Current status and scope for improvement of agricultural water productivity in the Indo-Gangetic River basin

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ABSTRACT

This paper assesses the agricultural water consumption and productivity of the predominant crop paddy rice and wheat for the Indo-Gangetic river basin (IGB) in South Asia. A new approach was adopted in the study to integrate census, remote sensing and weather data to assess crop water productivity (WP) across large scale. The average paddy field ET for rice for major growing period of June 10 to October 15 is 416 mm, which is 70% of rice potential evapotranspiration (ET_p, equals to ET_0*K_c). Average rice water productivity is 0.74 kg/m^3. The average evapotranspiration (ET_a) and WP of wheat is 299 mm and 0.94 kg/m^3 respectively. Significant variations were observed for the ET_a, yield and WP of rice and wheat. The scope for improvement of water productivity could be assessed by comparing ñhotò and ñbrightò spots in consultation with factors such as rainfall and topography. It is found while improving yield in long term will finally lead to improved WP, reducing non-beneficial ET from low yield areas is a effective approach to improve WP in short term. Integrated land, crop and water management is the key to sustainable development of the region.

INTRODUCTION

Water is one of the most critical inputs to agriculture for human survival. However, the level of water use differs significantly across regions, farming systems, canal command areas, and even farm plots (Molden et al., 2003). It is not clear how water is better used by crops hence contributing to improved productivity with all aspects of efforts, especially in large river basin across countries. To measure the effectiveness of these interventions, water accounting and water productivity analysis are required to understand water-agriculture system, i.e., the relation between water input and agricultural output.

There are various sources providing water to meet crop requirement: precipitation, irrigation, ground flux, soil moisture, and air moisture, among which rainfall and irrigation are the two major inputs. These two inputs are somehow monitored at certain level, e.g., rainfall from single station, irrigation diversion from head canal. However, the actual use of these inputs is not clear. One example is irrigation return flow which is often difficult to measure despite its significance in many regions. As many efforts are made to study the fate of return flows on the ground, the remote sensing data interpreted actual crop water consumption provides another way to assess crop water input and the crop productivity which is a response of water input. This approach provides spatially explicit water productivity assessment while avoids going into complex ground processes.

This paper presents a simple yet efficient approach to combine meteorological data, ground survey, national census with remotely sensed imagery to assess water use, yield, and finally crop water productivity for the Indo-Gangetic rice-wheat cropping system in South Asia. The spatial variation of water productivity maps was analyzed. Then the WP maps, together with yield, ET maps, and contributing factors, for example, rainfall map, land surface temperature maps were compared. The causes for variation and scope for improvement is discussed.

Indo-Gangetic river basin, the most populous basin in the world, covers a huge area of 2.25 million km^2 including Nepal, significant parts of India, Pakistan, Bangladesh and small parts of China and Afghanistan. Diverse climate, topography, and soil conditions exist in the basin. The climate is strongly characterized by monsoon with annual average precipitation varying from less than 100 mm to 4000 mm, most of which occurs during June to October. Three physiographic regions: Mountain areas, plains and delta are found originating from southern slope of Himalayas and extending towards two directions: southwest till Arabian Sea and southeast till Bay of Bengal. Out of the total drainage area, more than 50% (1.14 million km^2) is cultivated. Rice ï wheat rotation is the predominant cropping system in the region, mixed with cotton, sugarcane, pulses, millet, and jute etc. Crop sowing dates and growth length vary according to climate conditions, water availability, farmersô habits and crop varieties (Ullah et al., 2001).

METHODOLOGY

Rice and wheat are the predominant crops of the basin. Hence this study focused on these two major crops. The methodology adopted in this study involves three steps: crop dominance map to determine major rice-wheat cultivation extent; crop productivity map to map rice and wheat yield at pixel scale; ET map to calculate crop consumptive water use (ET). The water productivity is finally produced by dividing crop productivity map by ET map. Following section gave a summary of each step. Detailed description could be found at Cai and Sharma (2009).

Crop dominance map is the very first step to estimate crop yield and analyze ET by crops. Several LULC maps already exist in IGB including USGS Global LULC dataset; POSTEL global land cover map; IWMI Global Irrigated Area Map, and IWMI Indo-Gangetic LULC map. The two IWMI maps provide information for irrigated versus rainfed as well as groups of crops for each agricultural class. One groundtruth mission was carried out in early October to collect information on LULC, irrigation, crop, and social-economic set up. 2730 km were covered in 11 days with 175 GT samples collected. With input of the groundtruth data, all existing LULC data layers were brought together and synthesized to a crop dominance map.

Yield mapping involves district wise census data synthesis, and extrapolation to pixel wise using RS images. Three crop production datasets were collected including two from national sources, one from FAOSTAT. The datasets were verified with each other and normalized to the average values of nominal year 2005-06 at district level. Wealth of literatures suggested linear relationship between crop grain yield and NDVI at heading stage. MODIS 250m NDVI maximum value composite image of 29th August ï 5th September 2005 was used to extrapolate yield from district average to pixel wise employing the linear relationship.

ET maps are produced using Simplified Surface Energy Balance (SSEB) model in combination of weather station data and MODIS 8 day 1km land surface temperature (LST) products. Daily potential ET was calculated using Hargreaves method with data from 41 weather stations across the basin and FAO crop coefficient approach. The point potential ET was then extrapolated to surface using a minimum curvature spline technique. Pixel actual ET was calculated by multiply ET_p surface with an evaporative fraction grid generated from MODIS LST data.

RESULTS AND DISCUSSION

In this section we firstly present the current status of water productivity values for the predominant crops rice and wheat. The causes for variations were then analyzed together with rainfall, temperature and topography distribution. Finally scope for improvement was assessed by comparing ñhotò spots with ñbrightò spots with consideration of limiting factors.

Water productivity of rice and wheat

Average rice water productivity (figure 1) of the basin is 0.74 kg/m^3, with minimum, maximum and standard deviation values of 0.2, 2.04, and 0.37 kg/m^3 respectively (1% extreme pixels were sieved). The water productivity variation follows closely the pattern of yield variation. The ñbright spotò of Indian Punjab and adjoining areas, covering 6% of total rice area, have very high water productivity with an average value of 1.51 kg/m^3. However, as much as 19% of total rice areas have WP less than 0.5 kg/m^3, which occur mainly in Indian Madhya Pradesh, Bihar states and Bangladesh Dhaka division.

Some areas show different trends in WP variation compared to yield and ET map. A high WP strip, around 10-70 km in width, starts from 75.5E, 29N in southern Haryana State and goes towards the east till the Southern Bihar State, India (85.2E, 24N). The yield for this area is relatively low with an average value of 3.2 tons/ha. However, the average ET of the same area is as low as 277 mm, making the WP relatively high. The higher WP values here do not suggest satisfying performance in this case. Rather, it provides interesting clues to reveal the reasons for the differences, the potential for yield improvement, and the possible interventions by ñscaling upò to other areas.

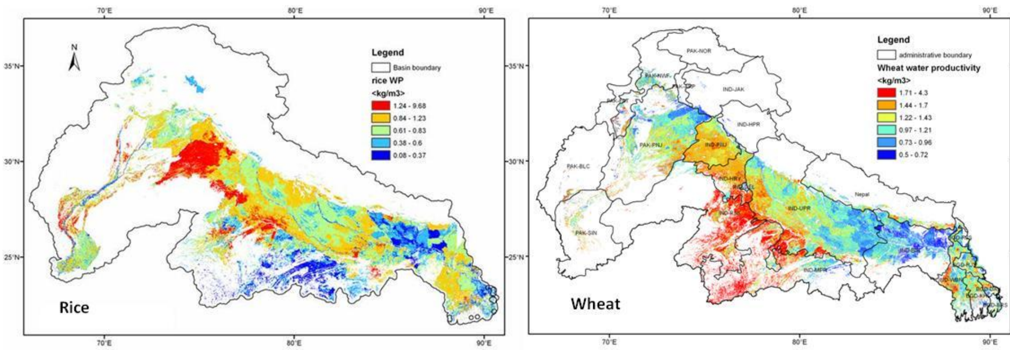

Figure 1. Water productivity of rice and wheat in IGB for year 2005-2006

The average WP of wheat is 0.94 kg/m^3 with standard variation of 0.66 kg/m3. Due to the extremely low ET in the Rajasthan and Madhya Pradesh states, water productivity in these areas showed higher values despite low yield. These states still cultivate low yielding traditional wheat varieties which incidentally have high cooking quality and fetch premium price in the market. The growing season in these states is also of shorter duration due to shorter winter period and early maturity of the crop. The high yield areas showed high water productivity values although they are not among the highest. The Bihar State in India has the largest areas with lowest WP, which means significant scope form improvement exists here. The downstream of Ganges shows relatively good performance despite high variability in yield.

The average rice WP expressed in US dollars in 2005 at local market price is 0.121 US \$/m^3, while for wheat it is 0.148 US \$/m^3. The average WP for sum of rice and wheat is 0.131 US \$/m^3 (figure 2). The spatial variation of WP is found to be different both from rice and wheat WP maps. The shared areas of rice and wheat cultivation are influenced by wheat more than rice. However, areas with low wheat WP but high rice WP and the other way around are found in many areas. The rice WP contributed 50.7% to the total WP due to larger cultivation area despite lower WP values (figure 2).

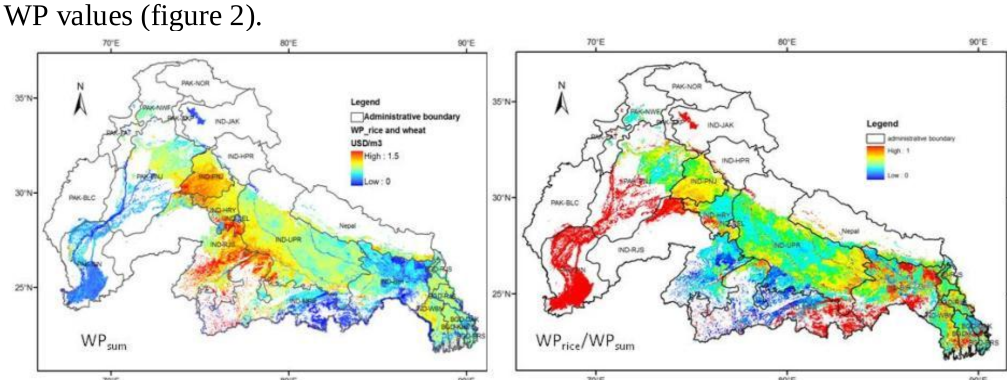

Figure 2. Average WP of rice-wheat rotation system in IGB and the contribution of rice.

Causes for variations

Rice and wheat water use and water productivity are relatively low with tremendous variation in Indo-Gangetic river basin. These variations could be explained by many reasons, for example, land fertility, water supply, crop management and climate conditions. This section tries to explore the major factors affecting water productivity in the basin. Figure 3 illustrates some important factors affecting water productivity. The rainfall measured from Tropical Rainfall Measurement Mission (TRMM) and the ratio of ET_a to ET_p, together with yield maps of rice and wheat are compared.

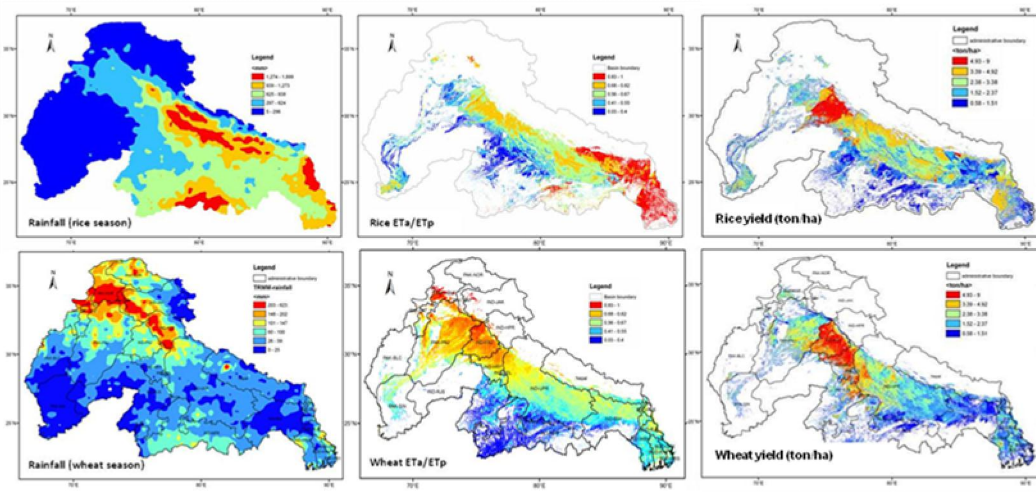

Figure 3. Comparison on factors affecting seasonal ET and yield of rice.

It is observed that the rainfall is much lower in Indus Basin in rice growing season but higher in Ganges Basin in wheat season. Both rice and wheat ET_a to ET_p ratio is higher in high rainfall areas. High rainfall means more water for evapotranspiration. However, it does not necessarily lead to higher yield and water productivity, as shown from the yield maps in figure 3 and WP maps in figure 1. This could be attributed to poor local crop and water management practices; especially the low fertilizer use, traditional varieties and crop disease and pests. Rainfall may occur at anytime. Hence higher rainfall area has more water to evaporate but could still suffer from water stress during crop critical growth period (especially the terminal grain filling stage) which drastically affects the final grain yield accumulation. This is especially true for rice because rice yield and rice water stress (as indicated by ET_a/ET_p) showed contradictory trends. Wheat yield and WP follows more closely the trend of ET. Wheat relies heavily on irrigation due to the low rainfall. Hence high yield and WP is always accompanied with intensive input including water.

Further analysis revealed weather conditions as reflected by reference ET have no direct link with actual ET. The inconsistence between yield and WP distribution against rainfall and weather conditions shows that the main constraint is not water availability or climate, but the timing of water supply and others on farm management. Well developed irrigation and drainage system together with matching management practices can help to maximize utilization of rainfall and achieve high yield and water productivity. Other land and crop interventions, e.g., leveling, insects and diseases control, fertilizer, variety, are also important factors to be considered along with water management.

Scope for improvement

Scope for improvement could be assessed from the ñbright spotsò in comparison to ñhot spotsò. The ñbright spotò in Indian Punjab State and adjacent areas, with 5% of basin rice and wheat cropping area, has high WP of 0.190 US $\$/m^3$. If the basin average value of 0.131 US $\$/m^3$ could be increased to the same as in bright spots. Then the basin could theoretically save 31% of agricultural water consumption with same quantity of production or increase 31% of production with same quantum of water input. Although this is limited by many constraining factors, a little bit increase in WP still has a lot of significance for regional food security.

The potential for rice and wheat is different both in terms of magnitude and areas of focus. Figure 4 shows the plots of water productivity to yield and yield to ET_a of rice. It could be observed water productivity generally increases with increment of yield, with a relatively lower pace because ET_a too increases with yield. The ñbright spotò of Indian Punjab is circled. The yield of this area is so high that it totally changed the slope of yield to ET_a (from S_3 to S_2). Some other areas also have similar ET_a, however, the yield is much lower. The scope for improvement of rice in the region will be to firstly target at the S_2 trend. That is, to improve the yield with similar water consumptions. In this process the water productivity could be expected to increase 15-30%. Final target would be to increase the yield levels of all areas to ñbright spotò values, during the process of which even ñbright spotò might improve, which could lead to another 10-20% improvement.

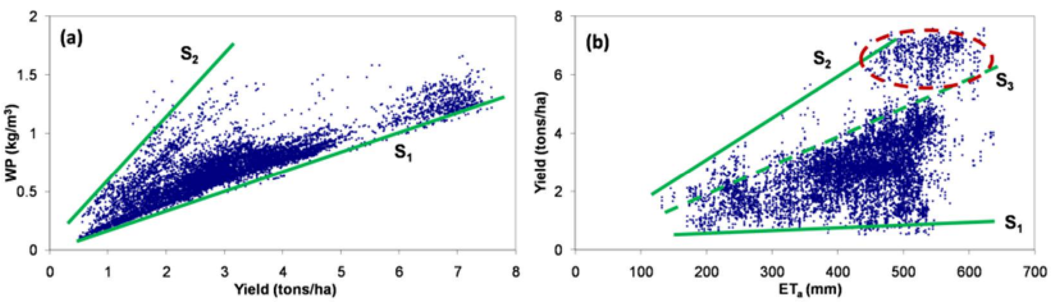

Figure 4. Relations between (a) water productivity and yield and (b) yield and evapotranspiration of rice

The above estimated potential for improvement is under optimal conditions, which assumes no irrigation water supply constraints, soil fertility could be improved to the same as in Indian Punjab. And land and crop management practices could all be improved at the level of Punjab. However, some constraints, for example soil, are not easy to be eased. Improving yield is a long term approach to improve WP and ensure sustainable development of the region. However, in the short term, reducing non-beneficial ET from low yield areas is a practical and convenient way of increasing WP and coping with water scarcity.

CONCLUSIONS

This paper presents the current status and scope for improvement of water productivity of the predominant crops rice and wheat in the IGB. The results, as determined by integrating census, remote sensing and weather data, show that the average water productivity of rice and wheat is relatively low compared to other part of the world. Significant variations were observed across the basin. An extremely outstanding ñbring spotò was found for both rice and wheat in Indian Punjab and the adjacent areas. Further analysis revealed the WP has no direct relation with climate conditions, though it might have low values in areas where rainfall is high and crop performance is poor. Irrigation water management plays critical role in sustaining high crop yield. Other land, soil and crop management practices too are important factors. Assessment on scope for improvement indicates great potential. With reference to ñbright spotò, WP of rice and wheat of the region could be improved 31%, which means a lot more production given same water consumption or much less water use for same production.

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