Water productivity assessment in ten river basins: the status and implications

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Abstract

This paper summarizes the results and findings of water productivity assessment in ten river basins across Asia, Africa and South America based on the Basin Focal Project of the Challenge Program on Water and Food (CPWF). The Asian basins, with intensive farming activities, have much greater agricultural outputs and higher water productivity. A large proportion of African farmers, however, live solely on little agriculture with significantly lower WP. High intra-basin variability was observed, which was attributed to many factors but mainly lack of inputs, poor water and crop management. Global assessment revealed that localized interventions are more suitable for closing up the gaps between “bright spots” and the large poorly performing areas. Priorities are different in different regions. While improving crop yields is a gradual process, achieving water saving help to reduce the pressure on basin water allocation. Basin water development also has to be balanced with environmental sustainability.

Key words: Agriculture, Basin, Water productivity

INTRODUCTION

The world is under enormous pressure to feed nine billion people by 2050 without comprising environment quality to a larger extent. The major production resources, land and water, are however becoming increasingly scarce for agricultural sector with the impacts of global changes such as more competitive demand in water from other sectors in the process of development, and uncertainties brought about by climate change. It has been pointed out that significant expansion of cultivated land is not feasible in most parts of the world (Bruinsma, 2003), and crops will see reduced water allocation (Rosegrant et al., 1997).

The additional food required to feed the growing population is likely to come from increased crop yields, which demands both technical and management innovations. Increased yields are often achieved through increased consumptive water use, i.e., evapotranspiration (Jensen, 1968). However agricultural water use already accounts for 70% of global fresh water withdrawal. De Fraiture et al. (2007) suggest that there would not be enough water if trends in food consumption and current practices of production continue. The challenge ahead would be to produce more food with minimum amount of water, that is, to increase agricultural water productivity (Cai and Sharma, 2010).

Obstacles for improving agricultural water management vary in different parts of the world. These are associated with many reasons including biophysical settings, social-economic status, culture and habits. It is extremely difficult to take a holistic view of all these and factor them in policy making processes. As part of the Basin Focal Projects (BFP) of the Challenge Program on Water and Food (CPWF), assessment of water productivity (WP) were carried out in ten river basins with different physical and social settings: the Yellow River in China, Mekong in Southeast Asia, Indus-Ganges in South Asia, Karkheh in Iran, Nile in eastern Africa, Limpopo in southern Africa, Niger and Volta in western Africa, São Francisco and a collection of basins in the Andes in South America.

WP indicators enable performance assessment and comparison for better water management, which is driven by water scarcity and increasing food demand (Cook et al. 2006, Ahmad et al. 2009). The objectives of this paper are to give an indication of water productivity across different locations of the world, and to draw inferences about the underlying reasons.

THE TEN RIVER BASINS

The ten river basins spread out in three continents in Asia, Africa and Latin America (figure 1). Home to approximately 1390 million people, the basins have diverse biophysical and socio-economic settings. Mean annual precipitation vary from less than 400 mm in the Karkheh Basin to more than 1800 mm in the Andes Basin. The basins are incomparably different in sizes with various intensity of agricultural activities (table 1).

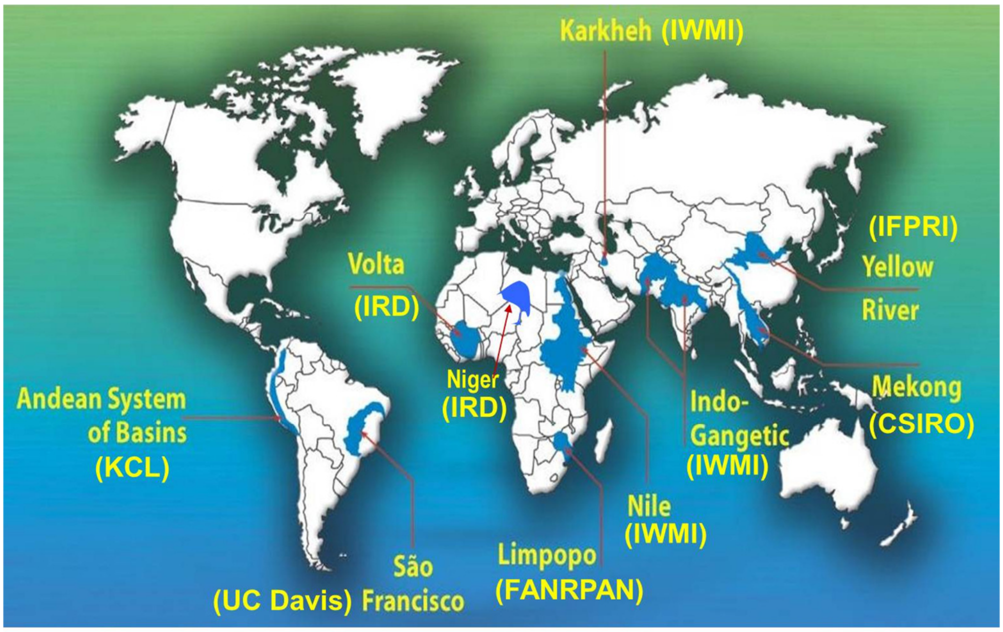

Figure 1. the ten river basins and their locations.

Table 1. Some basic characteristics of the ten river basins

Basin	Population (million)	Geographic area (million ha)	Cropland area (million ha)	% irrigated	Precipitation (mm)
Yellow river	189	79.5	16.3	46.0	452
Mekong	58.7	79.5	14.5	22.6	1516
Indus-Ganges	747	225	79.6	78.0	1254
Karkheh	4	5	1.5	31.0	358
Nile	160	310	26	21.2	563
Limpopo	14	41	2.3	10.6	530
Niger	94	127	0.5	15.0	
Volta	18.6	40	2.9	1.2	1300
Sao Francisco	16	64	13.6	2.4	561
Andes	89	380	14.0	22.1	1835

The ten river basins are at different development stages and have distinct differences in their social settings. The contribution of agriculture to GDP varies from 6.5% in the Limpopo to more than 50% in the Mekong, Nile, and Niger (Figure 2), and involves 23% to more than 90% of the basin population. The percentage rural poverty also varies widely, from 11% in the Yellow River to more than 70% in the Niger. The three Asian basins have the highest total and percentage rural population, closely followed by the African basins, but both are much lower in the Andes and the São Francisco. The contribution of agriculture to GDP and the incidence of poverty in the African basins are significantly higher than in other basins. Although the rural population in South American basins is relatively low, rural poverty is high. It is noteworthy that there is high variability in some transboundary basins where the characteristics of one country may skew the basin average.

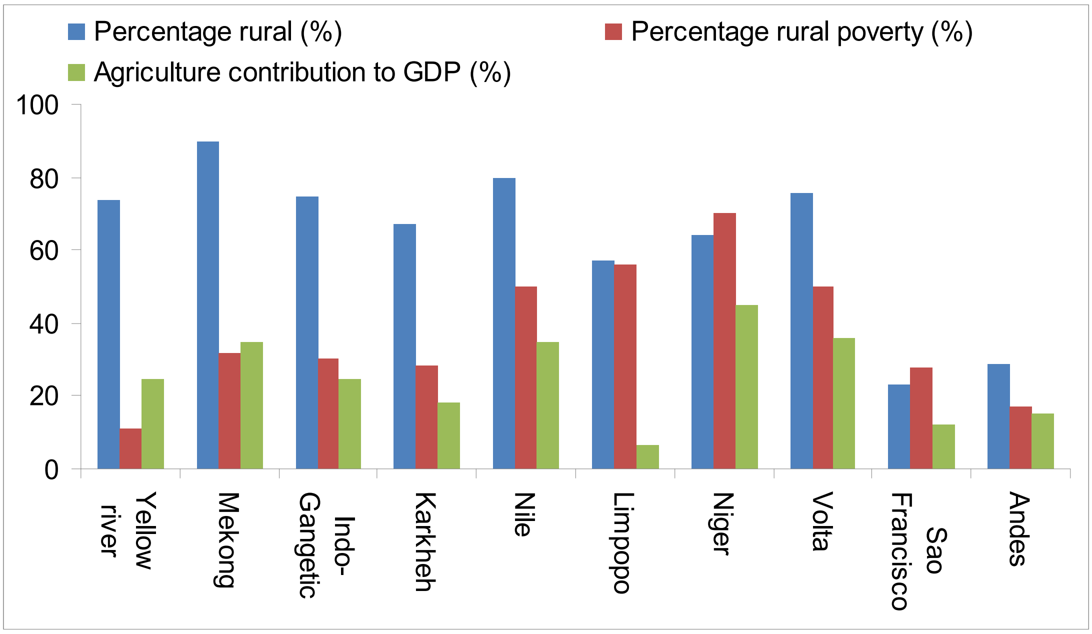

Figure 2. Rural population, poverty, and contribution of agriculture to GDP in the 10 BFP basins.

Irrigation development is diverse in the ten basins. The Indus-Ganges, with mean rainfall of 1250 mm, has by far the highest percentage of irrigated areas (78%), followed by the Yellow with 45%. The Volta and São Francisco have the lowest ratios of about 1%. Maize is the dominant crop in commercial cultivation in most basins except the Indus-Ganges, the Mekong, and the Niger. Wheat and rice are the dominant crops in the Yellow, Mekong, Indus-Ganges, Nile and Karkheh. The Niger, however, is dominated by millet and sorghum and São Francisco by fruit plantation such as banana, mango and grapes. Among major crops rice usually requires heavy irrigation. Wheat is also irrigated intensively in the Yellow and the Indus-Ganges. Maize in Africa and South America is mostly rainfed.

WATER PRODUCTIVITY ASSESSMENT AT BASIN SCALE

WP measures how the system converts water, together with other resources, into goods and services. It is defined as the ratio of net benefits from crop, forestry, fishery, livestock and other mixed agricultural systems to the amount of water used in the production process (Molden et al. 2010). The benefits can be measured with various terms including physical mass (kilogram), economic value (monetary) and nutritional value (calorie). The water input, denominator in the WP equation, also has a set of choices depending on the purpose of the examination and the availability of data. For example, irrigation diversion, gross/net inflow, evapotranspiration, and precipitation can all be used to calculate WP indicators. These variations give WP assessment flexibility and robustness as a tool to measure efficiency of water use.

The assessments of WP were carried out using various approaches and combining a range of datasets. The ten basins have diverse social and physical settings with different levels of data availability. Because crops dominate agricultural production and are the biggest water consumer, we gave them more attention in WP assessment. In some basins, where livestock and fisheries are important contributors, we also included them. The basic equation to calculate WP is:

$$WP = \frac{Output\ derived\ from\ water\ use}{Water\ input} \tag{1}$$

The numerator and particularly the denominator were determined using various methodologies such as field experiments, (agro-) hydrological modelling, spreadsheet calculations and remote sensing. Datasets come from sources such as field monitoring, household survey, official statistics, weather stations, remote sensing imagery, and literature review. Various datasets of different spatial scales from the field, through sub-catchments, to the basin were combined in the assessment by participating institutions of the project. More information can be found in Cai et al (2011) and at http://www.waterandfood.org/.

AGRICULTURAL PRODUCTIVITY, WATER USE AND WATER PRODUCTIVITY

Yields of the major crops (maize, wheat and rice) vary both across and within basins (Figure 3). All the three crops in the Yellow River have relatively high yields, although not the highest for maize and rice. The yields for the Nile in Egypt are very high for all three crops, although low yields elsewhere reduce the overall figures for the Nile. The Indus-Ganges basins, are the most populous and have the most intensive cultivation, but have relatively low yields overall for both rice and wheat, which are the major sources of food and income.

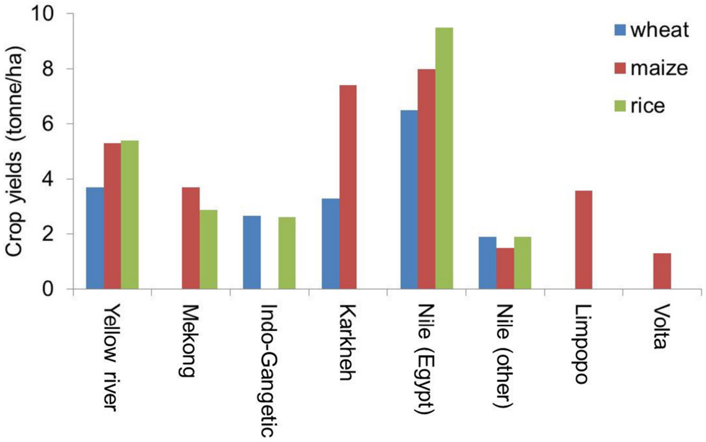

Figure 3. Average yield values of major crops in BFP basins.

There is large intra-basin variability in all the basins. The average yield of maize in the Limpopo is 3.6 ton/ha. While the irrigated commercial farms yield as high as 9 ton/ha, the large area of subsistence farms, which are threatened by frequent droughts and crop failure, yields less than 2 ton/ha. The Indian states of Punjab and Haryana, the “bright spots” in the Indus-Ganges basins, yield more than double elsewhere. The highest yields of rice among all BFP basins are in the Nile basin, because of the very high yields in the delta in Egypt. Elsewhere in the basin, including most of Ethiopia and Sudan, yields are very low. There is similar variability in the Mekong basin, where yields are high in the delta, but low in Cambodia and northeast Thailand.

WP values in terms of GVP divided by ET are available for some of the basins, and vary widely between them. For each cubic meter water consumed, irrigated crops in the Karkheh generate US$0.22, the Indus-Ganges US$0.13, while the Mekong only US$0.012-0.059. Crop yields in the Karkheh are high, which accounts for high crop WP. The Indus-Ganges basins also stand out with relatively high WP in spite of moderate yields, which contrasts with the Mekong basin with higher yields but much lower WP. Both basins have more than 1200 mm/year rainfall, slightly higher in the Mekong. However, the cropping intensity in the Indus-Ganges is much higher so that there is a high demand for water for irrigation. Farmers are therefore under pressure to increase water use efficiency. Crop diversification in the Indus-Ganges also contributes significantly to high WP. Cash crops such as millet, sugarcane and pulses greatly increase the economic returns to irrigation, and reduce the risks imposed by climate extremes such as floods and droughts.

Several basins produced WP in terms of ET of maize, rice and wheat separately so that we can compare the performance of the production systems of major food staples. The WP of maize is the highest in the Yellow river (0.97 kg/m^3), followed by the Mekong (0.58 kg/m^3). Maize is the single dominant crop in the Limpopo but WP is very low at 0.14 kg/m^3. The ET of the Limpopo basin is sum of year 2005 and that of other basins is sum of wheat growing season. However, even when we correct ET for the crop growth period in the Limpopo, which has pronounced seasonality, WP is still considerably lower than in the Yellow River. The difference is explained by the difference in yields of the mostly irrigated, high-yielding Yellow River compared with the rainfed, low-yielding Limpopo. WP of rice showed less variation. The Indus-Ganges leads all the basins with 0.74 kg/m^3, closely followed by the Yellow River (0.5 kg/m^3), the Mekong (0.43 kg/m^3) and the Nile (0.14-0.67 kg/m^3). Rice is an important component of regional food security in the Indus-Ganges and the Mekong and the areas of rice cultivation are much bigger than any other basins. The WP of wheat in the Yellow basin is 48% higher than that of the Indus-Ganges although wheat is a major crop in both basins.

Yields and WP of irrigated crops were compared with rainfed crops in some basins. As expected irrigated crops yield much higher than rainfed in all cases though WP showed different trends. In the Yellow basin yields of maize were 3.7 and 3.0 t/ha irrigated and rainfed respectively. In contrast, WP of irrigated maize is 0.97 kg/m^3 compared to rainfed 1.09 kg/m^3. Patterns in the Karkheh were different. Both the yields and WP of rainfed crops are lower than irrigated crops, which suggest that there may be several factors contributing to water productivity. In assessing WP performance, WP values have to be considered in relation to the specific basin setting and comparisons can only be made between the same settings.

There was wide spatial variability of crop WP within each of the basins. The coefficient of variation (CV) of maize, rice and wheat WP for the four Asian basins varied mostly from 0.3 to 0.5, with the extreme high of 0.7 for wheat in the Indus-Ganges and extreme low of 0.16 for rice in the Mekong. Higher CVs indicate higher levels of heterogeneity in the basin, suggesting greater chances to close up the gap between the good and the poor performers. Figure 4 illustrates the magnitude and variations of crop WP in the Nile and Indus-Ganges basins. The narrower range of WP for the Nile is contained within the broader variation of the Indus-Ganges. The magnitude of WP in the Indus-Ganges is greater than that of the Nile with an overlapping range. The intra-basin variability is also clearly spelled with the two pixel-based WP maps. There are bright spots in the upstream of the Indus and the delta of the Nile with average high WP of US$/m^3 0.19 and 0.20 respectively, which are 1.5 and 4.8 times of basin averages respectively. Understanding the reasons for the differences will help to assess the potential for improvement and to identify priority interventions in low performing areas. We discuss this aspect in later section in the paper.

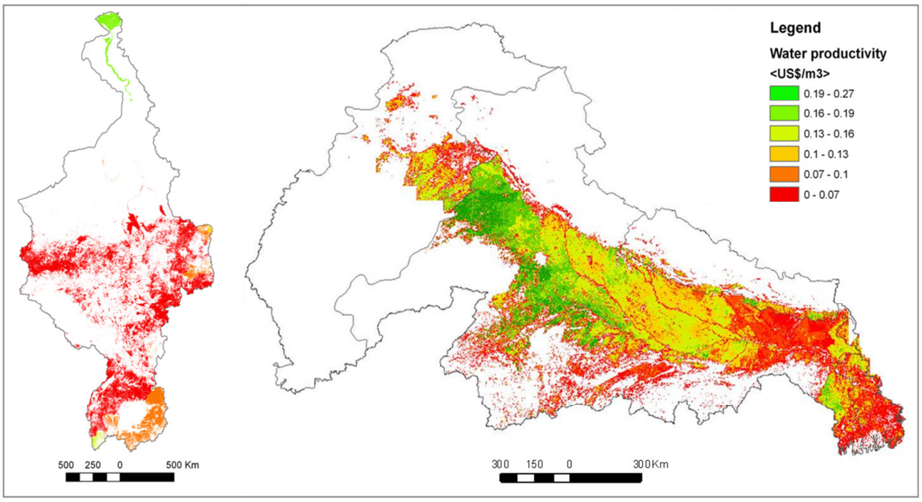

Figure 4.Crop water productivity and the variations in the Nile (left) and the Indus-Ganges basins (right).

DISCUSSIONS

Land and water productivity varies widely both across and within basins. The Asian basins, Yellow, Mekong, Indus-Ganges, and Karkheh have more productive farming systems than those in Africa and South America. There are many causes for the variation, some of which we discuss in this section, together with some of the threats to sustainable agriculture. Figure 5 illustrates some of the factors affecting water productivity in the Indus – Ganges Basin. The rainfall measured from TRMM, the MODIS land surface temperature, and the ratio of ET_a to ET_p (an indicator of water stress) is compared with each other for rice and wheat. The basin DEM, groundwater depth of the Indian part, and main river streams of the IGB are also included in the comparison. It shows crop performance has diverse variations in comparison to the constraining factors. The ET_p of rice is lower in the Ganges Basin, which is opposite to rainfall distribution. The well-performing Indian State of Punjab showed little water stress in spite of a deep groundwater table and low rainfall due to good irrigation infrastructure. Further analysis revealed that weather conditions as reflected by reference ET have no direct link with actual ET. Well-developed irrigation and drainage systems together with matching management practices can help to supply water during the dry spell, and drain the excess water from rainfall and shallow groundwater. Other land and crop interventions such as leveling, insects and diseases control, fertilizer and variety are also important factors to be considered along with water management.

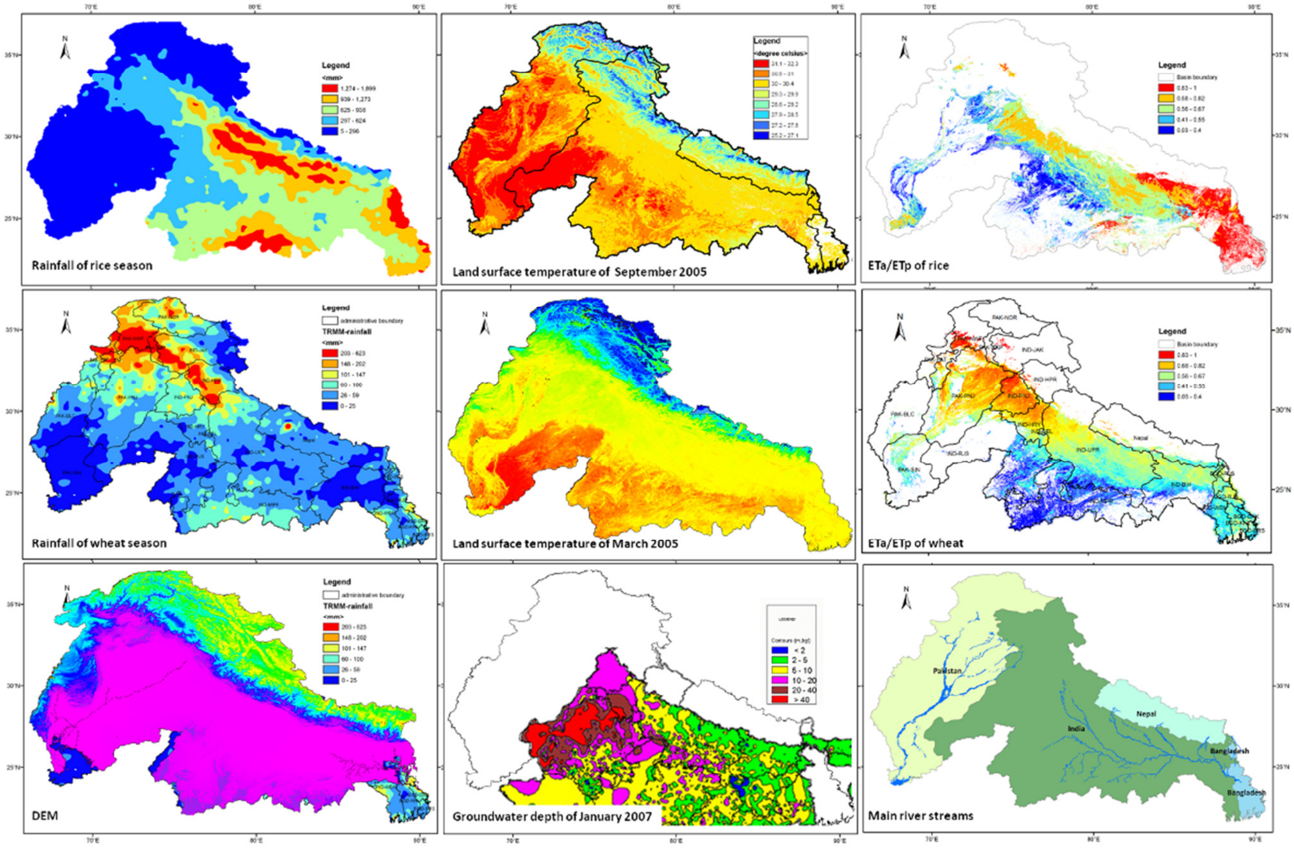

Figure 5. Comparison of potential factors contributing to the variation in water productivity of rice and wheat in the IGB.

Often site-specific technologies are required to achieve better outputs from land and water. For example, maize in the downstream parts of the Limpopo often suffers from water logging, indicating a need for improved drainage. It might also be practical however, to change cropping patterns to include more tolerant crops. Rice is an important crop in Ningxia Province, upstream in the Yellow River basin. However, the increasing demand on water reallocation from downstream provinces has put pressure on farmers to reduce 30 percent or more rice cultivation. In the Indian state of Punjab, rice irrigated with groundwater cannot by law be transplanted until the monsoon starts, avoiding high evaporation losses in the hot weather that precedes the monsoon. Monocrops are popular in the Indus-Ganges Plain for the convenience of supplying irrigation water and operation of farm machinery. In most other areas, however, crop diversification is important to improve overall land and water productivity and reduce risks. For example, the smallholder farmers in the Lao PDR have increased production of various upland crops while production of rice has remained static.

The level of socio-economic development has a big impact on agriculture. Hanjra and Gichuki (2008) suggested that, in most cases, the higher the contribution of agriculture to GDP the higher the incidence of poverty. In turn, this limits famers' capability to increase inputs to agriculture, improve WP, and cope with climate extremes such as droughts and floods. The contribution of agriculture to GDP is slightly lower in Asia and highest in the Nile, Volta, and Niger. The African basins mostly rely on rainfed agriculture with poor infrastructure, low inputs of fertilizer and irrigation, and consequently low crop yields and low crop WP. But the Limpopo and the Andes basins, which have the lowest contribution of agriculture to GDP, also have low agricultural and water productivity. The reason is that South Africa skews the mean because it is a relatively well-developed country with severe inequity of highly developed commercial agriculture juxtaposed with a large number of poor subsistence farmers. The latter, together with poor smallholders from other Limpopo countries are most vulnerable to the droughts that occur frequently.

Access to well-functioning markets is central to determining the overall value of agricultural production and net returns to farmers. Although agriculture is often subsidised, markets often are not accessible to many farmers. Subsistence farmers in the Limpopo basin are often obliged to sell their produce to big farmers, who have the resources and bargaining power to send it to distant markets (Rosemary and Johann 2009). In the Gazeira in Sudan, cotton is a mandatory crop financed and marketed by the government. It is increasingly grown at a loss as production falls because of the lack of incentives to the tenant farmers (AbdelKarim and Kirschke 2009). Price fluctuations have strong impacts on the value of agricultural crops regardless level of crop yields. For example, maize yields are similar in the riparian countries of the Limpopo basin, but local market prices are widely different in each causing huge differences in GVP and consequently the returns to land and water. Figure 6, discussed above shows that increases in crop yield and WP in the Mekong basin were totally offset by falls in the market price of rice. On the other hand, the minimum support price (MSP) of wheat and rice by the government of India provides good remuneration to the farmers but discourages them from diversifying into crops with lower water requirement (Joshi 2005).

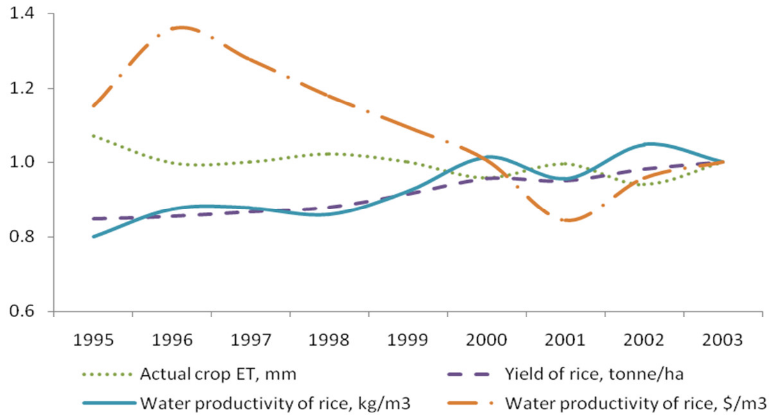

Figure 6. ET, yield and water productivity of rice in the lower Mekong basin. The data were normalized to 2003 values.

Although there have been continuous efforts to enhance the efficiency of agricultural systems, new threats are emerging, among which environmental degradation and climate change are the two major concerns. As agriculture develops it almost certainly has negative impacts on the environment (Bakkes *et al.* 2009). But the externalities can be managed to different degrees. Agriculture withdraws and consumes water that could be otherwise beneficial to other users including the environment (Molden et al. 2010). In closed basins, where there is competitive demand for water, the environment is often the loser. Environmental flows, which are the minimum flows required to maintain the health of rivers, are often ignored (Smakhtin and Anputhas 2006). The Yellow River ceased to reach the sea in the 1990s. This is no longer the case but the pressure of high demand for water keeps increasing. Although the national south-to-north water transfer project will deliver a good amount of water to the basin, environment flows are not considered due to the very high cost of diversion. The Indus is another closed basin where both surface water and groundwater are over exploited, causing drastic declines in groundwater table, which threatens sustainability of the agricultural systems that depend on it. In these cases the broadly-defined WP, including industry outputs, are increasing but at the expense of agricultural sustainability, which supports multi-billion rural populations.

For the limited quantity of water left in river channels and aquifers, water quality often becomes a major concern. A survey in the Yellow River in 2007 found that 33.8 per cent of the river system registered less than level five water quality, which is classified as not suitable for drinking, aquaculture, industry, or even agriculture (YRCC 2007). The Andes basin, due to their steep slopes, suffers from soil erosion in the upstream areas, which imposes another kind of water scarcity downstream due to loss of quality. In the Mekong basin, water quality issues are more often confined to water-poor areas, for example, water pollution in the Tonle Sap, quality of groundwater in Northeast Thailand, and water salinisation and acidification in the delta area of Vietnam (Kirby et al. 2009). In the lower parts of the Ganges basin (West Bengal, Bangladesh), arsenic contamination of groundwater is widespread and is linked to its over-exploitation. Degradation of water quality is mainly caused by effluents from cities and rural households, but also from agriculture itself. Non-point source pollution from agriculture is a major threat to water quality in areas of intensive irrigation, where irrigation is often accompanied by high fertilizer inputs. The severely degraded water quality results in threaten to water supplies and consequently, water productivity.

Climate change is projected to have various impacts on agricultural production systems. In spite of forecasts that total rainfall may increase in some regions, the available water to agriculture will likely fall if water storage, diversion infrastructure, and management remain at their current levels (Backlund et al. 2008). More extreme climatic events, such as shorter and more intense rainy seasons and longer and more intense dry seasons will make agriculture, especially rainfed agriculture, more vulnerable, and hence reduce agricultural WP. The faster snow melt caused by increased temperature will increase flows in the river channels in the short term but in the longer term flows will change their seasonality as rain replaces snow in the headwaters. The glaciers of the Tibetan plateau and surrounding mountains, boarding South and East Asia, will be significantly affected by global warming. The changes in this region could affect billion people in the East, Southeast, South and Central Asia, many of which depend on river diversion for irrigated agriculture. Sea level rises will adversely affect the deltas, causing greater risks of floods and saltwater intrusion. It is estimated in the Mekong basin more than one million people are expected to be affected by 2050 (Nicholls et al. 2007). Climate change also will have negative impacts on crop yields at global scale as a result of shorter growth periods and lower soil moisture caused by increased temperatures and more uneven distribution of rainfall (Lobell and Field 2007). Crop water-use efficiency will decrease both because of lower yields as well as increasing evaporation from bare soil (Xiao et al. 2009).

As described above, there is large variation in WP across basins as well as within basins. Crop WP from remote sensing at the pixel level provides explicit description of both the magnitude and the variation. The levels of WP for rice and wheat in the Indus-Ganges basin are plotted in figure 7. There are high coefficient of variation, 0.44 for rice and 0.70 for wheat, which are much larger than those for the world (Zwart and Bastiaanssen 2004). This is because remote sensing is capable of capturing every pixel in a basin including extreme spots. The CV of wheat is much higher than that of rice, meaning water management of wheat is more diverse compared with rice. This is because there is little rainfall during the wheat growing season and hence the crop heavily depends on irrigation. High

CV values indicate large differences in crop performance and crop water use. Improving the irrigation management of wheat is probably the most urgent and easiest way to improve basin WP.

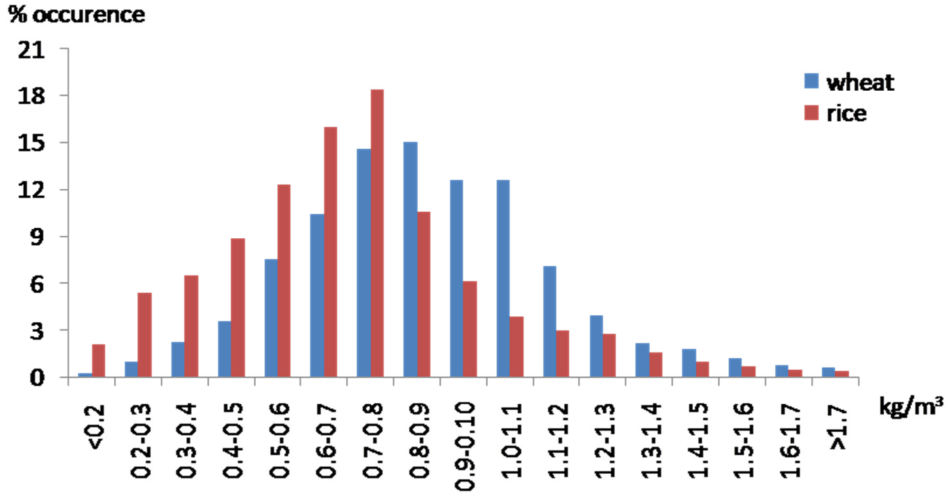

Figure 7. The histogram distribution of WP values for rice and wheat.

The potential for rice and wheat is different, both in terms of magnitude and areas of focus. Water productivity generally increases with increasing yield (Figure 8). The “bright spot” of the Indian Punjab clearly stands out in both plots (circled). The largest scope for improvement of rice in the region will be firstly in the low yield and low WP areas. While yield improvement is going to be a long term process involving seed innovations, reducing water consumption would be an effective approach to save more water from agriculture while maintaining similar yields in the short run.

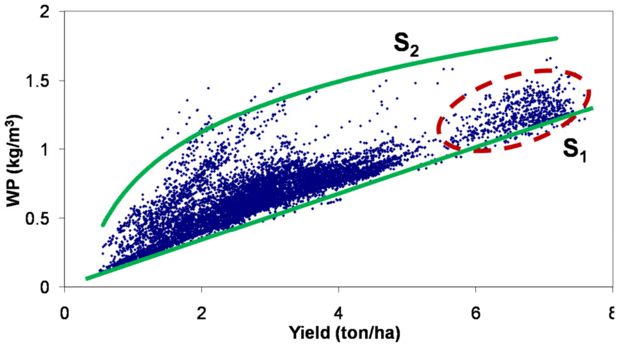

Figure 8. Relations between (a) water productivity and yield and (b) yield and evapotranspiration of rice in the Indus-Ganges basins, adapted from Cai and Sharma (2010).

Basin WP has important implications for regional food security and livelihoods, especially in places where there is poverty and crop production is low. Improved WP means more food, more income, less vulnerability to risks, and possibly less water used. Improving WP may leave more water for other sectors to produce more, which in turn contribute to regional development. The Africa continent withdraws less than 4% of its renewable water resources for agriculture (Hanjra and Gichuki 2008). Lack of inputs such as land preparation (energy), seeds, fertilizer, pesticides, and irrigation water limit the opportunity for productivity improvement. Increasing water productivity through higher yields and improved water use helps to enhance crop production, generate and stabilize income, boost employment, reduce consumer prices, and reduce costs. Mixed agricultural systems that include crops, livestock and fisheries help to distribute risks and maximize benefits from limited water resources. Cash crops are efficient in reducing poor communities’ vulnerability to natural disasters such as droughts (Mertz et al. 2005). The importance of livestock and fisheries are often underestimated. At the global level, livestock are responsible for around 20% of agricultural water ET (De Fraiture et al. 2007). With the changing diet of a wealthier population, consumption of milk, meat and fish is projected to double by 2050. Both livestock and fish can be part of integrated water management systems, with less additional water required for fish and more land management for livestock.

Conclusions

Agricultural WP is a key indicator to link basin water resources and agricultural outputs which sets a useful baseline for efficient agricultural water management. A holistic overview of agricultural production systems at the basin level can help to identify the issues that are relevant for informed policy-making. Agricultural WP is important to regional food security as well as to farmers' livelihoods. Increasing WP needs to consider the economic costs of doing so. While bright spots illustrate the potential for improvement, it might not be feasible to achieve same level of WP elsewhere in a cost-efficient way. Small-scale interventions, such as supplemental irrigation, are relatively easy to adopt with less investment, and could significantly improve agricultural WP.

The potential to save water is not as big as many think, but there is significant scope to improve WP. Different farming systems have different priorities in different locations. Markets play a key role in converting agricultural production to income. We note, however, the need to balance WP and environment.

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