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Consumptive water use in cropland and its partitioning: A high-resolution assessment

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Spatially explicit assessments of consumptive water use (CWU) are still at an early stage, and partitioning of *CWU* has rarely been studied on large scales. In this article, *CWU* is assessed for China's cropland with a spatial resolution of 30 arc-minutes. The partitioning of *CWU* is discussed through the simulation of transpiration ratios. The total *CWU* for Chinese cropland was 839 km^3/a during 1998—2002. Spatial distribution of *CWU* is closely related to cropland area and crop production with the highest *CWU* in the North China Plain. Transpiration accounts for two-thirds of *CWU*. The transpiration ratio is affected by precipitation and irrigation. Transpiration ratios are higher in irrigated systems than in rainfed systems when precipitation is low. Competition of water use will impose pressure on China's irrigation systems in the near future, and it will have a far-reaching effect on the partitioning of consumptive water use. Attention should be paid to green water management and technological improvements to guarantee China's water and food security.

GEPIC, evapotranspiration, evaporation, transpiration, transpiration ratio, China

1 Introduction

Spatially explicit assessments of consumptive water use (CWU) are at an early stage. *CWU* is the water use or removal from a water basin that renders it unavailable for further use[1,2]. For crop production, *CWU* refers to the total evaporative use of a crop during the crop growth period, often termed evapotranspiration (ET)[2]. Previous large-scale high-resolution assessments were often "blue" water biased towards irrigation water uses from surface or groundwater sources (blue water resources)[3,4]. Recently global spatially-explicit assessments that include agricultural water use originating from naturally infiltrated rainwater in the soil (green water resource)[2,5] have flourished.

It is very rare to partition *CWU* into productive and unproductive components especially on a large scale with high spatial resolutions. *ET* consists of transpiration from vegetation and evaporation from soil. Transpiration is regarded as a productive flux because it is closely related to the biomass accumulation of a plant. In contrast, evaporation is considered unproductive because it does not directly help plant growth. Accordingly, consumptive water use (CWU) can be partitioned into productive consumptive water use (CWU_p) and unproductive consumptive water use (CWU_u). Since the productive and unproductive fluxes are controlled by different biotic and physical processes, partitioning of *CWU* can improve the understanding of water uses in cropland ecosystems. In addition, partitioning is critical to accurately project the impacts of climate change on water uses in ecosystems[6], and it is also important in improving the accuracy of global climate models (GCMs)[7]. Very limited work on *CWU* partitioning has been reported because large-scale *ET* observations are not available and

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model estimates have not been accepted widely[7]. This article reports our latest findings of *CWU* and its partitioning for the cropland in China with a spatial resolution of 30 arc-minutes (around 50 by 50 km in each grid cell nearby the equator).

2 Method

2.1 Calculation of soil evaporation and plant transpiration

Soil evaporation (E) and plant transpiration (T) are calculated with a GIS-based Environmental Policy Integrated Climate (GEPIC) model. GEPIC simulates spatial and temporal dynamics of the major processes of the soil-crop-atmosphere-management system, e.g. hydrology, crop growth, crop water use etc.[8,9]. The GEPIC model computes E and T separately on a daily basis, as described by Ritchie[10]. Crop reference evapotranspiration ET_0 is first estimated with a Hargreaves method[11]. Potential plant transpiration T_p is simulated as a linear function of ET_0 and leaf area index LAI:

$$T_p = ET_0 \cdot LAI/3,\ 0 < LAI < 3, \quad (1)$$

$$T_p = ET_0, LAI \geqslant 3. \quad (2)$$

Potential soil evaporation E_p is calculated based on ET_0 and a soil cover index EA:

$$E_p = ET_0 \cdot EA. \quad (3)$$

The value of EA ranges from 0 to 1 according to the equation

$$EA = \exp(-0.05 \times CV), \quad (4)$$

where CV is the sum of the above ground biomass and crop residue in ton ha^{-1}.

Actual plant transpiration is equal to T_p when there is no water stress in soil. Otherwise, plant transpiration is reduced in response to water deficiencies. Actual soil water evaporation is estimated on the basis of the top 0.2 m of soil and snow cover, if any. When 5 mm or more snow is present, soil evaporation begins after snow has evaporated. The rate of soil evaporation is governed by soil depth and soil water content. GEPIC simulates ET on a daily basis. Precipitation and its frequency influence soil water availability, and hence influence daily actual ET. Details for the calculation of actual plant transpiration and soil evaporation can be found in ref. [12].

2.2 Calculation of consumptive water use

In each grid cell, *CWU* is the total amount of water consumed by crops in terms of *ET* during growing period.

$$CWU = 10 \times \sum_{c=1}^{N} (ET_r^c \times A_r^c + ET_i^c \times A_i^c), \quad (5)$$

$$CWU_p = 10 \times \sum_{c=1}^{N} (T_r^c \times A_r^c + T_i^c \times A_i^c), \quad (6)$$

$$CWU_u = 10 \times \sum_{c=1}^{N} (E_r^c \times A_r^c + E_i^c \times A_i^c), \quad (7)$$

where CWU, CWU_p, and CWU_u are consumptive water use, productive *CWU* and unproductive *CWU*, respectively, in m^3/a. ET is the actual transpiration of crop c under rainfed conditions (r) or irrigated conditions (i), while A is area of crop c in ha, N is the total number of crops selected. In this article, we have used 22 crop categories mainly due to the data availability; hence N=22. The number 10 is used to convert from mm to m^3/ha.

2.3 Data

The GEPIC model needs a list of spatially distributed input data. The most important ones include climate data, soil parameters and crop distribution information. Historical monthly climate (maximum temperature, minimum temperature, precipitation and the number of wet days) between 1998 and 2002 are obtained from the Climate Research Unit of the University of East Anglia (CRU TS2.1)[13]. The monthly data are then converted into daily data with a MODAWEC model[14]. Soil parameters include soil depth, percent sand and silt, bulk density, pH, organic carbon content, and they are obtained from Batjes[15]. Twenty-two crop categories are used in this article: wheat, maize, rice, barley, rye, millet, sorghum, soybeans, sunflower, potatoes, cassava, sugar cane, sugar beets, oil palm, rapeseed/canola, groundnuts/peanuts, cotton, pulses, coffee/cocoa, fruits, vegetables, and managed grassland/pasture. The crop distribution maps indicate the crop-specific harvested area in each grid cell, and they are collected from the Center for Sustainability and the Global Environment (SAGE) of the University of Wisconsin at Madison, USA[16]. Information on the irrigated area of each crop is obtained from the Institute of Physical Geography of the University of Frankfurt (Main), Germany[17]. The climate data, soil parameters and crop distribution information are all have a spatial resolution of 30 arc-minutes. Other data used in this article (e.g. elevation, slope etc.) are identical to those from Liu et al.[2]

3 Results and discussion

3.1 Consumptive water use (CWU) and consumptive blue water use (CBWU)

High intensity of *CWU* is mainly located in the eastern and southern parts of China (Figure 1(a)). In particular, the North China Plain (NCP) stands out to be a region with very high intensity of *CWU* (>1 billion m^3 in each grid cell). NCP consists of five provinces (i.e. Hebei, Henan, Shandong, Jiangsu, and Anhui) and two municipalities (i.e. Beijing and Tianjin). Besides the NCP, eastern parts of Hunan and Hubei, northern part of Jiangxi, eastern part of Sichuan, western part of Chongqing, middle part of Guangxi, and some part of Guangdong also have high *CWU*. In contrast, Western China and Northern China generally have low *CWU* in each grid cell.

The spatial distribution of *CWU* is closely related to the cropland area and crop production. The NCP is the bread basket of China. It accounts for 33% of the sown area of farm crops as well as the total grain production, although it has only 8% of the total land area of China. Intensity of cropland is relatively high in the NCP compared to other regions, especially those in the west, leading to high *CWU* in each grid cell.

The total annual *CWU* is 839 km^3 in China, which is about 21 times larger than total capacity of the Three Gorges Dam with a normal storage level at 175 m. Chapagain and Hoekstra[18] treat China as one simulation unit, and calculate a *CWU* value of 711 km^3, 15% less than the estimate of this study. Chapagain and Hoekstra use country average data for actual vapor pressure, daily maximum temperature, daily minimum temperature and percentage cloud cover for each country taken from the online database of the Tyndall Centre for Climate Change and Research[13]. *CWU* calculated with the average weather data in one country is quite different from that integrated from the grid-based *CWU* simulated with grid-based climate data.

There are no measured or statistical data on *CWU*. For the purpose of validation, consumptive blue water use (CBWU) is estimated with a spatial resolution of 30 arc-minutes, and the simulated *CBWU* is compared with

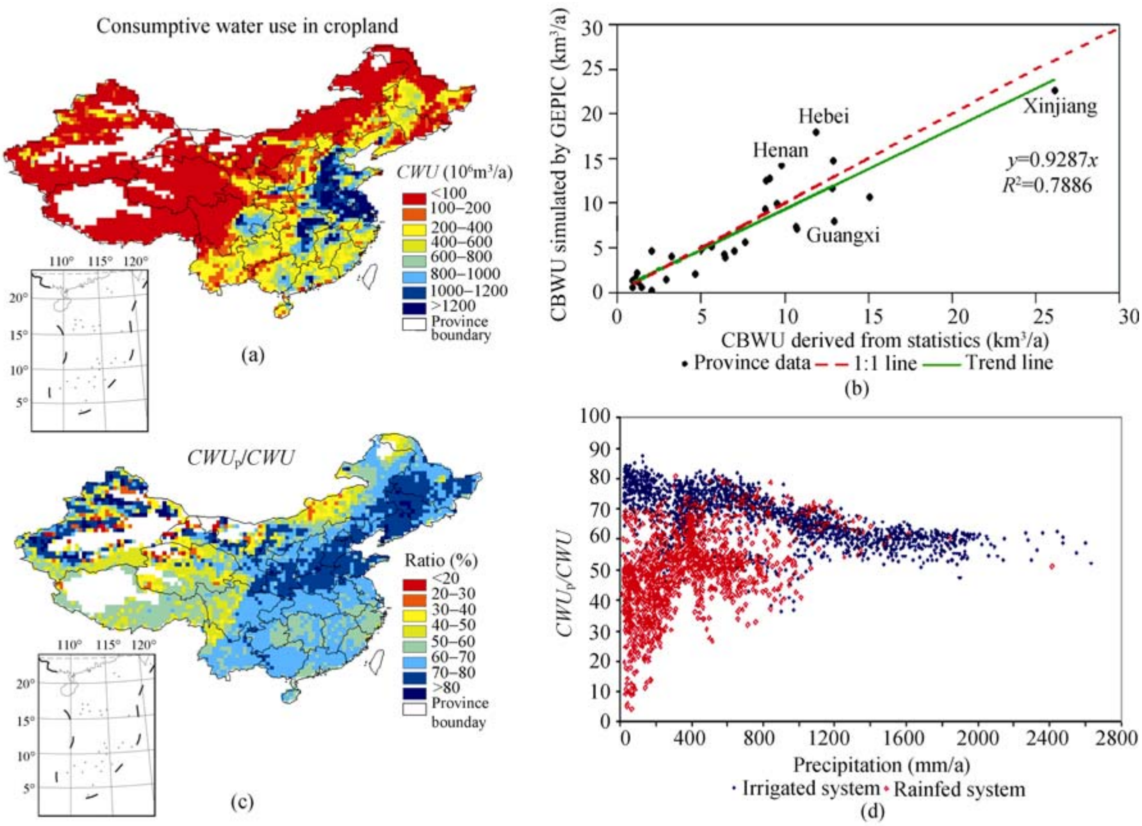

Figure 1 Simulated results of consumptive water use (CWU) and its partitioning. (a) Spatial distribution of *CWU* in cropland; (b) comparison between simulated and statistical consumptive blue water use (CBWU) in each province; (c) spatial distribution of transpiration ratio (T/ET or CWU_p/CWU); (d) transpiration ratio under rainfed and irrigated systems. Each dot represents one grid cell in Figure 1(c).

that derived from statistics at the national and provincial levels. Here *CBWU* is defined as the part of *CWU* coming from irrigation. In irrigated agricultural systems, in order to quantify the contribution of irrigation to *CWU*, two different soil water balances are performed. In one soil balance, it is assumed that soil does not receive any irrigation water. This water balance gives one value of ET (ET_1). In another water balance, it is assumed that soil receives sufficient irrigation. This balance gives another value of ET (ET_2). Irrigation is calculated as the difference between ET_2 and ET_1. The two-water-balances method is recommended by the Food and Agriculture Organization of the United Nations (FAO) to calculate the contribution of irrigation to *CWU*. The method for simulating *CBWU* and the spatial distribution of the *CBWU* are described in detail in Liu et al.[2]. The estimate shows that in China 25% of *CWU* or 213 km^3 is from irrigation. In 2000, the total agricultural water use in China was 378.4 km^3, of which 347 km^3 (91.6%) was used for irrigation[19]. However, delivery losses accounted for 37% of the 347 km^3 leaving 63% of the 347 km^3 (218 km^3) for evapotranspiration[19]. The total *CBWU* of 218 km^3 is comparatively very close to the estimate of 213 km^3 in this article.

The Water Resources Bulletin also reports agricultural water use for each province in China. This enables the comparison of statistical and simulated *CBWU* at a provincial level. Since project efficiency (ratio of ET to gross irrigation) is not available for all provinces, the national average of 63% is used here for all provinces except for a few where data are available. The exceptions include the provinces in the Haihe River Basin and Guangdong Province with a project efficiency of 80% and 45%, respectively.

The simulated *CBWU* compares very well with that derived from the statistical data with an r^2 value of 0.789 when the intercept is set to be 0 (Figure 1(b)). Xinjiang Uygur Autonomous Region has the highest *CBWU* in China. The simulated *CBWU* in this region is 22.7 km^3, which compares very well with that derived from statistics (26.2 km^3). The GEPIC model overestimates *CBWU* in a few provinces e.g. Henan and Hebei. Both the provinces are located in the NCP where water scarcity is very serious. When competition is high among different sectors, agriculture is often the first sector receiving insufficient water. This conflicts with the assumption used in the GEPIC model that there is always sufficient water available for all crops. This assumption largely explains the overestimation of the GEPIC model in Henan and Hebei provinces. Other reasons may also contribute to the difference, e.g. the application of drip and sprinkler irrigation. In provinces such as Guangxi, the *CBWU* derived from statistics is higher than that simulated by GEPIC. One possible reason is the use of the national average project efficiency. The project efficiency in Guangxi is likely to be lower than the national average because it is a less developed province with high precipitation.

3.2 Partitioning of *CWU*

The productive *CWU* (CWU_p) in China is estimated to be 550 km^3. This means two-thirds of the total *CWU* is productive, and is fed back to the atmosphere as transpiration. Transpiration ratio is defined as the ratio of transpiration to ET. High transpiration ratios (i.e. >70%) mainly occur in the NCP, northeast of China and a large part of Xinjiang Region (Figure 1(c)). Transpiration ratios are generally between 50% and 70% in Southeast China. Low transpiration ratios (i.e. <50%) are dominant in Southwest China (in particular Qinghai, Tibet, the western part of Sichuan, and the northern part of Yunnan) and Inner Mongolia. The NCP and the northeast of China have precipitation between 400 and 800 mm/a, and both regions have extensively irrigated area for crop production. In dry regions, irrigation is often applied when crops need the water the most. In this case, irrigation water is largely used in terms of crop transpiration, resulting in high transpiration ratios. Xinjiang has the lowest precipitation and there is no production without irrigation. Hence, the transpiration ratio is also high there. In the southeast of China, precipitation is high, and paddy rice is often planted. Paddy rice generally needs much deeper water surface than other field crops such as wheat and corn, resulting in high evaporation (low transpiration ratio). In the southwest, precipitation is generally lower than 600 mm/a. However, this region is located in a mountain area and the elevation is generally higher than 3500 m. The geographical situation is not suitable for crop growth. In addition, it is difficult to develop irrigation infrastructure in the mountain regions. Crops may not be harvested or have very low crop yield with drought, leading to low transpiration ratio. Similarly, in Inner Mongolia, precipitation is low and irrigation is not well developed. Transpiration ratio is also very low there.

When precipitation is lower than 1000 mm/a, transpiration ratio is significantly higher in irrigated systems than in rainfed irrigated systems (Figure 1(d)). As explained previously, irrigation provides water when it is the most needed by crops, and it is more likely to be used by crops than precipitation.

In irrigated systems, there is a decreasing trend of transpiration ratio when precipitation increases (Figure 1(d)). When precipitation is very low (e.g. in Xinjiang), irrigation plays a dominant role in providing water for crops, and it is used very efficiently by crops. With a higher level of precipitation, precipitation has a higher chance for unproductive water use as soil evaporation. In addition, irrigation may also be used as evaporation, particularly when irrigation is applied shortly before a precipitation event. When precipitation is higher than 1000 mm/a, the transpiration ratio ranges from 0.5 to 0.65. High precipitation normally occurs in the southeast. Since water is sufficient, the transpiration ratio is not affected by precipitation or irrigation.

In rainfed systems, when precipitation is low (e.g. <400 mm/a), transpiration ratios increase as precipitation increases. Very low precipitation often leads to failure to harvest in rainfed systems; hence transpiration ratio is low. A higher precipitation can enhance crop yield as well as transpiration. In this case, transpiration grows much faster than evaporation, leading to an increased transpiration ratio. When precipitation is higher than 400 mm/a, there is no clear relation between precipitation and transpiration in rainfed systems. Transpiration may further increase with higher precipitation. However, the higher precipitation also leads to higher soil evaporation.

The partitioning of *ET* between transpiration and evaporation is one of the most poorly understood processes. There is very limited research reporting the measured results on a large scale e.g. the entire China. It is not possible to validate our results with measured or statistical data. In situ measurements are also rare for the partitioning of *ET*. Kang et al.[20] reported the transpiration ratio of 67% for winter wheat and 74% for maize based on the measured *ET* by lysimeters and measured soil evaporation with micro-lysimeters at the Irrigation Experiment Station (34°20′N, 108°24′E) in Yang- ling, Shaanxi, China. For this site, the simulated results of this study show the transpiration ratio of 74%, the same as that of maize. Xie and Wu[21] calculated an average transpiration ratio of 76% at the Yucheng comprehensive experimental station (36°56′N, 114°36′E). This transpiration ratio is higher than the simulated result of around 60% from this study at the same site. It is believed that Xie and Wu[21] overestimated the transpiration ratio because they also reported a value of 105% for the transpiration ratio in April, which is not possible since *T* should not exceed *ET*.

4 Conclusion

CWU is assessed for China with a spatial resolution of 30 arc-minutes with the GEPIC model. The total *CWU* in China is 839 km^3. The spatial distribution of *CWU* is closely related to the cropland area and production. High intensity *CWU* is found in the eastern and southern parts of China, in particular the North China Plain (NCP). *CBWU* or *CWU* that is directly from irrigation, is 213 km^3, accounting for 25% of the total *CWU*. The simulated *CBWU* in each province compares very well with that derived from statistics, indicating a good performance of the model.

Partitioning shows that two-thirds of *CWU* is used in terms of transpiration in the cropland of China. The transpiration ratio is affected by both natural (e.g. precipitation) and anthropological (e.g. irrigation) factors. In general, it is higher in irrigated systems than rainfed systems when precipitation is low. Irrigation is more efficient than precipitation in providing productive water flows for crop growth. However, the regions with high transpiration ratios (the NCP, northeast and Xinjiang of China) are facing serious water scarcity. Future economic development and population growth will result in higher domestic and industrial water demands, imposing more pressures on irrigation water supply. It is expected that these regions will receive less irrigation water and farmers will turn some of their irrigated cropland to rainfed cropland. These changes will no doubt lead to a redistribution of the partitioning of *CWU*. Future agriculture has to heavily rely on water-saving techniques and better water management to guarantee food security. One objective of the water-saving agriculture is to decrease the unproductive soil evaporation without significantly affecting crop yield. Advanced irrigation techniques such as drip and sprinkler irrigation can achieve such purposes. The potential of these techniques in guaranteeing future water and food securities should be highlighted. According to our estimate, rainfed systems generally have low transpiration ratios. However, this does not mean that there are no ways to improve transpiration ratios in the rainfed systems. Effective measures of green water management (e.g. rainwater harvesting and mulching) and biotechnological advances of developing drought-tolerant varieties can help enhance crop yield without largely increasing soil evaporation[2]. There is a call for better green water management and technical improvements for the future water and food securities in China.

In this article, it is assumed that sufficient water is always available in irrigated area. However, in water scarce regions, limited irrigation is often a common practice. Limited irrigation is not taken into account mainly due to two reasons. First, the extent of limited irrigation is not known. Second, data on irrigation depth for limited irrigation are also not available. Ignoring limited irrigation will somehow overestimate the contribution of irrigation. Spatially explicit assessment of limited irrigation is a research theme to improve the simulation results from this study.

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