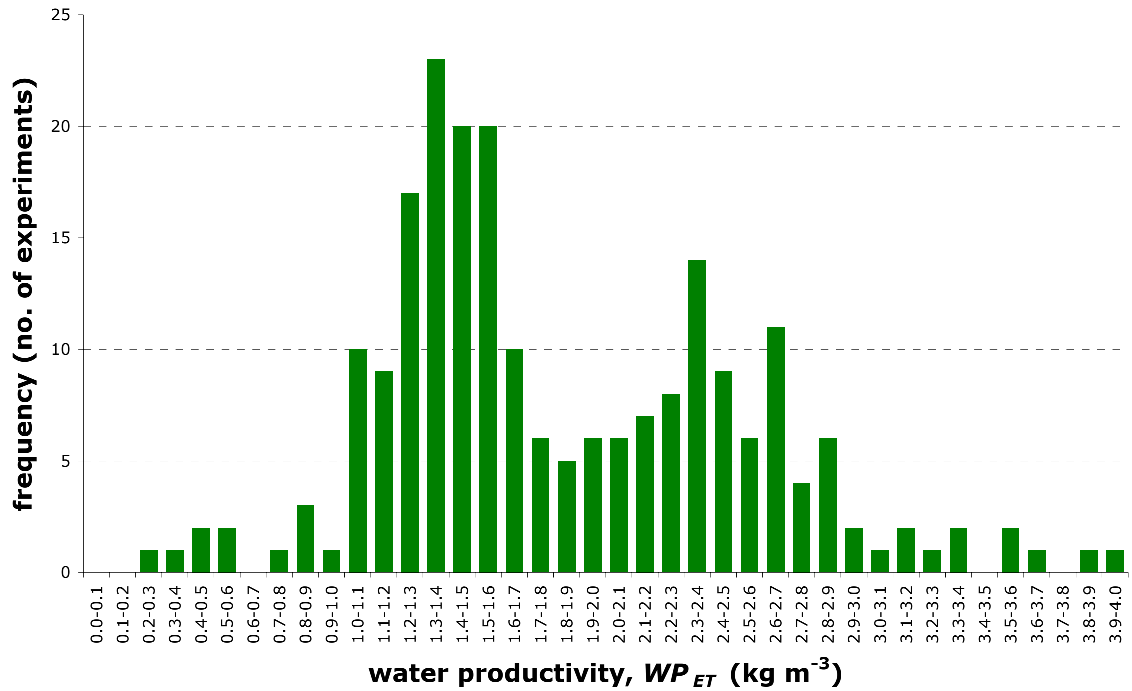
a: wheat (n = 412)



b: rice (n = 105)



c: cotton (n_{seed} = 126, n_{lint} = 66)

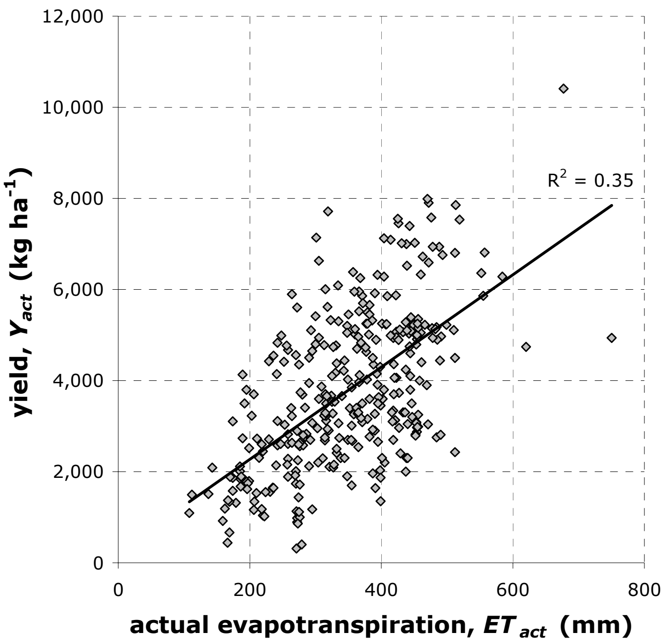


d: maize (n =233)

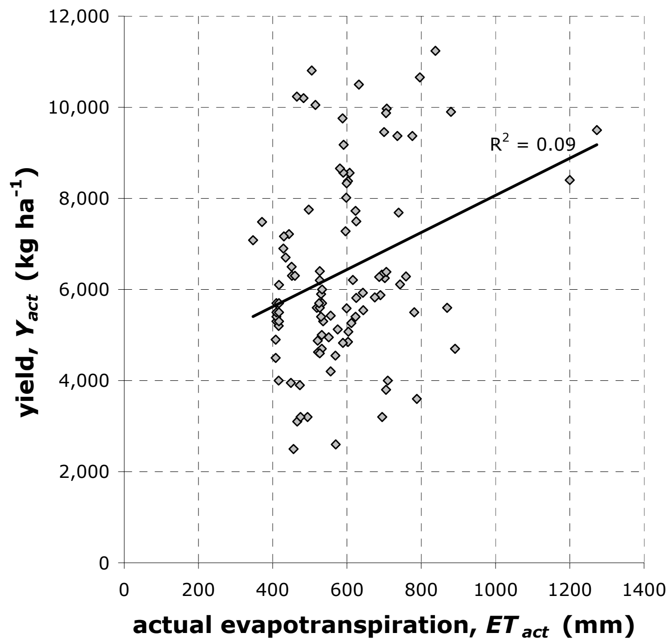
Figure 2-1: Frequency of water productivity (WP_{ET}) per unit water depletion for wheat, rice, cotton and maize.

2.3 Discussion

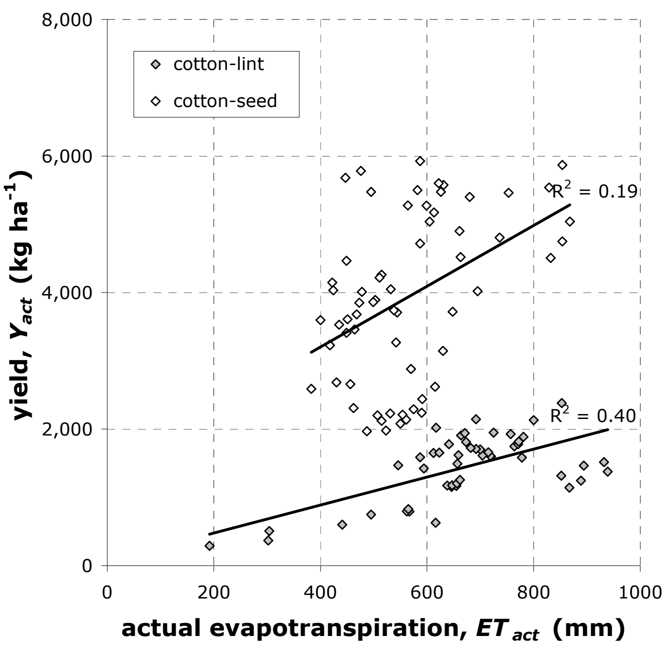
In Figure 2-2a-d, the yield is plotted against the ET_{act} for each of the four crops. All four graphs show that the Y_{act}-ET_{act} relation is not as straightforward as often is assumed: r-squared values are low: $\text{cotton}_{\text{lint}}$ has the highest correlation (r^2=0.39), followed by wheat (r^2=0.35), maize (r^2=0.33), $\text{cotton}_{\text{seed}}$ (r^2=0.19) and rice (r^2=0.09). The lesson learnt here is that Y_{act} (ET_{act}) functions are only locally valid and cannot be used in macro-scale planning of agricultural water management. A broad range in water productivity values for all four crops exists (see Table 2-2), which is caused by the many factors that influence the soil-plant-water relationship. In a search for first order explanations for the wide ranges in water productivity, only three aspects are discussed here: climate, irrigation water management and soil management.



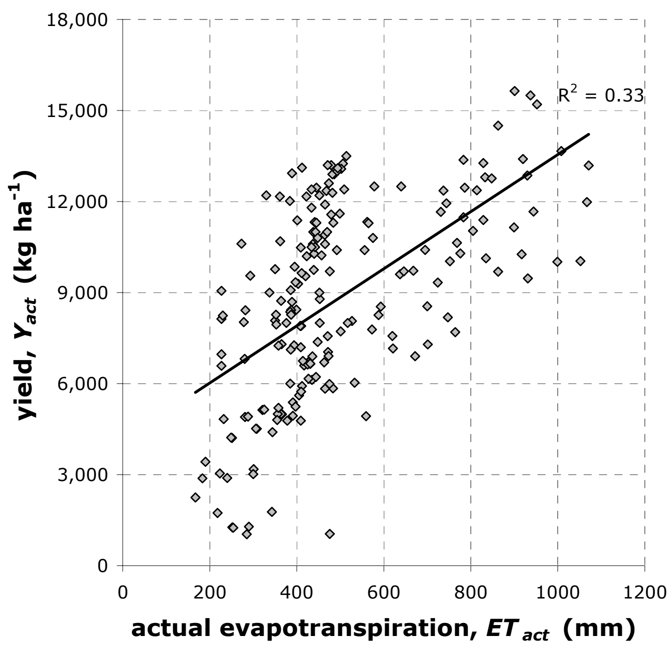
a: wheat



b: rice



c: cotton



d: maize

Figure 2-2: yield-evapotranspiration relations of wheat, rice, cotton and maize.

De Wit (1958) was among the first to describe the photosynthesis-transpiration relationship. Bierhuizen and Slayter (1965) researched the influence of climatic parameters on this relationship and found a proportionally inverse relation (reviewed and confirmed by Tanner and Sinclair in 1983) between vapour pressure deficit of the air and water productivity. Similar results were found by Stanhill (1960) for pastures grown at different latitudes. As the vapour pressure deficit generally decreases when moving away from the equator, water productivity is expected to increase with increasing latitude. This proposition was tested for the current dataset: for each experimental site (defined as each unique geographic location), the maximum water productivity of each crop is plotted against the latitude value of the experimental site. The maximum value is being taken to approach the optimal growing conditions with respect to soil fertility management and irrigation water application at a certain location. The result, depicted in Figure 2-3, confirms that water productivity decreases with lower latitude. It also shows that the highest water productivity values occur between 30 and 40 degrees latitude where a factor 2 to 3 difference in water productivity of wheat, rice and maize is detected when compared to areas between 10-20 degrees.

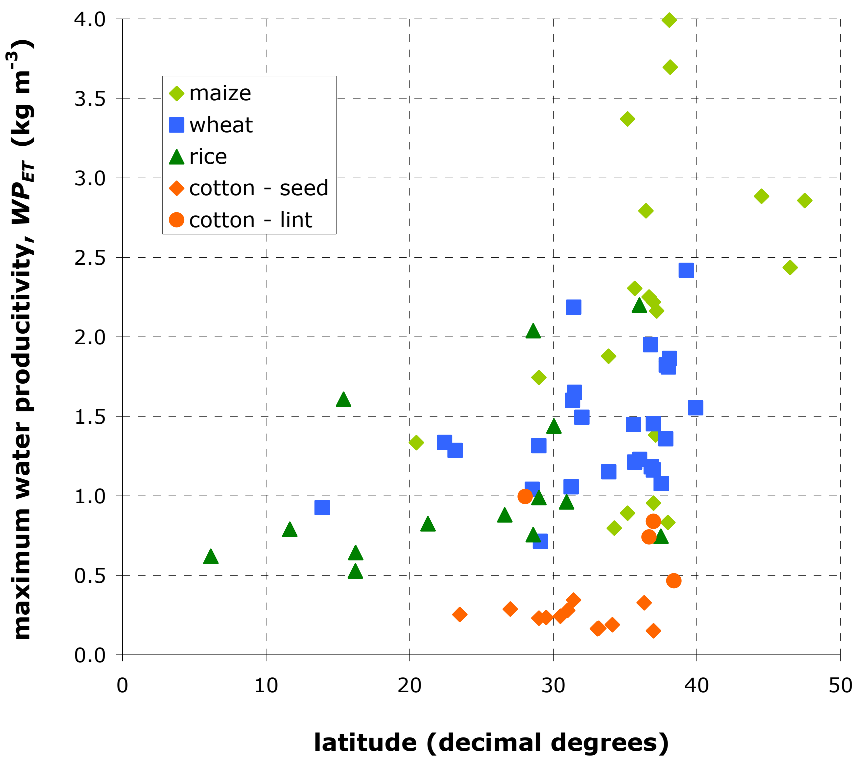


Figure 2-3: Relation between latitude and maximum water productivity (WP_{ET}) value per unit water depletion per location and per crop (both northern and southern latitude are considered positive).

Many examples from literature describe the influence of irrigation water management on water productivity (e.g. Oktem *et al*., 2003; Zhang *et al*., 1998; Yazar *et al*., 2002a; Kang *et al*., 2000a; Sharma *et al*., 1990). Deficit irrigation practices have been researched to quantify the effect on yield and to find optimum water productivity values. In Figure 2-4a and b, water productivity of wheat and maize are plotted against the net amount of irrigation water applied in various experiments. It was found that without irrigation water productivity in rainfed systems is low, but that water productivity rapidly increases when a little irrigation water is applied. According to the database, optimum values for water productivity are reached at approximately 150 and 280 mm of irrigation water applied for wheat and maize respectively (in addition to rainfall). Figure 2-4 demonstrates how water productivity can be increased while simultaneously saving water by reduced irrigations. A maximum water productivity will often not coincide with farmers' interests, whose aim is a maximum land productivity or economic profitability. It requires a shift in irrigation science, irrigation water management and basin water allocation to move away from 'maximum irrigation-maximum yield' strategies to 'less irrigation-maximum water productivity' policies. Besides the total amount of irrigation water applied, the timing of irrigation is important. Water stress during different growth stages affect water productivity differently; lower water productivity was measured in cotton experiments where water stress occurred during vegetative and early bud formation periods. Gentle stress during yield formation did not affect yield production, but reduced vegetative growth and would thus improve water productivity (Prieto and Angueira, 1999).

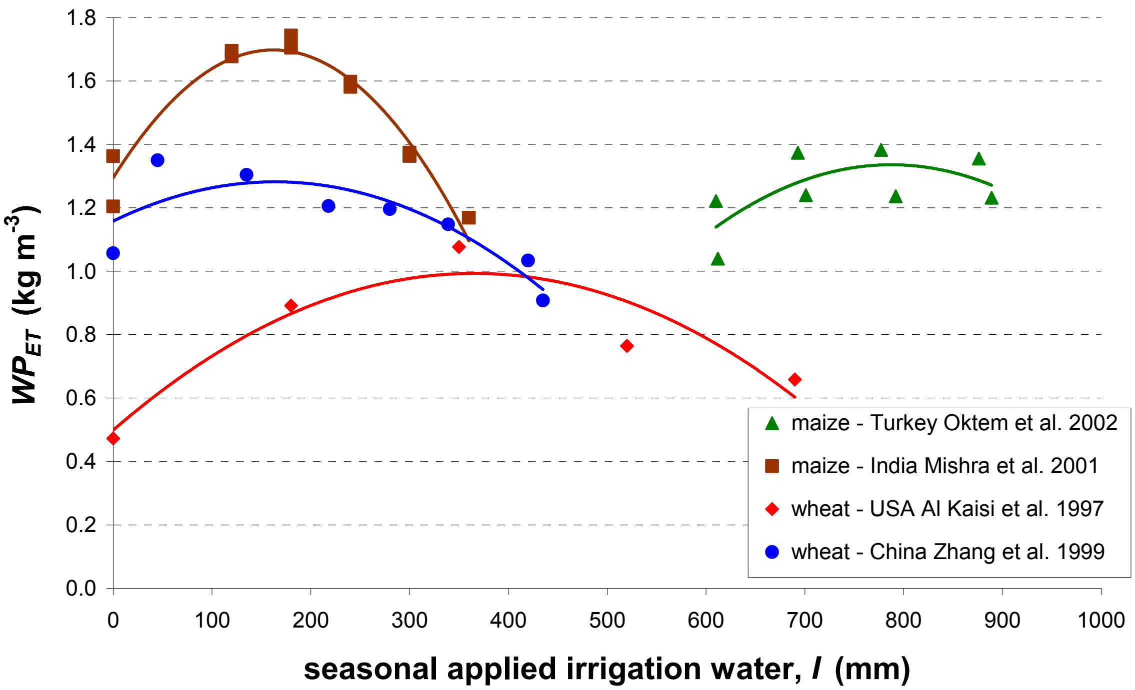


Figure 2-4: Relation between amount of irrigation water applied (I) and measured water productivity (WP_{ET}) per unit water depletion for four wheat and maize experiments.

The relationship between irrigation and water productivity in rice is not the same as found for wheat and maize. In rice cultivation, instead of traditional continuous flooding, other water management strategies, such as alternate wetting and drying (intermittent irrigation) and saturated soil culture, were researched. Analysis of alternate wetting and drying experiments in India by Mishra *et al*. (1990) shows that, although irrigation water is saved, there is no significant improvement in water productivity, which remains between 0.80 and 0.99 kg m^{-3} (n=24). For this specific study in India, the ET_{act} was not reduced because irrigation application was in excess of ET_{act}. Dong *et al*. 2001 found similar results and concluded that there was no significant difference between continuous flooding and alternate wetting and drying experiments; ten year average ET_{act} and water productivity amounted 590 and 591 mm and 1.49 and 1.58 kg m^{-3} for continuous flooding and intermittent irrigation experiments, respectively. On the other hand, Shi *et al*. (2003) measured in lysimeter experiments higher water productivity values for intermittent irrigation experiments (2.0 kg m^{-3}) compared with continuous flooding (1.6 kg m^{-3}), whereas yields were only 200 kg ha^{-1} lower). Moreover, ET_{act} in the intermittent experiment (347 mm) was 22 per cent lower compared to continuous flooding. For the sake of clarity, Seckler (1996) distinguishes "dry" and "wet" water savings: reduction in ET_{act} is a wet saving because the evapotranspired water is lost for future use in the basin. On the other hand irrigation water savings are dry savings as the water may be recycled within the basin for future use (unless it is polluted). As is shown by the results from Mishra *et al*. (1990) and Dong *et al*. (2001) intermittent irrigation is merely an example of a dry water saving as ET_{act} is hardly affected by reduced supplies.

Hatfield *et al*. (2001) reviewed the effects of soil management on water productivity by modification of the soil surface, such as tillage and mulching, and by improvement in soil nutrient status by adding nitrogen and/or phosphorus. A modification of the soil surface changes the processes of ET_{act} and is often found to be positively related to water productivity. Nutrients indirectly affect the physiological efficiency of the plant. In Figure 2-5 the nitrogen rate is plotted against the water productivity of wheat during studies in Niger, Syria and Uruguay. Water productivity increases when nitrogen is applied and reaches an optimum at a rate of approximately 150 kg ha^{-1}. On the other hand Corbeels *et al*. (1998) and Fernandez *et al*. (1996) did not measure significant differences when N fertilization was applied. Combined nutrient and irrigation supply levels are more commonly researched (e.g. Li *et al*., 2001; Pandey *et al.,* 2001; Oweis *et al*., 2000; Zima Szalokine and Szaloki, 2002). Optimum values for amount nutrient and irrigation water application can be found to maximize water productivity.

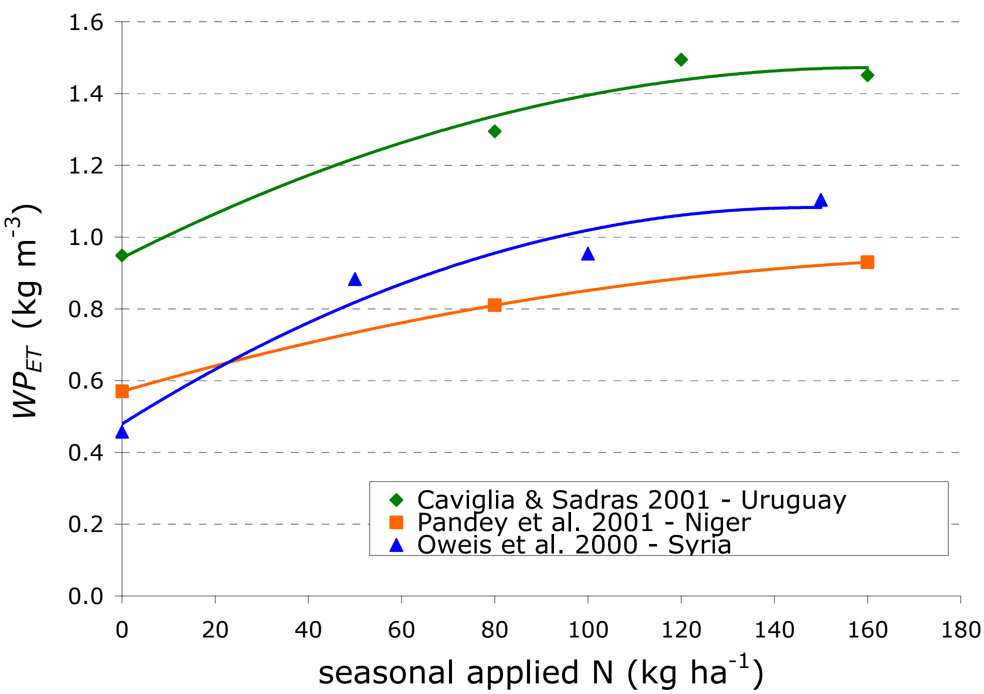


Figure 2-5: Relation between amount of nitrogen applied (N) and measured water productivity (WP_{ET}) per unit water depletion for wheat from experiments in three different countries.

2.4 Conclusions

The water productivity ranges for the four crops investigated are large as indicated by the high CV of 28–40% and are a logical consequence of the low correlation between ET_{act} and crop yield (r^2=0.09 to 0.39). This variability was mainly ascribed to 1) climate, 2) irrigation water management, and 3) soil (fertility) management, although more explanatory variables prevail. The climatic belt between 30 to 40 degrees latitude was found to be favourable for agriculture with regard to water productivity and this is likely to be related to vapour pressure deficit. In areas with marginal soils, application of fertilizer offers large possibilities for improvement of water productivity. The increase in water productivity is highest if small amounts of nitrogen (<80 kg ha^{-1}) are applied. Deficit irrigation practices were found to improve water productivity, sometimes even by more than 200 %. Plants are more efficient with water when they are stressed. It is therefore tentatively concluded that to achieve optimum water productivity in water short regions, it is wise to irrigate wheat and maize with less water as recommended for attaining maximized yields.

In rice cultivation the increase of water productivity when less water was applied could not be confirmed from the database; during many of the alternate wetting and drying and continuous flooding experiments there was no significant difference in water productivity. Water savings in rice are therefore a 'dry saving', because consumptive use is not or little affected.

The wide ranges in water productivity found suggest that agricultural production can be maintained with 20-40% less water resources provided that new water management practices are adopted.

Appendix 1: Summarized water productivity values from literature

WHEAT					
location	**min-max**	**median**	**n**	**experimental**	**reference**
	kg m^{-3}	**kg m^{-3}**		**year(s)**	
Parana, Argentina	0.55 – 1.49	1.04	7	1998 – 99	Caviglia & Sadras 2001
Merredin, Australia	0.56 – 1.14	0.95	11	1987	Siddique *et al*. 1990
Merredin & Mullewa, Australia	0.55 – 1.65	0.88	21	1991 – 95	Regan *et al*. 1997
Benerpota, Bangladesh	0.52 – 1.34	0.91	16	1988 – 92	Rahman *et al*. 1995
Quzhou, China	1.38 – 1.95	1.58	12	1988 – 89	Deju & Jingwen 1993
Xifeng, China	0.65 – 1.21	0.84	3	1988 – 91	Fengrui *et al*. 2000
Wangtong, China	1.49 – 2.67	2.23	9	1995 – 96	Jin *et al*. 1999
Gansu, China	0.58 – 1.45	1.00	4	1997	Li *et al*. 2001
Luancheng, China	1.07 – 1.29	1.26	3	1984 – 96	Wang *et al*. 2001
Yucheng, China	0.88 – 1.16	1.04	4	1986 – 90	Xianqun 1996
Beijing, China	0.92 – 1.55	1.19	10	1991 – 95	Zhang *et al*. 1998

various locations, China	0.85 – 1.86	1.17	28	1982 – 95	Zhang *et al*. 1999
Luancheng, China	1.28 – 1.82	1.63	18	1998 – 00	Zhang *et al*. 2003
West Bengal, India	1.11 – 1.29	1.19	3	1989 – 91	Bandyopadhyay & Mallick, 2003
Pantnagar, India	0.86 – 1.31	1.11	22	1983 – 85	Mishra *et al*. 1995
Uttar Pradesh, India	0.48 – 0.71	0.64	12	1993 – 94	Sharma *et al*. 2001
Karnal, India	0.27 – 0.82	0.67	18	1986 – 88	Sharma *et al*. 1990
Pantnagar, India	1.06 – 1.23	1.10	6	1979 – 85	Singh & Chauhan 1996
Gilat, Israel	0.60 – 1.60	0.85	20	1977 – 87	Amir *et al*. 1991
Meknes, Morocco	0.11 – 1.15	0.58	4	1993 – 95	Corbeels *et al*. 1998
Sidi El Aydi, Morocco	0.32 – 1.06	0.61	20	1995 – 99	Mrabet 2002
Konni, Niger	0.42 – 0.93	0.61	18	1996 – 98	Pandey *et al*. 2001
Faisalabad, Pakistan	0.70 – 2.19	1.28	52	1991 – 94	Waheed *et al*. 1999
Tel Hadya, Syria	0.48 – 1.10	0.78	36	1991 – 96	Oweis *et al*. 2000
Cukurova, Turkey	1.33 – 1.45	1.39	5	1991 – 92	Sezen and Yazar, 1996
Yellow Jacket (CO), USA	0.47 – 1.08	0.77	5	1993 – 94	Al-Kaisi *et al*. 1997
Grand Valley (CO), USA	1.53 – 2.42	1.72	14	1988 – 89	Kruse *et al*. 1991
Tashkent, Uzbekistan	0.44 – 1.02	0.73	8	2001 – 02	Kamilov *et al*. 2002
RICE					
location	**min-max**	**median**	**n**	**experimental**	**reference**
	kg m^{-3}	**kg m^{-3}**		**year(s)**	
Echuca, Australia	0.70 – 0.75	-	2	1997 – 98	Bethune *et al*. 2001
Zhanghe, China	1.04 – 2.20	1.41	20	1991 – 00	Dong *et al*. 2001
Nanchang, China	1.63 – 2.04	1.84	4	2002	Shi *et al*. 2003
Pantnagar, India	0.80 – 0.99	0.89	24	1983 – 84	Mishra *et al*. 1990
Raipur, India	0.46 – 0.82	0.46	5	1979 – 83	Sastri *et al*. 1985
New Delhi, India	0.55 – 0.67	0.67	7	2001	Singh *et al*. 2002
Punjab, India	0.87 – 1.46	1.15	24	1996 – 97	Singh *et al*. 2001
Muda, Malaysia	0.48 – 0.62	0.54	3	1988 – 94	Cabangon *et al*. 2002
Kadawa, Nigeria	0.50 – 0.79	0.59	3	1991 – 9-2	Nwadukwe & Chude 1998
Luzon, Philppines	1.39 – 1.61	-	2	1989 – 91	Bhuiyan *et al*. 1995
N'Diaye & Pont-Gendarme, Senegal	0.53 – 0.64	-	2	1990	Raes *et al*. 1992
Beaumont (TX), USA	1.37 – 1.44	-	2	1995	Roel *et al*. 1999
Belle Glade (FL), USA	0.88 – 1.34	1.21	7	1979 – 80	Shih *et al*. 1983
COTTON					
location	**min-max**	**median**	**n**	**experimental**	**reference**
	kg m^{-3}	**kg m^{-3}**		**year(s)**	
Santiago, Argentina*	0.50 – 1.27	0.84	30	1990 – 95	Prieto and Angueira 1999
various locations, Australia**	0.22 – 0.29	0.24	12	1996 – 99	Tennakoon & Milroy, 2003
Wangtong, China**	0.20 – 0.37	0.32	4	1994 – 97	Jin *et al*. 1999
Yucheng, China**	0.15	-	1	1988	Xianqun 1996
Be'eri, Israel**	0.22 – 0.35	0.28	12	1994	Saranga *et al*. 1998

Faisalabad, Pakistan*	0.38 – 0.58	0.49	16	1991 – 94	Waheed *et al*. 1999
Cordoba, Spain*	0.45 – 0.71	0.61	28	1985 – 86	Orgaz *et al*. 1992
Bornova-Izmir, Turkey*	0.38 – 0.48	0.43	12	1993 – 94	Anac *et al*. 1999
Cukurova, Turkey*	0.38 – 0.84	0.56	24	1994 – 95	Ertek and Kanber 2001
Harran Plain, Turkey**	0.50 – 0.74	0.59	10	1999	Yazar *et al*. 2002b
Wellman (TX), USA**	0.10 – 0.17	0.14	4	1992 – 95	Baumhardt & Lascano 1999
Halfway (TX), USA**	0.14 – 0.19	0.18	9	1995	Bordovsky & Lyle 1996
Five points (CA), USA**	0.14 – 0.24	0.20	3	1981	Howell *et al*. 1984
Five points (CA), USA**	0.22 – 0.33	0.27	15	1982 – 83	Howell *et al*. 1987
Maricopa (AZ), USA**	0.13 – 0.16	0.15	6	1993 – 94	Hunsaker *et al*. 1998
Tashkent, Uzbekistan**	0.54 – 1.70	1.06	6	2000 – 01	Kamilov *et al*. 2003
* seed yield ** lint yield					
MAIZE					
location	**min-max**	**median**	**n**	**experimental**	**reference**
	kg m^{-3}	**kg m^{-3}**		**year(s)**	
Azul, Argentina	1.84 – 2.79	2.35	5	1991 – 95	Navarro Dujmovich *et al*. 1996
Guaira, Brazil	1.12 – 1.33	1.21	3	1994	Libardi *et al*. 1999
Xifeng, China	1.26 – 2.31	2.00	3	1989 – 91	Fengrui *et al*. 2000
Wangtong, China	1.49 – 2.67	2.23	13	1995 – 96	Jin *et al*. 1999
Changwu, China	1.36 – 1.65	1.56	9	1987	Liu & Li 1995
Changwu, China	2.11 – 3.37	2.56	18	1996 – 97	Kang *et al*. 2000a
Gansu province, China	2.14 – 3.99	2.92	12	1997 – 98	Kang *et al*. 2000b
Yucheng, China	1.63 – 2.22	-	2	1989	Xianqun 1996
Luancheng, China	1.55 – 1.84	-	2	1998	Zhang *et al*. 2003
Szarvas, Hungary	1.28 – 2.44	1.85	16	1978 – 95	Zima and Szaloki 2002
Pantnagar, India	1.17 – 1.74	1.47	14	1993 – 95	Mishra *et al*. 2001
Tal Amara, Lebanon	1.36 – 1.89	1.64	6	1998	Karam *et al*. 2003
Fundulea, Romania	2.34 – 2.88	2.64	5	1991 – 94	Cracium and Cracium 1999
Sevilla, Spain	1.50 – 2.16	1.73	4	1992 – 93	Fernandez *et al*. 1996
Harran plain, Turkey	1.94 – 2.25	2.02	6	2000	Yazar *et al*. 2002a
Harran plain, Turkey	1.04 – 1.38	1.24	8	1998 – 99	Oktem *et al*. 2003
Cukurova, Turkey	0.22 – 1.25	1.01	12	1993 – 94	Gencoglan and Yazar 1999
Bushland (TX), USA	1.12 – 1.39	1.31	6	1995	Evett *et al*. 1996
Bushland (TX), USA	0.89 – 1.55	1.42	6	1993	Howell *et al*. 1995
Bushland (TX), USA	1.47 – 1.74	1.60	6	1989 – 94	Howell *et al*. 1996
Garden City (KS), USA	0.83 – 1.61	1.26	16	1994 –97	Norwood 2000
Blacksburg (VA), USA	1.34 – 3.26	2.67	6	1998 – 99	Roygard *et al*. 2002
Carolina Bays (SC), USA	0.36 – 1.57	0.65	8	1993	Sadler *et al*. 2000
Oakes (ND), USA	2.03 – 2.86	2.55	24	1989 – 91	Steele *et al*. 1994
Bushland (TX), USA	1.26 – 1.54	1.42	14	1994 – 95	Tolk *et al*. 1999
Bushland (TX), USA	1.13 – 1.68	1.48	6	1992	Yazar *et al*. 1999

3 SEBAL for detecting spatial variation of water productivity and scope for improvement in eight irrigated wheat systems*

3.1 Introduction

Due to the rapid growth in world population, the pressure on water resources is increasing (Rijsberman, 2006). In the future less water will be available for agricultural production due to competition with the industrial and domestic sectors, while at the same time food production must be increased to feed the growing population. In systems where water is becoming the limiting factor, agricultural production should be expressed per unit of water consumed instead of production expressed per unit land. It is inevitable that the production per unit water consumed, the water productivity, must be increased to meet this challenge (see e.g. Kijne *et al*., 2003; Molden *et al*., 2007). Spatial information on water use, crop production and water productivity will play a vital role for water managers to assess where scarce water resources are wasted and where in a given region the water productivity can be improved.

Currently, information on water productivity is often only available from experiments on a single field, so that results are limited to the local (environmental) conditions that can vary from year-to-year and to the specific soil, crop and water management practices . Crop water consumption cannot be routinely measured, and this hampers the introduction of the concept of crop water productivity per unit of water depletion in policy making and water management. Although water productivity is gaining importance for evaluating good management practices, there is no standardized framework that aids the calculations. Remote sensing can help to quantify water productivity spatially and for large areas.

The Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen *et al*., 2002; Bastiaanssen *et al*., 2005) is a robust remote sensing model that can be applied to estimate the different components of the energy balance of the earth surface and thus also actual evapotranspiration (ET_{act}). This model was extended to produce estimates of crop biomass production, so that crop yield, water use and water productivity can be obtained in an integrated way. Remote sensing in combination with crop production models has been acknowledged to be a powerful tool for estimating crop yields at various spatial scales: within fields, between fields and on a regional scale (e.g. Moran *et al*., 1995; Jongschaap, 2006).

The purpose of this paper is to show the conceptual framework for calculating crop yields, ET_{act} and water productivity with the SEBAL algorithm and to validate the results with data from field measurements. Although it is beyond the scope of this paper to explain the full theory behind SEBAL, an overview will be given in the next section. The

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Yaqui Valley, an area in north-western Mexico and dominated by irrigated wheat, is selected as a case study (Lobell *et al*., 2005). Beside the validation in Yaqui Valley, a model validation will be performed based on the results of biomass production, wheat yield and water productivity measurements and modelling results in Sirsa, India (Van Dam *et al*., 2006). The same modelling framework was applied in irrigated wheat systems in Pakistan, China, Egypt, India, the Netherlands and California. To show the scope of improvement, the coefficient of variation (CV) of WP_{ET} in the different systems was analysed and related to locally achievable maximum wheat yields.

3.2 Materials and methods

Research area

The Yaqui River coastal plain is a highly productive agricultural region in the state of Sonora, north-western Mexico, situated adjacent to the Gulf of California (see Figure 3-1). As being the original centre for the Green Revolution for wheat in Mexico, the basin has rapidly grown to over 225,000 cultivated hectares. The primary source for irrigation are two reservoirs, whose water is distributed through a network of canals. In addition, approximately 700 extraction wells discharge directly to the distribution canals. The area is dominated by wheat cultivation in the winter period, which was reported to be 85 per cent of the total cropped area (Lobell *et al*., 2003). Wheat is sown in late November – early December and is harvested in late April – early May. Farmers usually irrigate four to five times within the season and apply around 250 kg N per hectare.

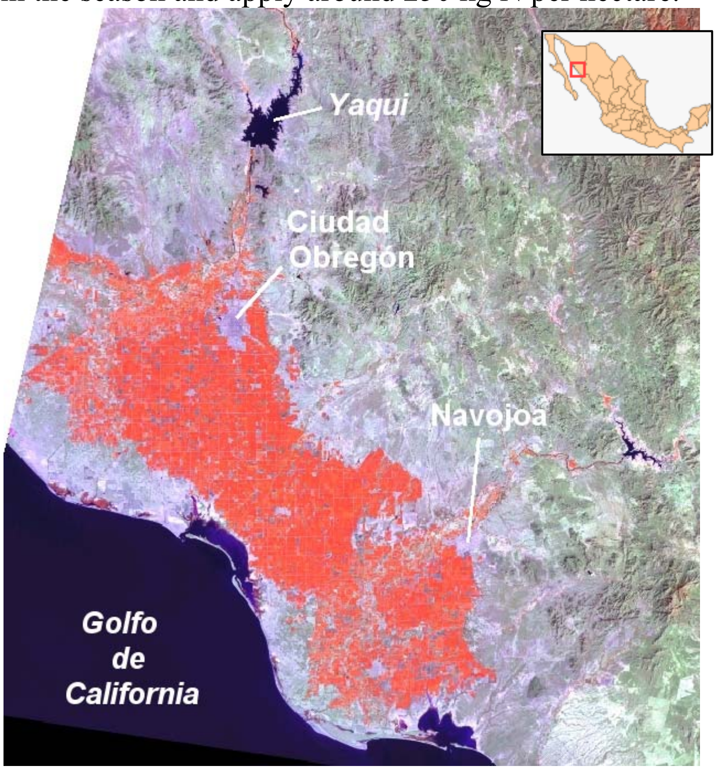


Figure 3-1: The Yaqui irrigation district in Mexico as seen on a false-colour Landsat image acquired on February 26 (2000). Green vegetation appears red on the image.

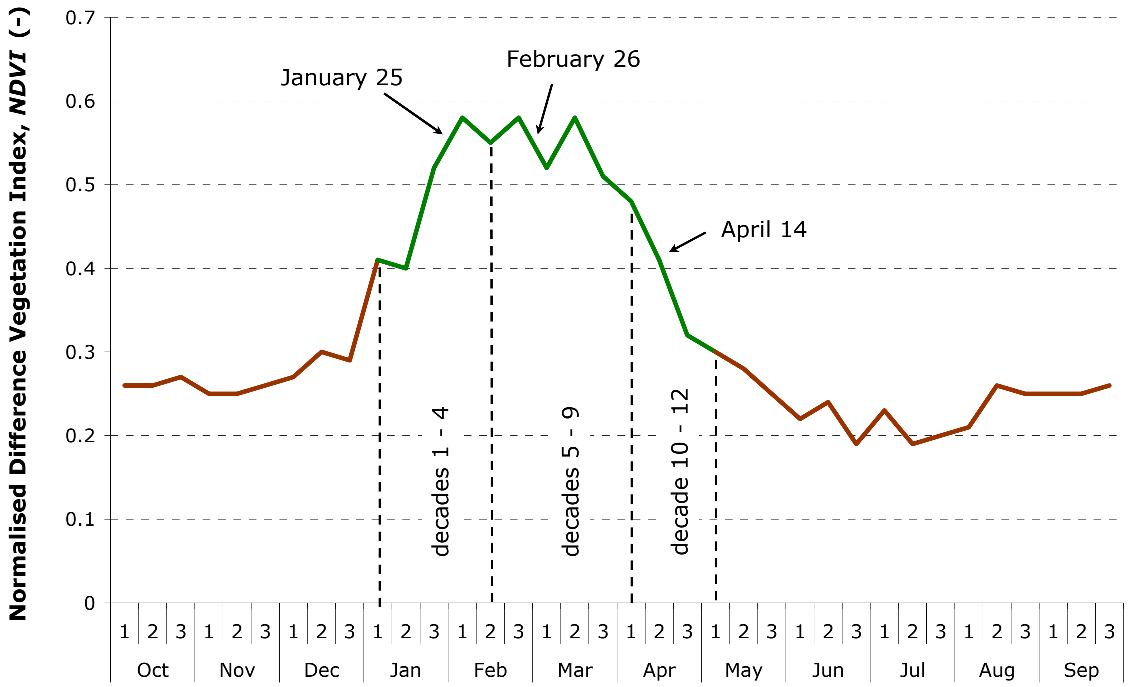


Figure 3-2: Average NDVI *from SPOT-VEGETATION sensor*† *for all 1 km pixels encompassed in the Yaqui irrigation district to depict the timing and length of the growing season. The bold part of the line indicates the length of the growing season that is analysed in this study. The dates in the figure are the Landsat acquisition dates that were used for the spatial disaggregation and time integration of the corresponding decades.*

Methodological framework

The SEBAL model was applied for the 1999-2000 winter season and although the growing season of wheat runs from November to April/May, the analysis of water productivity relates to January 1 and April 30 (see Figure 3-2). This period is used to calculate total cumulative evapotranspiration (ET_{act}) and above ground biomass production at high resolution with the SEBAL algorithm (Bastiaanssen and Ali, 2003). The SEBAL model calculates ET_{act} (or the latent heat flux, λE) for each image pixel from the energy balance equation:

$$\lambda E = R_n - G_0 - H \qquad (\mathrm{Wm^{-2}}) \qquad (3.1)$$

where R_n is the net radiation (W m^{-2}), G_0 is the soil heat flux (W m^{-2}) and H is the sensible heat flux (W m^{-2}). R_n is computed from satellite-measured broadband surface albedo, vegetation index and surface temperature, along with ground measurements of global radiation. G_0 is estimated as a fraction of R_n, surface temperature and vegetation index. H is estimated from surface temperature, surface roughness, and wind speed (see Figure 3-3). An essential component is the solution of extreme values for H, prior to its

† For more information on SPOT-VEGETATION and free data availability go to http://free.vgt.vito.be/

pixel-to-pixel computations. The extreme values agree with H=0 for water surfaces and $H=R_n - G_0$ for desert surfaces.

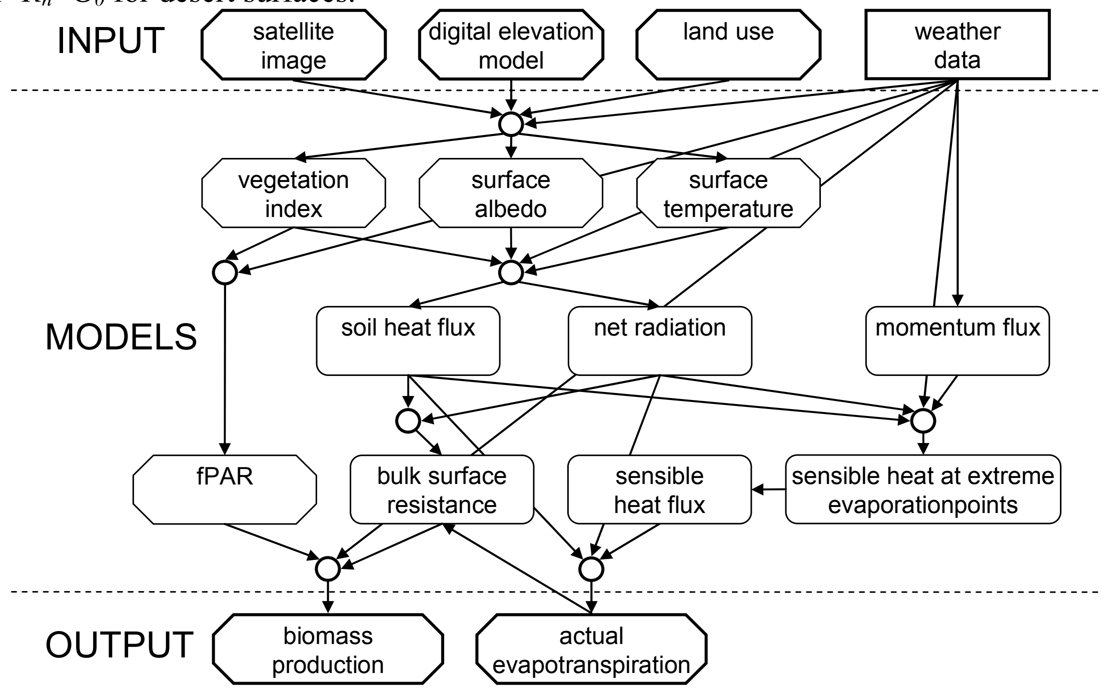


Figure 3-3: Schematic overview of the SEBAL model.

Above ground biomass production on a single image acquisition day (DM_{day}) is calculated by the SEBAL model as:

$$DM_{day} = 0.48 S^{\downarrow}_{EXO} \tau_{sw} f \varepsilon_{\max} \Phi_h \frac{s_a + \varphi\left(1 + \frac{r_{s,\min}}{r_{av}}\right)}{s_a + \varphi\left(1 + \frac{r_s}{r_{av}}\right)} 0.864 \qquad (\text{kg ha}^{-1}\ \text{d}^{-1}) \qquad (3.2)$$

where $S^{\downarrow}_{EXO}$ is the incoming shortwave radiation at the top of the atmosphere (W m^{-2}), τ_{SW} is the atmospheric transmissivity (-), $\varepsilon_{\max}$ is the maximum light use efficiency (g MJ^{-1}), Φh is the stomatal response to ambient temperature (-), s_a the slope of the saturated vapour pressure curve (mbar K^{-1}), φ the psychometric constant (mbar K^{-1}), r_s the bulk surface resistance (s m^{-1}), $r_{s,min}$ the minimum bulk surface resistance (s m^{-1}) and r_{av} is the aerodynamic resistance to water vapour transport (s m^{-1}). The resistances r_s, $r_{s,min}$ and r_{av} are routinely solved in the latent heat flux. The APAR/PAR fraction, (-), can directly be estimated from the *NDVI* (e.g. Hatfield *et al.*, 1984). In this study we used:

$$f = -0.161 + 1.257 NDVI \qquad (-) \qquad (3.3)$$

The SEBAL model was applied to satellite images from both the National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer (NOAA-AVHRR) and Landsat satellite images. NOAA-AVHRR images are characterized by a relatively high temporal resolution (once a day), but a low spatial resolution of approximately 1 kilometre. Landsat images have a high spatial resolution of 30 meter, but a low temporal resolution of 16 days. An analysis of the growing season solely based on Landsat images is practically impossible as the chance of almost all acquisitions during the season being cloud-free is very low in most wheat areas. On the other hand an analysis using only NOAA-AVHRR images would not give sufficient spatial detail. Therefore the advantages of both sensors are combined in this methodological framework where high and low resolution products are integrated to calculate total seasonal evapotranspiration and biomass production at field level.

Table 3-1: NOAA-AVHRR and Landsat image acquisition dates and related decades for the integration.

Decade	Period	NOAA-AVHRR	Landsat
1-4	January 1 – February 10	January 4, 12 & 28 (2000) February 10 (2000)	January 25 (2000)
5-9	February 11 – March 31	March 12, 16 & 20 (2000) February 19 & 23 (2000)	February 26 (2000)
10-12	April 1 – April 30	April 1, 10 & 26 (2000)	April 24 (2000)

Twelve cloud free NOAA-AVHRR images were selected (see Table 3-1) and processed using average meteorological inputs for the twelve corresponding decades and the bio-physical properties derived for the NOAA-AVHRR overpass days. These are surface albedo, *fPAR*, emissivity, evaporative fraction, surface roughness and bulk surface resistance. Measurements of daily air temperature, wind speed, relative humidity and radiation were acquired from a weather station located inside a wheat field (27º14'23"N, 109º51'20"W). These low resolution 10-daily totals of ET_{act} and biomass production were then disaggregated to field level by means of high resolution SEBAL generated ET_{act} and biomass production maps of three Landsat TM scenes (path/row: 34/41) that were acquired during the growing season on January 25, February 26 and April 24. It is indirectly assumed that conditions on the individual high resolution images are representative for the corresponding period that is considered. The following data fusion method was applied: 10-daily NOAA ET_{act} results were split into three periods that correspond with one of the Landsat dates (see Table 3-1). For each of these periods the NOAA-AVHRR-based ET_{act} was summed and an average ET_{act} was calculated for the entire Yaqui irrigation district $\left(\overline{ET_{NOAA,i}}\right)$. These average values were then multiplied with a relative ET_{act} map that was created by dividing the Landsat ET_{act} map $\left(ET_{ETM,j}\right)$ with an average value of the Yaqui irrigation district $\left(\overline{ET_{ETM,j}}\right)$. In this way the spatial patterns are taken from Landsat and the accumulated values from NOAA-AVHRR. The total seasonal ET_{act} (ET_{seas}) was then acquired by summing the downscaled products of the three periods (i):

$$ET_{seas} = \sum_{i=1}^{i=3} \left(\overline{ET_{NOAA,i}} \cdot ET_{ETM,j} \Big/ \overline{ET_{ETM,j}} \right) \qquad (\mathrm{m}^3\ \mathrm{ha}^{-1}) \qquad (3.4)$$

Where i is the NOAA period and j is the corresponding Landsat image. The same method to calculate ET_{seas} is applied to calculate seasonal biomass production (DM_{seas}) from NOAA-AVHRR and Landsat biomass production maps:

$$DM_{seas} = \sum_{i=1}^{i=3} \left(\overline{DM_{NOAA,i}} \cdot DM_{ETM,j} \Big/ \overline{DM_{ETM,j}} \right) \qquad (\text{kg ha}^{-1}) \qquad (3.5)$$

Water productivity (WP_{ET}) is defined as:

$$WP_{ET} = \frac{Y_{grain}}{ET_{seas}} = \frac{H_i \cdot DM_{seas}}{ET_{seas}} \qquad (\text{kg m}^{-3}) \qquad (3.6)$$

where Y_{act} is the total marketable grain yield (kg ha^{-1}) and ET_{seas} the seasonal water use by evapotranspiration (m^3 ha^{-1}). Grain yield is obtained by multiplying accumulated seasonal above ground biomass production (DM_{seas}) with a specific harvest index (H_i) for wheat. Wheat pixels were discriminated on the three Landsat images using an unsupervised classification (iso-clustering) with no ground truthing or field validation.

The ET_{act} calculations were validated with eddy-correlation measurements of the surface energy balance at one site located inside a large wheat field in Yaqui Valley (27º14'23"N, 109º51'20"W), which was carried out from January 8 to April 29 (2000) (Hoedjes *et al.*, 2002; Garatuza-Payan and Watts, 2005). Wheat grain yield was compared with field measurements and regional statistics from Yaqui Valley and with field measurements from Sirsa, India.

The same methodology was applied to other seven irrigation systems across the world. The number of high and low resolution satellite images that were used in these studies depended on the length of the growing season and the availability of cloud free images. In the cases of China, Pakistan, United States and the Netherlands, wheat was classified using an unsupervised classification with no field control data. The unsupervised wheat classification for Egypt and India was performed with field control measurements. Although for none of the eight areas the accuracy of the wheat classification was assessed, general accuracy figures for similar studies are between 80 and 90% (for an overview of classification performance of agricultural crops see Bastiaanssen, 1998). To depict the scope for improvement in each system, the coefficient of variation (CV) for WP_{ET} was analysed. In systems with a low CV, WP_{ET} is considered homogeneous and optimal. The CV in these systems is a target value for systems with a high CV. While maintaining the maximum value found within each system, the WP_{ET} values were linearly forced to higher values, so that the CV decreased to the target value. The scope of improvement was quantified by comparing average WP_{ET} with the new average target WP_{ET}.

3.3 Results and discussion

Evapotranspiration validation

The measured ET_{act} fluxes were first compared with the twelve ET_{act} intervals estimated by the SEBAL model of the corresponding 1 by 1 kilometre NOAA-AVHRR pixel. As eddy-correlation measurements started on January 8, no value for decade 1 was given; for comparison purpose ET_{act} in decade1 was set equal to the SEBAL estimate of decade 1. Figure 3-4 shows a good agreement between the cumulative measured (eddy correlation) ET_{act} per decade and the SEBAL estimated cumulative ET_{act} of the corresponding single NOAA-AVHRR-pixel. During February and early March, SEBAL ET_{act} is slightly higher, but runs equal with measured ET_{act} between decade 8 and 11. Cumulative measured ET_{act} is low in decade 12 (9.4 mm), but SEBAL ET_{act} produces a high value for the same period: 45.6 mm, a difference of 36 mm. Without calibration or parameter tweaking, the accumulated ET_{act} from SEBAL was 410 mm for 121 growing days. The eddy-correlation measurements revealed 363 mm, hence a difference of 13% if only the NOAA-AVHRR pixels are used.

The daily measured ET_{act} was also compared with the SEBAL Landsat ET_{act} on four different dates during the growing season. Two out of four days show good agreement: the difference between measured and estimated daily ET_{act} is 0.0 mm on January 24 and 0.4 mm on February 26 (see Figure 3-5). On the Landsat image of February 18 some haze was present above a large part of the Yaqui irrigation district including the measurement site. Due to haze an area appears colder on the satellite image than it actually is, causing higher SEBAL ET_{act} values. It was therefore decided not to use this image in the final ET_{act} map. On April 24 SEBAL ET_{act} is 1.0 mm higher than the measured value. This difference for the Landsat day appears consistent with the NOAA-AVHRR results: April 24 is in decade 12 for NOAA-AVHRR and both estimates are higher than the measured values.

The measured seasonal ET_{act} is considerably lower than the SEBAL estimated ET_{act} of the integrated NOAA-Landsat product: 364 vs. 410 mm respectively (see Figure 3-5). However, it should be taken into account that the SEBAL accumulated ET_{act} estimates cover 12 decades, starting from January 1 until April 30, whereas measurements were being made between January 8 and April 29. Extrapolation of the daily measured ET_{act} show that approximately 10 mm ET_{act} must be added to the total seasonal ET_{act} in order to consider the same twelve decades. Finally, it can be concluded that the difference between measured and estimated ET_{act} is entirely caused by the discrepancy in decade 12. No satisfactory explanation for this higher estimated value could be found, but it results in an overestimation of seasonal ET_{act} of 8.8 per cent. Wilson *et al*. (2002) compared the eddy-correlation measurements across 22 FLUXNET sites with different vegetation cover for 50 site-years. There was a general lack of energy balance closure and mean imbalance was around 20 per cent for all sites. A difference of 8.8 per cent between SEBAL estimated ET_{act} and eddy correlation measured ET_{act} is well within the range of this measurement error.

The average SEBAL-based ET_{act} of wheat in the entire Yaqui irrigation district (more than 190,000 ha) equals 403 mm (σ~37 mm). The coefficient of variation (CV) of 0.09 indicates an extreme homogeneity in spatial water consumption patterns. A detailed map of the spatial variation of ET_{act} is given in Figure 3-6A.

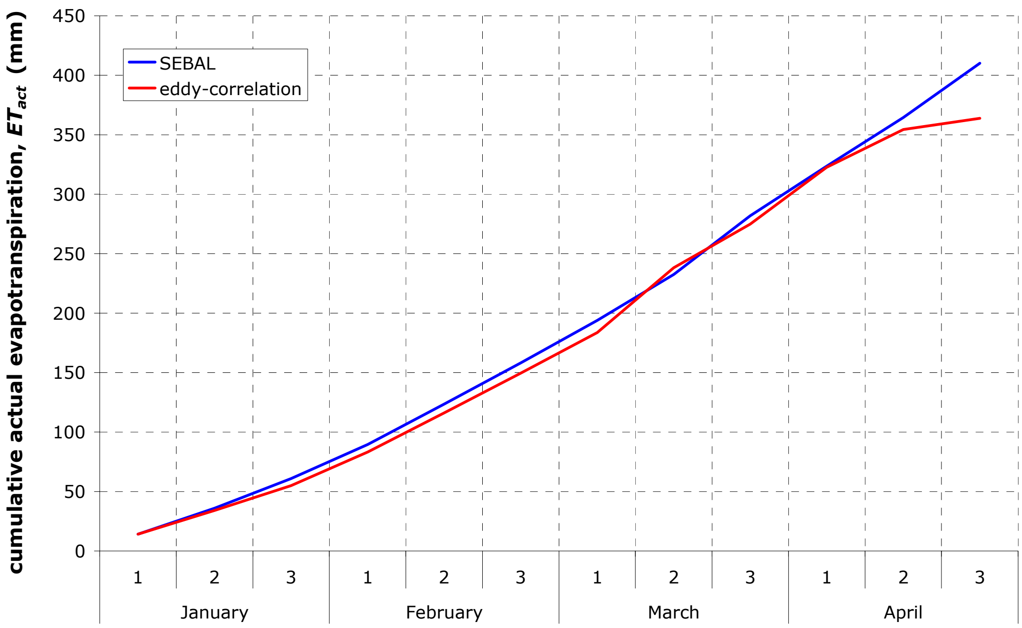


Figure 3-4: Cumulative measured eddy-correlation ET_{act} *and SEBAL estimated cumulative* ET_{act} *from the corresponding 1x1 km NOAA pixel.*

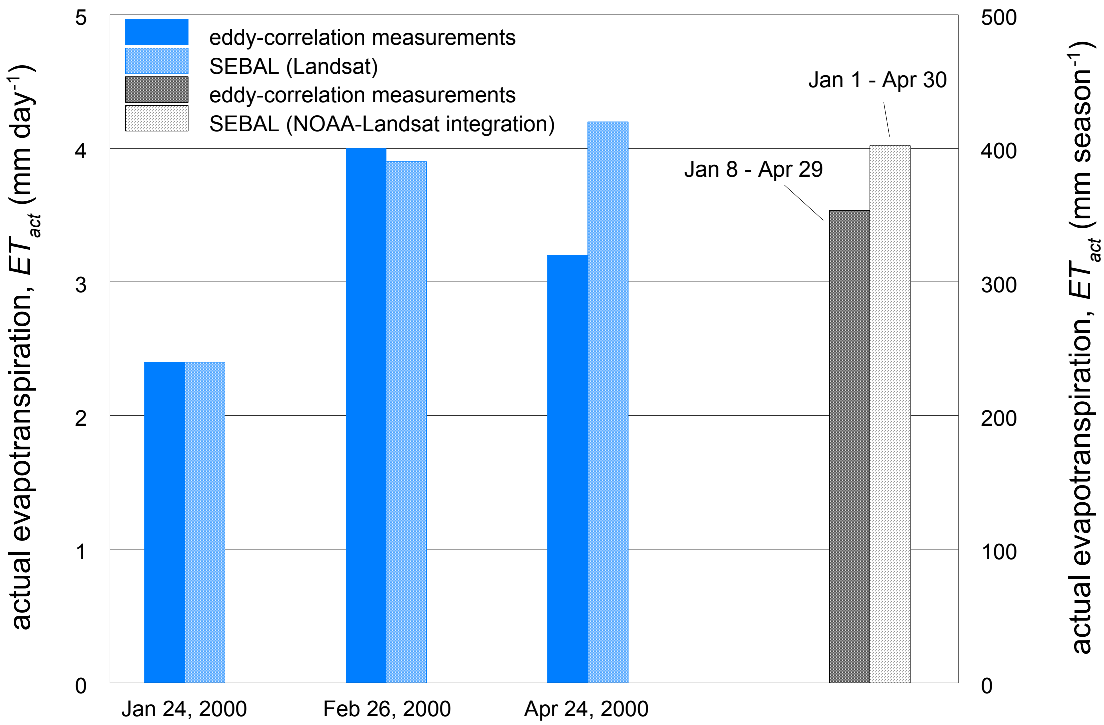


Figure 3-5: Measured ET_{act} *plotted against SEBAL daily* ET_{act} *of three Landsat acquisition dates and seasonal* ET_{act} *of the integrated Landsat-NOAA* ET_{act} *map computed according to equation 4.*

Biomass production and grain yield

Ideally, estimated wheat yields are validated with farmer reported yields in individual fields that are large enough to be distinguished separately on the wheat yield map. Unfortunately such measurements were not available for the 1999-2000 season that was analysed, and a spatial validation could not be organized. However, three other sources were consulted (see Table 3-2 and compared with the SEBAL yields.

Average estimated above ground biomass production for wheat in Yaqui irrigation district between January 1 and April 30 (2000) is 14.9 ton ha^{-1} (σ~ 2.3). This figure matches well with Del Blanco *et al*. (2000) who conducted 24 trials on wheat in Yaqui in 1999-2000 and found an average biomass production of 15.2 ton ha^{-1} (σ~2.3). Moreover they measured an average grain yield of 6.4 ton ha^{-1} (at 0% moisture), resulting in an average harvest index (H_i) of 0.42 (σ~0.040). Yield measurements were made in small plots, each with an area of 4.2 m^2, where wheat was grown under optimal growing conditions regarding weed control, irrigation management, soil fertility, etc. This may not be representative for the actual conditions in farmers' fields and average wheat yields for the entire Yaqui Valley are expected to be lower.

During the 2000-2001 winter season, a farmer survey was conducted that reported wheat yields from 80 different fields in the Yaqui Valley. Average yield in these fields equalled 6.3 ton ha^{-1} (at 12% moisture content) or 5.5 ton ha^{-1} (at 0% moisture content, σ~0.73) (Lobell *et al*., 2002). According to the official statistics, 191,281 hectares were cultivated with wheat in 1999-2000 and a total yield of 1,082,542 tons was reported (Lobell *et al*., 2003). This results in an average yield of 5.7 ton ha^{-1} at 12% moisture, being equivalent to 5.0 ton ha^{-1} when it is dried. A H_i of 0.37 at 0% moisture for wheat in Yaqui is reported by Lobell *et al*. (2003) and if this figure is applied to derive the wheat yields from the SEBAL biomass production map for Yaqui, an average wheat yield of 5.5 ton ha^{-1} (σ~0.87) is reached (at 0% moisture) (see Figure 3-6B). It can be summarized that on average SEBAL yields are 0.5 ton ha^{-1} higher when compared to the official statistics, but a comparison with farmer reported yields shows exact correspondence, both in area average figures, as well in the spreading of the yield data. It must be noted that the H_i is an important factor to determine final yields from biomass production maps. Better knowledge on the relation between biomass production and H_i will improve the accuracy of yield maps.

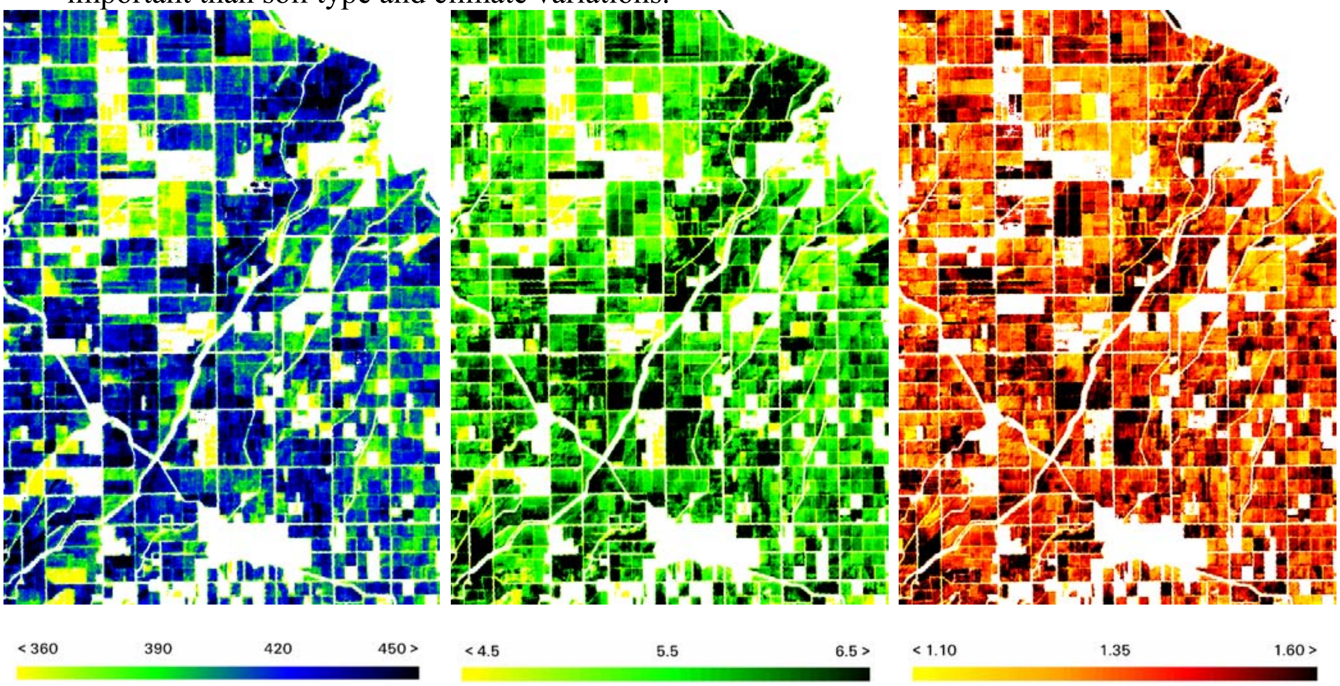
Table 3-2: Wheat yields in Yaqui Valley.

Location	average yield (ton ha^{-1})	remarks	source
Yaqui irrigation district	5.0*	official statistics, 1999-2000	Lobell *et al*., 2003
Ciudad Obregón	6.4	24 trial plots, 1999-2000	Del Blanco *et al*., 2000
Yaqui irrigation district	5.5*	80 fields, farmer reported, 2000-2001	Lobell *et al*., 2002

* corrected for 12% moisture content

SEBAL estimated wheat yields in Yaqui Valley depict a large range varying between 3 and 8 ton ha^{-1}. Large variations in ET_{act} are also observed, ranging from 250 to 450 mm. High yields can only be obtained when ET_{act} is high as well. This agrees with the fact that high yielding varieties from the Green Revolution consume relatively larger amounts of water.

Based on the above described results of yield and seasonal ET_{act} the water productivity of wheat was calculated spatially using equation 5. The average WP_{ET} of wheat for the entire Yaqui irrigation district equals 1.37 kg m^{-3} (σ~0.16, Table 3-3). As can be observed from Figure 3-6C and Figure 3-7, the range of WP_{ET} in Yaqui lies between 0.9 to 1.8 kg m^{-3}. Apparently WP_{ET} not only varies within the irrigation system, but also strongly between fields. This indicates that, besides climatology and regional soil physical properties and hydrological conditions, farm management, such as irrigation amount and timing, fertilization, weeding, choice of seed variety, crop rotation, etc., play an important role in the level of WP_{ET} that is reached. With respect to spatial variations of wheat yield in Yaqui Valley, Lobell *et al*. (2002) concluded that management differences were more important than soil type and climate variations.



a: ET_{seas} b: Y_{act} c: WP_{ET}

Figure 3-6: Detailed maps of seasonal evapotranspiration (mm), yield (ton ha^{-1}) and water productivity (kg m^{-3}) of large wheat fields in Yaqui irrigation district. The rectangular pattern is the result of 1 by 1 mile blocks into which the area originally was divided.

In Sirsa district, located in the western part of Haryana state (India), wheat yields were measured during the 2001-2002 *Rabi* season in 24 farmers plots (Van Dam *et al*., 2006). Average measured yield was 4.6 ton ha^{-1} (σ~1.3), while SEBAL yields were slightly lower: 4.0 ton ha^{-1} (σ~0.8). Agricultural fields in Sirsa are small and individual fields cannot be recognised on the Landsat images. This means that SEBAL yield values may be a mixture of the actual field, some surrounding fields and non-agricultural objects such as roads, houses and ditches. A slightly lower SEBAL wheat yield can thus be expected for such kind of landscape.

The calibrated SWAP-WOFOST simulation model for soil moisture flow, crop ET_{act}, carbon assimilation and crop growth, was used to estimate water productivity for wheat, in Sirsa district at field level and regional level (Singh *et al*., 2006; Van Dam *et al*., 2006). Simulated WP_{ET} at field level averaged 1.32 kg m^{-3} in 24 fields, while distributed modelling techniques for all fields in Sirsa District yielded average regional WP_{ET} for wheat of 1.20 kg m^{-3}. These values are close to the area average of SEBAL modelled values for WP_{ET} in Sirsa district which equalled 1.22 kg m^{-3}. Modelled wheat yields by SWAP-WOFOST averaged 4.4 ton ha^{-1} with an associated ET_{act} of 388 mm; both values are higher (4.3 and 7.0 % respectively) than SEBAL wheat yield and ET_{act}, but the water productivity is similar.

In the province of Zeeland, the Netherlands spring wheat yields of nine farms were predicted for the 2005 season using SEBAL (unpublished). The results were validated using measured yields from nine agricultural fields. On average measured yields were 3.5% higher than the remote sensing estimates. The consistency in yield predictions across three different continents reveals that SEBAL formulation is acceptable and good enough for further water productivity analysis.

Water productivity and scope for improvement

SEBAL was also applied to quantify water productivity for wheat dominated areas in China, India, Pakistan, Egypt, the Netherlands and California. In all studies SEBAL was used to estimate ET_{act}, yield and WP_{ET} according to the methodology described before. Table 3-3 summarizes the results of these studies and Figure 3-8 depicts the frequency histograms of WP_{ET} for each system. Large differences exist in WP_{ET} levels: the highest values occur in the Nile Delta, Egypt (1.52 kg m^{-3}), Kings County (CA), USA (1.44 kg m^{-3}) and Oldambt, The Netherlands (1.39 kg m^{-3}). The lowest average value was found in Sindh Province, Pakistan: 0.54 kg m^{-3}. Water productions in Pakistan are almost three times lower than in Egypt. This can be ascribed to both low yields and high ET_{act} levels. The correlation figures in Table 3-3 reveal that in all systems, except Sindh, the differences in WP_{ET} can be better explained by yield levels than by ET_{act}. The implication of this finding is that agronomical practices are more important for increasing crop water productivity than water management practices. Zachariasse (1974) concluded that farm management practices have more influence on yield than physical system properties. Average ET_{act} for all systems varies between 355 and 467 mm while yield levels range from 2.5 to 5.4 ton ha^{-1}. The range of average WP_{ET} detected by satellites goes from 0.54 kg m^{-3} in Sindh to 1.52 kg m^{-3} in Egypt. The consequence of this observation is that better crop growth conditions and alert crop management resulting in higher yields should be regarded as the major vehicle to improve crop water productivity.
A plausible range of WP_{ET} values for wheat is 0.6-1.7 kg m^{-3} and average WP_{ET}, based on 82 literature sources with measurements conducted in the last 25 years, is 1.09 kg m^{-3} (Zwart and Bastiaanssen, 2004). The average WP_{ET}, based on the eight areas in this study, is 1.11 kg m^{-3}. This comparison shows that the global data sets of Figure 3-8 display a good representation.

In this study the coefficient of variation (CV) was calculated for the population of WP_{ET} in each of the eight irrigation systems (see Table 3-3). Spatial spreading of WP_{ET} is instructive for possible water savings in given irrigation systems. A low CV value, such as in the Nile Delta, Kings County, Oldambt and Sirsa, indicates that the distribution of WP_{ET} within the system is homogeneous and that there is little scope for improvement. On the other hand the systems in Linxian County, Hebei Province and Sindh Province depict a high CV of 0.33, 0.33 and 0.22 respectively, and consequently increases in the regional average WP_{ET} can be achieved more easily in these systems than in systems with low CV. Moreover, Figure 3-7 shows that the average WP_{ET} decreases with increasing CV and this suggests that heterogeneity is responsible for low crop water production performance. A similar finding was made by Thiruvengadachari *et al*. (1997) who noticed CV-values of 0.30 in low productivity wheat fields in Haryana, India. It could be explained that heterogeneity is responsible for low yields and hence low crop water productivity.

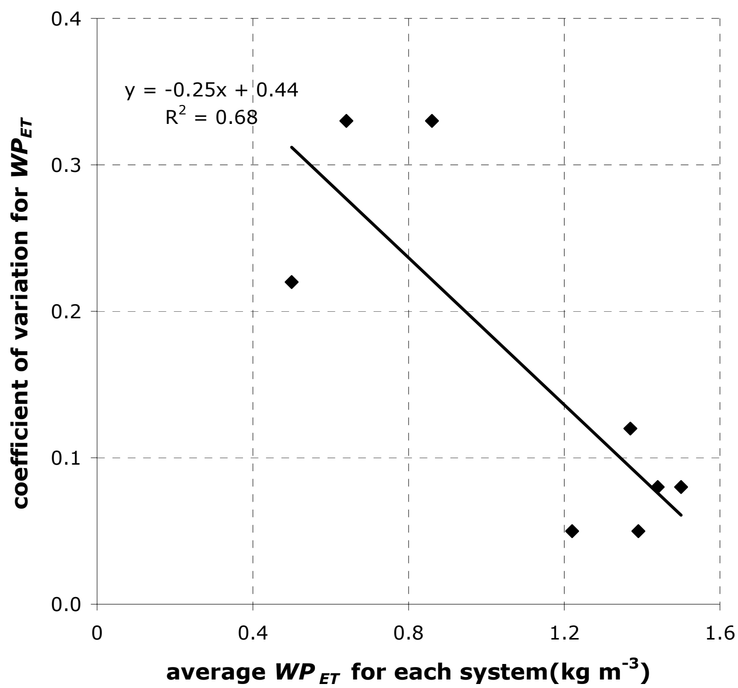


Figure 3-7: Average WP_{ET} *for each wheat system plotted against the coefficient of variation of* WP_{ET}.

Table 3-3: Key figures of the eight wheat systems that were analysed. The harvest index (H_i*), average* ET_{act}*, yield,* WP_{ET}*, maximum* WP_{ET}*, the coefficient of variation (CV) for* WP_{ET}*, and the correlation (ρ) between* WP_{ET} *and yield, and* WP_{ET} *and* ET_{act}*. The standard deviation (σ) for average* ET_{act}*, yield, and* WP_{ET} *is given between brackets. Maximum* WP_{ET} *is defined as the 98% percentile.*

Location		H_i (-)	average ET_{act} (mm)	average Y_{act} (ton ha^{-1})	average WP_{ET} (kg m^{-3})	max WP_{ET} (kg m^{-3})	CV for WP_{ET} (-)	ρ $WP_{ET} - ET_{act}$	ρ WP_{ET} – yield
Nile Delta, Egypt	(31.3°N;31°E)	0.36	355 (20)	5.4 (0.44)	1.52 (0.09)	1.65	0.06	0.02	0.72

Kings County (CA), USA	(36°N;119.5°W)	0.40	395 (19)	5.7 (0.59)	1.44 (0.11)	1.53	0.07	0.56	0.93
Oldambt, The Netherlands	(53.2°N;6.9°E)	0.40	372 (36)	5.2 (0.64)	1.39 (0.07)	1.52	0.05	0.33	0.67
Yaqui Valley, Mexico	(27.3°N;110°W)	0.37	403 (37)	5.5 (0.90)	1.37 (0.16)	1.69	0.12	0.21	0.83
Sirsa, India	(29.5°N;75°E)	0.39	361 (16)	4.4 (0.33)	1.22 (0.06)	1.35	0.05	0.41	0.86
Linxian County, China	(36.2°N;113.7°E)	0.40	436 (35)	3.8 (1.42)	0.85 (0.28)	1.24	0.33	0.58	0.96
Hebei Province, China	(39.5°N;117°E)	0.40	380 (50)	2.5 (0.96)	0.64 (0.21)	0.93	0.33	0.81	0.99
Sindh Province, Pakistan	(27°N;69.5°E)	0.39	467 (82)	2.5 (0.77)	0.54 (0.11)	0.72	0.22	0.27	0.05
Average			400	4.4	1.11	1.33	0.15		

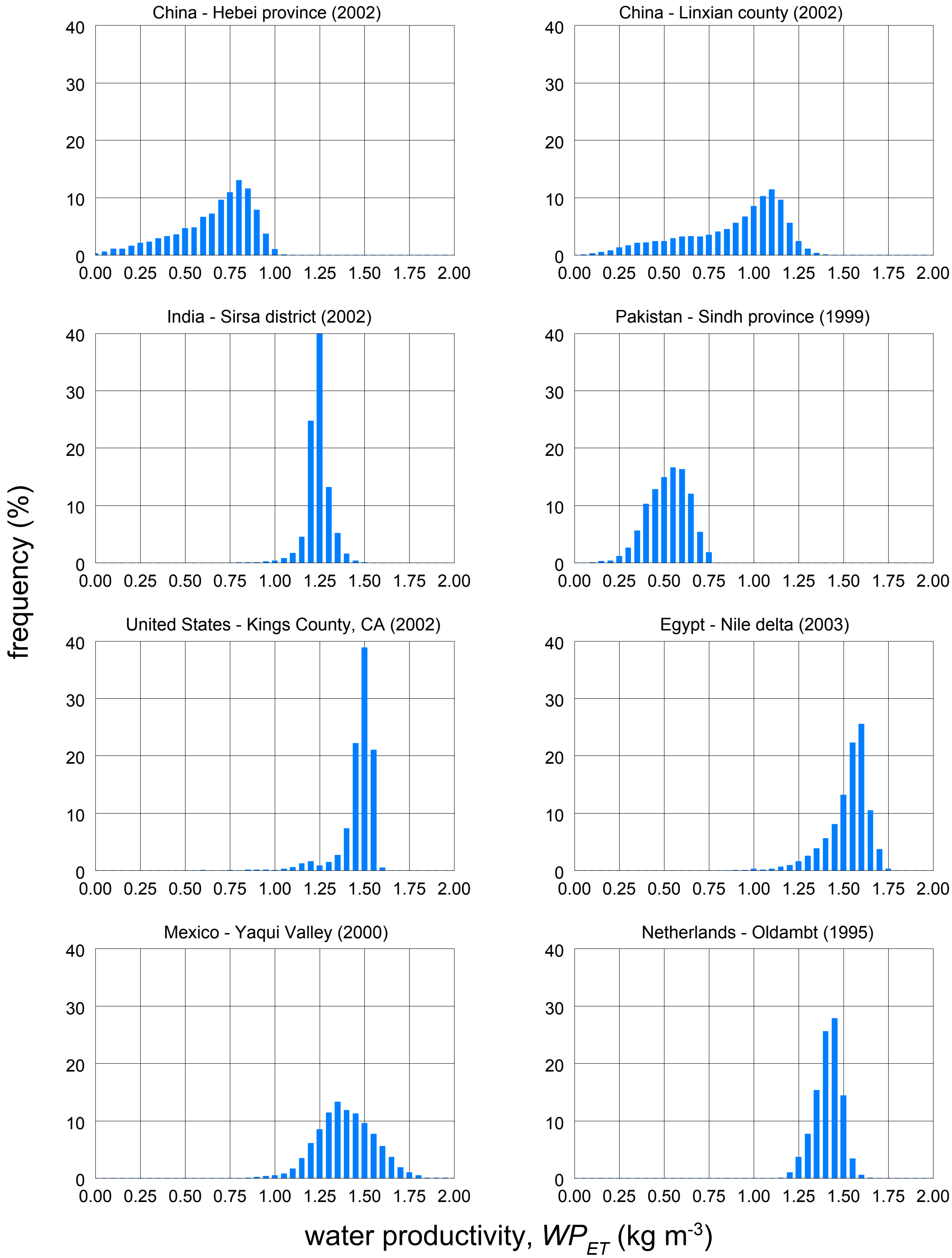


Figure 3-8: Frequency histograms of wheat water productivity (defined as the yield divided by the water use by evapotranspiration) in eight wheat systems in seven different countries.

To quantify the scope of improvement, the CV of all systems were forced to the lowest CV value found across the eight systems (0.05 in Oldambt and Sirsa), while maintaining the maximum value for WP_{ET} that can be obtained under practical circumstances. The 98% percentile is considered representative for opportunistic WP_{ET} values. This is visualized in the frequency histogram for WP_{ET} in the Yaqui Valley (see Figure 3-9). Pixels on the lower side (0.9-1.0 kg m^{-3}) are forced to values between approximately 1.3 and 1.4 kg m^{-3} to meet the criterium of a CV equalling 0.05, while maintaining the 98% percentile value of 1.69 kg m^{-3}. Fields or areas with significant scope for improvement are now spatially recognized. Such information gives water managers the opportunity to allocate plots with inefficient water use. Extension officers can direct their services to specific farms where crop water productivity is low. Water policy makers can also release sanctions to encourage farmers to increase their profit from scarce water resources.

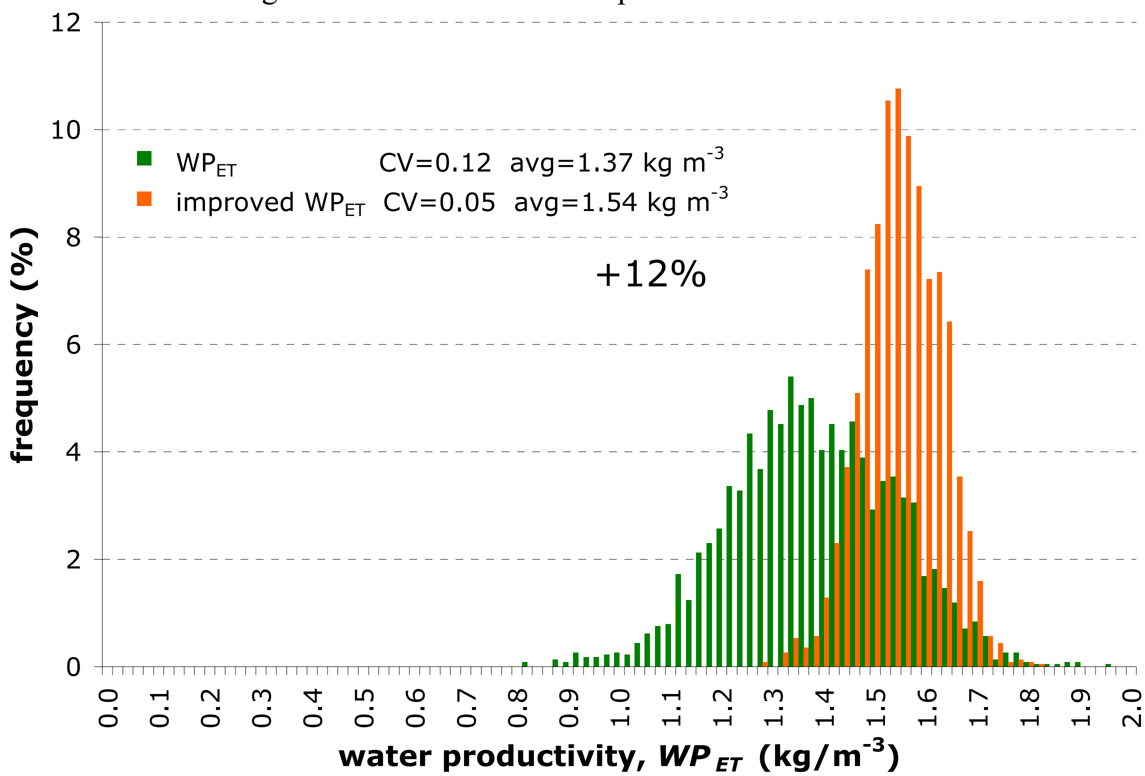


Figure 3-9: The original frequency distribution for WP_{ET} *in Yaqui, Mexico and the improved* WP_{ET} *that was forced to CV of 0.05 while maintaining the maximum value.*

Table 3-4: Improved average WP_{ET} *for eight irrigation systems at a coefficient of variation (CV) of 0.05. The percentage wise increase is given between brackets.*

Location	improved average WP_{ET} (kg m^{-3})
Nile Delta, Egypt	1.54 (+1%)
Kings County (CA), USA	1.47 (+2%)
Oldambt, The Netherlands	1.39 (0%)
Yaqui Valley, Mexico	1.54 (+12%)
Sirsa, India	1.22 (0%)
Linxian County, China	1.16 (+35%)

Hebei Province, China	0.87 (+34%)
Sindh Province, Pakistan	0.66 (+24%)
average	1.23 (+14%)

In Yaqui Valley WP_{ET} increases on average 12% from 1.37 to 1.54 kg m^{-3}, which implies that increasing wheat yield by 12% at the same ET_{act} is feasible. It can also be argued that the same yield can be obtained from 12% saving in water consumption. At for instance 40% overall irrigation water losses, 12% reduction of ET_{act} will translate into 17% less water diversions. Similar calculations were made for the other systems and are summarized in Table 3-4. The largest scope for improvement was found in Linxian County and Hebei Province where WP_{ET} can be increased maximally by 34 and 35% if all interventions are effective. Also in Sindh Province the ET_{act} can be reduced by 24% leading to substantial water savings in this area. On average for the eight systems WP_{ET} can be increased 14%. The first approximation of possible global water savings on irrigated wheat is thus 14% (consumption) and 20% (diversion), provided that 40% of diverted water is lost between the off take and root zone water storage.

3.4 Conclusions

The methodology proposed in this study proved to be accurate in estimating seasonal ET_{act} and yields of wheat at field level. The eddy-correlation measurements of ET_{act} correlated well with SEBAL estimated ET_{act}, and wheat yields were well within the range of yields that were measured in Yaqui Valley and Sirsa District. The analysis of WP_{ET} in the different irrigation systems showed that large variations exist in the levels of WP_{ET} that are achieved. The scope for improvement is largest in the systems where WP_{ET} is lowest (WP_{ET}<0.8 kg m^{-3}) and CV is highest (CV>0.3). The average increase in WP_{ET} is 14%, thus 14% of the water resources can be saved in consumption of irrigated wheat at maintained level of crop production which is equivalent to 20% saving in water diversion.

It is concluded that by applying this methodology, valuable information is generated for water resource planners and irrigation managers on the spatial distribution of water productivity. Using these maps, areas with low WP_{ET} can be detected and by relating them to spatial information on soil type, groundwater table, quality of irrigation water, farm management, etc. the underlying causes can be searched for. The most encouraging leap forward is that water productivity can not only be quantified for different areas (hence a comprehensive picture on wheat and water), but that also within region-variations can be detected. The latter is essential for the sake of demonstration that it is realistic to obtain a higher utilization of water resources under local environmental conditions. Although remote at itself sensing cannot provide the underlying reasons for variations, it can be used to identify farm plots with good and poor management practices. This is fundamental information for extension services, dissemination and farmers-help-farmers teach programs. Since water productivity is more tightly coupled to yield than to ET_{act}, increasing low yields seems the most straightforward solution to increase water productivity.

4 WATPRO: A remote sensing based model for mapping water productivity of wheat*

4.1 Introduction

The agricultural sector will require more water in the near future to provide more food, fibre and fuels (Kijne *et al*, 2003; Molden *et al*., 2007). Underlying reasons are a growing population that needs more food, a change in diet due to increased prosperity, and a recent focus on biofuels. While more water is needed for agriculture, the demand for water from other users - such as the industry, tourism and domestic sectors - is also increasing. This competition for water is resulting in a situation where the irrigation sector is unlikely to be allocated more water in the future in water-scarce areas. Moreover, climate change adds to the already existing pressures on water resources. It is within this global setting that the agricultural sector, being the largest water consumer, must adapt itself and make water use more productive to sustain food production for the coming generations. The challenge is to produce more food and animal feed from the same amount of water (Molden *et al*., 2009).

The productivity of water (WP_{ET}) can be expressed by the harvestable grain yield per unit of water consumption by evapotranspiration (Y_{act} / ET_{act}). It has the advantage of expressing the water unit of the equation as a true consumption; the evapotranspiration process withdraws water from soil into the atmosphere, water that is no longer available for downstream users (Molden and Sakthivadivel, 1999). Based on a review of water productivity measurements in literature from recent years, Zwart and Bastiaanssen (2004) presented plausible ranges of water productivity that can be expected globally for major crops based on carefully selected field experiments. These ranges, however, display a large variation as a result of growing conditions that vary from year-to-year and from location-to-location. On a global scale, differences in the physical water productivity are expected based on climatic variation. Bierhuizen and Slatyer (1965) reported an inverse linear relationship between vapour pressure deficit and water productivity. Steduto *et al*. (2007) and Sadras and Angus (2006) demonstrated an inverse linear relationship between water productivity and reference evapotranspiration. Considering that temperate climates have lower vapour pressure deficits and reference evapotranspiration than arid climates, crops may be grown with less water resources in the former climates.

There is a need for mapping and benchmarking water productivity to support a global understanding of where crops are grown with least water consumption, and where there is greatest scope for improvement. In addition to that, Zwart and Bastiaanssen (2007) proposed a methodology to assess water productivity variability within regions to identify plots with poor and with good water management practices. Their methodology allows analysis of spatial variation at field scale, and to quantify the scope for improvement within an irrigation system or region during a specific year. As water productivity is related to weather conditions, the level of water productivity may vary strongly from year to year, even if crop and water management are similar in both years. Other examples of

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regional water productivity mapping based on remote sensing and modelling are given by Bastiaanssen *et al*. (1999), McVicar *et al*. (2004), Van Dam *et al*. (2006), Immerzeel *et al*. (2008), Anderson *et al*. (2008), Mo *et al*. (2009) and Zwart and Leclert (2010). Although calibrated deterministic models allow scenario analysis, their major disadvantage is the detailed input that is required and which is usually not available spatially. On a global scale, Liu *et al*. (2007) modelled wheat yields and potential evapotranspiration to calculate water productivity. It is known, however, that water productivity rarely meets the potential values of evapotranspiration or maximum crop yields. Moreover, crop modelling requires spatial estimates of management data on irrigation, drainage, soil tillage and fertilization, which are not straightforward to describe, while remote sensing on the other hand provides a direct measurement of water productivity. Models are therefore considered less suitable to benchmark water productivity than remote sensing techniques since agronomic management data are usually not available at the higher scales.

To the authors knowledge, there exists no analysis that provides benchmark values for water productivity globally on the basis of crop and water measurements under actual field conditions. The objective of this paper is therefore to develop a simplified remote sensing based model of the water productivity of wheat (a major food crop globally), hereafter named WATPRO, with low input data requirements and applicable at high spatial resolution? detail. The point of departure is that the model should directly estimate water productivity, instead of estimating crop yield and evapotranspiration separately. The model was tested using a data set of measured water productivity values that was reported in the literature and summarized by Zwart and Bastiaanssen (2004). During a field campaign in Sirsa District, India, the water productivity was measured in farmer's fields and assessed at regional scale with remote sensing (Van Dam and Malik, 2003). Their results will also be used to validate the WATPRO model. The WATPRO model was applied on global remote sensing data sets to obtain a global benchmark map of water productivity for wheat (Zwart *et al*., 2010).

4.2 Water productivity model

In this study, water productivity (WP_{ET}) is defined as the ratio of harvestable wheat yield (Y_{act}) divided by the accumulated amount of water consumed by evapotranspiration during the growing season (ET_{act}):

$$WP_{ET} = \frac{Y_{act}}{\sum_{t=e}^{t=h} ET_{act}(t)} \quad (\text{kg m}^{-3}) \qquad (4.1)$$

where Y_{act} is the harvestable wheat grain yield at 14% moisture (kg ha^{-1}) and ET_{act} is the accumulated actual evapotranspiration computed for time period t for the growing season that runs from crop establishment (*t=e*) to harvest (*t=h*).

Wheat yield and dry matter production

Wheat grain yield can be approximated as the product of the accumulated dry matter production (*DM*) during the growing season multiplied by the harvest index (H_i), which is the fraction of above-ground dry biomass comprising grain, and a correction for the fraction of water present in the grain (θ_{grain}):

$$Y_{act} = H_i / (1-\theta_{grain}) \cdot \sum_{t=e}^{t=h} DM(t) \quad (\text{g m}^{-2}) \tag{4.2}$$

Monteith (1972) developed a theoretical framework that relates the absorbed photosynthetically active radiation (*APAR*) and the light use efficiency to plant dry matter production:

$$DM = APAR \cdot \varepsilon \quad (\text{g m}^{-2}) \tag{4.3}$$

where DM is the above ground dry matter production (MJ m^{-2}) and ε is the light use efficiency (g MJ^{-1}). *APAR* is calculated from:

$$APAR = f \cdot \chi \cdot \tau_{SW} \cdot S_{exo}^{\downarrow} \cdot 0.0864 \quad (\text{MJ m}^{-2}\ \text{day}^{-1}) \tag{4.4}$$

In this equation, the incoming shortwave radiation (0.3-3.0 μm) is calculated by multiplying the average extraterrestrial radiation ($S_{EXO}^{\downarrow}$ in W m^{-2}) during the growing season with a dimensionless atmospheric transmissivity (τ_{SW}). Only part of the incoming solar radiation can be absorbed by plants for photosynthetic processes. The fraction between the so-called photosynthetically active radiation (*PAR*, 0.4-0.7 μm) and $S_{EXO}^{\downarrow}$ is given by χ. *PAR* describes the amount of energy that is available for photosynthesis if the leaves intercept all radiation. *APAR* will be much lower than *PAR* as leaves transmit and reflect solar radiation. *APAR* is a function of the canopy reflectance at the upper side of the canopy, the amount transmitted through the canopy, and the amount that is reflected back to the canopy by the soil. These processes can be summarized in the *APAR*/*PAR* fraction f. Several authors have reported a linear relation between the *NDVI* and f (e.g. Hatfield *et al*., 1984; Asrar *et al*., 1992)

$$f = a \cdot NDVI + b \quad (-) \tag{4.5}$$

Where both *a* and *b* are empirical values that can be determined for different crops.

The light use efficiency ε for wheat is a constant that does not vary if environmental conditions are non-limiting (Monteith, 1972). However, both temperature and water availability can have a significant impact on the ε. Field *et al*. (1995) used the following:

$$\varepsilon = \varepsilon_{\max} \cdot W \cdot T_1 \cdot T_2 \quad (\text{g MJ}^{-1}) \tag{4.6}$$

where $\varepsilon_{\max}$ is the maximum light use efficiency (g MJ^{-1}), T_1 and T_2 are scalars for temperature effects on the light use efficiency. W is a water scalar that is defined as actual over potential evapotranspiration. In this study the evaporative fraction (Λ), which is the fraction between the energy actually used for evapotranspiration and the net available energy, is used instead, following Bastiaanssen and Ali (2003). T_1 and T_2 can be computed from the monthly average temperature (T_{mon}) and the monthly average temperature during the month of maximum leaf area index (T_{opt}) (Field *et al*., 1995):

$$T_1 = 0.8 + 0.02T_{opt} - 0.0005T_{opt}^2 \quad (-) \tag{4.7}$$

$$T_2 = \frac{1}{1+\exp\left(0.2T_{opt} - 10 - T_{mon}\right)} \cdot \frac{1}{1+\exp\{0.3\left(-T_{opt} - 10 + T_{mon}\right)\}} \quad (-) \tag{4.8}$$

Eq. 4.2 can now be rewritten as the summation of the dry matter production per period (t) between emergence and harvest of the crop, multiplied by the harvest index and corrected for the grain water content:

$$Y_{act} = H_i/(1-\theta_{grain}) \cdot \sum_{t=e}^{t=h} \left\{(a \cdot NDVI + b) \cdot \chi \cdot S_{EXO}^{\downarrow} \cdot \tau_{SW} \cdot \varepsilon_{\max} \cdot \Lambda \cdot T_1 \cdot T_2\right\}(t) \cdot 0.864 \ \ (\text{kg ha}^{-1}) \tag{4.9}$$

Actual evapotranspiration

Actual evapotranspiration (ET_{act}) is an important component of the energy balance in cropped land:

$$R_n = G_0 + H + \lambda E \quad (\text{W m}^{-2}) \tag{4.10}$$

where Rn is net radiation (W m^{-2}), G_0 is the soil heat flux (W m^{-2}), H is the sensible heat flux (W m^{-2}) and λE is the latent heat flux that is associated with the actual evapotranspiration. The energy balance can be rewritten to:

$$\lambda E = \Lambda \cdot \left(R_n - G_0\right) \quad (\text{W m}^{-2}) \tag{4.11}$$

where Λ is the dimensionless evaporative fraction and $R_n - G_0$ equals the net available energy available for evapotranspiration. On time scales of one day or more, the soil heat flux can often be ignored and thus the latent heat flux λE is a function of Λ and R_n only. The net radiation for daily time steps can be expressed as the difference between the net shortwave and net longwave radiation (De Bruin and Stricker, 2000):

$$R_n = (1-\alpha) \cdot S_{EXO}^{\downarrow} \cdot \tau_{SW} - 135 \cdot \tau_{SW} \quad (\text{W m}^{-2}) \tag{4.12}$$

where α is the surface albedo (-). The daily actual evapotranspiration expressed as a latent heat flux (W m^{-2}) can thus be estimated from the evaporative fraction, surface albedo, incoming terrestrial radiation and atmospheric transmissivity:

$$ET_{act} = \sum_{t=e}^{t=h} \left\{\Lambda \cdot \left((1-\alpha) \cdot S_{EXO}^{\downarrow} \cdot \tau_{SW} - 135 \cdot \tau_{SW}\right)\right\}(t) \cdot 0.35 \quad (\text{m}^3\ \text{ha}^{-1}) \tag{4.13}$$

where 0.35 is a conversion factor to express ET_{act} in m^3 ha^{-1}.

Water productivity

After substituting equations 4.9 and 4.13 into equation 4.1, the water productivity (WP_{ET}) can be written as:

$$WP_{ET} = \frac{H_i \cdot \sum_{t=e}^{t=h} \left\{ \left(a \cdot NDVI + b \right) \cdot \chi \cdot S_{EXO}^{\downarrow} \cdot \tau_{SW} \cdot \varepsilon_{\max} \cdot \Lambda \cdot T_1 \cdot T_2 \right\} (t) \cdot 0.864}{\left(1 - \theta_{grain} \right) \cdot \sum_{t=e}^{t=h} \left\{ \Lambda \cdot \left(\left(1 - \alpha \right) \cdot S_{EXO}^{\downarrow} \cdot \tau_{SW} - 135 \cdot \tau_{SW} \right) \right\} (t) \cdot 0.35} \quad (\text{kg m}^{-3}) \tag{4.14}$$

If spatial and temporal varying input parameters are averaged for the growing season (*e* to *h*), equation 4.14 can be rewritten as:

$$WP_{ET} = \frac{H_i \cdot \left(a \cdot \overline{NDVI} + b \right) \cdot \chi \cdot \overline{S_{EXO}^{\downarrow}} \cdot \overline{\tau_{SW}} \cdot \varepsilon_{\max} \cdot \overline{\Lambda} \cdot \overline{T_1} \cdot \overline{T_2} \cdot 0864}{\left(1 - \theta_{grain} \right) \cdot \overline{\Lambda} \cdot \left(\left(1 - \overline{\alpha} \right) \cdot \overline{S_{EXO}^{\downarrow}} \cdot \overline{\tau_{SW}} - 135 \cdot \overline{\tau_{SW}} \right) \cdot 0.35} \quad (\text{kg m}^{-3}) \tag{4.15}$$

After omitting the atmospheric transmissivity and the evaporative fraction, Eq. 4.15 can be simplified into:

$$WP_{ET} = \frac{H_i \cdot \left(a \cdot \overline{NDVI} + b \right) \cdot \chi \cdot \overline{S_{EXO}^{\downarrow}} \cdot \varepsilon_{\max} \cdot \overline{T_1} \cdot \overline{T_2} \cdot 0864}{\left(1 - \theta_{grain} \right) \cdot \left(\left(1 - \overline{\alpha} \right) \cdot \overline{S_{EXO}^{\downarrow}} - 135 \right) \cdot 0.35} \quad (\text{kg m}^{-3}) \tag{4.16}$$

This implies that water productivity (WP_{ET}) can be estimated from four spatial variables: 1) broadband surface albedo α, 2) vegetation index *NDVI, 3)* the extraterrestrial radiation $S_{EXO}^{\downarrow}$, and 4) air temperature (T_{mon}) to compute T_1 and T_2. Both *NDVI* and α are typical remote sensing parameters which can be derived at different spatial and temporal resolution from narrow band satellite measurements. Model parameters $PAR / S_{EXO}^{\downarrow}$ fraction χ and the maximum light use efficiency $\varepsilon_{\max}$ can be held globally constant. This practically implies that all key variables can be obtained from routine satellite measurements.

The innovation of Eq. 4.16 is that both evaporative fraction (Λ) and atmospheric transmissivity (τ_{SW}) can be omitted. This is a significant advantage since both these parameters are difficult to measure or estimate in the space and time domain. The evaporative fraction has been recognized as being the most difficult parameter of the surface energy balance to describe (Shuttleworth, 1989). This analysis, however, does not provide separate estimates of yield and actual evapotranspiration.

Following Moran *et al*. (1995), the $PAR / S_{EXO}^{\downarrow}$ fraction χ is set at 0.48. Monteith (1972) concluded that the maximum light use efficiency is constant and if crops are not short of water, it will only vary between C3 and C4 crops. Bastiaanssen and Ali (2003) presented an overview of measured values of ε for wheat crops, and based on their review they propose $\varepsilon_{\max}$ to be 2.5 g MJ^{-1} for wheat. Myneni and Williams (1994) analysed the relationship between the *NDVI* and the *APAR*/*PAR* fraction f under varying conditions.

They found that a scale-invariant linear relationship exists for backgrounds of moderate brightness (i.e. not bright sandy or dark peaty soils) if *NDVI* measurements are corrected for atmospheric and bidirectional effects. Several authors have reported linear relationships for different crops. The average a and b of two spring wheat experiments (Asrar *et al*., 1984 and Hatfield *et al*., 1984) will be used in the application of the model (1.23 and -0.149 respectively). After replacing the constants in Eq 4.16, water productivity can now be estimated from:

$$WP_{ET} = \frac{H_i \cdot \left(1.23 \cdot \overline{NDVI} - 0.149\right) \cdot \overline{S^{\downarrow}_{EXO}} \cdot \overline{T_1} \cdot \overline{T_2} \cdot 3.444}{\left(\left(1 - \overline{\alpha}\right) \cdot \overline{S^{\downarrow}_{EXO}} - 135\right)} \quad (\text{kg m}^{-3}) \qquad (4.17)$$

4.3 Model sensitivity and performance

To obtain a better understanding of the behaviour of the WATPRO model, a sensitivity analysis was performed. WATPRO was applied four times to calculate WP_{ET} , each time varying one of the inputs and keeping the others constant. Representative global seasonal average values of the four spatially variable inputs were set at 0.38 (*NDVI*), 0.16 (α), 350 W m^{-2} ($S^{\downarrow}_{EXO}$) and 16^{o}C (T_{opt}). For each parameter a range was set, which was based on the minimum and maximum values of the seasonal averages, which were derived from the application of the WATPRO model for wheat at a global scale (Zwart *et al*, 2010).

Two different sources were consulted to test the model's performance: 1) field measurements of water productivity reported in the literature and incorporated in a data base by Zwart and Bastiaanssen (2004), and 2) spatially measured, modelled and validated water productivity reported by Van Dam and Malik (2003). The data base by Zwart and Bastiaanssen was updated with eleven more recent publications and now contains results from field experiments on wheat yields and water use by evapotranspiration that were conducted on 39 different locations globally. The measurements were conducted in experimental fields where crop growth and water use were monitored under different growing conditions, such as varying irrigation water management (amount and timing of application) and fertilizer management (amount N applied). All sources, except one, provide the results from identical experiments repeated during more than one season. For all of the included experiments, multi-seasonal average evapotranspiration, wheat grain yield, water productivity, geographic location and sowing and harvest times were calculated. If provided, the measured harvest indices were also included in the data base (see *Table 4-1*).

The WATPRO model (Eq. 4.17) was applied at the 39 locations (see Figure 4-1) and the modelled water productivity values were compared with the measured ones. As described in the previous section, six out of ten input parameters were taken from literature sources. For the remaining (*NDVI*, surface albedo, air temperature) global data sets were used. Few publications provide air temperature and therefore these were extracted from the climate grids of the Water and Climate Atlas from the International Water Management Institute (IWMI) derived from the University of East Anglia climate grids (New *et al*., 1999). The SPOT-Vegetation sensor provided 10-daily *NDVI* maps since April 1998. An average *NDVI* time series was calculated to represent a normal growing season to be used as input for the model. The average *NDVI* for each of the 36 10-daily periods was calculated from the ten years (1998-2008) that were available. Seasonal extremes in the average *NDVI* were minimized by excluding the minimum and maximum *NDVI* value at each location. As the geographic position and start and end of the growing season of the experiment were provided by the literature source, the seasonal *NDVI* values for each experimental location could be extracted from the maps. A similar multi-year average global data set was available for the broadband surface albedo: spatially complete global spectral surface albedos (Moody *et al*., 2005). This data set contains 23 cloud-free and gap-filled surface albedo images that are averaged from the period 2000 to 2004. Each image is representative of a 16-day time period. The spatial resolution is 1 arcminute, which is equal to approximately 1.6 km at the equator. The surface albedo images are public domain and available from the MODIS Atmosphere ftp-site*.

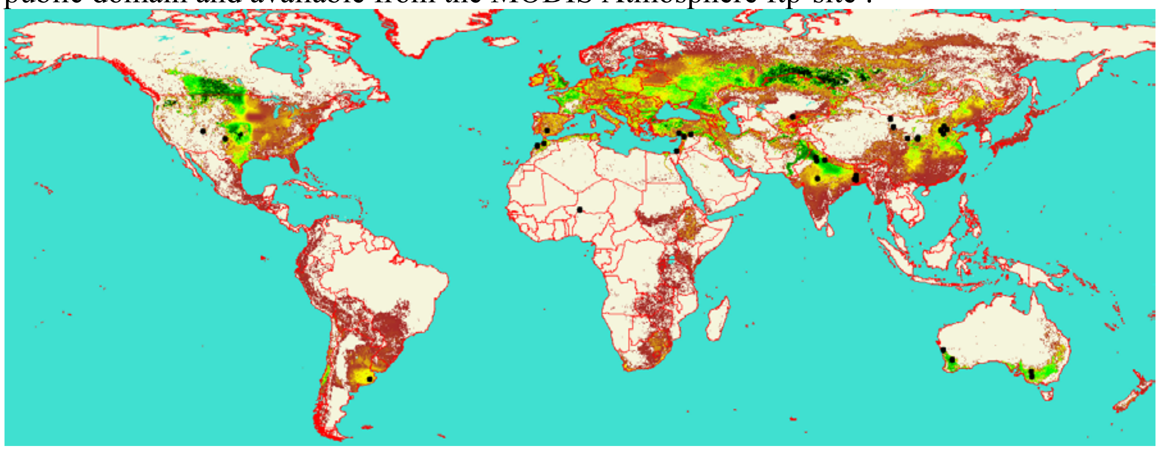


Figure 4-1: Location of the 39 experimental sites where water productivity was measured and for which water productivity was modelled. The points are superimposed on the wheat fraction map that shows the spatial dominance of wheat across the world (Leff et al.*, 2004) , and the degree to which the sites represent global wheat growing areas.*

WATPRO was applied to 10-day time steps using the SPOT-VGT 10-daily period system as a basis. In this system each month is divided in three periods, where the first period runs from day 1 to 10, the second from day 11 to 20, and the third period runs from day 21 to the end of the month. With the provided geographic location of the 39 experimental locations, and the start and end dates of the growing season, the seasonal average values of the NDVI, broadband surface albedo, extraterrestrial radiation and air temperature can be extracted from the maps. If provided by the literature source, the water productivity model included a harvest index measured in the experiments. However, not all provided a measured harvest index, and for those cases the average harvest index value from the other experiments, being 0.35, was applied. The reported water productivities in this paper assume a 14% grain moisture content.

In an extensive study in Sirsa District (Haryana, India) the water productivity of wheat, amongst other crops, was studied (Van Dam and Malik, 2003). Five sites were intensively monitored during the 2001-02 agricultural season in terms of irrigation supply, crop development, soil moisture and salinity (Singh *et al*., 2006). The sites were located in an alluvial plain with wheat being the major winter crop. The sites were selected to have different crop rotation (wheat-rice or wheat-cotton), irrigation water

* ftp://modis-atmos.gsfc.nasa.gov

supply (canal, pump or a combination), and soil and ground water conditions. The fields were managed by farmers under actual fields conditions, and this situation therefore differed from traditional experimental sites where yields, ET_{act} and WP_{ET} are measured in small fields on experimental stations and under optimal conditions. The measured water productivity in the fields was compared with WAPTRO modelling results of the pixel in which the fields were located. For the application of WATPRO, the *NDVI* and surface albedo were taken from the SPOT-VGT 1998-2008 and the MODIS 2000-2004 average data sets respectively. An analysis of the *NDVI* time series revealed that the *NDVI* depicted little variation from year-to-year and therefore in this specific case, differences are not expected to arise from the use of the average data sets. The low variation between years is possibly caused by the fact that the wheat areas are largely irrigated from ground water and they are thus not dependent on water availability from precipitation or irrigation.

During this study, WP_{ET} was also assessed spatially using satellite imagery and the SEBAL algorithm. Both wheat yields and seasonal actual evapotranspiration were quantified using NOAA-AVHRR satellite images at a resolution of 1 by 1 kilometre. For the application in Sirsa District the modelling period was fixed from November 1 to April 30 (Van Dam and Malik, 2003), whereas wheat yields were obtained with a fixed H_i of 0.39 and a θ_{grain} equalling 11%. The SEBAL WP_{ET} map was compared and validated using the same field measurements of yields and ET_{act}. The WATPRO model was applied to the same region, using the same H_i, θ_{plant} and modelling period. The original surface albedo and *NDVI* imagery were not available, and therefore these were substituted with the MODIS surface albedo and SPOT-VGT *NDVI* data sets as described before. Since the WATPRO model is derived from the SEBAL principles, the comparison is not a validation of Eq. 16. It may show, however, whether WATPRO, with its simplifications and assumptions, can spatially predict WP_{ET} similar to SEBAL.

4.4 Results and discussion

The sensitivity of WATPRO towards the four spatial input parameters is depicted in Figure 4-2. If the global average values are applied, the average WP_{ET} amounts 1.06 kg m^{-3}. It can be seen that WP_{ET} is least sensitive to air temperature during maximum crop development (T_{opt}); values higher than 16°C have almost no impact whereas at lower temperatures WP_{ET} is maximally reduced by 17% (compared to the average 1.06 kg m^{-3}). Both surface albedo and *NDVI* have a positive linear relationship with WP_{ET}, though the impact of the surface albedo is much smaller (maximally 18%) than the impact of *NDVI* on WP_{ET} (81%). Finally, at values of seasonal average extraterrestrial radiation lower than the average 350 W m^{-2}, WP_{ET} levels are 57% lower. However, this difference is smaller (16%) for values higher than the global average of 350 W m^{-2}. This analysis reveals that WP_{ET} of wheat can be expected to be high if *NDVI* is high and radiation is low.

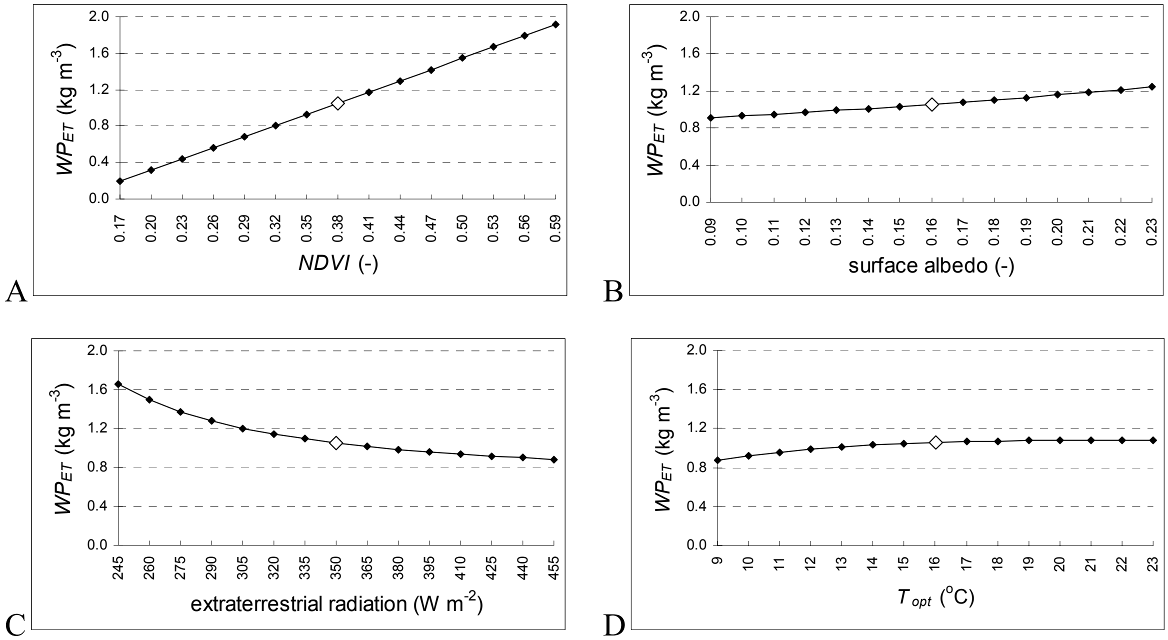


Figure 4-2: Sensitivity of WATPRO to variation in the four spatial inputs: (A) NDVI*, (B) surface albedo, (C) extraterrestrial radiation and (D) temperature during maximum crop development. The white bullets indicate the average value of the parameters.*

The NDVI and surface albedo values were extracted from the 39 experimental locations where water productivity was measured. Wheat experiments are usually conducted in small fields located on experimental farms or field stations, whereas the *NDVI* values are an average of an area of approximately 1 by 1 kilometre. The time profiles of the *NDVI* and surface albedo were plotted and checked for consistency with the average sowing and harvest dates during the experiments. As was shown in the sensitivity analysis, the seasonal average *NDVI* has a strong impact on the final levels of WP_{ET}. In 19 locations the inputs were found to be unsuitable to apply WATPRO for two reasons: first of all, a mismatch was found between the growing season that was reported for the experiments and the establishment of the crop and the harvest data that could be derived from the profiles. Secondly, the *NDVI* profile does not represent a typical wheat season. The *NDVI* profile of the *NDVI* and surface albedo are plotted for two locations (Figure 4-3). The first location (Mallee, Australia) shows an *NDVI* profile that is representative of wheat, whereas the second (Yellow Jacket, USA) shows interference by a summer crop between the first period in July and the first period of August. The latter was therefore excluded from further comparison with the WATPRO model. The remote sensing derived *NDVI* was in those cases not representative of the experimental sites and conditions and these were excluded from further analysis. The remaining 20 locations were situated in an area surrounded and dominated by other wheat fields and considered suitable for comparison with modelled water productivity.

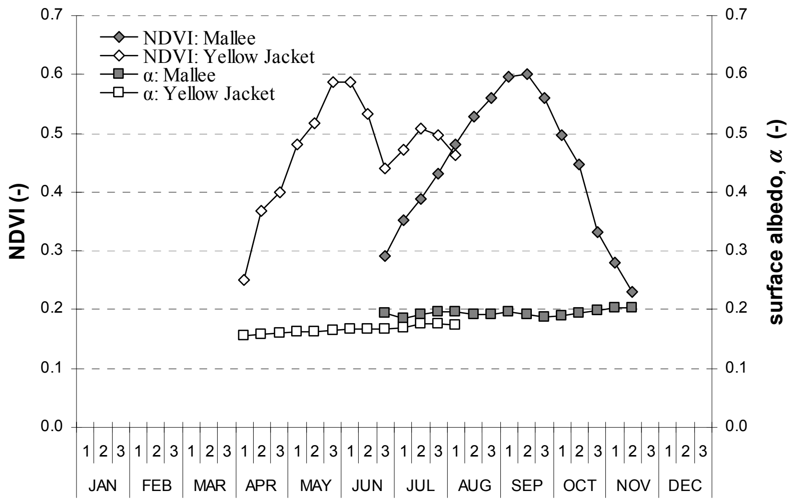


Figure 4-3: Examples of time profiles of the NDVI and surface albedo (α) on two selected locations: Mallee, Australia (Latta and O'Leary, 2003) and Yellow Jacket, USA (Al-Kaisi et al.*, 1997). The values were extracted from 1 by 1 kilometre SPOT-VGT using the reported dates of the growing season.*

Figure 4-4 depicts the measured versus modelled crop water productivity in 20 experimental locations. The average measured water productivity is 1.00 kg m^{-3} and the average WATPRO modelled water productivity is similar at 0.99 kg m^{-3}. Also the ranges are very similar: measured values are between 0.52 and 1.42 kg m^{-3}, whereas modelled values vary between 0.54 and 1.54 kg m^{-3}. There is, however, only a weak positive correlation between modelled and measured values (r^2 equals 0.15). The comparison between experiment measurements and modelling results shows that differences of more than 50% occur (see *Table 4-1*), although there is no consistent overestimation or underestimation of WP_{ET}. In Mullewa, Australia, modelling results are 56% higher, but in Merredin, Australia (also reported by Regan *et al*., 1997) there is no difference between the average of the experiments and the modelled WP_{ET} (both 1.32 kg m^{-3}).

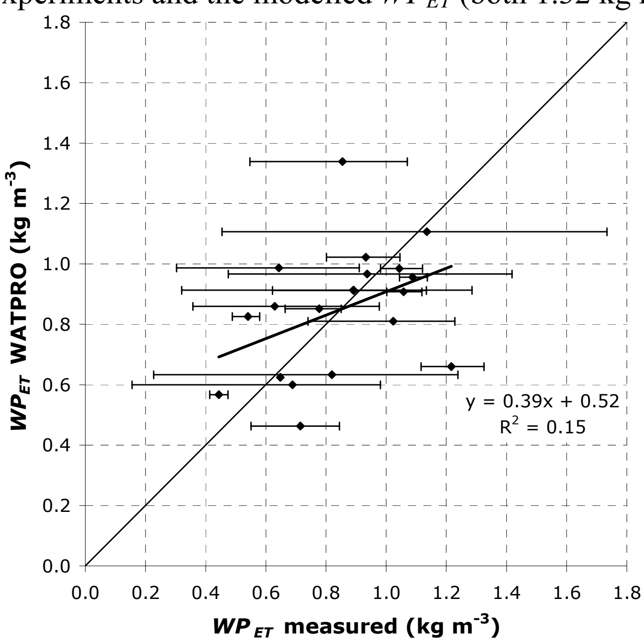


Figure 4-4: Measured versus modelled water productivity (WP_{ET} *in kg* m^{-3}*). Each point represents the average of the measured and modelled* WP_{ET} *at one experimental location. In each point a wide range of measured values is included that varies from experiments under rainfed to full irrigation conditions, from no fertilization to high-fertilization rates, and from year to year. The minimum and the maximum measured water productivity at a location are indicated by the horizontal bars.*

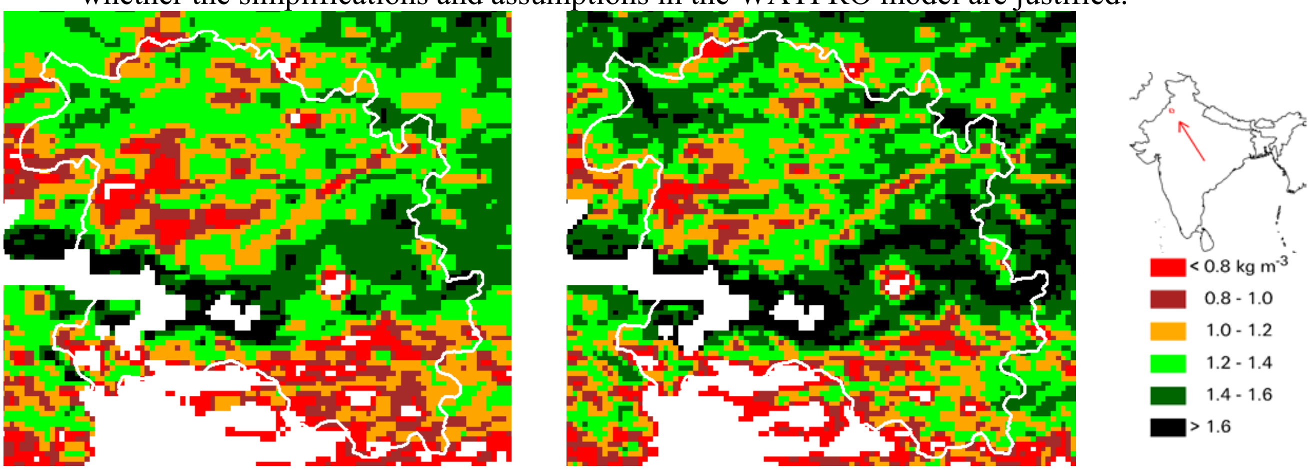
Beside the model performance, the low correlation and, in certain cases, large differences between measured and modelled WP_{ET}, can be attributed to three major reasons that are related to model input data and scale. Firstly, the modelled water productivity is calculated with inputs (*NDVI*, surface albedo and air temperature) that are averaged over several years, whereas the measurements were conducted during specific years (*Table 4-1*); hence, the periods of consideration are not identical. It is for example known that water productivity is influenced by weather conditions during the growing season, which may vary strongly from year to year. Secondly, in 7 of the 20 experiments, the harvest indices were not measured. An average of the harvest indices of the remaining experiments was used instead, and for individual experiments this can result in an offset of up to 19% (*Table 4-1*). Thirdly, the WATPRO water productivity model is applied to 1 by 1 kilometre pixels. The experiments are conducted at only a fraction of the 1 square kilometre and it is therefore unclear how representative the experiments are of the surrounding 1 by 1 kilometre of land. Usually, in field experiments the timing of irrigation and the irrigation water and fertilizer quantities are varied to study the effects on crop yield, water consumption and water productivity. The average of all experiments in one study site was calculated and assumed to be representative of the varying management and field conditions in the surrounding 1 by 1 kilometre over which water productivity is modelled. Despite all the shortcomings, it can be seen from Figure 4-4 that in 12 out of 20 experiments, modelled WP_{ET} is within the range of measured minimum and maximum WP_{ET} (i.e. 60%).

Table 4-1: Reported values of water productivity (WP_{ET}) *and harvest index* (H_i) *for wheat, and the modelled water productivity. The experiments were first summarized and reported in Zwart and Bastiaanssen (2004). Experimental results reported in literature sources after 2003 were added to this data base.*

source	location, country	experimental years*	H_i reported (-)			WP_{ET} reported (kg m^{-3})			WP_{ET} WATPRO (kg m^{-3})	difference (%)
			min	avg	max	min	avg	max		
Bouthiba *et al*., 2008	Chlef, Algeria	1997-2001 (4)	0.28	0.35	0.45	0.46	0.73	1.08	0.98	+34%
O'Leary and Connor, 1997	Dooen, Australia	1988-1991 (4)	0.33	0.35	0.37	0.95	1.08	1.20	1.20	+11%
Latta and O'Leary, 2003	Mallee, Australia	1985-2000 (16)	not measured			1.15	1.21	1.29	1.12	-7%
Regan *et al*., 1997	Merredin, Australia	1991-1992 (2)	0.26	0.33	0.40	0.64	1.32	1.92	1.32	0%
Regan et al., 1997	Mullewa, Australia	1992-1995 (3)	0.28	0.38	0.44	0.69	0.99	1.21	1.54	+56%
O'Leary and Connor, 1997	Walpeup, Australia	1988-1991 (4)	0.34	0.35	0.37	1.22	1.27	1.31	1.09	-14%
Rahman *et al*., 1995	Benerpota, Bangladesh	1988-1992 (4)	0.35	0.36	0.37	0.77	1.04	1.28	1.07	+3%
Shunqing *et al*., 2003	Gucheng, China	1997-1999 (3)	not measured			0.36	0.95	1.37	0.75	-21%
Xinyuan *et al*., 1993	Nanpi, China	1986-1990 (4)	0.39	0.41	0.42	0.91	1.19	1.40	0.97	-18%
Mandal *et al*., 2005	Bhopal, India	1998-2001 (3)	0.28	0.36	0.48	0.63	1.09	1.57	1.12	+3%
Mishra *et al*., 1995	Pantnagar, India	1983-1985 (2)	not measured			1.17	1.23	1.29	1.04	-15%
Amir *et al*., 1991	Gilat, Israel	1977-1987 (10)	0.31	0.36	0.41	0.41	0.75	1.02	1.18	+57%
Mrabet, 2002	Sidi El Aydi, Morocco	1995-1999 (4)	0.24	0.28	0.33	0.58	0.63	0.67	0.97	+54%
Lopez-Bellido *et al*., 2007	Cordoba, Spain	1995-2003 (6)	not measured			0.79	0.90	0.98	1.00	+11%
H. Zhang *et al*., 1998	Tel Hadya, Syria	1991-1996 (5)	0.30	0.39	0.46	0.47	1.04	1.43	1.11	+7%
Cayci *et al*., 2009	Haymana, Turkey	2003-2005 (2)	not measured			0.27	0.80	1.09	0.72	-10%
Sezen and Yazar, 2006	Koruklu, Turkey	1993-1996 (3)	0.27	0.32	0.35	1.31	1.42	1.52	0.81	-43%
Baumhardt and Jones, 2002	Bushland, USA	1990-1995 (6)	not measured			0.49	0.52	0.55	0.67	+29%
Schneider and Howell, 2001	Bushland, USA	1997-1999 (2)	0.22	0.28	0.31	0.67	0.83	0.96	0.54	-35%
Kamilov *et al*., 2002	Tashkent, Uzbekistan	2001-2002 (2)	not measured			0.70	0.75	0.80	0.76	+1%

* the total number of experimental years is between brackets

The comparison of field measured versus WATPRO modelled WP_{ET} in Sirsa District, India is depicted in Figure 4-6. One out of five sites was located outside the area classified as wheat (see Figure 4-5) and could not be compared with the modelling results. The remaining four sites, however, showed acceptable results. Measured values varied from 1.22 to 1.56 kg m^{-3} and their differences from modelled WP_{ET} were small, varying from only 1.6 to 6.9%. During the same study by Van Dam and Malik (2003), the water productivity of wheat, rice and cotton was assessed spatially using the SEBAL algorithm. The water productivity map of wheat is depicted in Figure 4-5A. This map was compared with the WATPRO map for wheat (Figure 4-5B). Since both the SEBAL and the WATPRO models are based on the same principles, a comparison will only show whether the simplifications and assumptions in the WATPRO model are justified.



A. SEBAL B. WATPRO

Figure 4-5: Water productivity (kg m^{-3}) in Sirsa District, Haryana, India, modelled and validated in 2001-02 (A) and WATPRO WP$_{ET}$ *during this study (B). The white line indicates the administrative boundaries of Sirsa District.*

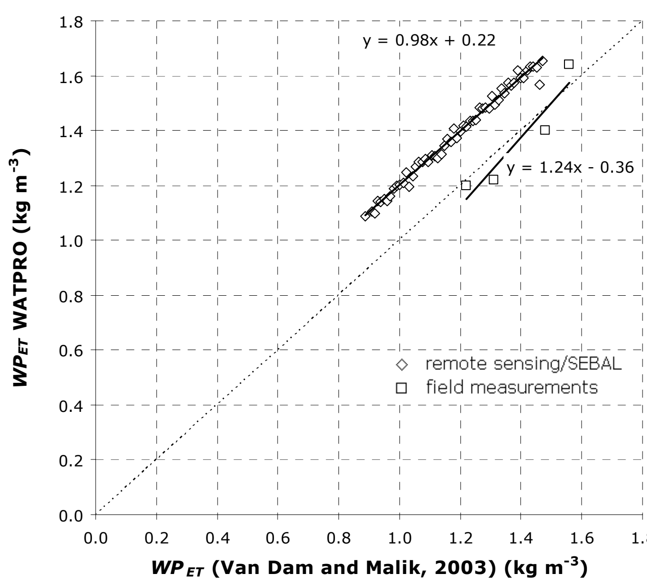


Figure 4-6: Relationship between SEBAL water productivity (◊), measured water productivity (□) (Van Dam and Malik, 2003) and WATPRO WP_{ET}*. The SEBAL map (Figure 4-5A) was divided into discrete classes of 0.01 mm. For each class the average* WP_{ET} *of the corresponding pixels in the WATPRO* WP_{ET} *map (Figure 4-5B) was calculated.*

A visual interpretation of the WP_{ET} maps reveals that both models show very similar patterns despite the difference in model complexity and the source of satellite data used. An exception is the upper North West corner of Sirsa District where WATPRO predicts significantly higher values. As is shown in Figure 4-4, WATPRO WP_{ET} is on average 22% higher than SEBAL WP_{ET}. This holds for the entire spectrum between the 5 and 95% percentiles (slope of 0.98). This analysis shows that WATPRO can reproduce the same variation as SEBAL does, but it is unclear what causes the higher values predicted by WATPRO. Since the offset is 22% for the entire range, an explanation could be related to the different *NDVI* and surface albedo data sets that were used. The calibration of the NOAA-AVHRR may have resulted in lower *NDVI* and surface albedo values. Moreover only 6 images - 1 per month - were used to cover the wheat season, whereas in the WATPRO application 3 images per month were used. The good correlation with the field measurements and the strong correlation spatially with the SEBAL results provide confidence that the WATPRO model is able to predict the spatial variation of WP_{ET} from limited data resources. This is essential for preparing local action plans that aim to improve water productivity.

4.5 Conclusions

The WATPRO model that was developed to estimate water productivity can be applied globally with simple input data, and provides a new approach to water productivity modelling. Spatial inputs are entirely derived from global remote sensing data sets of *NDVI* and surface albedo. The growing season of wheat was determined accurately from the same *NDVI* data set. Modelling of water balance components mostly requires detailed inputs, including actual evapotranspiration and crop production which can only be estimated with a high degree of uncertainty. Growing seasons are usually obtained from data sets that provide country-wide averages. The WATPRO model on the other hand considers the lumped result of all the hydrological and crop production processes, which are captured in remote sensing data sets, to estimate water productivity directly and without complex procedures. Although the simplicity of the model and its inputs provides significant advantages over traditional modelling, the remote sensing approach does not allow e.g. scenario analysis such as the impact of climate change or changing water availability on water productivity. By definition, the use of remote sensing allows only the investigation of past events. Another drawback to the WATPRO model is its dependency on the harvest index, but this problem is also unresolved in most crop growth models. Traditional models, if applied to field studies, are calibrated against measured yields, or, when applied for regional studies, are calibrated against census data, thereby avoiding the issue of the harvest index.

The validation of a model that uses remote sensing data as inputs is complex. Since the model directly provides WP_{ET} and not the yields and evapotranspiration separately, the model cannot be validated with measured or reported yields and evapotranspiration. Moreover, there are only limited literature sources available to validate the modelled WP_{ET}. Since none of these sources provide measurements of both the water productivity and the inputs to the model (e.g. *NDVI* and surface albedo, but also light use efficiency or *APAR*), alternatives had to be used. A fixed maximum light use efficiency and grain water content were used, and average *NDVI* and surface albedo were taken from global remote sensing data sets. Consequently errors are introduced since 1) the scales of the experimental measurements and the remote sensing data sets do not match, 2) the years in which the experiments were conducted differ from the years for which the remote sensing data sets are representative, and 3) fixed constants are used for parameters that may vary among experiments under actual conditions. The low correlation that was found between measured and modelled WP_{ET} is therefore not surprising. It is encouraging, however, that the average values and the ranges of measured and modelled WP_{ET} of all locations are similar. The comparison with measured WP_{ET} in farmer's fields surrounded by other wheat fields in Sirsa District overcame the scale issue. Over a range of WP_{ET} as low as 1.22 to as high as 1.56 kg m^{-3}, values were similar to the WATPRO modelling results with differences of only 1.6 to 6.9%. The WATPRO model is based on the SEBAL procedures to estimate biomass production and actual evapotranspiration. The SEBAL model has been satisfactory validated for various crops and vegetation types under different environmental conditions (see Bastiaanssen *et al*. (2005) for an overview of validation studies, and Zwart and Bastiaanssen (2007) for a validation of the biomass component). The good spatial correlation with the SEBAL model that was found for the case study in India also provided confidence that the WATPRO-derived WP_{ET} map was accurate. Ideally, WATPRO results should, however, be spatially validated with validated maps of water productivity from different sources. This is done in a global application of WATPRO, where modelling results from two different sources are compared with global data sets on water productivity (Zwart *et al*., 2010).

5 A global benchmark map of water productivity for rainfed and irrigated wheat*

5.1 Introduction

Ensuring food security for a growing population in a world with a changing climate is a major challenge for the coming decades. Reducing malnutrition and meeting the food requirements for the projected additional 2-3 billion people, a growth mainly taking place in developing countries, demands major investments in agriculture. Alongside with food security comes the challenge to provide agriculture with sufficient water resources which are required for the advocated increase in production (Molden *et al*., 2007). It is estimated that by 2050 an additional 5,600 km^3 of evapotranspired water per year is required to meet the food demands, if no gains in water productivity are made (Falkenmark and Rockstrom, 2004). Water requirements are defined here as the vapour flow, or evapotranspiration, that is associated with plant production and that diffuses into the atmosphere. The physical water productivity, defined as the crop yield divided by the total water depletion through evapotranspiration, is a performance indicator to determine whether systems use their resources efficiently or not (Molden and Sakthivadivel, 1999; Bastiaanssen *et al*., 1999).

In farmer's fields, the level of water productivity obtained is determined by many factors which include management of irrigation water (H. Zhang *et al*., 1998; Geerts and Raes, 2009) and fertilizers (Caviglia and Sadras, 2001), selection of crop variety (Siddique *et al*., 1990), soil tillage (Mrabet, 2002), mulching (Huang *et al*., 2005), planting distance (Giunta and Motzo, 2004), and environmental conditions which include soil type, water quality (Nangia *et al*., 2008) and weather conditions (Sadras and Angus, 2006), amongst others. Farmers often make economics-based decisions on, for example, the use of fertilizers or modern seeds, or the timing and quantities of irrigation water applied to his field, which determine the actual water productivity that is attained. In a related study, a comparison of eight wheat systems worldwide was conducted to analyse the spatial variation of water productivitities using remote sensing derived yields and evapotranspiration at field level (Zwart and Bastiaanssen, 2007). This study revealed that the scope for improvement was highest in areas where the crop yields were low, and where the spatial variation in water productivity was high.

The spatial distribution of water productivity at a global scale is, however, poorly understood. Current knowledge is limited to syntheses of reported water productivites in scientific literature (e.g. Zwart and Bastiaanssen (2004) for irrigated maize, cotton, rice and wheat, Sadras and Angus (2006) for wheat under Mediterranean conditions, and Bouman *et al*. (2007) for rice). As noted before, these results are highly specific to the location, the crop, water and soil management practices, and to the years in which the experiments were conducted. They can therefore only provide plausible ranges for water

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* This chapter is submitted to Agricultural Water Management as "Zwart, S.J., W.G.M. Bastiaanssen, C. de Fraiture, D.J. Molden, 2009. *A global benchmark map of water productivity for rainfed and irrigated wheat*".

productivty that can be expected in an area. A first attempt to provide a global picture of the spatial distribution of water productivity at a reasonable resolution was performed by Liu *et al*. (2007) who used the GEPIC model to simulate wheat yields and to estimate seasonal evapotranspiration to derive water productivity. The performance of these models, however, depends largely on good quality input parameters, such as soil physical characterisitcs, plant parameters, and management data on irrigation and fertilizers, which may often not be available or accurate at a global scale. In the absence of these data, general statistics of the FAO have been used.

Globally, there is a diverse range of economic and environmental conditions where gains in water productivity can be achieved. It is believed that on a global level there is considerable scope for improvement in the physical water productivity, but not everywhere (Molden *et al*., 2009). Raising water productivity shows most promise in areas where water productivity is low and the so-called green water resources are largely unused. Due to the non-linear relationship between yield and water productivity, areas with low yields show the highest potential increase in water productivity (Rockstrom *et al*., 2007). Based on a literature study of field-measured water productivity, Sadras and Angus (2006) concluded, while focussing on wheat grown in dry climates, that water productivity of wheat in Australia, USA, China and the Mediterranean basin was 32 to 44% lower than a maximally attainable values of 2.2 kg m^{-3}. These measurements, however, were conducted in small experimental plots that may not reflect the actual conditions in agricultural fields. It was acknowledged by the authors that grain yields are generally overestimated in small experimental plots.

Global benchmark values and regional statistics on water productivity are fundamental to understanding where a gap in water productivity exisits, where systems perform well, and where improvements are still possible. A global water productivity map may also serve as a start to spatially analyse and explain the underlying reasons for a gap in water productivity, and where and how action should be taken to improve the productivity of water. Moreover, global information on water productivity allows uniform intercomparison of river basins, countries or irrigation systems, and it could provide a basis for discussions on virtual water trade for global water saving (De Fraiture *et al*., 2004; Chapagain *et al*., 2006).

The purpose of this paper is to develop a global map of the water productivity of wheat, as wheat is the major staple crop in the world. This map will provide benchmark levels of actual water productivity under average conditions at the beginning of this millennium. WATPRO, the water productivity model developed by Zwart *et al*. (2010), will be applied at a global scale and at high resolution of approximately 1 by 1 kilometre. The WATPRO model estimates water productivity directly from remote sensing measurements, instead of first determining yields and water use by evapotranspiration separately. Moreover, it uses remote sensing data products as input. Traditional models require detailed information on e.g. on-farm management factors (such as the quantity of irrigation water and fertilizer, and their quantities and timing of application), soil characteristics, meteorological measurements, etc. as input to simulate wheat yields, to estimate seasonal evapotranspiration and assess water productivity (see e.g. Singh *et al*., 2006; Immerzeel *et al*., 2008). These inputs are difficult to obtain and WATPRO basically circumvents these problems by estimating water productivity directly.

A major challenge in the application of the water productivity model is to determine on a pixel-by-pixel basis *where* and *when* wheat is growing. An innovative approach is presented to determine the crop establishment and harvest date by mathematically describing the *NDVI* time profiles of vegetation. The derived harvest dates are compared with statistics from reported harvest dates by the FAO (1978) and the USDA. The information on the start, end and length of the growing season, together with an existing global wheat dominance map, is used to identify wheat dominant areas. This paper compares the results with global water productivity modelling information by Liu *et al*. (2007) for which they used the GEPIC model, and with the country-level virtual water content, being the inverse of water productivity, reported by Chapagain and Hoekstra (2004). The virtual water content was derived by combining official country statistics of wheat yields from FAOSTAT with the crop water consumption from AQUASTAT. A first attempt to explain the spatial patterns of the derived water productivities by WATPRO is made by relating it to seasonal totals of precipitation and reference evapotranspiration.

5.2 Materials and methods

Water productivity model

Zwart *et al*. (2010) developed the WATPRO model to estimate water productivity (WP_{ET}) using remote sensing derived products as inputs. WATPRO directly estimates WP_{ET} and does not need to solve crop yields (Y_{act}) or evapotranspiration (ET_{act}) explicitly. The model combines the framework of Monteith (1972), that calculates dry matter production (*DM*) as a function from the absorbed photosynthetically active radiation (*APAR*) and the light use efficiency of the plant ($\varepsilon_{\max}$), with an energy balance approach to estimate the latent heat flux (λE) that is converted into ET_{act}. *APAR* is the total energy that can potentially be absorbed by a plant for photosynthetic processes (*PAR*). The fraction of *PAR* to *APAR, f,* is linearly related to the *NDVI* (e.g Hatfield *et al*., 1984). *PAR* is the fraction of the total solar energy ($S_{IN}^{\downarrow}$) that reaches the surface of the earth, which is a product of the extraterrestrial radiation ($S_{EXO}^{\downarrow}$), the atmospheric transmissivity (τ_{SW}) and the PAR/$S_{IN}^{\downarrow}$ fraction, χ. Under actual field conditions, the maximum light use efficiency ($\varepsilon_{\max}$) is reduced by water stress and air temperature (T_{air}) stress. Two temperature reduction functions (T_1, T_2) are introduced to describe the effects of temperature on $\varepsilon_{\max}$ (Field *et al*., 1995), while the water stress scalar is replaced by the evaporative fraction following Bastiaanssen and Ali (2003). *DM* is now a function of five spatially distributed inputs, and two inputs that can be held globally constant:

$$DM = f\left(NDVI, \tau_{SW}, S_{EXO}^{\downarrow}, T_{air}, \Lambda, \chi, \varepsilon_{\max}\right) \tag{5.1}$$

Actual evapotranspiration (ET_{act}), being equal to the latent heat flux term of the surface energy balance, can be expressed as the net available energy multiplied by the evaporative fraction (Λ), where Λ describes the energy partitioning. The net available energy is the net radiation (R_n) minus the soil heat flux. However, over longer peiods the soil heat flux is negliable compared to the net radiation and it may therefore be ignored. De Bruin and Stricker (2000) developed an empirircal relationship to estimate R_n, as a function of $S_{EXO}^{\downarrow}$, τ_{SW} and the broadband surface albedo (α). This implies that ET_{act} can now be estimated as a function of four spatially variable terms:

$$ET_{act} = f\left(\Lambda, \alpha, \tau_{SW}, S_{EXO}^{\downarrow}\right) \tag{5.2}$$

It was shown by Zwart *et al*. (2010) that in both the production and the evapotranspiration terms of the water productivity equation, the atmospheric transmissivity and the evaporative fraction, parameters which are difficult to estimate spatially and in time, can be ommitted. With seasonal averages as input, WP_{ET} can now be calculated as:

$$WP_{ET} = \frac{H_i \cdot \left(a \cdot \overline{NDVI} + b\right) \cdot \chi \cdot \overline{S_{EXO}^{\downarrow}} \cdot \varepsilon_{\max} \cdot \overline{T_1} \cdot \overline{T_2} \cdot 0864}{\left(1 - \theta_{grain}\right) \cdot \left(\left(1 - \overline{\alpha}\right) \cdot \overline{S_{EXO}^{\downarrow}} - 135\right) \cdot 0.35} \quad (\text{kg m}^{-3}) \tag{5.3}$$

where H_i is the harvest index (-), a and b are dimensionless empirical parameters that linearly relate PAR to $APAR$ through the $NDVI$, and θ_{grain} represents the grain moisture content at harvest, which is kept constant at 0.14 for this study. Eq. 5.3 will hereafter be referred to as the WATPRO model. For quality reasons, wheat is usually harvested when this moisture level is reached. The modelling period is the growing season running from the moment of establishment (t=e) to harvest (t=h). This implies that the water productivity can be estimated from only four spatial variables: $NDVI$, $S_{EXO}^{\downarrow}$, T_{air} and α in association with a few constants. Both $NDVI$ and α can be obtained from standard remote sensing products. Reference is made to Zwart *et al*. (2010), for a full description of the water productivity model and how it is derived and validated.

Table 5-1: Values and sources of input parameters for benchmarking water productivity model (Eq. 5.3)

parameter	value	spatial resolution	temporal resolution	representative period	source
χ	0.48	-	-	-	Moran *et al*. (1995)
$\varepsilon_{\max}$	2.5	-	-	-	Bastiaanssen and Ali (2003)
a, b	1.23, -0.149	-	-	-	Asrar *et al*. (1992), Hatfield *et al*. (1984)
H_i	0.35	-	-	1980-2007	average H_i from CWP database (Zwart and Bastiaanssen, 2004). See appendix A.
NDVI	variable	≈1 km	10-daily	1998-2008	SPOT-VGT synthesized 10-daily products available from http://free.vgt.vito.be
e, *h*	variable	≈1 km	daily	1998-2008	date of crop establishment and harvest, derived for this study from the SPOT-VGT *NDVI* data set
α	variable	1 arc-minute ≈1.6 km at equator	16-daily	2000-2004	MODIS continuous surface albedo product (Moody *et al*., 2005) available from ftp://modis-atmos.gsfc.nasa.gov
T_{mon}, T_{opt}	variable	10 arc-minute ≈16 km at equator	monthly	1961-1990	IWMI Water and Climate Atlas, monthly temperature climate grids available from http://www.iwmi.cgiar.org/WAtlas
$S^{\downarrow}_{EXO}$	variable	≈1 km	10-daily	-	calculated for each pixel using Allen *et al*. (1998)

Global application
The model was applied using 10-day time steps (three per month), in conjunction with SPOT-VGT *NDVI* maps. The modelling period was determined using the SPOT-VGT *NDVI* time profiles; this method, as well as the method to detect wheat dominant pixels and areas, is outlined later in this section. An overview of the inputs that were used in this study to derive the wheat water productivity benchmark map is provided in Table 5-1. ε_{max} is set at 2.5 g MJ^{-1} following Bastiaanssen and Ali (2003), whereas a value of 0.48 is accepted for χ (Moran *et al*., 1995). The empirical parameters *a* and *b* were measured in wheat experiments reported by Asrar *et al*. (1992) and Hatfield *et al*. (1984), and the average *a* and *b* of both experiments, 1.23 and -0.149 respectively, were used for the application of the model. The average extraterrestrial radiation for each 10 day period is calculated using the middle Julian day of each 10-day period following standardized procedures on radiation as described by Allen *et al*. (1998).

Harvest index
The harvest index is a crop-specific parameter that defines the fraction of grain, the economically valuable part of the plant, to the total above-ground biomass production. For wheat it is considered to be a fairly stable feature within a given climate zone unless the plant suffers severe stress from low nutrients, temperature (cold or heat) or water deficits (see Hay (1995) for a review of the harvest index for various crops). In plant modelling, environmental stress indicators are used, during specific crop stages, to reduce, the potential harvest index (see e.g. Raes *et al*. (2009) for a description of FAO's AquaCrop model), or to reduce the speed of grain filling after anthesis (Fletcher and Jamieson, 2009). In recent decennia the harvest index has been shown to have improved significantly over time due to plant breeding, and variations are seen between old and new varieties (e.g. Hay, 1995 and Sinclair, 1998). On a global scale the use of a single potential harvest index therefore does not seem valid. The implementation of an increasing harvest index after anthesis requires a precise knowledge of the start and the length of the phenological stages, which is, at this stage, not possible to derive from remote sensing imagery at a global scale.

There is no known global database of the harvest index that can be used to compare values commonly measured in temperate climates or in dry climates. As an alternative, a literature survey was conducted to find the range of harvest indices that have been commonly measured. The results are summarized in Appendix 1. An average harvest index of 0.35 was found, based on 15 experiments globally, but there is a large range varying from 0.22 (Corbeels *et al*., 1998) to values higher than 0.50 (Amir *et al*, 1991). It is likely that in countries with temperate climates, the harvest index will generally be higher due to lower water and nutrient stress, than in countries in Mediterranean, semi-arid and arid climate zones, where water shortages and heat stress occur more often. For the global application, the average harvest index value of 0.35 was used as a fixed constant, though it is realized that this may reduce spatial variation in the final water productivity levels on the benchmark map.

Air temperature

The mean monthly air temperature values (T_{mon}) that are necessary in the two reduction functions for maximum light use efficiency (T_1, T_2) are derived from the climate grids of the Water and Climate Atlas from the International Water Management Institute (IWMI) which are based on the University of East Anglia climate grids (New *et al*., 1999). These grids are based on measurements between 1961 and 1990 from over 30,000 meteorological stations. The air temperature during maximum crop development (T_{opt}), which is required to calculate T_1 and T_2 (Field *et al*., 1995), was determined by selecting the period where SPOT-VGT *NDVI* during the growing season was maximum. This assumes that maximum photosynthesis occurs at favourable temperature conditions.

Surface albedo

The broadband surface albedo was obtained from a global data set of spatially complete spectral surface albedos (Moody *et al*., 2005) for all surface types and actual management conditions. This data set contains cloud-free and gap-filled surface albedo images recorded every 16 days over a 5-year period from 2000 to 2004. The spatial resolution of this data set is 1 arc-minute, which is equal to approximately 1.6 km at the equator. The surface albedo images are public domain and available from the MODIS Atmosphere ftp-site[8]. The five years that are available are averaged to obtain a representative average surface albedo input data set. The 16-day images are linearly interpolated to the 10-daily periods to serve as input for the model.

NDVI

There are two remote sensing systems that provide global NDVI time series operationally at an acceptable resolution. SPOT-Vegetation (SPOT-VGT) provides global cloud free NDVI composite products since April 1998 having a spatial resolution of approximately 1 km at the equator and a temporal resolution of 10 days. MODIS/Terra provides 16-daily NDVI products at 250 metre resolution since April 2000. Both sources are public domain and can be downloaded through data portals on the internet. The MODIS/Terra provides the most detailed data, but in terms of disk resources and computation requirements, and the lower temporal resolution, the SPOT-VGT NDVI time series is preferred. An average NDVI is calculated for each of the 36 10-daily periods from the ten years (April 1998 to March 2008) that were available. In order to minimise seasonal extremes in the NDVI averages, the minimum and maximum NDVI value at each location are excluded. The implication is that the resulting water productivity maps will display longer-term average results.

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[8] ftp://modis-atmos.gsfc.nasa.gov

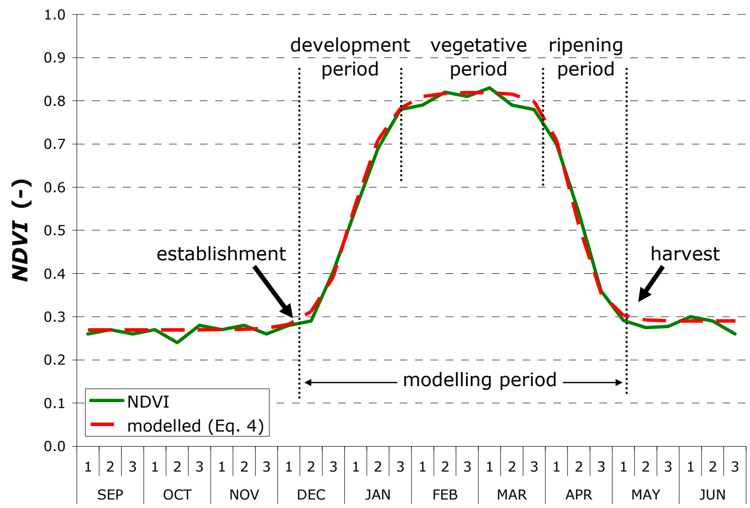


Figure 5-1: Algebraic function (Eq. 5.4) used to describe the curves of the NDVI time profiles. A data set from Yaqui, Mexico (Zwart and Bastiaanssen, 2007) has been used for this example.

Where and when is wheat growing

Wheat is cultivated in a large variety of climates, varying from temperate (e.g. northwest Europe) to semi-arid (e.g. north Africa), which results in large variation in the length and timing of the growing season. Country-wise information on cropping seasons of various crops is available from FAO (1978). The AQUASTAT database mostly focuses on irrigated crops in dry climates, whereas the Crop Explorer system[9] from the United States Department of Agriculture (USDA) provides cropping season information for selected countries and from different sources. Within larger countries, such as the USA, China and Australia, the growing season may vary significantly as is shown by the latter source. As an alternative to these sources, the cropping season of wheat was determined in this study by using the annual time profiles of SPOT-VGT *NDVI* images. The major advantage is that instead of a country-wise average, the growing season becomes a pixel-wise input to the water productivity model. An example of a typical *NDVI* profile of a wheat-dominated area is depicted in Figure 5-1; from bare soil to the establishment of the crop the *NDVI* values are low, but an increase is shown after that. Thereafter, the *NDVI* curve reaches its highest values during the vegetative stage. During the ripening period the crop becomes yellowish and the *NDVI* values drop until the moment it is harvested. An algebraic function was used, similar to Fischer (1994), which describes the *NDVI* profile mathematically:

$$NDVI = a + \frac{b}{1+\exp\left(-\frac{J-d}{c}\right)} - \frac{e}{1+\exp\left(-\frac{J-g}{f}\right)} \tag{5.4}$$

The function was applied on a global scale for each pixel to match the *NDVI* profiles accurately. The Julian day (J) of crop establishment and harvest as well as the length of

[9] www.pecad.fas.usda.gov/cropexplorer/

the season the *NDVI* curve can be extracted from the model's parameterization results (*a* to *g*). A full description of this methodology and the application at a global scale is given by Zwart *et al*. (2010), whereas the section below outlines some of the major findings.

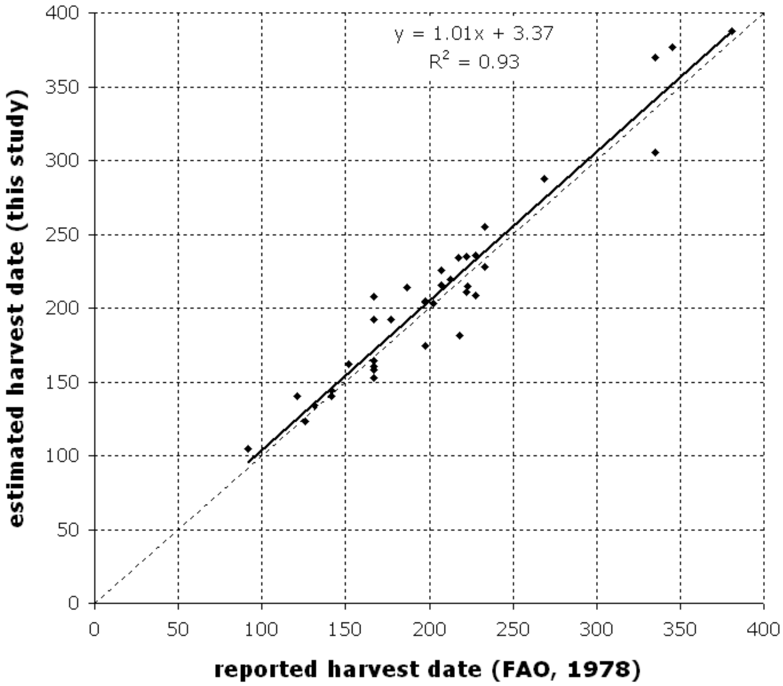


Figure 5-2: Relationship between harvest dates that were reported by countries (FAO, 1978) and the estimated country-averaged harvest dates from this study (in Julian days).

As depicted in Figure 5-2 a good correlation (r^2=0.93) was found over a large range between the modelled harvest dates of wheat and the average harvest dates that were reported by countries following surveys from FAO (1978) (in Julian days, *J*). Wheat harvest takes place as early as the start of April in India (*J*=92) to mid August in Sweden and Denmark (*J*=233) in the northern hemisphere, and in the southern hemisphere from early December (*J*=335) in South-Africa to mid January (*J*=16) in Chile. The largest differences, between 31 and 41 days between modelled and reported harvest dates, are found for Argentina, Uruguay, South Africa, Afghanistan and Italy, though there is no systematic under- or overestimation. The average total length of the growing season, defined as the vegetative period from crop establishment to harvest, is 160 days (n=89, σ=20.3). This does not include dormancy periods during the winter season.

This function, together with the WATPRO model, can be applied only in rainfed or irrigated wheat dominant areas where the interference with other crops is minimal or absent. Mixed agricultural areas show *NDVI* time profiles where the values remains high at the end of the wheat season due to influence of other crops that have peak *NDVI* values during this period. By using threshold values on the global maps of the start, end and length of a vegetative period, wheat dominant areas were extracted. Non-wheat areas were removed from the global wheat dominance map (Leff *et al*., 2004) and non-agricultural areas were excluded manually using GoogleEarth. This generates more reliable statistics that can be used for water productivity improvement studies.

5.3 Results and discussion

The WATPRO model (Eq. 5.3) was applied on a global scale using the input data described in Table 5-1 and the crop establishment and harvest dates that were derived from the *NDVI* time profiles. The results are shown in Figure 5-3, which depicts the high resolution water productivity benchmark map for wheat, applicable to the beginning of this millennium, and in Table 5-2, which summarizes average water productivity values for the ten major wheat producing countries. There is large global variation in water productivity, but also within countries. The average global value is 0.86 kg m^{-3}, though WP_{ET} may reach values up to 1.80 kg m^{-3}. The global range of WP_{ET}, defined by the 5 and 95% percentiles, is 0.2-1.5 kg m^{-3}, which is slightly lower than the range of 0.6-1.7 kg m^{-3} which is based on 412 experiments in small plots reported in 28 literature sources and summarised by Zwart and Bastiaanssen (2004). It must be noted here that, since the model was applied on wheat dominant areas only, these results do not encompass all wheat cultivated regions globally. Agricultural wheat areas in Ukraine, Russia, Kazakhstan, Canada and USA are expected to be larger (Leff *et al*., 2004) than the areas depicted in Figure 5-3.

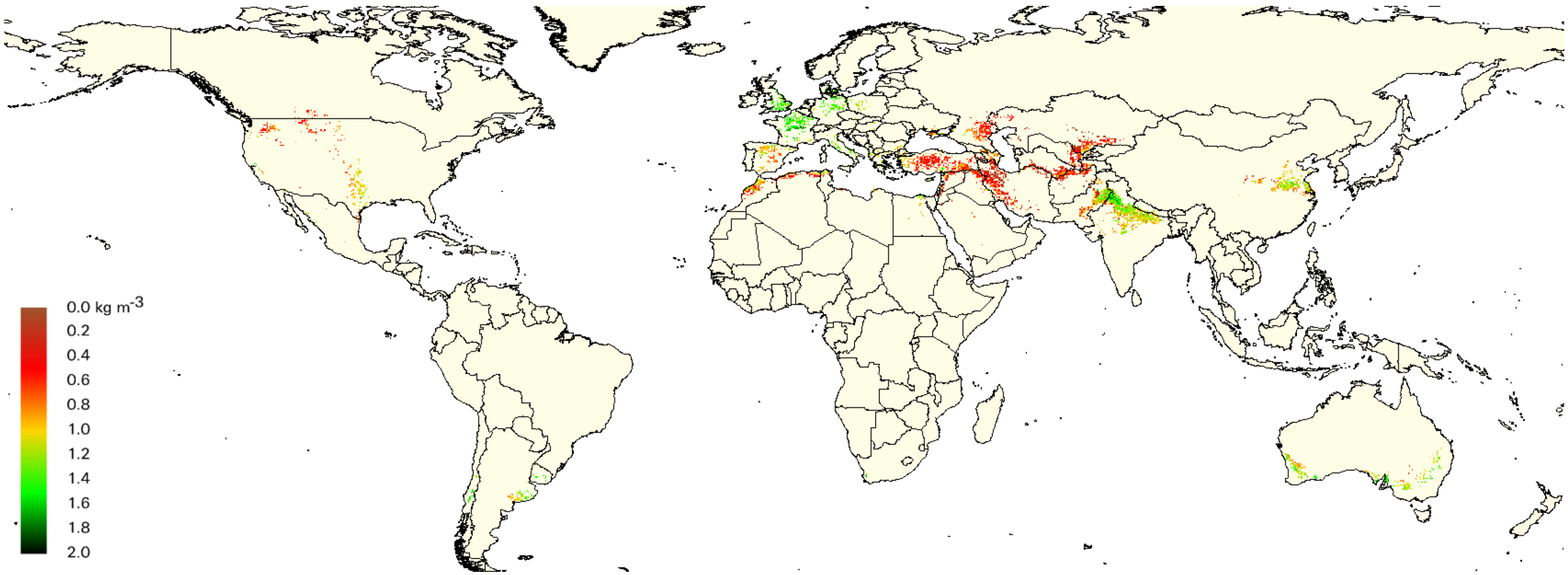
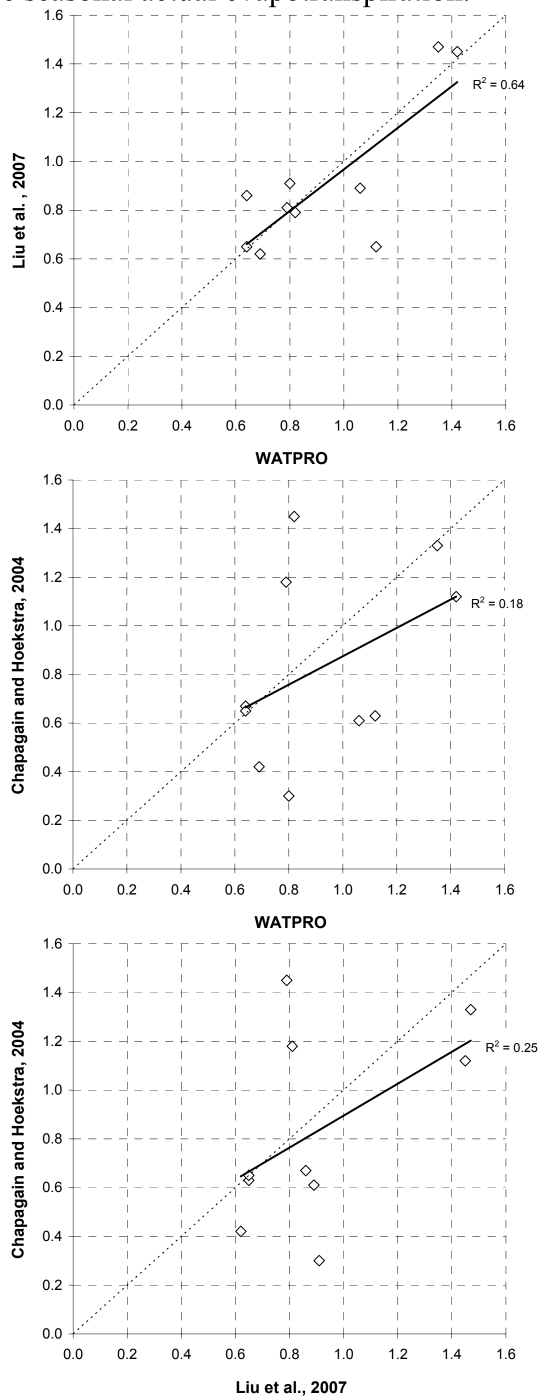


Figure 5-3: Water productivity benchmark values for water productivity of wheat (in kg m-3).

The highest values of WP_{ET} are found in the European temperate climate zone where country averaged WP_{ET} in for example Ireland, United Kingdom, Germany and France amounts to 1.45, 1.36, 1.35 and 1.42 kg m^{-3} respectively. Similar values can also be found in large areas of the Indo-Gangetic Basin in India and Pakistan, in irrigated wheat systems in Australia, and in wheat areas along the Yellow River in China. The average WP_{ET} in these countries is, however, much lower: Pakistan (0.80), India (1.06), Australia (1.12) and China (0.82 kg m^{-3}). In North Africa, WP_{ET} appears to be strongly correlated with water availability from irrigation and/or precipitation. Water abundant regions or systems in e.g. north Tunisia and Egypt depict values between 1.2 and 1.6 kg m^{-3}, but in rainfed systems with low precipitation rates, values between 0.4 and 0.8 kg m^{-3} are more common. Similar patterns can be seen in countries with Mediterranean and semi-arid climates in the Middle East, Turkey, Iran and Central-Asia, where WP_{ET} was shown to be generally low. On the North American continent, low WP_{ET} values (0.4-0.7 kg m^{-3}) are found in the Canadian states and the northern states of the USA, which could be possibly related to extensive farming practices and low seasonal rainfall. When moving south within the wheat belt, WP_{ET} steadily increases to 1.0 to 1.3 kg m^{-3} in the most southern states. The average water productivity value of 0.78 kg m^{-3} is higher than the average value of 0.61 kg m^{-3} for the North American Plains given by Angus and Sadras (2006) (Figure 5-5). Along the Pacific coast in Oregon, in California's San Joaquin Valley, or in the irrigated Yaqui Valley in Mexico, WP_{ET} values are generally higher between 1.2 and 1.5 kg m^{-3}. Similar levels of WP_{ET} were found by Zwart and Bastiaanssen (2007) for the Yaqui Valley (1.37) and for Kings County (1.44 kg m^{-3}) in the southern San Joaquin Valley.

Two different sources were consulted to test the performance of the WATPRO model at a global scale. First of all, Liu *et al*. (2007), hereafter abbreviated as LIU, published a water productivity map for wheat based on modelling efforts with the GEPIC model. The model relies on generalized country statistics on fertilizer use, water application, cropping calendars, soil characteristics, etc., which are mostly provided by the FAO through its FAOSTAT and AQUASTAT portals. Wheat yields were simulated at a 30 arc-minutes resolution (approximately 50 kilometres at the equator) and calibrated extensively using country reported wheat yields from FAOSTAT for a period between 1995 and 2004. The reference evapotranspiration was estimated using the Hargreaves method and is based on extraterrestrial radiation and air temperature only (Hargreaves and Samani, 1985). Actual evapotranspiration is the sum of the modelled evaporation and transpiration, which are computed separately following a method that is similar to Ritchie (1972). The simulated water productivity for wheat was reported as a map at 30 arc-minutes resolution and as national averages. Secondly, Chapagain and Hoekstra (2004), hereafter abbreviated as C&H, calculated actual evapotranspiration using the FAO method (Allen *et al*., 1998). This method is based on multiplying a reference evapotranspiration by a crop-specific crop-factor, which varies during the season, to estimate the whole-season crop evapotranspiration. It was acknowledged by the authors that this method may overestimate evapotranspiration since no crop stress is considered. General cropping calendars, also provided by AQUASTAT, were used to define the modelling period. Crop yields were directly obtained from FAOSTAT statistics reported by the member countries. Since both LIU and C&H use the FAOSTAT country statistics on wheat yields to calibrate yield simulations (LIU) or to calculate water productivity directly (C&H), their difference in water productivities will mainly be the result of the different methods that were used to calculate seasonal actual evapotranspiration.



A

B

C

Figure 5-4: Performance of (A) WATPRO versus the GEPIC model (Liu et al.*, 2007), (B) WATPRO versus the method by Chapagain and Hoekstra (2004), and (C) the GEPIC model against the method of Chapagain and Hoekstra. The water productivity benchmark* *map was aggregated to country level to allow comparison. The country average* WP_{ET} *(kg m^{-3}) of the ten major wheat producing countries is depicted.*

Table 5-2: Summary of water productivity (WP_{ET} *in kg m^{-3}) of the ten major wheat producing countries estimated in this study (WATPRO) and by Liu* et al. *(2007), LIU, and Chapagain and Hoekstra (2004), C&H. The percentage difference between WATPRO and LIU and C&H is shown between brackets.*

country	production* (Megatonnes)	area* (km^2)	WATPRO (kg m^{-3})	LIU (kg m^{-3})		C&H (kg m^{-3})	
Australia	19.1	122,382	1.12	0.65	(-42%)	0.63	(-44%)
Canada	22.8	96,870	0.64	0.86	(+34%)	0.67	(+5%)
China	97.4	236,219	0.82	0.79	(-4%)	1.45	(+77%)
France	35.3	51,401	1.42	1.45	(+2%)	1.12	(-21%)
Germany	22.1	30,296	1.35	1.47	(+9%)	1.33	(-1%)
India	71.3	265,317	1.06	0.89	(-16%)	0.61	(-42%)
Pakistan	20.4	82,919	0.80	0.91	(+14%)	0.30	(-63%)
Russia	44.0	228,518	0.69	0.62	(-10%)	0.42	(-39%)
Turkey	19.8	90,348	0.64	0.65	(+2%)	0.65	(+2%)
USA	55.2	201,541	0.79	0.81	(+3%)	1.18	(+49%)
average			0.93	0.91	(-2.2%)	0.83	(-11%)

* averages from FAOSTAT between 2000 and 2007

Table 5-2 summarizes average water productivity for the ten major wheat producing countries modelled in this study, and by LIU and C&H. The results for all countries are depicted in Appendix 2. The modelled average WP_{ET} for wheat in this study was 0.93 kg m^{-3}, whereas LIU was on average 2.2% lower (0.91 kg m^{-3}), and C&H 11% lower (0.83 kg m^{-3}). The latter is consistent with an anticipated overestimation of evapotranspiration, which reduces water productivity estimates. On a country level, a good correlation is found with LIU (r^2=0.64; see Figure 5-4); in six out of ten countries, the difference between both models is equal to or less than ten percent. Major differences are, however, found for Australia (-42%) and Canada (34%). For Australia, both LIU and C&H provide a lower average WP_{ET} of 0.65 and 0.63 kg m^{-3} respectively. Sadras and Angus (2006), who defined southeast Australia as a mega-environment for benchmarking water productivity, provide a range of 0.3-1.7, and an average WP_{ET} of 0.99 kg m^{-3} using five literature sources with experimental measurements (see also Figure 5-5). Other authors, not cited in the study by Sadras and Angus, provide similar ranges of measured water productivity for wheat in southwest Australia: 0.56-1.14 kg m^{-3} (Siddique *et al.*, 1990) and 0.55-1.65 kg m^{-3} (Regan *et al.*, 1997). More recently Hochman *et al.* (2009) modelled water productivity for 334 fields in various regions in Australia and average values per region ranged from 0.83 to 1.04 kg m^{-3}. Hence, the estimates for the Australian continent in this study seem reasonable. For Canada, LIU provides a 34% higher WP_{ET} of 0.86, whereas the results of this study and C&H are very similar with only a 5% difference. On the other hand Sadras and Angus (2006) show even lower values of 0.61 kg m^{-3} for the North American Plains, which includes Canada (Figure 5-5). It is uncertain what causes these differences, but in the case of Canada, the areas that are compared are significantly different since, due to the interference of other crops, only a small wheat dominant area could be extracted (see Figure 5-3). The correlation between WATPRO's results for the 10 major wheat countries and C&H is very low (r^2=0.18) and values are on average 11% lower for C&H. Also the relation between LIU and C&H is low (r^2=0.25). Only in Germany and Turkey was a good agreement (less than 10% difference) obtained among all three models.

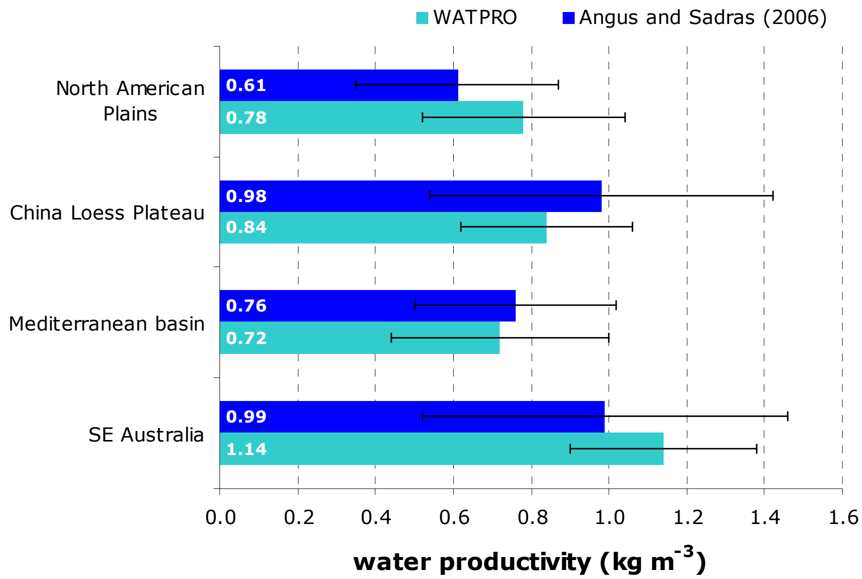


Figure 5-5: Water productivity for four "mega-environments" from field experimental results in various literature sources (summarized and reported by Angus and Sadras, 2006), and water productivity estimated by WATPRO. The black horizontal bars indicate the standard deviation, while the average values are shown in white numerals.

The large variations in water productivity may offer significant scope for improvement in many locations in the world. In order to be able to define where improvements are possible and what measures ought to be taken to create higher levels of water productivity, the factors that determine the current levels of water productivity must be understood. Plant growth and water use are driven by environmental conditions that can or cannot be controlled by humans, and include carbon availability from the air (Hsiao and Bradford, 1983), plant water availability (Tanner and Sinclair, 1983), soil fertility (Nangia *et al*., 2008) and climate (De Wit, 1958;), amongst others. In this study, two variables, the climate and the water availability, are discussed. Several authors have pointed out the conservative behaviour of water productivity to the atmospheric demands which can be represented by the vapour pressure deficit, D (Bierhuizen en Slatyer, 1965; Tanner and Sinclair, 1983). Studies in Argentina (Abbate *et al*., 2004) and in South Eastern Australia (Rodriguez and Sadras, 2007) showed a non-linear inverse negative relation between D and WP_{ET}. More recently, it was argued that D should be replaced by the accumulated reference evapotranspiration, $ET_{0,}$ in order to normalize for the climate (see Asseng and Hsiao (2000) and Steduto and Albrizio (2005)). The latter was tested in this study by comparing WP_{ET} with the seasonal accumulated ET_o. Monthly ET_o maps of the Climate and Water Atlas of the International Water Management Institute (IWMI) were used, together with the maps of the start and end of the growing season to calculate the seasonal ET_o so that the same period for the growing season is considered. The seasonal ET_o map was divided into zones of 10 mm steps. For each of these zones, the average WP_{ET} of the corresponding pixels of the WP_{ET} map was calculated. The result, depicted in Figure 5-6, shows the inverse negative relation between WP_{ET} and ET_o. In areas with seasonal ET_o lower than 300-450 mm, associated with the temperate climates (e.g. France, United Kingdom), average WP_{ET} is fairly constant between 1.1 to 1.2 kg m^{-3}. Between 450 and 750 mm, the average WP_{ET} decreases almost linearly by 46% until 0.59 kg m^{-3}. In the arid climates where atmospheric demands during the wheat growing season are even higher than 750 mm (such as in regions in North Africa or Central Asia), average levels of WP_{ET} vary between 0.52 and 0.60 kg m^{-3}. The reference evapotranspiration is a climatic factor that cannot be controlled by farmers unless growing seasons are adjusted or when crops are grown in climate controlled greenhouses. The figure does show however, that climatic or weather conditions affect the levels of water productivity significantly.

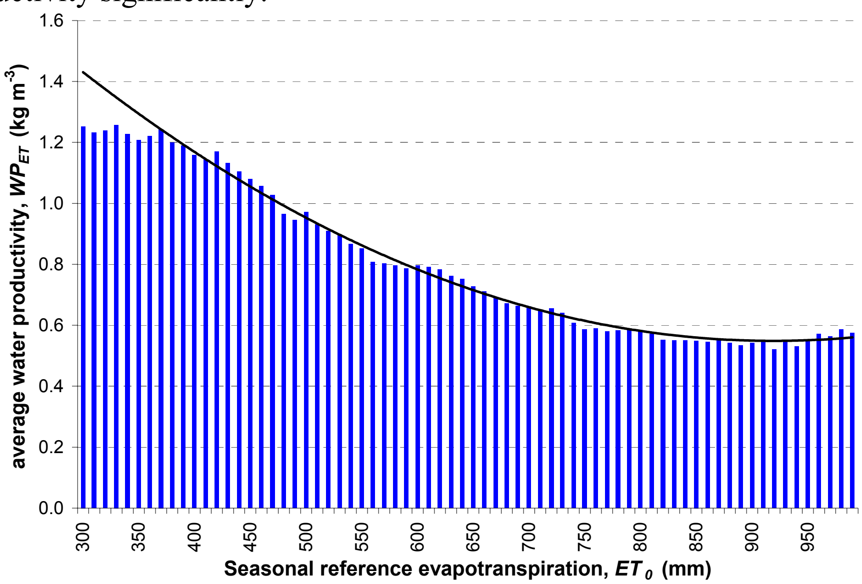


Figure 5-6: The water productivity versus the seasonal reference evapotranspiration (ET_0*).*

In a similar way, the effect of water availability on WP_{ET} was analysed using spatial precipitation patterns from the Tropical Rainfall Measurement Mission (TRMM). It is acknowledged that by substituting plant water availability with precipitation, several processes are ignored such as the initial soil water content at the start of the season, groundwater use through capillary rise, irrigation and run-off. However, since precipitation is in many regions the only source of water, it serves as a first step to understanding global variations in water productivity related to the availability of water. Seasonal precipitation was obtained from monthly calibrated precipitation products from TRMM that are freely available from NASA[10]. The maps cover the globe between 50 degrees latitude north and south, thereby omitting wheat growing areas in the analysis that are located in e.g. Great Britain, Ireland, Denmark and Sweden. A representative year was created by averaging the monthly maps for the years 2000 to 2008, and computing the total precipitation during the wheat season.

[10] http://neo.sci.gsfc.nasa.gov

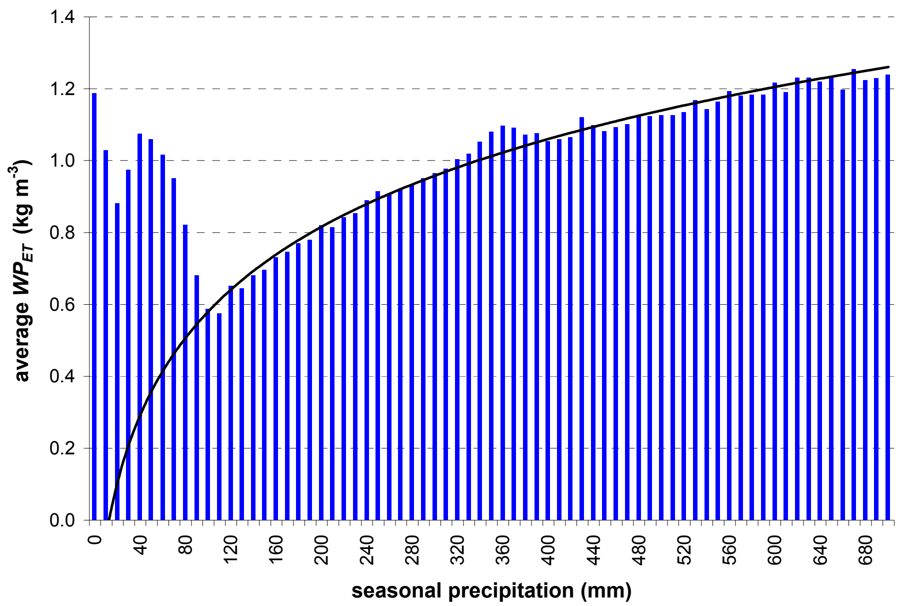


Figure 5-7. The water productivity versus the seasonal precipitation from calibrated monthly products provided by Tropical Rainfall Measurement Mission (TRMM).

As can be seen from Figure 5-7, precipitation strongly impacts the levels of water productivity of wheat. In areas where precipitation is lower than approximately 130 mm, average water productivity levels are higher than 1.0 kg m^{-3}. These are usually irrigated systems in arid climates. From 130 to approximately 300 mm of seasonal precipitation, the average WP_{ET} strongly increases from 0.6 to 1.0 kg m^{-3}. After 300 mm, average WP_{ET} continues to increase, but with a lower slope. After 600 mm seasonal precipitation, the trend shows mixed results, probably caused by the smaller selection of wheat areas with these high precipitation rates. The graph shows the importance of water availability for water productivity. Major improvements can be made in low rainfall zones, where seasonal precipitation is lower than 300 mm. Similar conclusions were drawn by Rockstrom *et al*. (2007) who found that major improvements can be achieved in rainfed agriculture with low yields. Large gains in water productivity can also be achieved with supplemental irrigation. Zwart and Bastiaanssen (2004) showed for several experiments that water productivity is low under rainfed conditions, but it may increase sharply if supplemental irrigation is applied. At full irrigation or over-supply of irrigation water, the water productivity remains constant or it even decreases under certain conditions. Under such conditions, deficit irrigation practices are a promising option (Fereres and Soriano, 2004), although the link between water stress and water productivity varies among crops (Geerts and Raes, 2009).

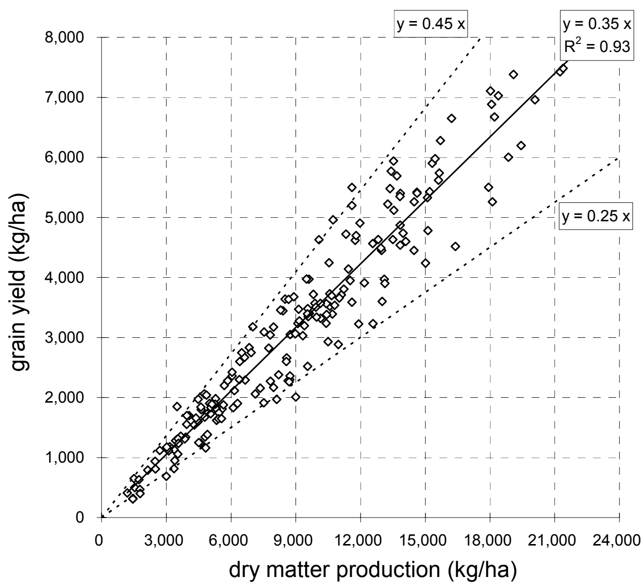
5.4 Conclusions

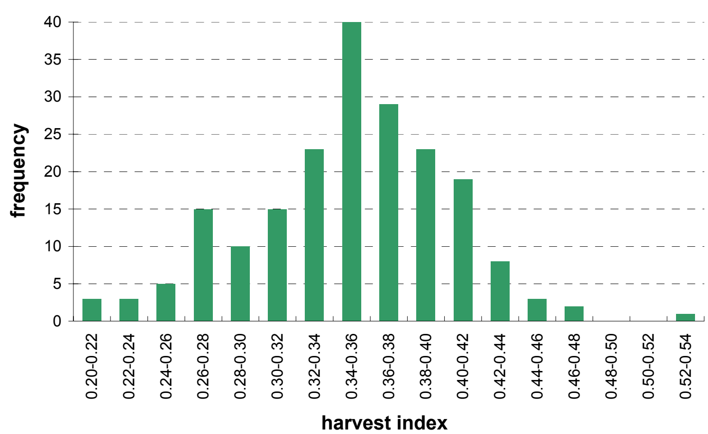
The approach used in this study to assess water productivity is entirely new. The WATPRO model, designed to use only spatial inputs from remote sensing data, was applied on a global scale at high resolution. Remote sensing data sets that were averaged over multiple years to represent the normal situation at the beginning of the millennium, were used to benchmark water productivity of wheat. The growing season of wheat was derived from the *NDVI* profiles on a pixel-by-pixel basis. The approach thereby differs from traditional modelling studies, which require inputs on climatology, soils and agronomic practices that are usually not available at the spatial detail for which they are applied. WATPRO is based on the actual situation in the field, which is captured in the surface albedo and the *NDVI*. It has therefore much lower data requirements compared to traditional models. A major constraint in the application is that WATPRO could be applied only for wheat dominant areas and not for areas with mixed agricultural patterns. A mixture of crops makes it impossible to map the harvest date accurately and the *NDVI* data is then mixed with different NDVI signatures from surrounding lands. The conversion of dry matter production into the harvestable yield component, through the grain moisture content and the harvest index, provides a source of error. There are no known databases for the harvest index and there is no generally accepted relationship between total biomass production and the harvest index. In this study a fixed harvest index of 0.35 was used, based on a review of 15 experiments globally, though it was shown that the majority of the harvest index values varies from 0.25 to 0.45.

It was found that the spatial variation of water productivity of wheat at a global scale is high, both between and within countries. Values range from as low as 0.2 up to 1.8 kg m^{-3}, indicating that there is a large scope for improvement. As a first step to understanding this spatial variation, the water productivity map was linked to global data sets of rainfall and reference evapotranspiration to analyse water availability and climatic demand. The analysis shows that the highest levels of water productivity are achieved in areas with high seasonal rainfall totals and low seasonal reference evapotranspiration. However, in drier climates with higher reference evapotranspiration and lower rainfall totals, water productivity levels decreased rapidly unless irrigation was applied. To gain a full understanding of the current levels of water productivity that were found in this study, and to define the scope for improvement for regions or countries, the analysis should be expanded to include other parameters. Soil fertility and water availability are probably the most dominant factors that affect water productivity, although various agronomic practices (selection of variety, planting distance, etc.) will also have an impact. Soil fertility is linked to soil type and the application of fertilizers. The FAO holds a global database of fertilizer use by country and also a global map of major soil types, which could both be linked to the water productivity benchmark map. Precipitation was used in this study to analyse the impact of water availability on water productivity. Although a major part of the global wheat production is cultivated under rainfed conditions, the impact of irrigation on water productivity was clearly visible, and a future analysis should therefore distinguish between rainfed and irrigated agriculture. This will also improve understanding of the impact of measures like supplemental irrigation and water harvesting on water productivity in different regions under varying environmental conditions. A major advantage of the WATPRO/remote sensing modelling approach is that the factors affecting water productivity are not input to the model, thereby allowing a fully independent analysis. By changing the harvest index, and by updating the constants a, b, $\varepsilon_{\max}$ and θ_{grain}, WATPRO can also be applied to other crops. Finally, the WATPRO results facilitate the planning of food production in relation to limited water resources for agriculture. It provides insights into virtual water trade and food security issues. A thorough understanding of the complex processes that lead to certain levels of water productivity will assist policy and decision makers to define priority areas, to set goals for improvement, and to define and justify the type of investment or measures that are made to make agriculture more productive under increasing pressure on fresh water resources.

Appendix 1: Harvest index, H_i

Depicted below is the relationship between field measured wheat yield and dry matter production with data from 18 different locations under varying regional conditions (climate, soil) and varying local conditions (varying irrigation and/or fertilizer management, wheat variety, etc.). See the table below for an overview of the locations, the years of measurement and the literature source. One point represents the average yield and dry matter production from more than one experiment with the same irrigation and/or fertilizer management but during different years with varying weather conditions). A total of 196 points is included, but as one point represents the average of multiple year experiments, this graph may reflect the results of measurements from more than 500 individual experimental plots. The frequency histogram of all measurements is also depicted below: values vary from 0.20 to 0.52, whereas the average harvest index of all experiments amounts to 0.35.





country	location	experimental years	source
Argentina	Parana	1998-1999	Caviglia and Sadras, 2001

Australia	Merredin	1991-1992	Regan *et al.*, 1997
Australia	Mullewa	1992-1995	Regan *et al.*, 1997
Bangladesh	Benerpota	1988-1992	Rahman, 1995
Bangladesh	Ishurdi	2002-2005	Ali *et al.*, 2007
China	Beijing	1993-1995	J. Zhang *et al.*, 1998
China	Dingxi	1997-1998	Huang *et al.*, 2005
China	Nanpi	1986-1990	Wang *et al.*, 2001
China	Zhangye	2003-2004	Zhang *et al*, 2006
India	New Delhi	1979-1981	Aggarwal *et al.*, 1986
Israel	Gilat	1978-1979	Amir *et al.*, 1991
Morocco	Meknes	1993-1995	Corbeels *et al.*, 1998
Morocco	Settat	1995-1999	Mrabet, 2002
Syria	Tel Hadya	1991-1996	H. Zhang *et al.*, 1998
Turkey	Koruklu	1993-1996	Sezen and Yazar, 2006

Appendix 2: Country average WP_{ET}

Modelled wheat water productivity (kg m^{-3}) from this study (WATPRO) and the GEPIC model (LIU, Liu *et al.*, 2007), and from a combination of FAOSTAT and AQUASTAT national statistics (C&H, Chapagain and Hoekstra, 2004). The 64 countries are sorted in descending order according to the total national average production between 2000 and 2007 (in Mega-tonnes).

country	production (Mega-tonnes)	WATPRO (kg m^{-3})	LIU (kg m^{-3})	C&H (kg m^{-3})
China	97.38	0.82	0.79	1.45
India	71.29	1.06	0.89	0.65
USA	55.17	0.79	0.81	1.18
Russian Federation	44.02	0.69	0.62	0.42
France	35.33	1.42	1.45	1.12
Canada	22.75	0.64	0.86	0.67
Germany	22.10	1.35	1.47	1.33
Pakistan	20.38	0.80	0.91	0.30
Turkey	19.79	0.64	0.65	0.65
Australia	19.07	1.12	0.65	0.63
Argentina	14.89	1.16	0.53	1.36
United Kingdom	14.57	1.36	1.80	2.00
Ukraine	14.34	0.88	0.56	1.39
Kazakhstan	12.09	0.39	0.49	0.45
Iran	12.04	0.38	0.56	0.34
Poland	8.65	1.16	1.04	1.99
Italy	7.34	1.21	1.09	0.49
Algeria	2.16	0.72	0.32	0.37
Iraq	2.07	0.59	-	-
South Africa	2.07	1.57	-	-
Greece	1.97	1.05	0.54	0.82
Serbia	1.87	1.15	0.87	1.46
Chile	1.65	1.42	0.80	0.69
Belgium	1.65	1.27	1.70	0.86
Azerbaijan	1.46	0.83	0.61	0.68
Slovakia	1.46	1.10	0.74	2.15
Austria	1.43	1.10	1.02	1.02
Tunisia	1.29	0.95	0.41	0.36
Netherlands	1.11	1.39	1.52	1.62
Belarus	1.06	0.20	-	-
Kyrgyzstan	0.98	0.52	0.44	0.31
Croatia	0.84	0.98	0.80	0.60
Ireland	0.81	1.45	1.89	1.95
Moldova	0.73	0.90	0.44	1.22

Egypt	7.15	1.22	1.18	1.08	Tajikistan	0.57	0.65	0.41	0.15
Spain	6.09	0.91	0.84	0.82	Switzerland	0.53	1.28	1.11	1.34
Romania	5.20	0.97	0.66	1.32	Uruguay	0.40	1.44	0.59	1.11
Uzbekistan	5.15	0.45	0.86	0.73	Macedonia	0.28	0.94	0.55	1.00
Denmark	4.64	1.35	1.73	1.50	Albania	0.27	1.09	0.93	-
Syria	4.46	0.67	0.56	0.45	Bosnia-Herzegovina	0.26	1.04	0.62	0.43
Hungary	4.38	1.09	0.88	1.80	Armenia	0.24	0.61	0.49	0.63
Czech Republic	3.95	1.08	0.95	0.85	Portugal	0.24	1.07	0.39	0.47
Morocco	3.65	0.82	0.42	0.22	Georgia	0.16	0.86	0.55	0.69
Bulgaria	3.25	1.05	0.71	1.22	Israel	0.16	1.01	-	-
Mexico	3.11	1.05	0.98	0.94	Lebanon	0.13	0.62	0.48	0.61
Afghanistan	2.91	0.40	-	-	Libya	0.12	0.74	-	-
Saudi Arabia	2.43	0.62	1.07	0.51	Luxembourg	0.07	1.38	-	-
Turkmenistan	2.43	0.53	0.55	0.52	Jordan	0.03	0.51	0.30	0.28
Sweden	2.25	1.23	1.73	1.28	Montenegro	0.01	1.06	-	-

6 Discussion and conclusions

The major goal of this research was to benchmark the physical water productivity in agriculture at various spatial scales. Benchmarking should thus provide values of water productivity that are currently attained. It forms a starting point for future analysis and by understanding the limiting and constraining factors for higher water productivities, the scope for improvement can be defined at e.g. regional or national level. The benchmarking of water productivity was achieved by 1) using the existing literature for a field scale analysis, by 2) using an established model (SEBAL) to determine regional variation, and by 3) developing a model (WATPRO) to benchmark water productivity at a global level. These results were analysed and related to climatic conditions (evaporative atmospheric demand), soil fertility (the use of nitrogen), and water availability (irrigation and precipitation). This yielded recommendations for future actions on where and how to promote and improve the productive use of fresh water resources.

6.1 The current levels of water productivity

Field scale

The first step was to establish a water productivity database for the four major crops in the world, namely wheat, rice, cotton and maize. Results from field experiments reported in the international literature over the last 25 years were consolidated in a database to provide up-to-date ranges of feasible water productivity values. The most researched crop is wheat, followed by maize, rice and cotton. The ranges found were higher than those reported some 25 years earlier in the FAO33 publication by Doorenbos and Kassam (1979). For example, this research provides a plausible range of 0.6 - 1.7 kg m^{-3} for water productivity of wheat (with an average of 1.1 kg m^{-3}), whereas a much lower range of 0.8 - 1.0 was provided by FAO33 in the 1970's. For the other three researched crops, it was also found that the water productivity values in FAO33 are on the conservative side. This might partially be related to the development of crops that are able to produce higher yields, and to improved soil fertility and water management.

However, caution must be exercised when interpreting these findings. First of all, the results encompass data from trials that are conducted in rather small experimental fields under optimal conditions. It was noted before by Davidson (1962) that grain yields are usually overestimated in small plots when compared to farmer's fields. Sadras and Angus (2006) detected a difference of 22% between water productivity measured in large fields in comparison to experimental plots. Secondly, the methods that are used to estimate actual evapotranspiration are usually based on a water balance approach. The different terms of the water balance and the soil moisture storage difference are measured or estimated, and actual evapotranspiration is estimated as a residual term. The interaction between the root zone and groundwater is difficult to measure and often ignored. Also, the process of rainfall interception is often disregarded (Savenije, 2004). Thirdly, from several experiments that are included in the database, the aim was to evaluate the impact of measures to increase water productivity such as mulching or plastic covers for example, to reduce evaporation from the soil (e.g. Baumhardt and Jones, 2002). Such results may therefore not reflect the general agronomic practices by farmers in a region, but represent only an optimal water productivity that is feasible under specific management practices. Finally, it can be noticed that the results are mainly conducted in drier areas where water is a scarce resource. Almost no experimental results are reported from the temperate areas with abundant water supply, although several authors have stressed the importance of the influence of climate on water productivity (Bierhuizen and Slatyer, 1965; Tanner and Sinclair, 1983; Abbate *et al*., 2005; Steduto *et al*., 2007).

Regional scale

The large differences in water productivity at the local scale, and the fact that only little information is available for temperate climates, were addressed by analysing eight global agricultural regions where wheat is dominant. The SEBAL model was applied to assess water productivity spatially with a high spatial resolution of 30 by 30 metres. This study revealed that the system-wide average water productivity in five out of the eight systems was higher than the global average of 1.1 kg m^{-3}. This included diverse regions such as the Nile Delta in Egypt (1.52 kg m^{-3}), Oldambt region in the Netherlands (1.39 kg m^{-3}) and the irrigated Yaqui Valley in north-western Mexico (1.37 kg m^{-3}). The highest values, 1.6 kg m^{-3} and higher, were found in the irrigated systems of the Nile Delta and the Yaqui Valley. Water productivity of wheat in Sindh Province in Pakistan and Hebei Province in China showed the lowest average values of 0.54 and 0.64 kg m^{-3} respectively. The average of the eight systems was, however, equal to the global average of 1.1 kg m^{-3}.

Another important finding is that water productivity appears to be tightly related to crop yields rather than water consumption. System average seasonal actual evapotranspiration varied between 355 (-11%) and 467 mm (+19% from the average of the eight systems of 400 mm), whereas average crop yields vary from 2.5 (-43%) up to 5.7 tonnes (+52% from the average of 4.4 tonnes). It was shown by Steduto *et al*. (2007) that the relation between biomass production and transpiration is fairly linear when normalised for atmospheric demand. This implies that in systems with high yields, the total water consumption is more beneficial; as a result of the linear transpiration-biomass production relationship, the beneficial transpiration in the high production systems is higher. Since our results indicate that total water consumption is fairly constant, the fraction of the non-beneficial soil evaporation must be lower. Therefore, interventions aiming at improving yields may positively impact the beneficial water consumption.

Global scale

The SEBAL approach allows objective spatial analysis and comparison of crop systems at high resolution. The major drawback, however, is that specific years are analysed. It is well known that weather conditions during a growing season, or water availability, can vary greatly from year to year, and therefore have a strong impact on the values that are attained. The WATPRO model, which can be considered a simplified derivative of SEBAL, was developed, tested and applied at a global scale using remote sensing data sets comprising multiple-year averages of surface albedo and NDVI. The input data sets represented the average conditions at the beginning of this millennium, thereby allowing a global benchmark study with the same conditions for each pixel that was analysed. This global analysis revealed that the highest water productivity values at national level are obtained in West European countries such as Ireland (1.45), the United Kingdom (1.36), Germany (1.35) and France (1.42 kg m^{-3}). It is, however, not uncommon for irrigated wheat in drier countries to attain water productivity values that are similar to those mentioned for Western Europe, though on average the water productivity in such water scarce countries is lower due to the low values associated with rainfed agriculture. Examples of major wheat growers in dry regions are Pakistan (0.80), India (1.06), Australia (1.12), Egypt, (1.22) and China (0.82 kg m^{-3}). Regions where water productivity is very low include Central-Asia, the Middle-East (with the exception of Egypt and Israel), Iran, Turkey and North-Africa, where country averages range from approximately 0.4 to 0.7 kg m^{-3}. The global average water productivity value amounts to 0.86 kg of wheat grain produced per cubic metre of water evapotranspired. This is lower than the global average value in prior studies reported in the literature, but is well within the range of 0.8 to 1.0 kg m^{-3} that was given by FAO33.

When estimating water productivity, a significant source of error may be introduced when converting the seasonal biomass production into harvestable yields by means of a crop specific harvest index. For the global (wheat) application, a fixed harvest index of 0.35 was used, which was based on an average of results found in 18 experiments from different regions of the Earth. The range of harvest index (0.25-0.45) is, however, large.. For a study of eight different wheat systems (chapter 3), average harvest indices varying from 0.36 to 0.40, were applied. These harvest indices were based on research reported in the literature for the specific regions. The harvest index is not fixed, however, but spatially variable due to a large number of influences which are related to the plant's growth. Water stress during the phenological periods of flowering and grain-filling affects the numbers of grains being formed and their accumulating weight (Passioura, 2005). However, crop variety, nutrient status and planting distance, all closely related to the farmer's agronomic decisions, also affect the fractions of total biomass and the weight of the grains. A consequence of the spatial variation in the harvest index, as well as the absolute values of the harvest index, the results from the application of the SEBAL and WATPRO models at regional and global scale respectively, may be higher. The work by Fereres and Soriano (2007) provides some quantified relations between total biomass production and the harvest index, for varying degrees of water supply and vapour pressure deficits. However, these relations appear to be highly variable between crops. Hence, more research is required to explain variations in harvest index.

The need to improve water productivity to safeguard future food production and provide water to other users of scarce freshwater resources has been outlined extensively in chapter 1. Appropriate measures need to be designed and implemented that focus on real water savings in agriculture while maintaining production, and on improving crop productivity while increasing water productivity. This requires major investments in the agricultural sector that should target areas where improvements are actually feasible. The focus should be on areas where a gap in water productivity exists. This raises two major questions that need to be answered. First of all, what is the actual (benchmark) and the potential water productivity in a specific location, and scope for improvement? Secondly, what are the underlying reasons for the gap in water productivity?

6.2 Defining the scope for improvement

This work has shown that large variations in measured and modelled water productivity exist between experiments at various locations globally, between fields within specific regions, and between countries globally. It is uncertain what the potential water productivity is, and whether such a value can be attained at every location. The field scale water productivity database showed maximum measured values of 2.6 kg m^{-3} for wheat, though the 98% percentile of the frequency histogram yielded a value of 2.2 kg m^{-3}. Angus and Van Herwaarden (2001) used a frontier concept on a scatter plot of measured evapotranspiration and wheat grain yields in rainfed areas of Australia. Based on data published in 1984, they found a maximum water productivity of 2.0 kg m^{-3}. In a similar approach to determine maximum water productivity using more recent data from Mediterranean climates in South-eastern Australia, China's Loess Plateau, the Mediterranean Basin and the North American Great Plains, Sadras and Angus (2006) found a maximum value of 2.2 kg m^{-3}. For each of the four "mega-environments" the authors also define the scope for improvement to reach the attainable maximum values in each region, which ranged from 32 to 44%. Their findings are based on experimental results from a limited number of sites for each mega-environment, and it is therefore questionable how realistic these ranges are. It is, however, unlikely that all farmers can attain the potential water productivity for many reasons which include spatial variation in environmental conditions (climate, soil) within a region (e.g. Abbate *et al*, 2005; Rodriguez and Sadras, 2007; Sadras and Rodriguez, 2007), and the discrepancy between farmers objectives of attaining maximum yields or economic profit instead of maximum water productivity. For example, Oweis *et al*. (1998) showed that under Mediterranean conditions the maximum water productivity is attained with sub-optimal wheat yields.

A different (remote sensing and modelling) approach was used in this study to understand where improvements in water productivity are feasible and what the scope for improvement is. The magnitude of variation within a system, defined by the coefficient of variation (CV), and the maximum value, defined as the 98% value of the frequency histogram, needs to be known. The frequency distribution of modelled water productivity was analysed and a percentage potential increase was defined by linearly forcing the coefficient of variation to 5% while maintaining the maximum value found (chapter 4). This implicitly assumes that 1) within a system some variation continues to exist due to varying environmental conditions, and 2) the maximally attainable value is defined under actual conditions in a specific year, rather than by a hypothetical value under optimal, but uncontrollable environmental conditions. The scope for improvement was then analysed for specific years and under actual conditions. This study revealed that only a limited scope for improvement is possible in the irrigated wheat systems investigated in India, Egypt, USA and the Netherlands, whereas the largest gains could be made in Pakistan (+24%) and in both systems in China (+34% and +35% respectively). These eight systems depict, however, only a fraction of the total wheat growing areas, and they are not necessarily representative of wheat grown in specific countries or agro-climatic zones. The analysis with the WATPRO model did show that there is a large range in water productivity globally, and that scope for improvement may be assumed, but not everywhere. This requires a better understanding of the range in current water productivity levels attained in given regions, countries or river basins.

6.3 Explaining the variation and options for improvement

The underlying reasons for variations in water productivity were discussed and outlined extensively in the previous chapters. Controllable agronomic choices by farmers such as the choice of a crop variety (drought resistance, harvest index, length of growing season), planting distance, nutrient availability (fertilization), water availability (quantity and timing of irrigations, water harvesting techniques), soil tillage (ploughing, mulching, weeding), etc. all affect the water productivity attained in the field. This results in a high spatial variation which was shown in the review of reported experimental results, and the regional analysis of wheat systems. Non-controllable environmental factors that impact on water productivity include climate (evaporative demand from the atmosphere) and soils. Two controllable factors (nutrients and water availability) and one uncontrollable factor (climate) were addressed to explain the variations that were found, and that could lead to measures or recommendations that promote the productive use of water.

Atmospheric demand

The impact of evaporative demand from the atmosphere is proven by many authors such as Bierhuizen and Slatyer (1965) who related transpiration efficiency to vapour pressure deficit, and Steduto *et al*. (2007) who related vapour pressure deficit and reference evapotranspiration to biomass transpiration efficiency for sorghum, sunflower, wheat and chickpea. They concluded that reference evapotranspiration provides a better relationship than vapour pressure deficit. At a regional or continental scale, water productivity was shown by Abbate *et al*. (2005) to be related to climate conditions for irrigated and rainfed wheat experiments across different locations in Argentina, and by Rodriguez and Sadras (2007) for wheat grown in various locations in Australia. In chapter 2 of this study, the maximum water productivity for each experimental location stored in the database was shown to have a weak, positive correlation with latitude, which was explained by the more temperate conditions in latitudes further away from the equator (see Figure 2-3).

This study is the first to relate water productivity to seasonal reference evapotranspiration at a global scale (see Figure 5-6). In temperate climates where seasonal reference evapotranspiration is lower than 400 mm, water productivity is on average twice as high as in arid areas, where reference evapotranspiration exceeds 750 mm. Reference evapotranspiration is a factor that has to be considered when farming wheat, since simple and affordable measures for farmers to reduce the total seasonal reference evapotranspiration do not exist. Measures that can be taken are 1) changing the agricultural growing season to a period with less evaporative demand (e.g. by changing from summer to winter crops or by earlier sowing), and 2) selecting modern varieties with a shorter growing season to reduce the total reference evapotranspiration (Passioura, 2006).

Soil fertility and fertilizers

Soil fertility is a controllable factor that impacts water productivity. It was shown that the increased use of fertilizers has a positive impact on water productivity. Water productivity was plotted against the total applied nitrogen (N) over the growing season. Three sources provided experimental results from Niger (Pandey *et al*., 2001), Uruguay (Caviglia and Sadras, 2001) and Syria (Oweis *et al*., 2000), where both parameters were measured and reported. Water productivity was low in plots without fertilizer (usually control plots in experimental trials). In all 3 experiments, water productivity increased sharply if small amounts of nitrogen (0-80 kg ha^{-1}) were applied. Thereafter the curve continued to increase, but at slower rates (see Figure 2-5). This indicates that the largest improvements in water productivity can be made in agricultural areas with low inputs (including fertilizers), rather than in areas where the use of fertilizers is already high. However, water availability may constrain the use of fertilizers by farmers. If water diversions for irrigation are unreliable, or rainfall is highly unpredictable, investments in fertilizer are not profitable or too risky to invest in. This should be recognized when defining policy for improvement and investment. In such areas, a combined approach should be adopted where fertilizers and supplemental irrigation (or irrigation improvement) are promoted to increase water productivity (Oweis *et al.*, 2000).

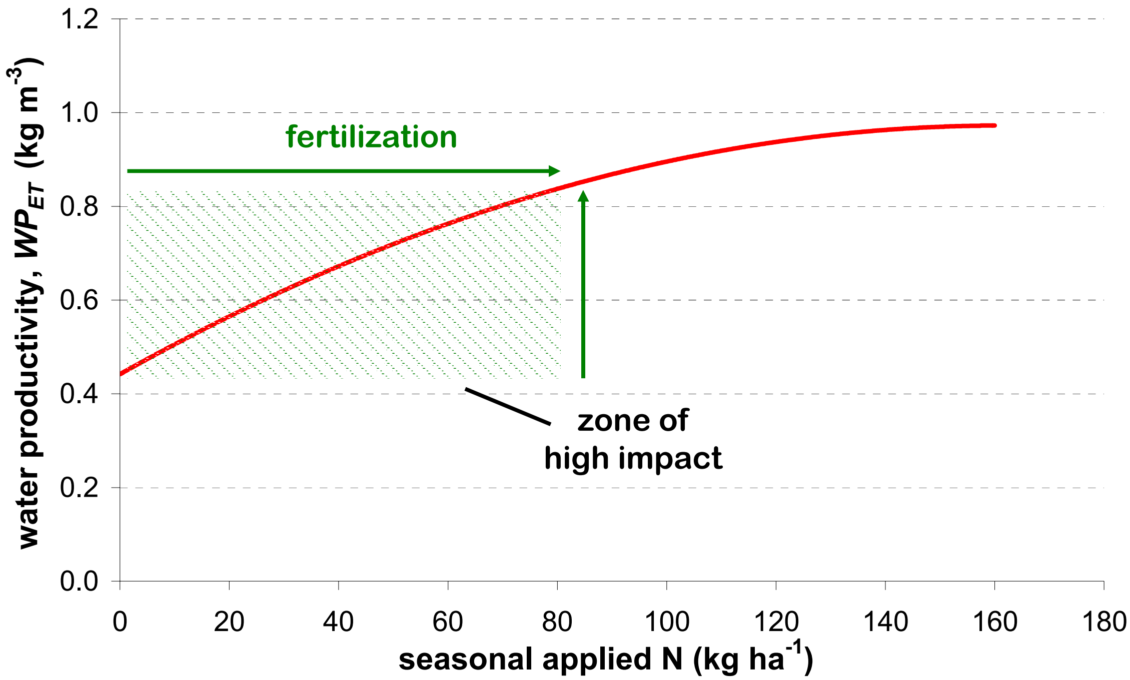


Figure 6-1: The impact of applied nitrogen (N) on water productivity levels and the effect of the use of fertilizers to increase water productivity. Hypothetical data are used.

Water availability and management

Water availability, whether under rainfed or irrigated conditions, strongly impacts the water productivity values that are found in the field. In this research, only seasonal totals of rainfall and applied irrigation water were considered. The timing of rainfall or irrigation events was not investigated, although it is realized that these also impact crop production and evapotranspiration. At field level, four experiments, two on maize (Turkey, Oktem *et al.*, 2002; India, Mishra *et al.*, 2001) and the other two on wheat (USA, Al Kaisi, 1997; China, Zhang *et al.*, 1999), were conducted to measure the amount of applied irrigation water as well as the water productivity. Although, the total amounts of water applied in a season varied strongly from no-irrigation (rainfed conditions) to 900 mm, all four experiments depicted a parabolic function. With no irrigation water applied, water productivity was low, but it increased strongly when limited water was added to the root zone. Under highest levels of irrigation, the water productivity was again lower (see Figure 2-4). Similar finding were reported by Oweis *et al*. (2000) who found that maximum wheat yields were obtained at full irrigation, though maximum water productivity was reached at 2/3 of the seasonal irrigation water requirement. Wheat yields under stressed conditions were, however, only slightly lower than under highest irrigation level. Similar conclusions were drawn by Hargreaves (1975) who showed for different climates that the highest crop water productivity for cereals is obtained at a moisture adequacy (i.e. ratio of the actual moisture available to the amount for which the yield is maximum) of 0.394, which proves that significant water deficits enhance water productivity.

This field scale analysis proves that under rainfed conditions water productivity can be increased significantly if supplemental irrigation is applied, or if rainwater is harvested and retained in the root zone. Harvesting of rain water focuses on reducing losses due to deep drainage, runoff and soil evaporation (Passioura, 2006). Crops with quick leaf expansion shade the soil earlier, and soil evaporation is therefore lower. Variation in row spacing, seeding rate, soil cover and soil tillage also affect soil evaporation and infiltration of water to the root zone (Van Herwaarden and Passioura, 2001).

Similarly, the field scale studies showed that water productivity increases when crops receive less water than the maximum that is required to meet the full crop water demand (Figure 6-2). Deliberately stressing crops may improve the water productivity and may have only a limited effect on final crop yields if crops are exposed to water stress during certain phenological stages (Fereres and Soriano, 2004). Major reasons for an increased water productivity as a result of deficit irrigation are a reduction of soil surface evaporation, a better partitioning of reproductive and vegetative biomass (a higher harvest index), a better synergy between fertilizers and irrigation, and a reduction of negative growing conditions (waterlogging, anaerobic conditions in the root zone, pests and diseases). Deficit irrigation diminishes irrigation water applications and improves water productivity, though it requires high level management skills and a reliable supply of water to irrigate crops during drought sensitive phenological stages (flowering, grain filling). It is also believed that drought-tolerant and drought-sensitive varieties of crops react differently to deficit irrigation, and caution should be exercised when exposing crops to deficit irrigation practices (Geerts and Raes, 2009).

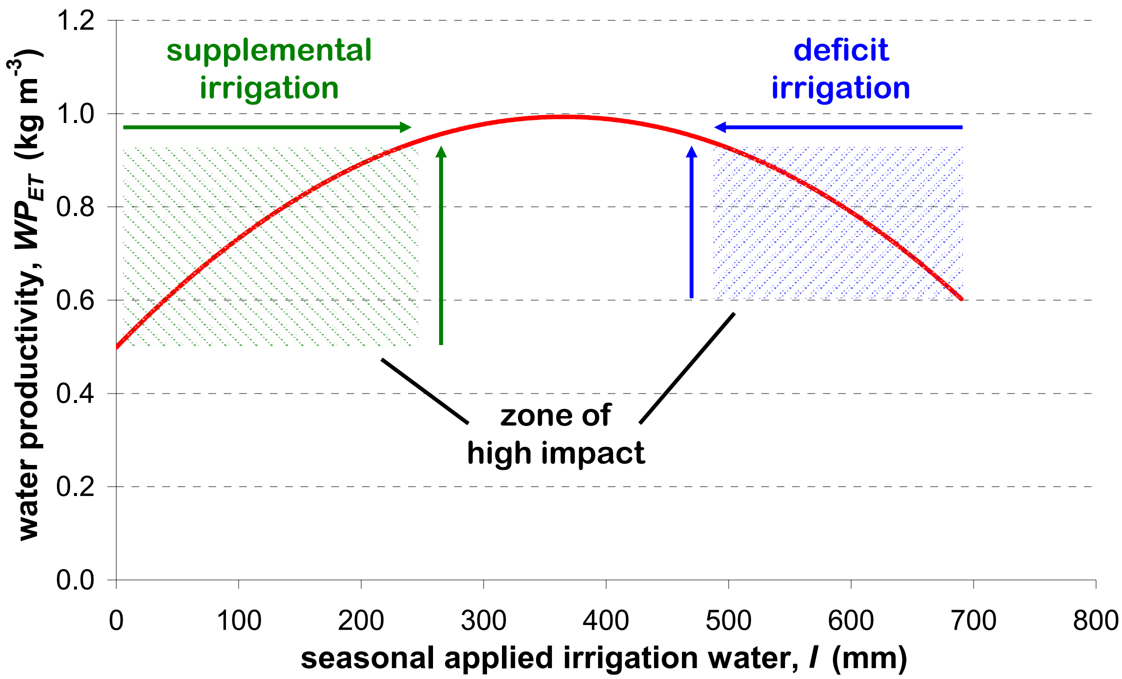


Figure 6-2: The impact of applied irrigation water (I) on water productivity levels, and the effect of two irrigation practices (supplemental and deficit irrigation) on increasing water productivity. Hypothetical data are used.

The analysis above focussed on the effects of irrigation water at field scale. It is important, however, to recognize that approximately 80% of the crops are cultivated under rainfed conditions. The global water productivity map was therefore analysed using global precipitation data sets. It was found that total seasonal precipitation strongly affects the level of water productivity attained. With approximately 600 mm precipitation or more, water productivity is around 1.2 kg m^{-3}. With half of this precipitation, it decreases linearly to approximately 1.0 kg m^{-3} (Figure 6-3). Thereafter, water productivity levels decrease faster until levels are reached where precipitation is insufficient and irrigation water becomes dominant. Unlike the example in Figure 6-2, the data presented below are based on a global data set that includes all climate zones where seasonal reference evapotranspiration varies between 300 and 1000 mm. The data in the figure below are not standardized for atmospheric demand and represent global average conditions. When interpreting this figure, it should be realized that due to climatic constraints, the scope for improvement is not the same everywhere, but dependent on climatic conditions during the growing season. However, the zone where precipitation ranges from roughly 40 to 280 mm is believed to depict the highest scope for improvement in water productivity.

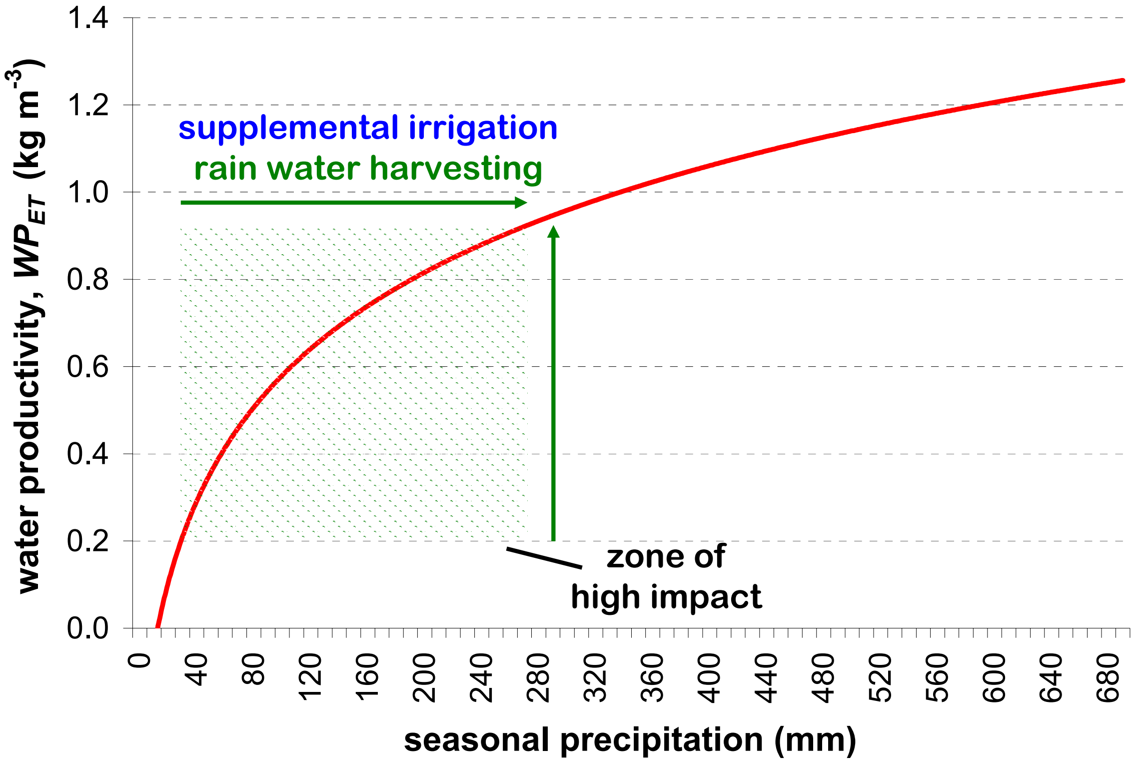


Figure 6-3: The impact of water availability from rainfall on water productivity at a global level (see also Figure 5-7).

6.4 Final considerations

Water productivity in agriculture must be improved and it is generally believed that this is feasible. But where are the major potentials and what are the constraints? Two systems may show the largest potentials: rainfed agriculture in region with low and erratic rainfall, and intensively irrigated areas.

In areas where limited and unreliable rainfall prevails, the use of fertilizers is inhibited as the costs of fertilizers as well as the risk of failure are high. It was shown, though, that the largest scope for improvement in water productivity is possible where limited quantities of fertilizers are used, and where crops are cultivated under rainfed conditions. Investing in rain water harvesting techniques and/or systems for supplemental irrigation, in combination with improved agronomic management and the use of fertilizers, may give a significant boost to the productive use of water resources within a basin. The impact of a planned intervention on the hydrological cycle must be considered since increased yields are associated with higher evaporative losses. This may impact on water availability to downstream users (Seckler, 2006; Comprehensive Assessment of Water in Agriculture, 2007; Perry, 2007). The importance of rainfed agriculture to global food production is, however, still underestimated and it requires a change in conceptual thinking to stress the importance of investments aiming at upgrading rainfed agriculture (Falkenmark and Rockstrom, 2006). Sub-Saharan Africa is often mentioned as a region where significant gains can be made (Rockstrom and Barron, 2007; Rockstrom *et al.*, 2009), but also

Central Asia, Iran, Turkey and the Middle-East were shown from the global analysis to depict low water productivity (Molden *et al*., 2010).

Improvements in irrigated agricultural systems can be made using deficit irrigation strategies. However, the increase in water productivity is thought to be more moderate than in rainfed areas (Molden *et al*., 2010). This study revealed that the scope for improvement is lower in systems with a high average water productivity. Also, the large scale introduction of deficit irrigation management requires a change in mind set by farmers to move from maximizing irrigation for maximized yields, to deliberately stressing crops to maximize water productivity. Moreover, deficit irrigation requires a higher level of management skills, as yields may go down and the risk of crop failure increases. This is contradictory to investments in rainfed systems, which aim at increasing yields and reducing the risks of crop failure, which finds more support from farmers.

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Curriculum Vitae

Sander Zwart is a mixed pixel from the three northern provinces of the Netherlands. He was born in Drachten, Friesland on March 30,1976 from a Frisian father and a Stellingerwerver mother. He lived for 18 years in Roden, Drente and went to Nienoordcollege in Leek, Groningen. Since his childhood his dream was to become a tropical doctor to help people in need, but after being refused admission by lot to the study of medicine, his mother drew his attention to amateurish-looking guidance materials for the study of Tropical Land Use from the Agricultural University in Wageningen. He decided to go for one year to Wageningen, and then again join in the lottery for admission to medicine. This never happened. Feeling at home in Wageningen and enjoying the new life with new friends and an intriguing study programme, he decided to finish Tropical Land Use. During his studies, Sander stayed six months in Lahore Pakistan thanks to a traineeship with Euroconsult. Later he spent three months in Palermo, Sicily, Italy, and to Simferopol, Crimea, Ukraine to conduct field work for the three M.Sc. theses he wrote. Together with study mates and friends Corné van der Sande and Floris Groesz, Sander followed more and more courses in GIS and remote sensing at the department of Geo-information. After discovering they had already fulfilled half of the requirements, they decided to enter the M.Sc. programme Geo-information Science. In January 2002, after seven and a half years of studying, Sander graduated with two M.Sc. degrees; one in Irrigation and Water Engineering, and one in Remote Sensing. That same year Sander joined WaterWatch in Wageningen, where he could combine and develop his multi-disciplinary expertise in many projects related to water management, agriculture and remote sensing. In 2003 Sander started his Ph.D. research on water productivity with Wim Bastiaanssen as his supervisor. This work was entirely conducted in his spare time. Sander wrote six peer-reviewed articles, of which four were used for this thesis, and he contributed to four other scientific articles. His first article, a review of crop water productivity measurements, has been cited more than 80 times since the end of 2004 and it is quoted in *the top10 most cited articles* of the Elsevier journal *Agricultural Water Management*.

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