Water Productivity Assessment for the Yellow River Basin

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ABSTRACT

Agricultural water productivity (WP) has been recognized as an important indicator of agricultural water management. Using data from sixty counties from upstream, middle stream, and downstream sub-basins, this study assesses the WP for irrigated (WPI) and rainfed (WPR) crops in the Yellow River Basin (YRB) in China and extends the analysis to the entire basin. WPI and WPR are calculated for major crops (corn, wheat, rice, and soybean) with experimental, statistical, and empirically estimated data. The spatial variability of WP and the water and energy factors are analyzed with regard to climate, land cover, and agricultural practices. Results show that although irrigated yield is significantly higher than the rainfed yield for corn and soybean in different regions of the YRB, WPI is slightly lower than WPR for the these two crops. This can be explained by the synchronized pattern of precipitation and solar energy in the YRB, which allows effective use of precipitation for crop growth. As expected, irrigation stabilizes the crop production per unit of water consumption. WPI and WPR vary spatially from upstream to downstream, with both climate and water supply conditions linked to irrigation systems. The water factor has stronger effects on both crop yield and WP than the climate factor. Among the sub-basins, the midstream region faces more critical agricultural water management issues from the perspectives of both crop yield and WP.

1. INTRODUCTION

The study of water productivity (WP) originated from the International Water Management Institute (IWMI) in the late 1990s. Molden (1997) extended the concept of water use efficiency to explicitly account for the outcomes (production or benefit) of water use, and he and his colleagues at IWMI defined the extended term as WP. WP measures the production or benefit from one unit of water used for crops, as well as for fish, forests, and livestock in its broadest sense. Following Molden's work, Kijne et al. (2003) presented a collection of papers that discussed the definitions, applications, and case studies of WP. Numerous studies have been published since then. For example, a more recent paper by Playan and Mateos (2006) further discussed the various definitions of WP and its applications. In this paper, we focus on agricultural water productivity, which is defined as crop yield or profit per unit of crop evapotranspiration (ET) (Kijne et al. 2003).

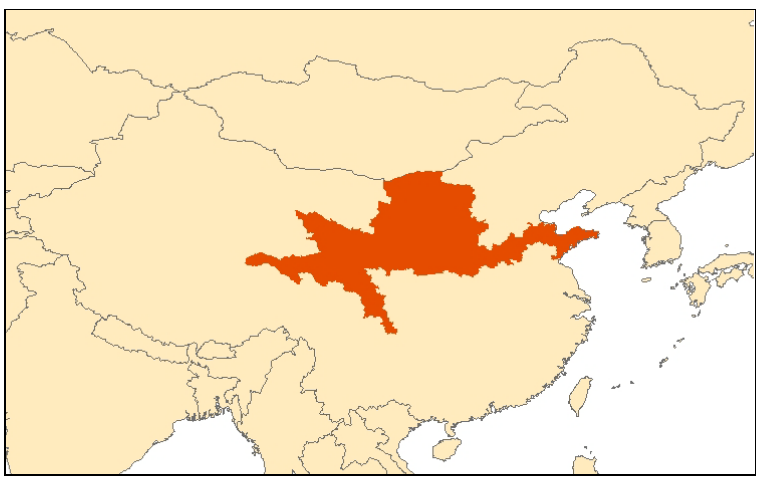
Many studies have tried to make the WP concept more operational. Bouman (2007) proposed a conceptual framework with four mechanisms to assess crop WP at different scales: (1) increasing transpiration, (2) increasing the crop root zone water storage size, (3) increasing the proportion of non-irrigation water inflows into the storage pool, and (4) decreasing the non-transpirational water outflows of the storage pool. Some empirical results were provided at the plant, field, and agricultural landscape levels. Morison et al. (2008) examined previous physiological studies and concluded that improvements in both agronomic and physiological understanding have led to recent increases in water productivity for some crops.

A number of studies used field measurements to calculate the actual value of WP for different crops in different areas. For example, based on 84 other published studies, Zwart and Bastiaanssen (2004) estimated the average value of WP for wheat, rice, cotton with seed, cotton of lint only, and maize are 1.09, 1.09, 0.65, 0.23, and 1.80 kg/m^3, respectively. These values are higher than those published by the Food and Agriculture Organization (FAO). Meanwhile, the range of WP is large, such as for wheat, 0.6–1.7 kg/m^3; rice, 0.6–1.6 kg/m^3; cotton with seed, 0.41–0.95 kg/m^3; cotton of lint, 0.14–0.33 kg/m^3; and maize, 1.1–2.7 kg/m^3. The variance is due to (1) climate, (2) irrigation water management, and (3) soil (fertility) management. In addition, at the crop field level, Guzha et al. (2005) found the use of humanure and ecofert treatment could improve WP by above 10% in rain-fed maize production; Ilbeyi et al. (2006) found early sowing, cooler highland environment, and additional supplemental irrigation in the spring could increase the WP of wheat; and Teixeira et al. (2007) found that the WP of vineyards was extremely high in both physical and economical terms.

Meanwhile, numerous studies used hydrological models, remote sensing data, and geographical information systems to assess WP at larger scales. To name a few, van Dan et al. (2006) and Vazifedoust et al. (2008) applied a field-scale hydrologic-agronomic model coupled with GIS and satellite data to analyze field and regional WP. The analysis showed that improved crop husbandry, reallocation of canal water from fresh to saline groundwater areas, and reduction of seepage losses in saline groundwater areas are effective measures to increase overall WP. Zwart and Bastiaanssen (2007) used the Surface Energy Balance over Land (SEBAL) algorithm and satellite images to quantify spatial variation of crop yield, evapotranspiration, and WP. The results showed a large spatial variability of WP in the study area. Wesseling and Feddes (2006) also used remote sensing data to estimate actual ET and WP, from which they discussed how to upscale the concept of water productivity from field to regional scale.

In this paper, we apply the WP concept to the Yellow River Basin (YRB), the second largest basin in China (Figure 1). The YRB is of utmost importance for China in terms of food production, natural resources, and socioeconomic development. The basin contains 13% of the total cultivated area in China, but it holds only 3% of the country's water resources (CMWR, 2002). Since 1949, over 3,100 reservoirs have been built in the basin with a total storage that reached 70 km^3 in 1999, after the Xiaolangdi Reservoir was completed in the middle stream portion of the Yellow River. This combined storage exceeds long-term average annual runoff in the river (58 km^3 based on hydrologic records from 1919 to 1975). Meanwhile, the expansion of irrigated area has been especially rapid, from 0.8 million hectares in 1950 to 7.5 million hectares in 2000 (Li, 2002). This irrigation growth, combined with rapid growth in industrial and municipal water demands, has dramatically increased water withdrawals throughout the basin. Increased water withdrawals have in turn interrupted flow in the lower Yellow River and lead to declining groundwater levels, disappearing lakes, and siltation (Giordano et al., 2004).

Figure 1. The location of the Yellow River Basin



Both Chinese and international researchers have conducted many studies for the assessment of the WP in the YRB. Zhu et al. (2003) used historical data (1974-1998) on irrigation water and crop production to estimate the WP in Kaifeng City, located in the middle stream of the YRB. The study found that crop pattern (e.g., rice types) and irrigation schedule are major factors of WP in the area and proposed measures such as joint water use from wells and channels, increasing water price, and optimized control of water allocation to improve WP. Bouman et al. (2007) applied a simulation model to estimate crop yield and WP, as well as water balance components of alternative wetting and drying and aerobic rice in Liuyuankou Irrigation System, a typical conjunctive surface-groundwater irrigation system in the lower YRB. This study found that with a shallow water table, large amounts of water input were saved without yield loss by applying alternate wetting and drying or adopting completely rainfed conditions; while most of the irrigation water savings were caused by decreased percolation, the amount of irrigation water saved depended on the amount of rainfall. Khan et al. (2008) used remote sensing and GIS data coupled with groundwater modeling to evaluate water saving options in Liuyuankou Irrigation System in the Yellow River basin. Groundwater table rising leads to significant evaporation loss in the area, and reducing the non-beneficial evaporation from fallow land is important for increasing the WP. Groundwater simulation results showed that fallow evaporation could be reduced between 14.2% (25.5 million m^3) and 45.3% (81.4 million m^3) by interventions such as canal lining and groundwater pumping. The reduction in non-beneficial evaporation loss implies more available water for other uses and the achievement of higher WP.

In this paper, we use experimental data, statistical data, and empirically estimated data to analyze major crops (corn, wheat, rice, and soybean) in 461 counties in the YRB. WP values for rainfed crops and irrigated crops are estimated separately and maps of WP by crop are generated for the whole basin. We analyze the spatial variability of WP with regard to the spatial variability of climate, land cover, and agricultural practices. We then provide a case study of WP assessment in the context of a large basin and present implications for water and land management in the YRB.

2. METHODOLOGY AND DATA REQUIREMENT

Hundreds of counties (461) in the YRB are used as the basic spatial units for the analysis. The first step for WP assessment is to collect data on the main agricultural production systems, including the water data such as precipitation, irrigation application, and crop ET; and crop data such as yield and area by crop. Challenges arise with incomplete or unknown data, particularly for split irrigated and rainfed crops. To assess WP for irrigated and rainfed crops separately, we adopt a method presented by Cai et al. (2007) to retrieve split irrigated and rainfed area and yield using gross crop production data and hydrologic and agronomic inputs. We also map WP by crop for the entire basin by interpolating from the WP assessment for the 461 counties. These maps provide information for WP spatial pattern analysis. In particular, we conduct Budyko curve analysis to assess the relationship between WP and water and energy across different spatial scales.

Retrieval of irrigated and rainfed crop data

Cai et al. (2007) proposed a method to split harvested area and yield for irrigated and rainfed crops in a region given gross area and yield; and climatic, agronomic, and economic data for crops. *Irrigated area is defined as the physical land crop area that uses water additional* to *effective rainfall through an irrigation system or local water sources*; *rainfed area is defined as a cropped area that only utilizes effective rainfall, which is the portion of rainfall that is available to meet consumptive crop water requirements, excluding surface runoff and deep percolation*. In contrast, irrigated areas use surface runoff by diversion (withdrawal) and/or groundwater by pumping in addition to effective rainfall. The method based on the principle of general maximum entropy (GME), which combines incomplete data, empirical knowledge, and a priori information, was applied by Cai et al. (2007) to derive desired information. Data requirements for the GME model include:

- Crop data, including total crop area, gross crop yield, crop growth period and stages by month, crop ET coefficient (kc) (Doorenbos and Pruitt, 1977), crop response coefficient to water stress (k_y) (Doorenbos and Kassam, 1979), and crop value indicator (e.g., producer's crop prices, crop trade prices; FAOSTAT www.faostat.org)
- Climate data, including monthly rainfall in the study area and reference crop evapotranspiration (*ET0*) (Allen et al., 1998)
- Land and water data, including total irrigated land (*TIA*), multi-planting factor (*MP*), and monthly total irrigation water withdrawal in the study area (*TIW*).

Based on these data items, the following items are computed and used for the retrieval of the irrigated and rainfed crop area and yield:

- Monthly crop potential evapotranspiration (*ETC*) (Doorenbos and Pruitt, 1977, Allen et al., 1998)
- Monthly effective rainfall (*PE*) (USDA-SCS, 1967)
- Irrigation water withdrawal by month

It has been demonstrated that this method provides reasonable estimates of irrigated and rainfed crop area and yield under different spatial scales (as large as the entire YRB and as small as one county in Texas, USA). This model is used in this paper at the county level to retrieve the crop data and to calculate the WP in the YRB.

Budyko curve analysis

Budyko curve, proposed by Budyko (1948 and 1974), describes the partitioning of average precipitation (P) into average potential evapotranspiration (Ep) and average actual evapotranspiration (Ea) based on simple physical relationships (Figure 2). This concept has proven useful for understanding catchment energy and water balances (Donohue et al., 2007). The x-axis in the Budyko curve figure is the ratio between potential evapotranspiration and precipitation (E_p/P), which is a climatic index. Larger E_p/P usually occurrs in a relatively dry area, where the potential evapotranspiration is larger than total rainfall. On the other hand, smaller E_p/P represents a humid area. When E_p/P is equal to 1, it represents the division between water limited area ($E_p/P>1$) and energy limited area ($E_p/P<1$).

The y-axis is the ratio between actual evapotranspiration and precipitation (E/P). Under normal circumstances, E/P should be less than one due to the water balance constraint. However, if 1) a transboundary water transfer occurs or 2) deep groundwater is pumped, E/P can be higher than one. Therefore, "E/P=1" can be used as an indicator of water use limit.

Human water use such as irrigation has changed catchments' hydrologic processes. Assuming that there is no transboundary water transfer, the annual water balance in a basin is represented as:

$$\Delta S = P - E - Q \qquad (1)$$

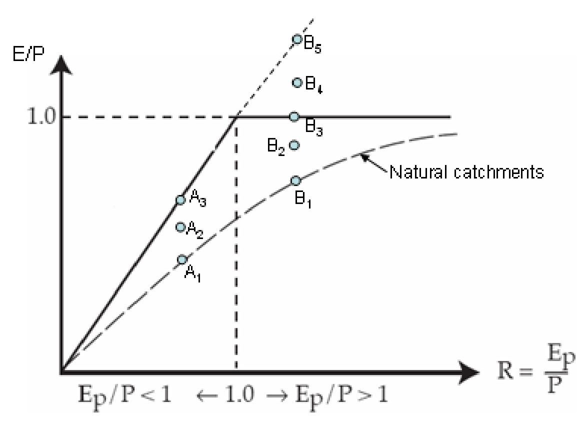
$$E_c = W - R \qquad (2)$$

$$E = E_n + E_c \qquad (3)$$

Where

S	=	storage
P	=	precipitation
Q	=	runoff
W	=	human water withdrawal
R	=	return flow
E_n	=	evaporation without human interferences
E_c	=	consumptive human water use, such as evaporated irrigation water use

Figure 2: Budyko curve.



For a humid area, three points (A_1, A_2, and A_3) are used to demonstrate the analysis.

- A_1: a natural status
- A_2: actual ET (E) increases, but $E<P$ and $\Delta S+Q=P-E>0$. If $\Delta S=0$, then $Q>0$, stream flow is not totally depleted but decreased, and the same for groundwater. S may increase locally. The hydrologic system will approach a new equilibrium.
- A_3: $E=E_p<P$ then $\Delta S+Q=P-E_p>0$. The groundwater level or/and streamflow achieves the minimum bound and the system will approach a new equilibrium.

In general, agriculture development in a humid area is sustainable with regards to water, but energy can be a limiting factor.

For an arid area, five points (B_1- B_5) are used to demonstrate the analysis.

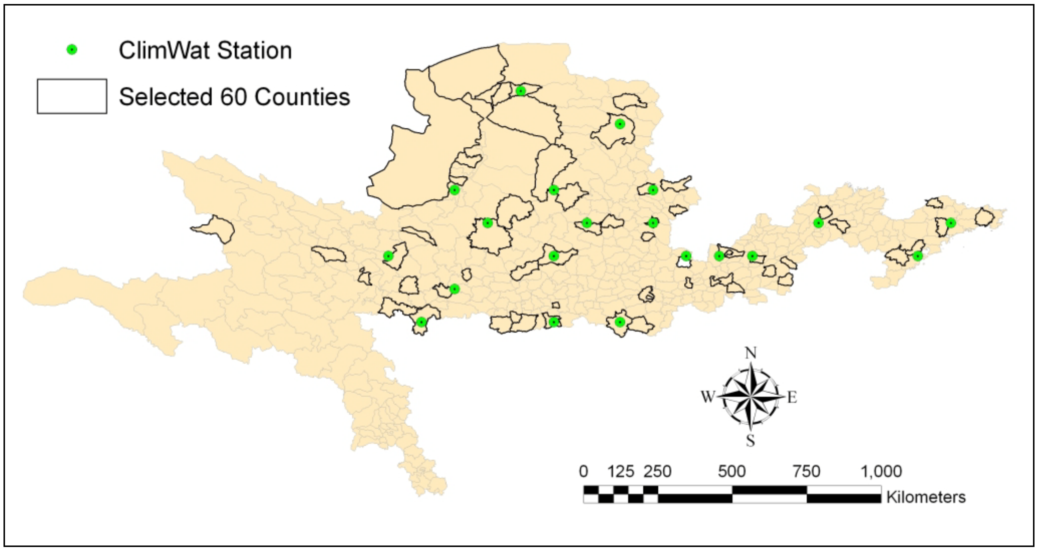
- B1: a natural status
- B_2: $E<P$, $\Delta S+Q=P-E>0$, groundwater level or streamflow decreases and the system will approach a new equilibrium.
- B_3: $E=P$ and $\Delta S+Q=0$, if $Q>0$, then S decreases which causes a gradual decrease of Q until $Q=0$; if $Q=0$, then $\Delta S=0$ and the streamflow can be totally depleted
- B_4: $P<E<E_p$ and $\Delta S+Q<0$, if $Q>0$, then S decreases which causes Q to decrease gradually until $Q=0$; if $Q=0$, then $\Delta S<0$, S decreases gradually and the streamflow will be totally depleted, while the groundwater will decrease gradually
- At B_5, groundwater decreases at the maximum rate

Generally, agriculture development is sustainable in the B_2 region, but unsustainable with regards to water in regions B_3~B_5.

Data sources

The major data sources for the GME model that splits irrigated and rainfed crop data are as follows: The gross crop area and yield were were provided by Dr. Liangzhi You from the International Food Policy Research Institute (IFPRI). The data items include crop area and production data for four crops: rice, corn, soybean, and wheat at the county level, 1980-2003; as well as total irrigated area (TIA), total labor, and fertilizer usage in the year 2003. The climate data were acquired from the FAO CROPWAT database: CLIMWAT (FAO, 2009). CROPWAT is a computer program that calculates the reference crop evapotranspiration (ET0) and effective rainfall (PE) at a CLIMWAT station. There are 20 CLIMWAT stations located in the YRB (Figure 3) and the ET0 and PE for these stations are computed by CROPWAT and used by the GME model.

Figure 3. The CLIMWAT stations in the YRB



Budyko curve analysis requires rainfall and actual and potential evapotranspiration (ET). Rainfall data used in this paper were obtained from the CRU dataset (http://www.cru.uea.ac.uk/). The CRU TS 2.1 dataset comprises 1,224 monthly grids of observed climate from 1901-2002 and covers global land surface at 0.5 degree resolution. This study uses the annual average rainfall from 1961-1990. We interpolate the rainfall data so that the spatial resolution matches the ET dataset; the county average is then computed based on the grid data. Actual and potential ET were obtained from University of Montana and University of Washington. Cleugh et al. (2007), Mu et al. (2007a), and Mu et al. (2007b) at University of Montana estimated ET from the earth land surface using MODIS (Moderate Resolution Imaging Spectroradiometer), a popular remote sensing dataset. Based on the Penman-Monteith (P-M) equation, the assessment of ET incorporates surface stomatal resistance and vegetation information derived from MODIS land products to estimate daily actual and potential ET. The outputs were aggregated to values with 8-day time intervals at a 0.05 degree spatial resolution. University of Montana provided the ET data for the period 2000-2006. However, the estimated actual ET is found to be lower than that observed in the YRB region. We obtained the estimated actual ET for one year (2001) from University of Washington, which is also based on MODIS but calibrated to the observation (Tang et al., 2009). We compared the two data sources to finalize the actual ET values used in this study.

3. RETRIEVED IRRIGATED AND RAINFED CROP AREA AND YIELD

In total, we selected sixty counties (Figure 3) from 461 counties to evaluate the irrigated/rainfed area aggregation. Selection was based on the locations of the CLIMWAT stations. We established the GME model for each of the sixty counties using the crop and climate data described in the previous section. The irrigated and rainfed crop area and yield of four crops are displayed in the Appendix in Table A1 and Table A2, respectively. The percentages of irrigated area to the gross area in the sixty counties are 100%, 89%, 100%, and 83% for rice, corn, wheat, and soybean, respectively, and 94% for all of these crops. The average irrigated crop yield for rice, corn, wheat, and soybean are 5.4, 5.3, 3.7, and 1.4 ton/ha, respectively, compared to the average rainfed crop yield of 3.0 and 1.4 ton/ha for corn and soybean, respectively. Table 1 shows the average values of irrigated and rainfed area (AI and AR) and yield (YI and YR) by sub-basin.

It should be noted that some local assessments show the existence of rainfed wheat in the downstream of the basin, while this study indicates zero rainfed wheat. This may be due to the definition of rainfed crop area. There exist some crop areas which are not served by any irrigation system and are classified as rainfed area. However such areas can still be irrigated by local water sources (e.g., rainfall harvest facilitates such as ponds or tanks). In this study, such areas are identified as irrigated. On the other hand, probably the FAO CROPWAT data set (e.g., ET and effective rainfall) may not cover the rainfed areas. By the CROPWAT stations in the downstream of the basin, effective rainfall is less than one-third of the crop ET, which makes irrigation necessary.

Table 1: Irrigated and rainfed area and yield, actual ET, effective rainfall by sub-basin of the YRB

	Crops	Basin-wide	Middle stream	Downstream
AI (1,000 ha)	**Rice**	25.3	13.0	12.3
	Corn	540.2	254.3	284.9
	Wheat	1141.0	536.4	597.7
	Soybean	149.6	80.6	69.0
AR (1,000 ha)	**Rice**	0.0	0.0	0.0
	Corn	68.8	30.3	37.9
	Wheat	0.0	0.0	0.0
	Soybean	30.1	14.3	15.8
YI (ton/ha)	**Rice**	5.4	5.5	5.3
	Corn	5.3	5.0	5.7
	Wheat	3.7	2.8	4.4
	Soybean	1.4	1.2	1.7
YR (ton/ha)	**Rice**	0.0	0.0	0.0
	Corn	3.0	1.9	4.0
	Wheat	0.0	0.0	0.0
	Soybean	1.4	1.0	1.9

We created the AI ratio map (Figure 4) for the entire YRB by interpolating the 60 counties' results to the whole basin. It shows that the most intensive irrigated area is located in the northwestern part of the middle-stream basin, where several major irrigation districts are located. The irrigation water requirement is computed as ET0 discounted by PE. The annual irrigation water requirement summed over the months in the crop growth season is shown in Figure 5, which is also created by interpolating the 60 counties' results. The spatial pattern of irrigation water requirement mostly matches with that of the irrigated area. The highest irrigation water requirement in the northwestern part of the middle-stream basin is close to 1 meter.

Figure 4. The distribution of the ratio of irrigated area to gross area in the YRB

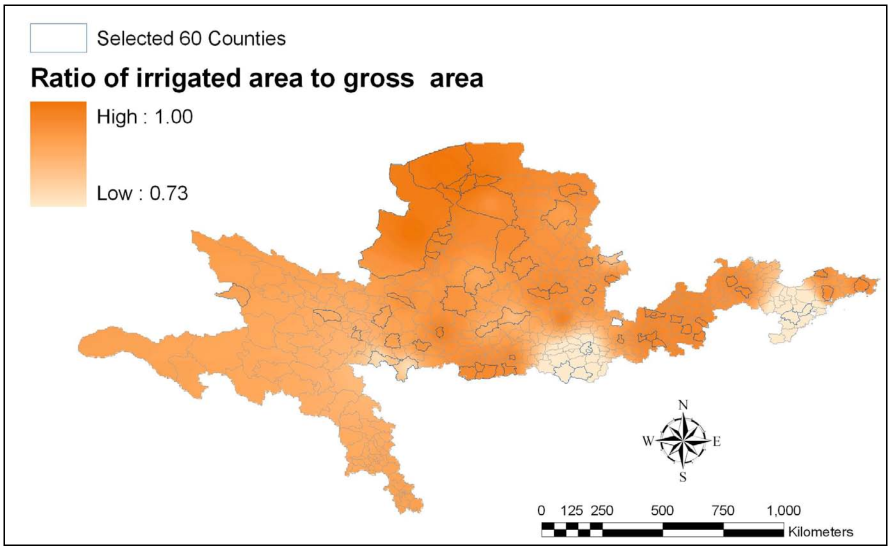
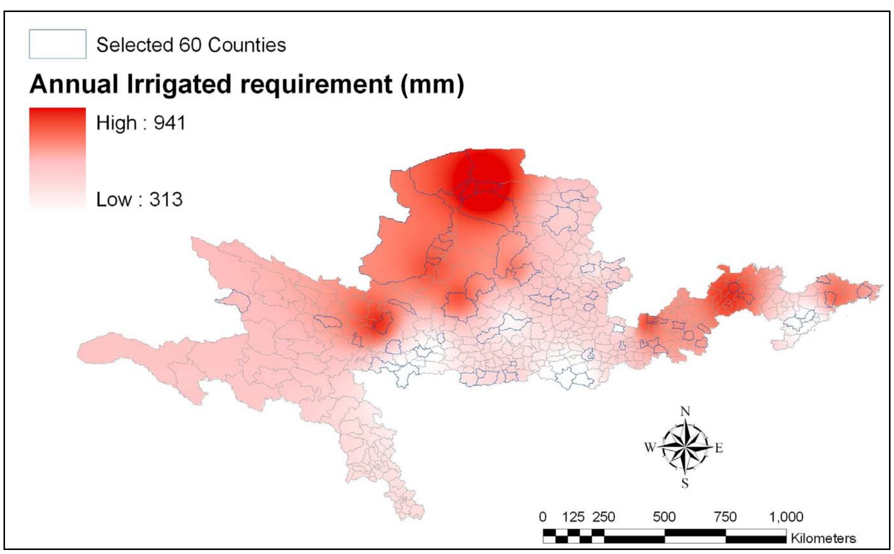


Figure 5. Irrigation requirement (mm) in the YRB



4. WATER PRODUCTIVITY ANALYSIS

The WP values are calculated for irrigated (WPI) and rainfed (WPR) crops for the selected 60 counties as given in the Appended Table A3. Note that the actual ET for irrigated crops include both effective rainfall and irrigation water consumption, and for rainfed crops include effective rainfall only. The mean and standard deviation of WPI and WPR for different crops are given in Table 2.

Table 2. Area-Weighted WPI and WPR for different regions in YRB

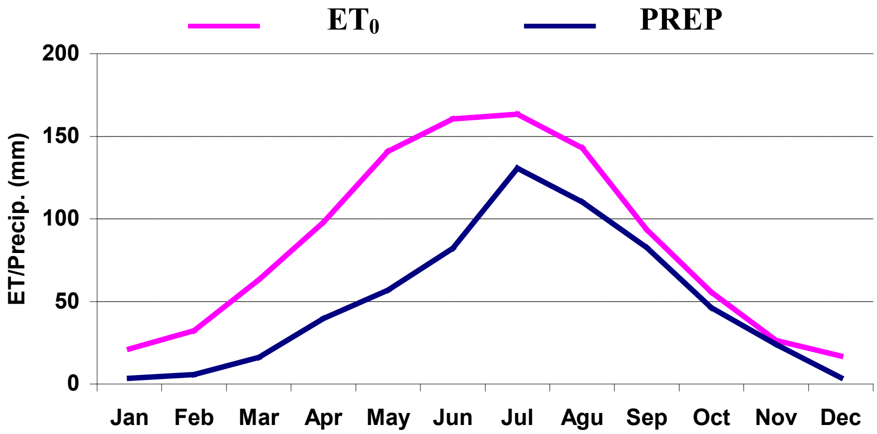
Region/Crops	WPI (kg/m^3)				WPR (kg/m^3)			
	Rice	Corn	Wheat	Soybean	Rice	Corn	Wheat	Soybean
Basinwide average	0.50	0.97	1.39	0.26	-	1.09	-	0.41
standard deviation	0.25	0.32	0.51	0.13	-	0.36	-	0.16
Middle stream	0.49	0.94	1.16	0.26	-	0.68	-	0.28
standard deviation	0.22	0.33	0.49	0.13	-	0.35	-	0.15
Downstream	0.51	0.99	1.57	0.27	-	1.41	-	0.52
standard deviation	0.26	0.30	0.34	0.12	-	0.33	-	0.12

The modeled results from this study mostly fit the ranges from previous studies. The average value for WP of rice from Zwart and Bastiaanssen (2004) is 0.6–1.6 kg/m^3, and the average WP for corn from Zwart and Bastiaanssen (2004) is 1.1–2.7 kg/m^3. WPI for wheat is similar to that assessed by Zwart and Bastiaanssen (2004).

It is interesting that WPR for corn and soybean are slightly higher than WPI, although the variation of the WPR (over the sixty counties) is also higher than the variation of WPI. This implies that from upstream to downstream regions of the YRB, the irrigated corn and soybean may not be as efficient as rainfed crops with regard to water productivity, but irrigation stabilizes the crop production per unit of water consumption, which is expected.

This result is related to the synchronized pattern of precipitation and solar energy in the YRB and most of the area in China (Figure 6). Reference evapotranspiration (ET0), which indicates the solar heat flux in plant growth, moves in concert with precipitation. The coincidence of water and radiation provides conditions highly favorable to crop growth. This favorable pattern also explains the fact that a large portion of irrigated crops in the YRB belongs to the category of supplementary irrigation, which only uses irrigation water as a supplement to effective rainfall for crops during dry periods.

Figure 6. Monthly reference crop evapotranspiration (ET_0) and precipitation (PREP) in the YRB (multiple-year average)



It is more informative to compare the WPI and WPR for four crops at the sub-basin scale. The YRB is divided into upstream, middle stream, and downstream as shown in Figure 7, and the WPI and WPR by crop (rice, corn, wheat, and soybean) are shown in Figure 8. As can be seen, for both corn and wheat, the spatial variability of WP in the downstream region is smaller than the middle and upstream, which is consistent with the spatial variability of climate in those regions. The WPRs for soybean are generally larger than the WPIs for soybean. Downstream WPR and WPI for soybean are more stable spatially, and the mean value is higher than that in the upstream and middle stream regions.

Figure 7. The sub-basin division for the YRB

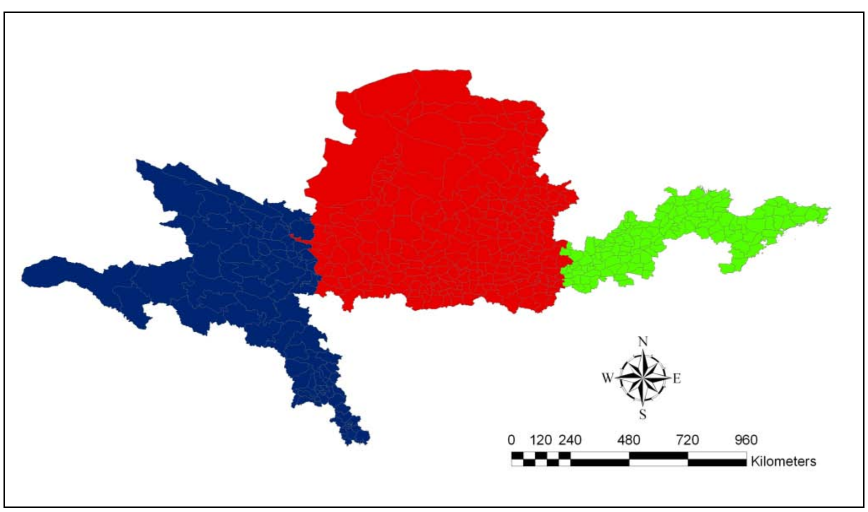
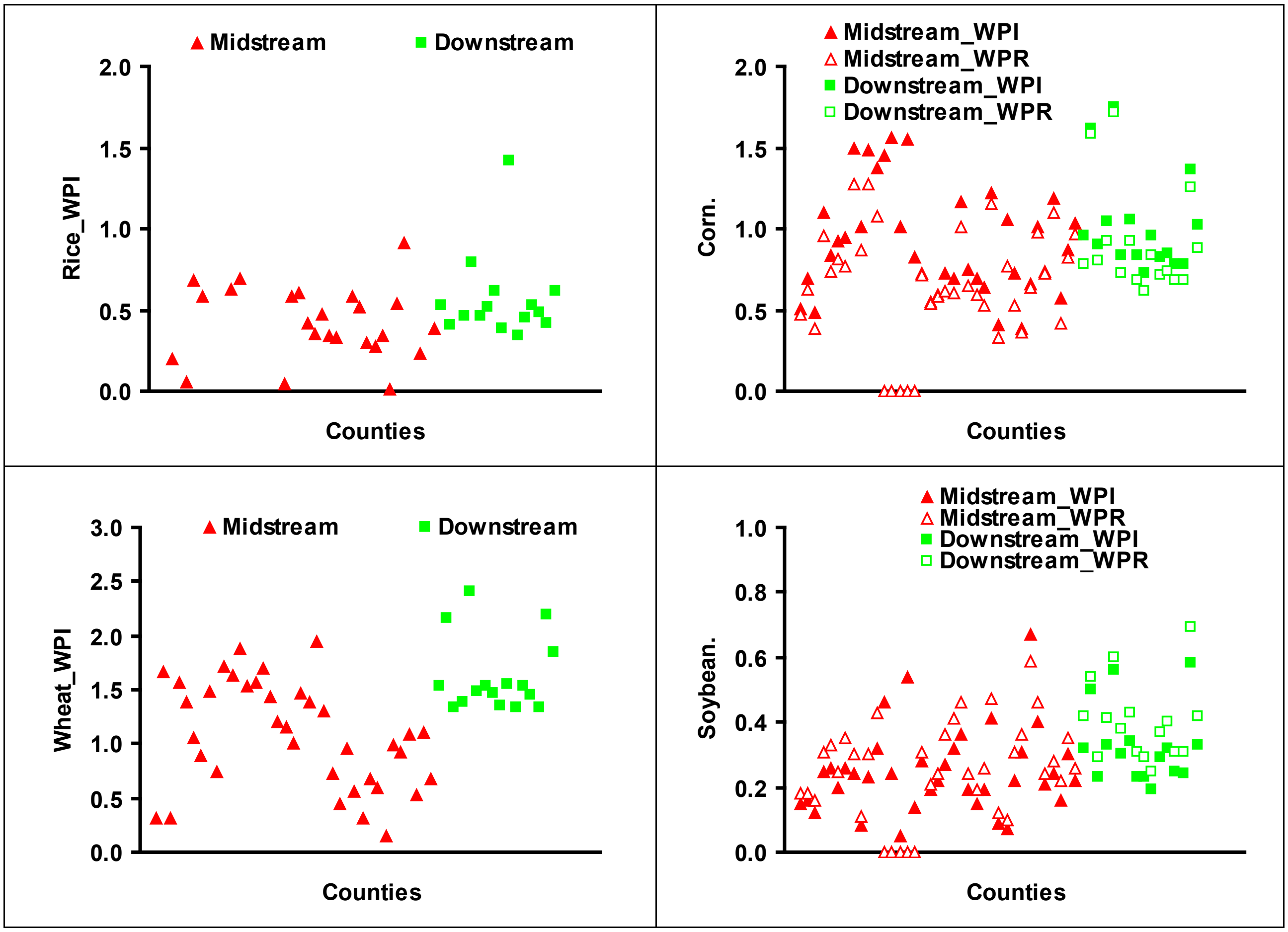


Figure 8. The WPI and WPR comparison for four different crops



Using crop area as the weighting factor, the irrigated and rainfed water productivity for all crops can be calculated for the 60 selected counties (Figure 9 and Figure 10) and interpolated to the entire YRB. One can see that the spatial patterns of WPI and WPR contrast each other in the middle stream and are similar in the downstream. The values of WPI range from 0.31 to 2.17 kg/m^3. The high WPI values have a similar spatial pattern to the AI ratio and irrigated water requirement map (Figure 4 and Figure 5). The values of WPR have a wider range, from 0.0 to 1.4 kg/m^3. The counties with higher WPR are located at the southeastern part of the basin, where the rainfall is relative sufficient. The maps shown in these figures were created by interpolation of the 60-county results.

Figure 9. Basin-wide average WPI for the YRB

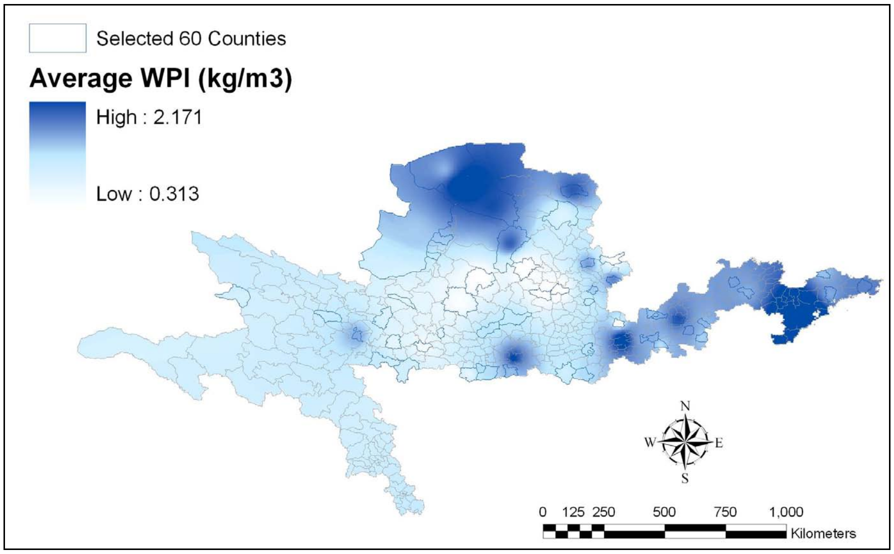
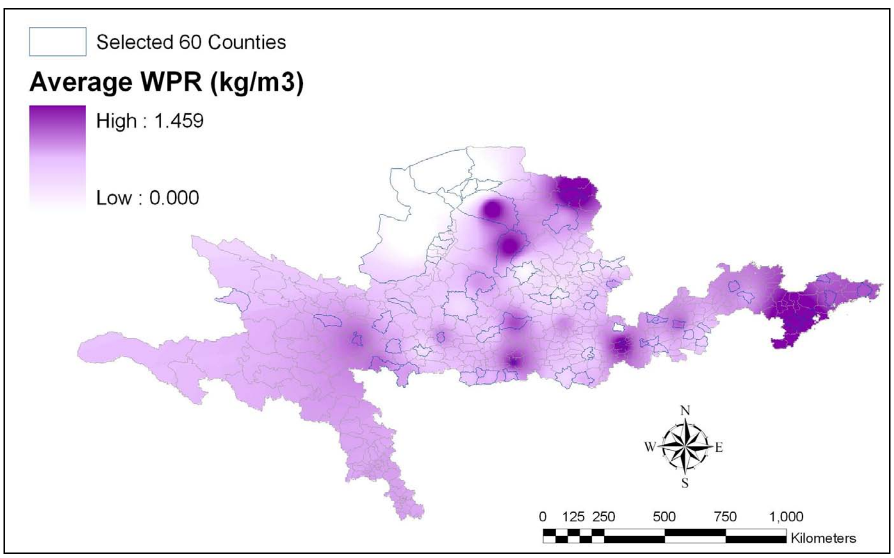


Figure 10. Basin-wide average WPR for the YRB



5. ANALYSIS OF WATER AND ENERGY FACTORS BASED ON BUDYKO CURVE

The Budyko curve analysis is conducted with three elements: 1) the spatial scaling effect, 2) the impact of land cover, and 3) combined WP and Budyko curve analysis using a 3-D Budyko curve.

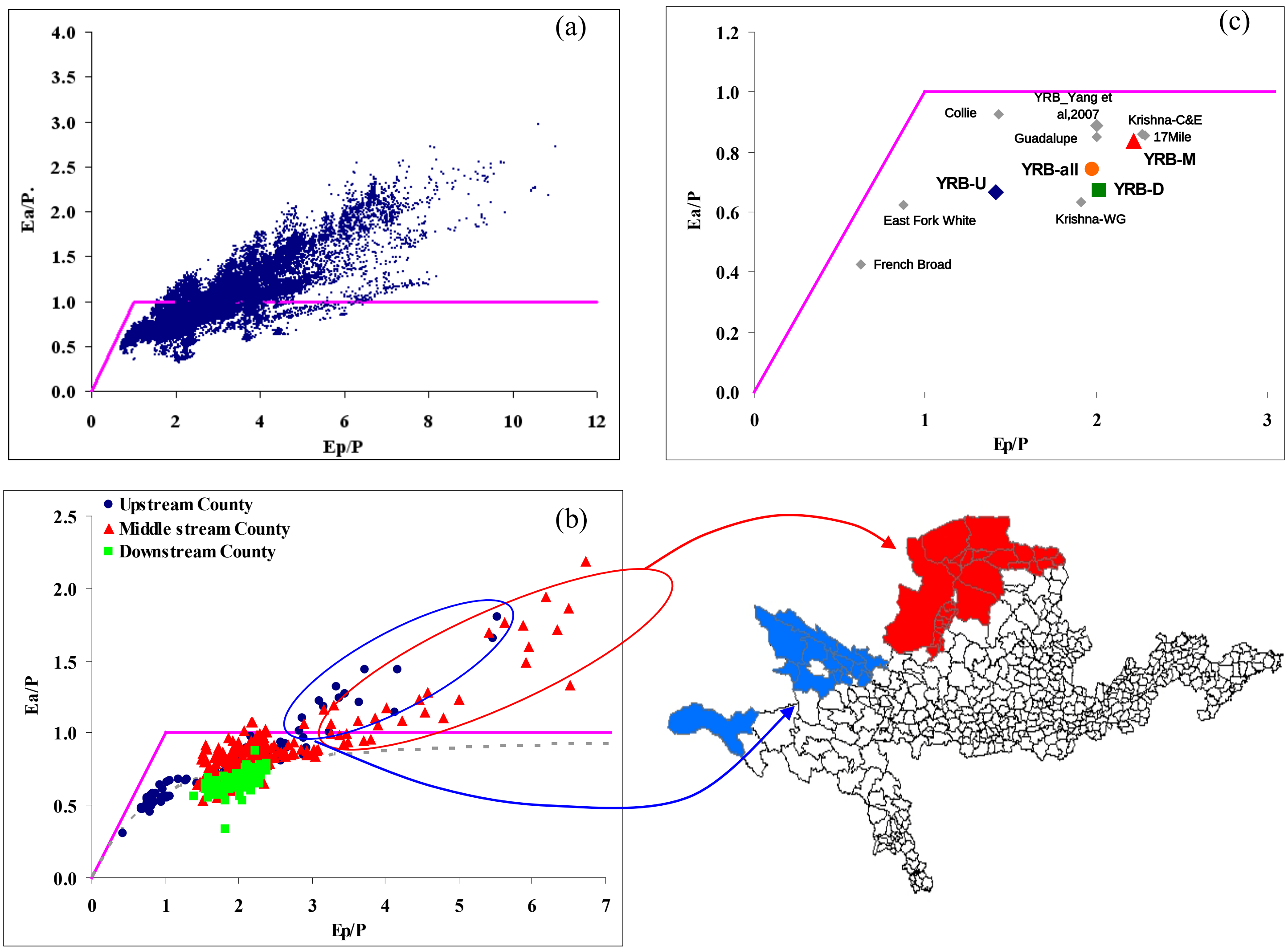
Spatial scaling effect

We used the long-term average actual ET from University of Montana (modified by the 2001 values from University of Washington), long-term average potential ET from University of Montana, and long-term precipitation from CRU to calculate the spatial scaling effect of the Budyko curve analysis, which is presented in Figure 11. Figure 11a shows the result obtained using original 0.05 degree cell resolution. There are more than 40,000 cells located in the YRB, and the E_a/P and E_p/P ratio are calculated using the above data. It is clear that about 30% of the cells are located above the "$E_a/P=1$" line. In these cells, the actual ET is higher than the precipitation, which implies an unsustainable water usage in these areas. If we aggregate the cell results to the county level, we can have 461 counties located in YRB, and every county has approximately 100 cells. Figure 10b shows that only 10% of the counties are located above the "Ea=1" line. In other words, at county level the fraction of the area with unsustainable water usage is reduced compared to the assessment at the pixel level. This implies that within the counties, some water regulation facilities exist, which make water more evenly distributed in the spatial domain. Some middle stream and upstream counties are still located above the "$E_a/P=1$" line. These counties are physically located in the northwestern region of the basin, an area that is the most water stressed in the YRB (Figure 11b). Most of the upstream and downstream counties are located under the "$E_a/P=1$" line.

Figure 11c presents the results at both the sub-basin and whole basin levels. The sub-basin division follows Figure 7. The results from previous studies for other basins in the world are compared in Figure 11c. These basins include: 1) Asia: Yellow River by Yang et al. (2007), Krishna River by Biggs et al. (2007); 2) North America: Guadalupe River in the United States for dry climate, East Fork White River for medium climate, and French Broad River for wet climate by Wagener et al. (2007); and 3) Australia: Collie River by Tromp et al. (2005), and Seventeen Mile River by Montanari et al. (2006). Regarding average E_a/P and E_p/P for YBR sub-basins and the whole basin, all regions are located under the "$E_a/P =1$" line. Middle stream is the driest in the basin and is located in the uppermost right corner, while the upstream region of the YRB is wetter than the middle stream region and is located close to the "$E_p/P =1$" line. For world wide comparison, Krishna River – central east region and Seventeen Mile River are drier than the YRB. It should be noted that the difference between Yang et al. (2007) and this paper may be due to the fact that Yang et al. (2007) did not use the observed actual evapotranspiration data. They calculated the actual ET by a general water balance equation (i.e., ET equals precipitation minus runoff).

It should also be noticed that when the spatial scale is increased from pixel to county to basin scale, the absolute values of E_a/P and E_p/P ratios decrease. The maximum E_a/P can be as high as 3.0 at the pixel scale, and the values are 2.3 and 0.8 at county and basin scales, respectively. The same occurs for E_p/P ratio. The maximum E_p/P value is 1.0, 6.5, and 2.3 at pixel, county, and basin scales, respectively.

Figure 11. The spatial scaling effect of Budyko curve analysis in the YRB

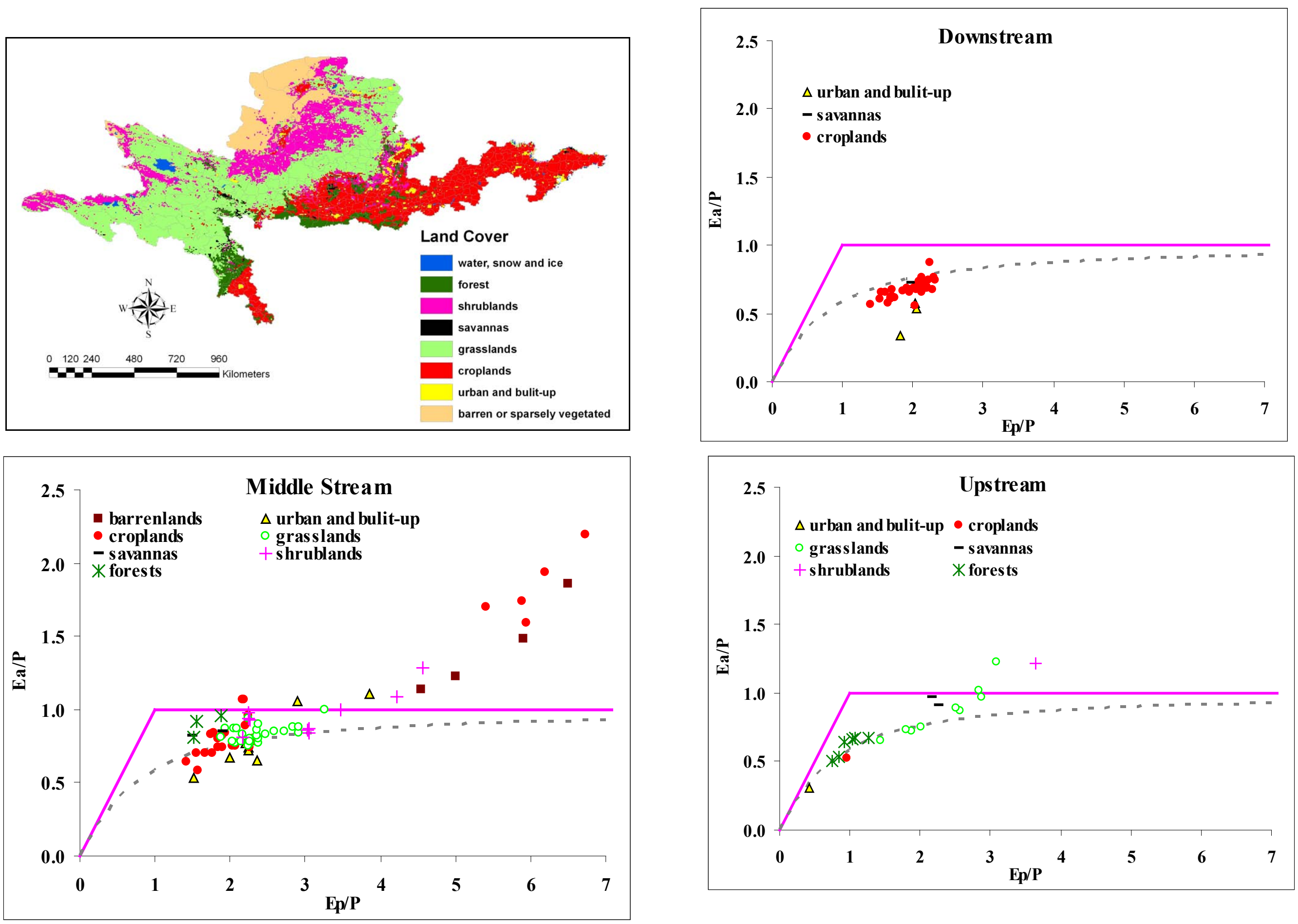


Land cover analysis

One extension for the Budyko curve analysis is to superimpose land cover types with the Budyko curve result. The land cover data was downloaded and processed from MODIS 12: MODIS/TERRA Land Cover Type Yearly L3 Global 0.05 Deg CMG V004. The results are aggregated to the county level using the 0.05 degree resolution grids. The most dominating land cover type is selected as representative of each county. In total, 150 counties are selected for the analysis, and the results are displayed in Figure 12. Approximately 95% of the downstream counties are classified as croplands by MODIS data. Most of the land in the middle stream region has mixed land cover types, with about one quarter each croplands, grasslands, shrublands, and barrenland. A few forest lands are located in the southern part of the middle stream. Upstream land has 90% grasslands, 5% forest, and 5% croplands, shrublands, and others.

Downstream counties have three major land cover types (Figure 12). Croplands have higher E_a than urban areas since water is used for irrigation in croplands. The northwestern part of the the middle stream, where the major irrigation districts are located (croplands), has a high E_a/P ratio. Meanwhile, some barren-lands (desserts) in this area also have a high E_a/P ratio. The vegetation on such lands might cause ET to be higher than precipitation. In the southern region, forest areas have higher E_a/P ratios than croplands, and croplands have higher values than urban areas. Such results are anticipated because forest areas, which have multiple canopy layers, have higher actual ET than croplands. Grasslands have similar E_a/P ratios as croplands. This means that the actual ET of these two land cover types might be the same in the YRB. In the upstream, some counties classified as grasslands and located in the northwestern part have higher E_a/P ratios as well. In the southern part, the pattern is the same as that of the middle stream, i.e., forest areas have higher E_a/P ratio than croplands and urban areas.

Figure 12. The land cover analysis on Budyko curve results at county level



Budyko curve/Crop yield and WP analysis

To evaluate the effect of water (Ea/P) and energy (Ep/P) on the crop yield, one additional dimension is added to the Budyko curve analysis (Figures 13-16).

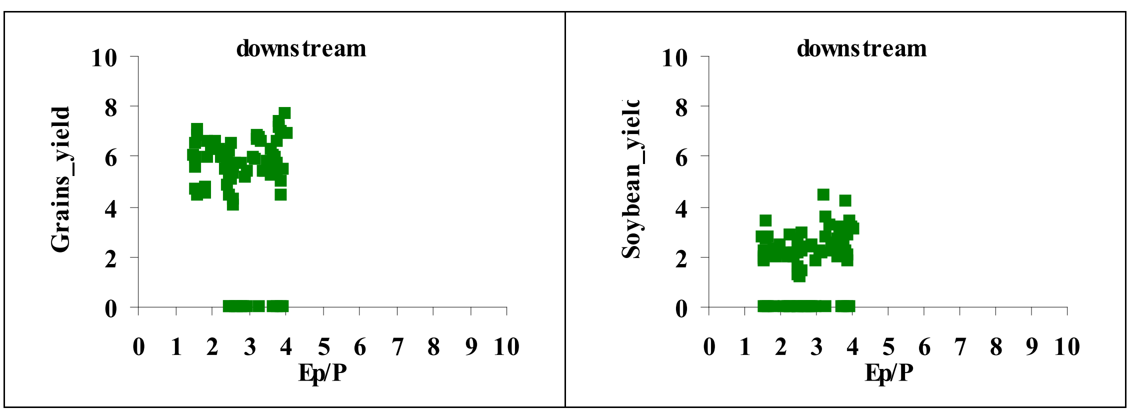
Due to data limitations, analysis for only one year (2001) is undertaken. The 2001 annual E_a is acquired from University of Washington, annual E_p from University of Montana, and annual P from CRU. The crop yield is the actual 2001 crop yield obtained from IFPRI (rice, corn, and wheat are lumped as grains). The results of grain yield versus Ea/P and Ep/P for downstream, middle stream, and upstream are given in Figure 13, 14, and 15, respectively. The figures in 3-D (yield, Ea/P, and Ep/P) for the sub-basins are given in Figure 16.

E_p is an indicator of solar energy, and E_a is an indicator of both energy and water availability. The range of E_p/P shows the heterogeneity of climates. The middle stream region of the YRB has the most diverse climates in the basin, and the downstream region has the least. The range of E_a/P shows the heterogeneity of water availability. The midstream region of the YRB also has the most diverse water use relative to precipitation in the basin.

In all regions, particularly the downstream and midstream, high crop yield moves together with high ratio of E_p/P. This is consistent with previous knowledge that a region with a higher level of solar energy has a higher crop yield, if water is not limited. For the midstream, the E_a/P is greater than 1.0 and is as high as 3.0, which shows irrigation application is as large as twice that of local precipitation in some counties.

The impact of water availability (E_a) on crop yields in the midstream region is the strongest among the three regions (this can be seen by the slope of the regression function; the middle stream region has the largest slope). In the downstream and upstream regions, it appears that the yield of both grains and soybean are more affected by other inputs. This result is also supported by the 3-D figure that charts WPI/WPR, E_a/P, and E_p/P (Figure 17). For downstream counties, neither WPI nor WPR is sensitive to E_p/P. Thus the midstream region has more critical agricultural water management issues from the perspective of both crop yield and WP.

Figure 13. Downstream crop yield vs. Budyko curve analysis



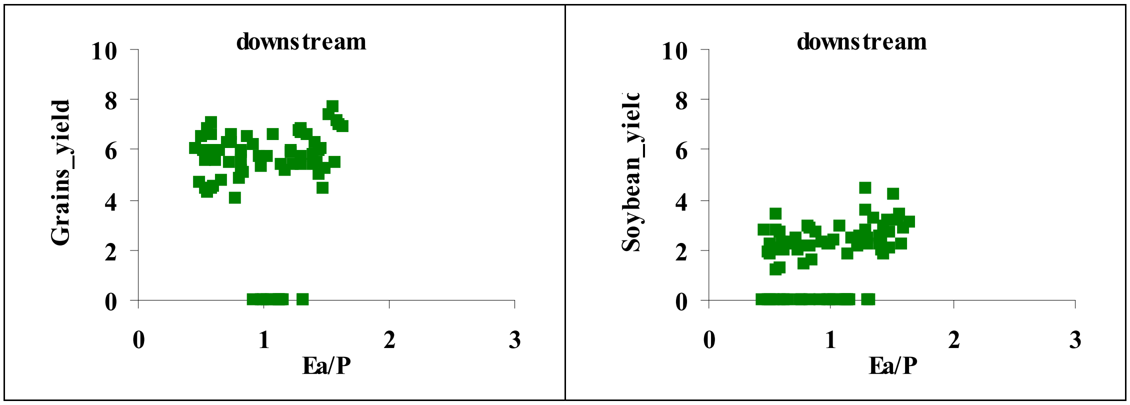


Figure 14. Middle stream crop yield vs. Budyko curve analysis

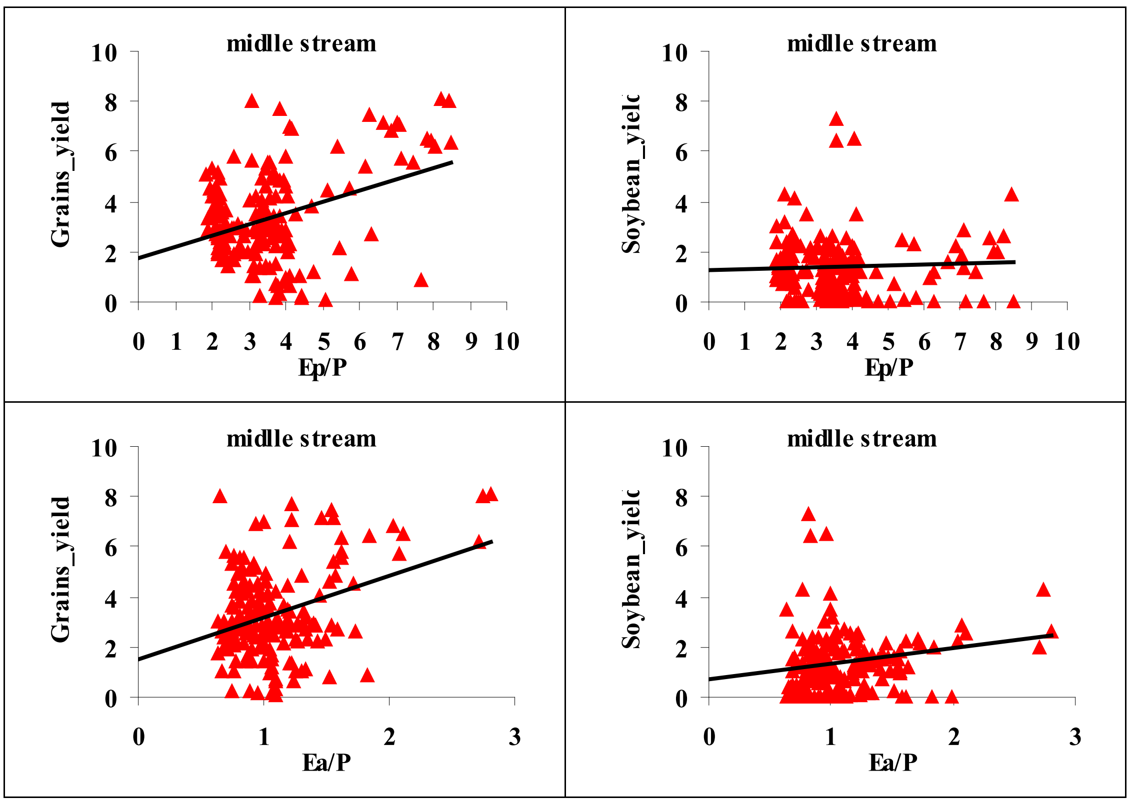


Figure 15. Upstream crop yield vs. Budyko curve analysis

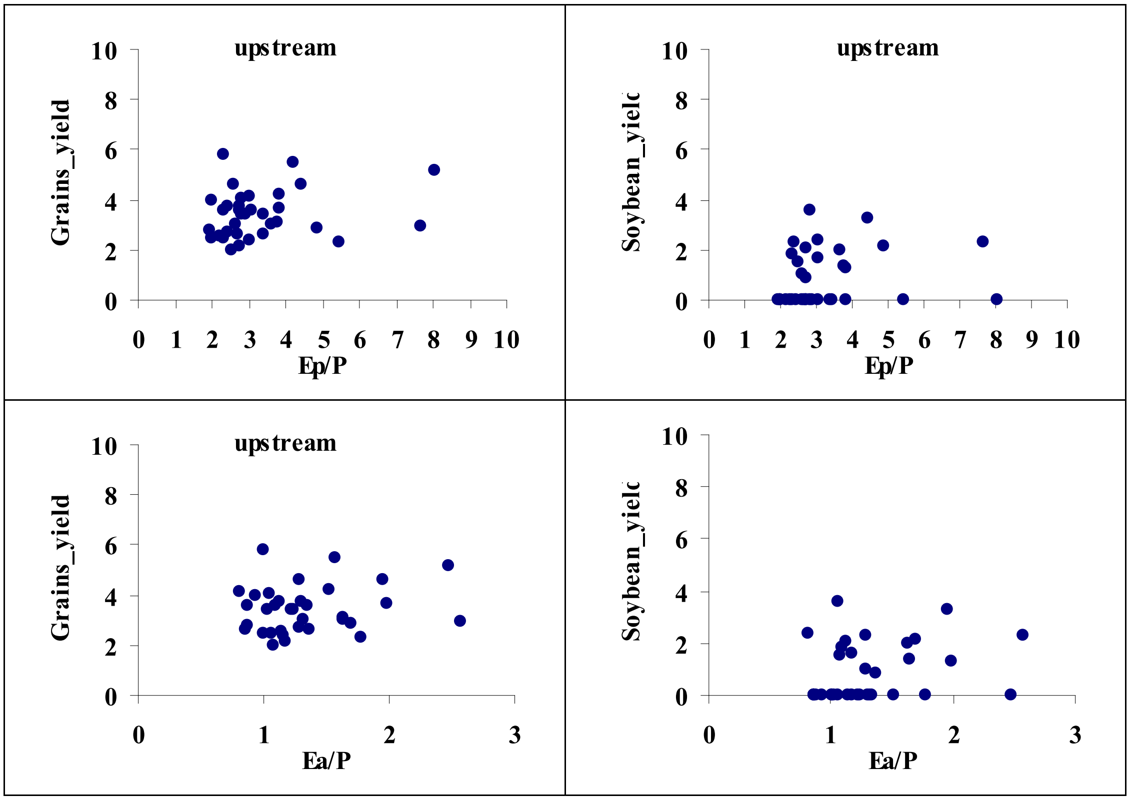
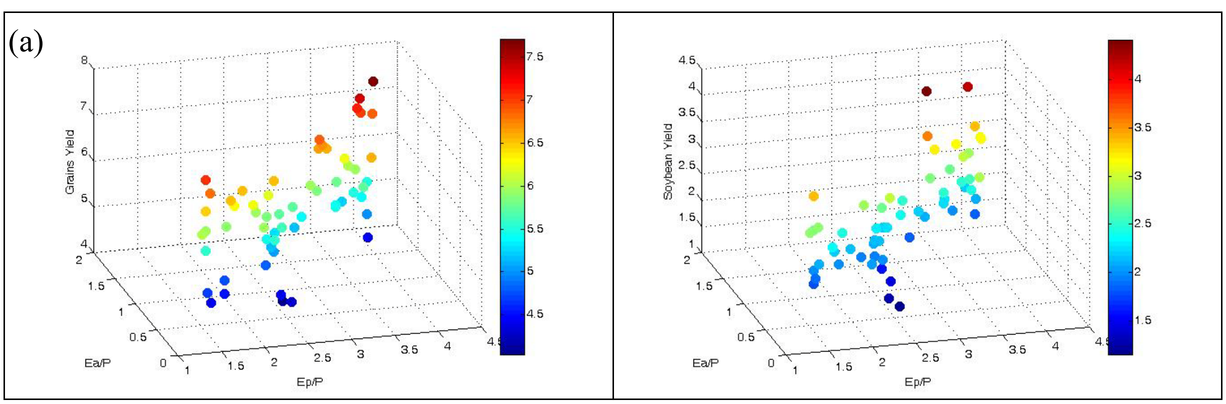


Figure 16. The 3-D Budyko curve analysis: yield, E_a/P, and E_p/P for (a) downstream, (b) middle stream, and (c) upstream of the YRB



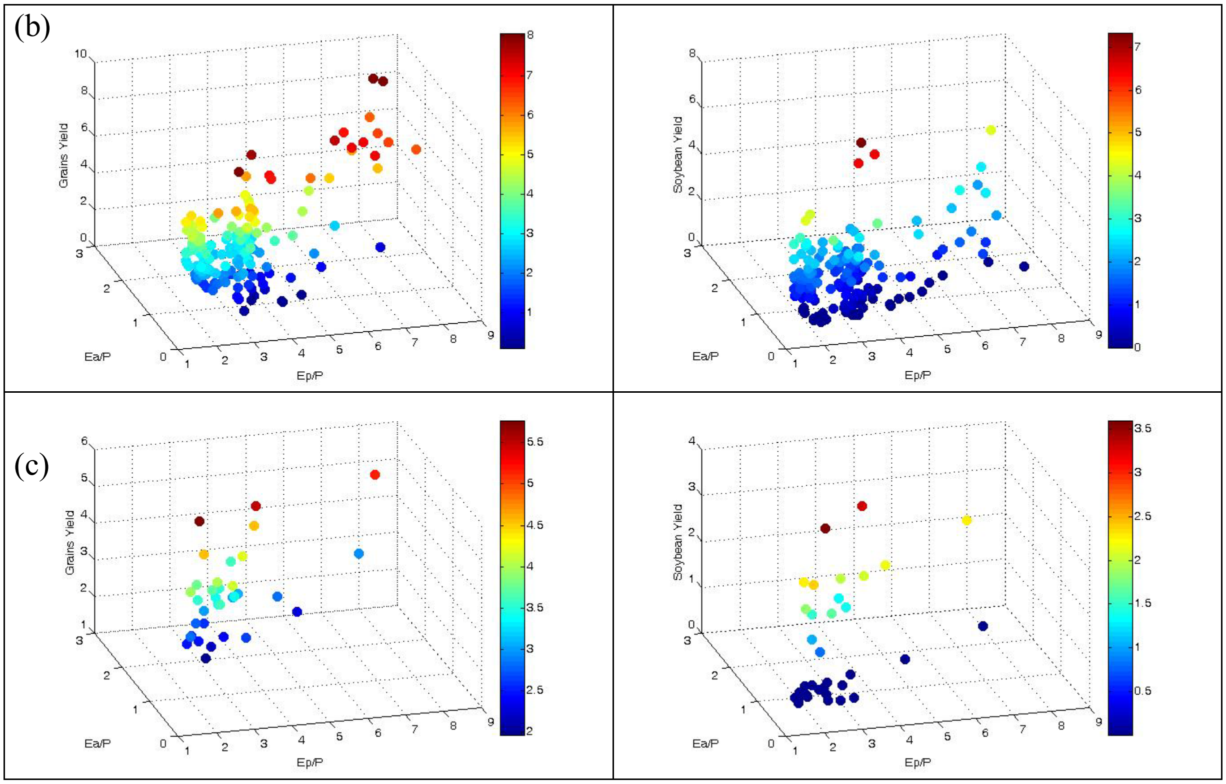
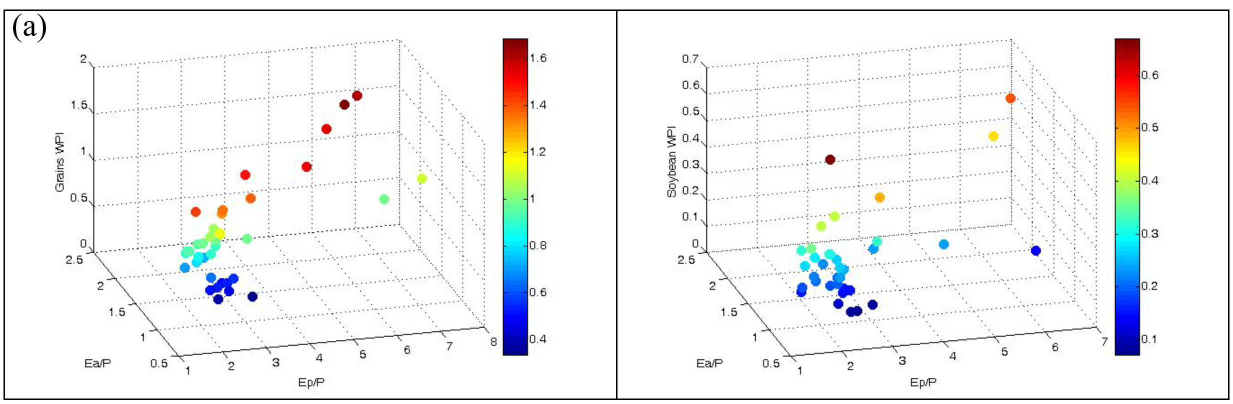
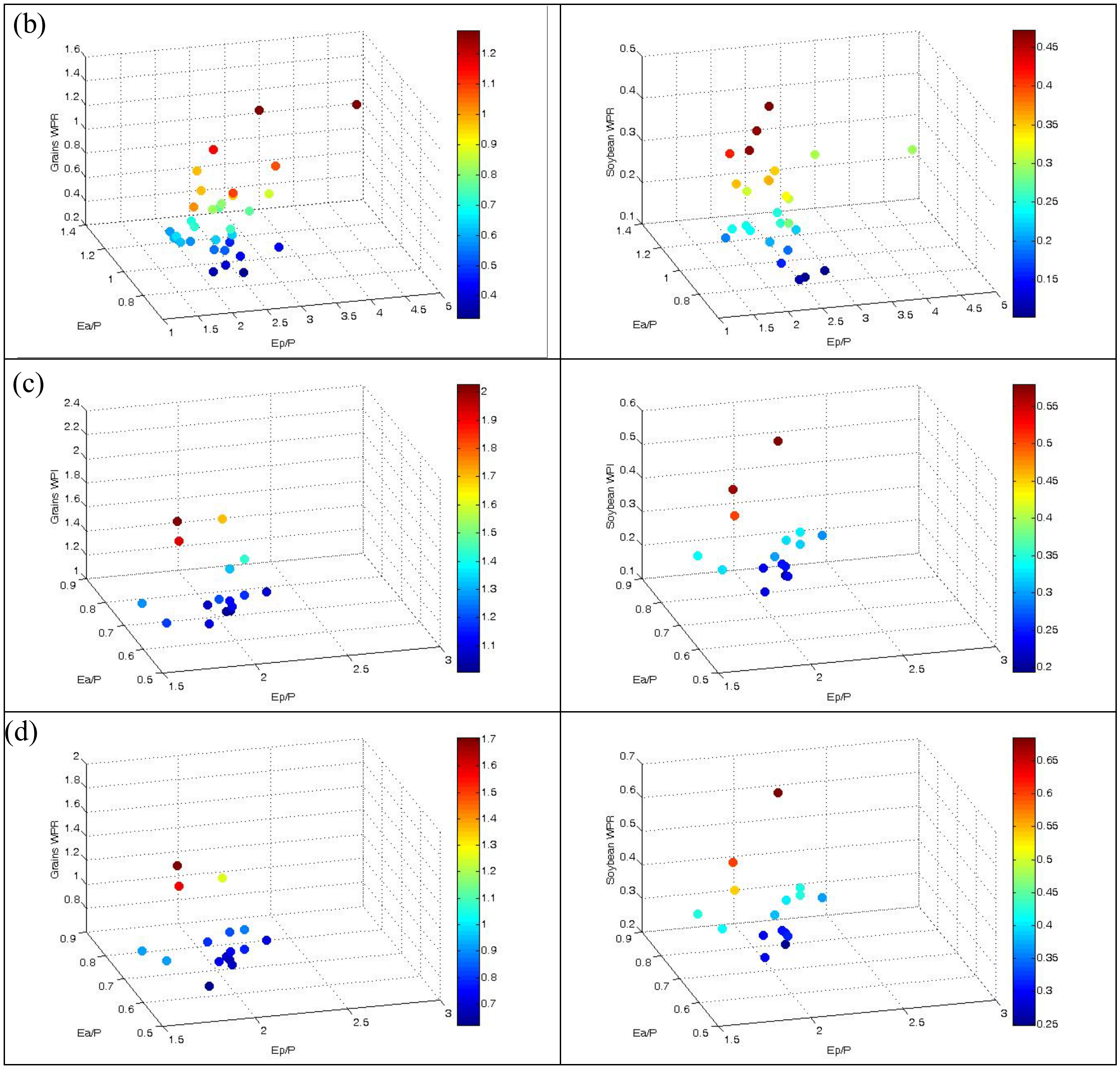


Figure 17. The 3-D Budyko curve analysis: WP, E_a/P, and E_p/P for (a) middle stream WPI, (b) middle stream WPR, (c) downstream WPI, and (d) downstream WPR




(b)
Grains WPR
Ea/P
Ep/P
Soybean WPR
(c)
Grains WPI
Soybean WPI
(d)
Grains WPR
Soybean WPR

6. CONCLUSIONS

As water stress increases, improving agricultural water productivity (WP) is recognized as an important approach to achieving global food security. This study assesses the WP for irrigated (WPI) and rainfed (WPR) crops in the Yellow River Basin (YRB) in China using the county-level data. The spatial distribution of WPI and WPR, as characterized by water and energy factors and engineering conditions, are also analyzed.

All rice and wheat are irrigated across the YRB. Wheat grows during the winter-spring seasons, during which precipitation is very limited (less than 30% based on the CROPWAT data). A small part of corn and soybean is rainfed (11% for corn and 17% for soybean). However, a large portion of irrigated crops in the YRB belongs to the category of supplementary irrigation due to the synchronized pattern of precipitation and solar energy in the YRB.

Although irrigated yield is in general significantly higher than the rainfed yield for corn and soybean in different regions of the YRB (with the exception of soybean in the downstream, where rainfed yield is even higher than irrigated yield), WPI is slightly lower than WPR for corn and soybean. This implies the irrigated crops may not be as efficient, in terms of water productivity, as rainfed crops for particular crops in the YRB. Efficient water productivity is also related to the synchronized pattern of precipitation and solar energy in the YRB. As expected, irrigation stabilizes the crop production per unit of water consumption. WPI and WPR vary spatially from upstream to downstream, with both climate and water supply conditions related to irrigation systems.

We use the Budyko curve to analyze water and energy factors of crop yield and WP. The water factor is particularly sensitive to spatial scale, i.e., high water stress is found at the pixel scale but relatively low water stress levels appear at larger scales (e.g., counties, sub-basin, and basin). This result reflects the impact of water regulation over space in the YRB through engineering measures such as groundwater pumping and surface water diversion. Comparing the water and energy factors over different land covers, it is found that croplands have higher water consumption than urban lands but lower than forest lands. An extended Budyko curve analysis (with an additional dimension of crop yield or water productivity) shows that the water factor (E_a/P) has a stronger effect on both crop yield and WP. Among the sub-basins, the middle stream region faces more critical agricultural water management issues regarding both crop yield and WP since both are more sensitive to water deficit than in other regions.

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APPENDIX

Table A1. Irrigated and rainfed area of four crops in 60 selected YRB counties

County/Crop	AI (1000ha)				AR (1000ha)				Sum AI ratio
	Rice	Corn	Wheat	Soybean	Rice	Corn	Wheat	Soybean	
HeZheng		0.98	6.86	0.00		0.51	0.00	0.00	**0.94**
YangQu		4.75	0.28	2.84		0.28	0.00	0.36	**0.92**
LouFan	0.01	1.39	5.09	1.40	0.00	0.08	0.00	0.18	**0.97**
ShiLou		2.87	8.05	2.84		0.13	0.00	0.14	**0.98**
TaiGu	0.01	4.47	11.12	1.76	0.00	0.23	0.00	0.17	**0.98**
JieXiu	0.07	4.65	11.39	2.73	0.00	0.24	0.00	0.26	**0.97**
HuoZhou	0.04	6.33	11.83	2.69	0.00	0.33	0.00	0.25	**0.97**
XiangNing		5.83	15.05	0.85		0.26	0.00	0.04	**0.99**
TuMoTeZuo		10.53	13.03	0.44		0.49	0.00	0.02	**0.98**
ZhunGeEr		4.59	1.84	1.79		0.21	0.00	0.09	**0.96**
HangJin	0.01	4.85	3.57	0.31	0.00	0.23	0.00	0.02	**0.97**
WuShen	0.17	4.17	2.87	0.08	0.00	0.17	0.00	0.00	**0.98**
LinHe		10.98	31.71	0.19		0.00	0.00	0.00	**1.00**
WuYuan		6.79	29.46	0.20		0.00	0.00	0.00	**1.00**
WuLaTeHou		4.17	2.36	0.26		0.00	0.00	0.00	**1.00**
HangJinHou		12.51	24.68	0.35		0.00	0.00	0.00	**1.00**
ALaShanZuo		3.47	3.32	0.22		0.00	0.00	0.00	**1.00**
LuanChuan	0.01	5.04	10.72	0.31	0.00	4.35	0.00	1.41	**0.74**
MianChi	2.02	3.84	22.14	0.29	0.00	3.32	0.00	1.33	**0.86**
LuShi	1.54	5.53	16.45	0.91	0.00	4.77	0.00	4.23	**0.73**
Chang'An	3.75	25.88	40.80	0.95	0.00	1.36	0.00	0.06	**0.98**
ZhouZhi	1.54	25.69	31.59	1.13	0.00	1.35	0.00	0.07	**0.98**
GaoLing	0.18	14.37	17.04	0.48	0.00	0.75	0.00	0.03	**0.98**
Mei	0.76	14.79	20.71	0.81	0.00	0.78	0.00	0.05	**0.98**
TaiBai	0.05	8.24	15.17	1.41	0.00	0.43	0.00	0.09	**0.98**
YanChuan		4.05	11.88	2.83		0.18	0.00	0.14	**0.98**
Fu	0.49	4.33	7.63	0.88	0.00	0.60	0.00	0.48	**0.93**
HengShan	1.67	5.96	4.75	9.44	0.00	0.24	0.00	0.44	**0.97**
DingBian	0.02	2.12	8.37	2.16	0.00	0.59	0.00	0.09	**0.95**
PingChuan	0.13	1.00	7.89	0.24	0.00	0.28	0.00	0.01	**0.97**
Qin'An	0.00	10.37	28.11	0.35	0.00	1.18	0.00	0.13	**0.97**
LongXi	0.01	1.83	0.01	24.30	0.00	0.95	0.00	0.00	**0.96**
Min	0.08	2.23	13.23	0.61	0.00	1.16	0.00	0.73	**0.90**
Li	0.40	5.79	23.16	0.36	0.00	3.01	0.00	0.43	**0.90**
GaoPing		11.37	12.38	7.86		0.71	0.00	1.05	**0.95**
Huan	0.00	2.75	24.23	2.86	0.00	0.77	0.00	0.12	**0.97**
Ning		5.95	34.60	3.38		0.82	0.00	1.83	**0.94**
JingYuan	0.03	0.79	9.90	0.13	0.00	0.09	0.00	0.05	**0.99**
ShangHe	1.42	23.02	35.32	4.29	0.00	1.00	0.00	0.21	**0.98**
JiaoZhou	0.13	13.00	36.26	0.28	0.00	9.35	0.00	7.07	**0.75**
LongKou		18.13	21.71	1.31		0.92	0.00	0.11	**0.98**
LaiYang	0.04	25.75	38.66	4.43	0.00	1.30	0.00	0.37	**0.98**
ZhuCheng	1.06	23.05	50.55	0.19	0.00	16.57	0.00	4.77	**0.78**

LiangShan	0.22	14.39	39.29	10.58	0.00	0.69	0.00	0.58	**0.98**
WenDeng	0.48	20.66	41.26	3.17	0.00	1.04	0.00	0.26	**0.98**
ZouPing	0.30	33.41	52.45	4.58	0.00	1.45	0.00	0.22	**0.98**
Juye	0.62	13.90	50.48	10.73	0.00	0.67	0.00	0.59	**0.98**
JuanCheng	0.01	12.55	40.07	8.41	0.00	0.60	0.00	0.46	**0.98**
AnYang	0.09	26.21	51.81	4.15	0.00	1.25	0.00	0.21	**0.98**
XinXiang	1.69	7.93	12.75	0.69	0.00	0.38	0.00	0.03	**0.98**
YanJin	1.44	9.84	29.07	2.98	0.00	0.47	0.00	0.15	**0.99**
FengQiu	4.44	13.92	43.16	8.96	0.00	0.66	0.00	0.45	**0.98**
BioAi	0.25	10.73	17.21	1.12	0.00	0.67	0.00	0.15	**0.97**
QingFeng	0.08	18.44	37.63	3.10	0.00	0.88	0.00	0.17	**0.98**

Table A2. Irrigated and rainfed crop yield of four crops in 60 selected YRB counties

County/Crop	**YI (ton/ha)**				**YR (ton/ha)**				**Sum YI ratio**
	Rice	**Corn**	**Wheat**	**Soybean**	**Rice**	**Corn**	**Wheat**	**Soybean**	
HeZheng		3.57	2.59	0.05		2.14	0.00	0.04	**0.74**
YangQu		2.47	0.72	0.78		1.15	0.00	0.56	**0.70**
LouFan	1.82	3.33	3.90	0.80	0.00	1.55	0.00	0.58	**0.82**
ShiLou		2.58	0.83	0.67		0.84	0.00	0.41	**0.77**
TaiGu	0.48	5.57	3.98	1.31	0.00	2.21	0.00	0.87	**0.79**
JieXiu	6.37	4.28	3.51	1.41	0.00	1.70	0.00	0.93	**0.86**
HuoZhou	5.47	4.69	2.65	1.07	0.00	1.86	0.00	0.71	**0.84**
XiangNing		5.04	2.28	1.48		1.64	0.00	0.92	**0.77**
TuMoTeZuo		7.47	3.29	1.25		2.75	0.00	0.81	**0.77**
ZhunGeEr		5.06	1.67	0.44		1.87	0.00	0.29	**0.77**
HangJin	6.87	7.40	3.77	1.24	0.00	2.73	0.00	0.80	**0.85**
WuShen	8.06	7.80	4.18	1.92	0.00	2.30	0.00	1.14	**0.86**
LinHe		8.93	4.76	2.99		0.00	0.00	0.00	**1.00**
WuYuan		9.59	3.89	1.59		0.00	0.00	0.00	**1.00**
WuLaTeHou		6.19	3.94	0.30		0.00	0.00	0.00	**1.00**
HangJinHou		9.54	4.30	3.54		0.00	0.00	0.00	**1.00**
ALaShanZuo		5.01	3.62	0.90		0.00	0.00	0.00	**1.00**
LuanChuan	0.48	3.52	2.75	1.47	0.00	2.28	0.00	1.22	**0.70**
MianChi	6.24	2.66	2.62	0.99	0.00	1.73	0.00	0.82	**0.83**
LuShi	6.51	2.88	2.31	1.14	0.00	1.87	0.00	0.94	**0.82**
Chang'An	4.77	3.85	3.54	1.57	0.00	1.43	0.00	0.99	**0.85**
ZhouZhi	4.01	3.71	3.31	1.82	0.00	1.38	0.00	1.15	**0.84**
GaoLing	5.45	6.28	4.67	2.04	0.00	2.34	0.00	1.29	**0.84**
Mei	3.85	4.03	3.12	1.07	0.00	1.50	0.00	0.68	**0.85**
TaiBai	3.81	3.68	1.73	0.86	0.00	1.37	0.00	0.54	**0.84**
YanChuan		3.46	1.15	1.09		1.12	0.00	0.68	**0.76**
Fu	6.20	5.70	2.16	2.01	0.00	2.99	0.00	1.51	**0.78**
HengShan	6.06	2.35	1.43	0.52	0.00	0.70	0.00	0.31	**0.91**
DingBian	3.25	6.01	0.84	0.43	0.00	1.51	0.00	0.24	**0.86**
PingChuan	2.87	4.17	1.82	1.32	0.00	1.05	0.00	0.73	**0.85**
Qin'An	3.52	1.72	1.33	1.47	0.00	0.88	0.00	1.11	**0.80**
LongXi	0.08	2.84	0.67	1.40	0.00	1.70	0.00	0.53	**0.69**
Min	5.45	4.35	2.06	1.84	0.00	2.61	0.00	1.42	**0.77**

Li	9.31	3.19	1.92	0.94	0.00	1.91	0.00	0.73	**0.85**
GaoPing		5.98	2.71	1.27		2.83	0.00	0.92	**0.73**
Huan	2.43	3.27	1.40	0.94	0.00	0.82	0.00	0.52	**0.86**
Ning		4.07	2.51	1.48		2.13	0.00	1.11	**0.71**
JingYuan	4.06	4.64	1.50	1.07	0.00	2.37	0.00	0.80	**0.78**
ShangHe	5.75	6.11	5.07	2.11	0.00	1.93	0.00	1.27	**0.86**
JiaoZhou	3.55	6.90	4.49	2.35	0.00	4.62	0.00	2.03	**0.72**
LongKou		5.15	3.74	1.44		2.08	0.00	0.95	**0.77**
LaiYang	4.68	5.93	3.90	2.02	0.00	2.39	0.00	1.34	**0.82**
ZhuCheng	6.81	7.44	4.98	2.62	0.00	4.98	0.00	2.27	**0.75**
LiangShan	4.62	4.74	4.07	1.78	0.00	1.80	0.00	1.15	**0.84**
WenDeng	5.36	5.96	4.32	2.10	0.00	2.41	0.00	1.40	**0.82**
ZouPing	6.73	5.33	4.84	1.56	0.00	1.68	0.00	0.94	**0.88**
Juye	3.81	4.05	3.68	1.37	0.00	1.54	0.00	0.88	**0.84**
JuanCheng	14.31	5.45	4.23	1.16	0.00	2.07	0.00	0.75	**0.90**
AnYang	3.64	5.10	4.25	1.92	0.00	1.97	0.00	1.29	**0.82**
XinXiang	4.73	5.25	4.90	2.11	0.00	2.04	0.00	1.41	**0.83**
YanJin	5.59	4.86	4.64	1.62	0.00	1.88	0.00	1.08	**0.85**
FengQiu	5.07	4.84	4.27	1.60	0.00	1.87	0.00	1.07	**0.84**
BioAi	4.59	6.83	5.54	3.07	0.00	3.23	0.00	2.24	**0.79**
QingFeng	6.25	5.77	5.01	1.97	0.00	2.19	0.00	1.27	**0.85**

Table A3. Water productivity for irrigated (WPI) and rainfed (WPR) crops

County/Crop	**WPI(kg/m^3)**				**WPR(kg/m^3)**			
	Rice	**Corn**	**Wheat**	**Soybean**	**Rice**	**Corn**	**Wheat**	**Soybean**
HeZheng		0.83	1.24	0.01		0.8	0	0.01
YangQu		0.51	0.31	0.15		0.47	0	0.18
LouFan	0.2	0.69	1.67	0.16	0	0.63	0	0.18
ShiLou		0.48	0.32	0.12		0.39	0	0.16
TaiGu	0.05	1.1	1.57	0.25	0	0.96	0	0.31
JieXiu	0.68	0.84	1.38	0.26	0	0.74	0	0.33
HuoZhou	0.58	0.92	1.05	0.2	0	0.81	0	0.25
XiangNing		0.94	0.89	0.26		0.77	0	0.35
TuMoTeZuo		1.49	1.49	0.24		1.28	0	0.3
ZhunGeEr		1.01	0.75	0.08		0.87	0	0.11
HangJin	0.63	1.48	1.71	0.23	0	1.27	0	0.3
WuShen	0.69	1.37	1.64	0.32	0	1.08	0	0.43
LinHe		1.45	1.88	0.46		0	0	0
WuYuan		1.56	1.54	0.24		0	0	0
WuLaTeHou		1.01	1.56	0.05		0	0	0
HangJinHou		1.55	1.7	0.54		0	0	0
ALaShanZuo		0.82	1.43	0.14		0	0	0
LuanChuan	0.04	0.73	1.21	0.28	0	0.71	0	0.31
MianChi	0.58	0.55	1.15	0.19	0	0.54	0	0.21
LuShi	0.6	0.59	1.01	0.22	0	0.58	0	0.24
Chang'An	0.42	0.72	1.47	0.27	0	0.62	0	0.36
ZhouZhi	0.35	0.69	1.38	0.32	0	0.6	0	0.41
GaoLing	0.47	1.17	1.94	0.36	0	1.01	0	0.46

Mei	0.34	0.75	1.3	0.19	0	0.65	0	0.24
TaiBai	0.33	0.69	0.72	0.15	0	0.59	0	0.19
YanChuan		0.64	0.45	0.19		0.53	0	0.26
Fu	0.58	1.22	0.96	0.41	0	1.15	0	0.47
HengShan	0.52	0.41	0.56	0.09	0	0.33	0	0.12
DingBian	0.3	1.05	0.31	0.07	0	0.77	0	0.1
PingChuan	0.27	0.73	0.68	0.22	0	0.53	0	0.31
Qin'An	0.34	0.38	0.6	0.31	0	0.36	0	0.36
LongXi	0.01	0.66	0.15	0.67	0	0.64	0	0.59
Min	0.54	1.01	0.99	0.4	0	0.98	0	0.46
Li	0.91	0.74	0.92	0.21	0	0.72	0	0.24
GaoPing		1.19	1.08	0.24		1.1	0	0.28
Huan	0.23	0.57	0.52	0.16	0	0.42	0	0.22
Ning		0.87	1.11	0.3		0.82	0	0.35
JingYuan	0.39	1.03	0.68	0.22	0	0.97	0	0.26
ShangHe	0.53	0.96	1.54	0.32	0	0.78	0	0.42
JiaoZhou	0.41	1.62	2.16	0.5	0	1.58	0	0.54
LongKou		0.9	1.34	0.23		0.8	0	0.29
LaiYang	0.46	1.04	1.39	0.33	0	0.92	0	0.41
ZhuCheng	0.79	1.75	2.4	0.56	0	1.71	0	0.6
LiangShan	0.46	0.84	1.49	0.3	0	0.73	0	0.38
WenDeng	0.52	1.05	1.54	0.34	0	0.92	0	0.43
ZouPing	0.62	0.84	1.47	0.23	0	0.68	0	0.31
Juye	0.38	0.72	1.35	0.23	0	0.62	0	0.29
JuanCheng	1.42	0.96	1.55	0.19	0	0.83	0	0.25
AnYang	0.34	0.82	1.33	0.29	0	0.71	0	0.37
XinXiang	0.45	0.85	1.53	0.32	0	0.74	0	0.4
YanJin	0.53	0.78	1.45	0.25	0	0.68	0	0.31
FengQiu	0.48	0.78	1.33	0.24	0	0.68	0	0.31
BioAi	0.42	1.36	2.2	0.58	0	1.25	0	0.69
QingFeng	0.62	1.02	1.84	0.33	0	0.88	0	0.42