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ORIGINAL PAPER

Modeling the role of irrigation in winter wheat yield, crop water productivity, and production in China

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Abstract Irrigation plays an important role in increasing food production in China. The impact of irrigation on crop yield (*Y*), crop water productivity (CWP), and production has not been quantified systematically across regions covering the whole country. In this study, a GIS-based EPIC model (GEPIC) was applied to simulate *Y* and CWP for winter wheat (*Triticum aestivum* L.) in China at a grid resolution of 5 arc-minutes and to analyze the impacts of reducing irrigation water on wheat production. The findings show that irrigation is especially important in improving CWP of winter wheat in the North China Plain (NCP), the "bread basket" of China. On average, the provincial aggregate CWP was 56% higher under the irrigated than that under the rainfed conditions. The intensification of water stress and the associated increase in environmental problems in much of the NCP require critical thoughts about reducing water allocation for irrigated winter wheat. Two scenarios for irrigation reduction in the NCP provinces are presented: reducing irrigation depth (S1), and replacing irrigated winter wheat by rainfed winter wheat (S2). The simulation results show that S1 and S2 have similar effects on wheat production when the reduction in irrigation water supply is below 20% of the current level. Above this percentage, S2 appears to be a better scenario since it leads to less reduction in wheat production with the same amount of water saving.

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Introduction

Agriculture is the largest water user in China, accounting for nearly 70% of total water withdrawals (MWR 2005). Irrigation plays a vital role in increasing crop yields (Huang et al. 2002). Accounting for 40% of China's total arable land, irrigated land produces 75% of China's total food grain (Jin and Young 2001). Irrigation together with the application of agro-chemicals increases grain production, and helps improve farmers' incomes (Jin and Young 2001). Water shortage could greatly affect the total domestic grain production. As the largest wheat producer and consumer in the world, China's domestic wheat production could significantly influence world food trade (Lohmar 2004; Ahmadi-Esfahani and Jensen 1994). The reduction in cereal production due to severe drought resulted in 20 million tons of food imports in 1995, accounting for 10% of the total world cereal exports (FAO 2005).

The average per capita annual water resources availability in China is slightly above 2,000 m^3 (MWR 2005). The spatial distribution is highly uneven. In the northern and western parts of China, the water resources availability is below the national average, whereas in the South and the East it is above. In the

North China Plain, where winter wheat is concentrated, it is about 500 m^3 per capita (MWR 2005). Given the limitation in water resources and the continuous increase in food demand, it is necessary to improve crop production per unit of water use. Defined as the ratio of crop yield to actual evapotranspiration (ET), crop water productivity (CWP) combines two important and interrelated processes in agricultural systems: crop yield and water consumption. It is an important indicator of water use efficiency. There have been some studies on CWP in different locations in China (Zhang et al. 1999; Jin et al. 1999; McVicar et al. 2002; Huang et al. 2004). However, a systematic assessment of CWP in different geographical locations covering the whole country has not been conducted so far. This is partly due to the limitations of the traditional methods for estimating CWP on a large scale. Field experiments and crop growth models are two commonly used methods to determine crop yield, ET, and CWP. The main shortcomings of field experiments are that they are time consuming, costly and cannot be easily extrapolated to other seasons and geographic locations (Liu et al. 2007). As for crop growth models, most of them are preferentially used for point or site specific applications. The collection and editing of the input data for crop growth models for a large number of locations are generally complex and difficult.

The integration of the crop growth model with GIS provides an effective way to estimate CWP with relatively high spatial resolution and on a large geographical scale. We developed a GIS based EPIC model, GEPIC, to simulate crop yield, ET, and CWP simultaneously. Combining the advantages of GIS and EPIC, the GEPIC model can be used for studies on local, national and global scales. The model has been successfully applied in estimating crop yield and CWP for wheat (*Triticum aestivum* L.) on a global scale with a spatial resolution of 0.5 arc-degree (Liu et al. 2007).

In this paper, we applied the GEPIC model to study the crop-water relationship for winter wheat in China. Wheat is selected because of its importance for China and its high dependence on irrigation. Wheat in China is the second largest crop after rice in terms of harvested area and production (FAO 2005) and uses more than 70% of the total irrigation water in the North China Plain (NCP) (Li et al. 2005). Wheat imports accounted for nearly 40% of the total cereal imports in the period 1995–1999 (FAO 2005). Of the total wheat production, winter wheat accounts for 85–90% of both planting area and production in China (SBB 2004).

Materials and methods

The GEPIC model

The GEPIC model is a GIS-based EPIC model designed to simulate the spatial and temporal dynamics of the major processes of the soil-crop-atmosphere-management system. It takes into account factors relating to weather, hydrology, nutrient cycling, tillage, plant environmental control and agronomics. In EPIC (version 3060), the crop growth sub-model simulates potential crop growth, actual crop growth, and crop yield in a daily time step. Potential increase in biomass for a day is estimated using Monteith's approach (Monteith 1977). The daily potential biomass is adjusted for stress from five factors (water, temperature, nitrogen, phosphorus and aeration) in proportion to the extent of the most severe stress during that day (Williams et al. 1989). Crop yield is estimated by multiplying the above-ground biomass at maturity with a water stress adjusted harvest index for the particular crop (Williams et al. 1989). The EPIC model offers five methods for estimating potential evapotranspiration: Hargreaves and Samani (1985), Penman (1948), Priestley and Taylor (1972), Penman and Monteith (1965), and Baier and Robertson (1965). When wind speed, relative humidity, and solar radiation data are not available, the Hargreaves or Priestley-Taylor methods provide options that give realistic results in most cases. In this study, the Hargreaves method is employed to estimate potential evapotranspiration. Actual evapotranspiration is calculated by an approach similar to that of Ritchie (1972). The detailed description about the EPIC model can be found in Williams et al. (1989).

In this paper, crop water productivity is defined with Eq. 1.

$$\mathrm{CWP} = Y/\mathrm{ET} \tag{1}$$

where CWP is crop water productivity in kg m^{-3}, Y is the seasonal crop fresh yield in kg ha^{-1}, and ET is seasonal crop water consumption in terms of evapotranspiration in m^3 ha^{-1}. In this study, a fresh yield is calculated using a moisture content of 14% as suggested by Bessembinder et al. (2005).

In order to specify the contribution of irrigation to CWP, we further define RCWP and ICWP in Eqs. 2 and 3 for irrigated areas:

$$\mathrm{RCWP} = \frac{Y_r}{\mathrm{ET}_r} \tag{2}$$

$$\mathrm{ICWP} = \frac{Y_i - Y_r}{\mathrm{ET}_i - \mathrm{ET}_r} \quad (3)$$

where RCWP and ICWP are rainfed and irrigation crop water productivity, respectively, on irrigated land. Y_i is the yield at irrigation level *i*. Y_r is the yield contributed by rainfall on irrigated land. ET_i and ET_r represent the ET with irrigation level *i* and without irrigation, respectively.

The earlier version of the GEPIC model simulates crop yield and water dynamics grid by grid. The GEPIC model first transfers raster input data into EPIC required input files. The model simulates crop yield, ET and CWP for each grid cell. The output files are used to create output maps [see details about the GEPIC model in Liu et al. (2007)]. In order to reduce simulation numbers, we modified the GEPIC model in this study by introducing a concept of a homogenous simulation unit. A homogenous simulation unit is a group of grids containing a unique combination of soil, land use and climate conditions. By introducing this concept, grids with the same homogenous unit are simulated simultaneously.

Input data

The spatial and temporal resolutions of the data sets used in this paper are listed in Table 1.

The statistical data for winter wheat were obtained from the CHINAGRO project (Fischer 2005), which is a project on ''Policy decision for sustainable adaptation of China's agriculture to globalization'' supported by European Union (INCO-DEV ICA-2000-20039), the Chinese and Dutch Governments, and the IIASA member countries. The CHINAGRO project collected statistical data for crop yield, production, sown area and total fertilizer application for rainfed and irrigated winter wheat separately. Based on the statistics, rainfed winter wheat existed in 1,094 counties, and irrigated winter wheat existed in 1,569 counties. In most of the counties, both rainfed and irrigated winter wheat are planted. Per hectare fertilizer application rate was calculated by dividing total fertilizer application by total sown area of the respective winter wheat in each county. Fertilizer was separated into nitrogenous, phosphate, potassium and compound fertilizer. The ratios of these four types of fertilizer were only available at the provincial level (SSB 2001). In this study, we assume that the ratios are homogenous for all the counties within a province.

The digital elevation model (DEM) data were obtained from the 1 km resolution (30 arc seconds) digital elevation model GTOPO30 of the US Geological Survey (USGS) (EROS Data Center 1998). Terrain slopes were obtained from the 1 km resolution (30 arc-seconds) HYDRO1K digital raster slope map, which defines the maximum change in the elevations between each cell and its eight neighbors (United States Geological Survey 2000).

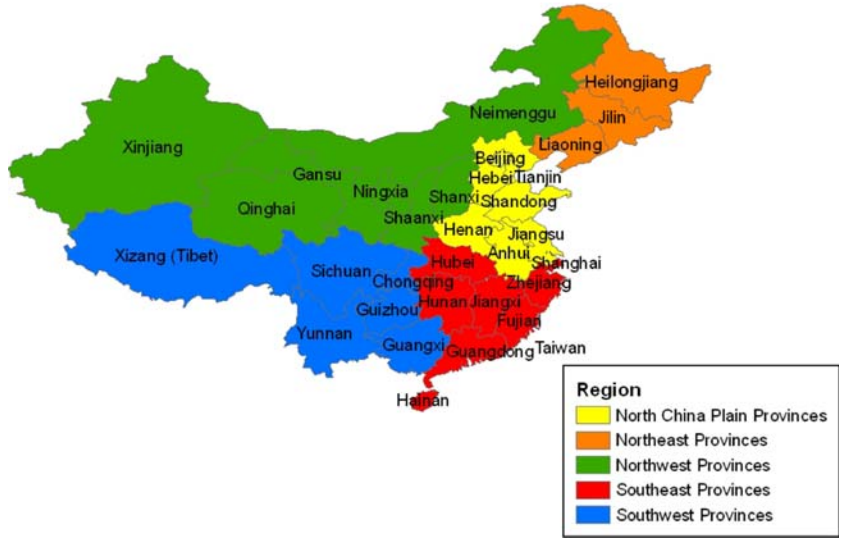
The daily maximum and minimum temperatures and precipitation data for the period 1977–1993 were derived from the Global Daily Climatology Network (GDCN) (Version 1.0) (Gleason et al. 2002). Daily climate data from 1994 to 2004 were downloaded from the website of the National Climate Data Center (NCDC) (http://www.ncdc.noaa.gov). Detailed description on the climate data source is given by Liu et al. (2007).

The Digital Soil Map of the World (DSMW) (FAO 1990) provides basic soil parameters of depth,

Table 1 Datasets used in this paper

Datasets	Spatial reference	Source
1. Statistical rain-fed crop yield	County averages	Fischer (2005)
2. Statistical irrigated crop yield	County averages	Fischer (2005)
3. Statistical rain-fed crop sown area	County averages	Fischer (2005)
4. Statistical irrigated crop sown area	County averages	Fischer (2005)
5. Daily climate data (precipitation, minimum and maximum temperature)	534 stations	Data for 1997–1993 from Gleason et al. (2002); Data for 1994–2004 from National Climate Data Center
6. Soil data–depth, texture	5 arc-minutes	FAO (1990)
7. Soil data–pH, organic carbon	5 arc-minutes	Batjes (1995)
8. Fertilizer application	County averages	Fischer (2005)
9. Ratio of N, P, K and compond fertilizer to total fertilizer	Provincial averages	China Statistical Yearbook (2001)
10. Digital elevation model (DEM)	30 arc-seconds	EROS Data Center (1998)
11. Terrain slope	30 arc-seconds	USGS (2000)
12. Cultivated land map	5 arc-minutes	Fischer (2005)

Fig. 1 Regional delimitation



percentage of sand, silt and clay. It is derived from the FAO-UNESCO Soil Map of the World (SMW) at an original scale of 1:5 million, which is one of the most comprehensive soil maps so far with global coverage (Nachtergaele 1996). Other soil parameters are available from ISRIC-WISE international soil profile data set (Batjes 1995). These data sets include the parameters such as pH, organic carbon content, etc. They are linked to the digital soil map of the world.

In this study, 5 arc-minutes were taken as the spatial resolution for simulation (approximately 8.3 km near the equator). The DEM and terrain slope maps were transferred into 5 arc-minutes maps using the average values from the finer 30 arc-seconds maps. It was assumed that crops are only harvested in the grid-cells where cultivated land exists. The cultivated land map was obtained from the CHINAGRO datasets (Fischer 2005).

The default crop parameters for wheat in EPIC were used in the simulation. In China, the crop-specific parameters used in the EPIC model have only been calibrated for a few locations based on experimental studies, e.g. Ansai in Shaanxi province (Lu 2000). Calibration of crop parameters for all the provinces (or counties) has not been conducted. Nevertheless, an earlier application of GEPIC by the authors of this paper has shown that the simulated crop yield and CWP using EPIC default parameters agreed well with the measured crop yield and CWP for wheat in many locations in China (Liu et al. 2007). Crop calendars in different regions were obtained from the CHINAGRO datasets (Fischer 2005). The information of sowing time and maturity time in each county is included.

There are two options for irrigation and fertilization in the EPIC model: user specified and automatic. The automatic option allows the model to decide when and how much to irrigate or fertilize based on input triggers (water and N plant stress levels), maximum annual applications, and minimum time interval between applications. We selected the automatic irrigation and fertilization option in this study, because of the difficulty in obtaining the irrigation and fertilization schedule data in different regions. The automatic option allows 'optimal' timing of water and fertilizer application, and assumes that local farmers have perfect knowledge in water and fertilizer management. This option may somewhat results in higher simulated yields and CWP than those in reality. But before the availability of more detailed management data like the timing of irrigation and fertilization, this option will remain the most practical assumption in applying a crop growth model.

Regional delimitation

The research area in this study includes 31 provinces, municipalities and autonomous regions (for convenience, they are all called ''provinces'' here) in mainland China. The country is divided into five main regions: the North China Plain, Northeast, Northwest, Southwest, and Southeast (Fig. 1). Each of the regions consists of several provinces. There are different regional delimitations in the literature based on various purposes (Shi and Lu 2001). The delimitation in this study takes two major factors into account: the geographical location of provinces (which is closely related to the climate conditions), and the importance of winter wheat production. For example, the North

Table 2 The percentage of winter wheat sown area/production to national total in five regions in 2000 (Fischer 2005)

Regions	Rain-fed winter wheat area (%)	Irrigated winter wheat area (%)	Rain-fed winter wheat production (%)	Irrigated winter wheat production (%)
NCP provinces	32	71	43	79
Northwest provinces	29	13	17	9
Southwest provinces	31	11	31	8
Southeast provinces	8	5	9	4
Northeast provinces	0	0	0	0
China	100	100	100	100

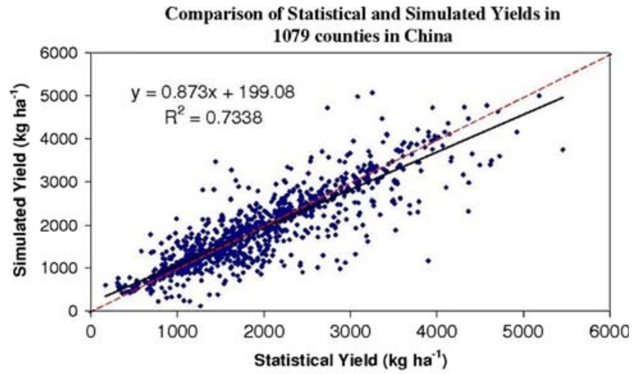


Fig. 2 Comparison between simulated and statistical rainfed winter wheat yields at county level

China Plain is the most important region for winter wheat production. All the provinces in this plain are grouped into one region.

The North China Plain (NCP) accounts for about 50% of the national wheat production (Li et al. 2005). It produces over 40% of rainfed winter wheat, and nearly 80% of irrigated winter wheat of the country (Table 2). The region consists of the provinces of Hebei, Shandong, Henan, Anhui, Jiangsu, and municipalities of Beijing and Tianjin. The soil of the NCP originates from sediments deposited by the Yellow River and is the largest alluvial plain of eastern Asia. The plain is generally a flat low land, with elevations mostly below 50 m above sea level, and the terrain slopes mainly smaller than 5%. The fertile soil, the flat land and the climate are favourable for growing winter wheat. Next to the NCP provinces, the Southwest and Northwest provinces are also important for winter wheat production (Table 2). The Southeast provinces account for a small percentage, while the Northeast provinces are marginal in winter wheat production.

Validation of the model

The GEPIC model was first applied to simulate crop yield for 1,094 counties where rainfed winter wheat existed. The performance of the GEPIC model was tested by comparing the aggregated average simulated and statistical yields of rainfed winter wheat in 1,079 counties (Fig. 2). A total of 15 counties were dropped in the comparison because the simulation results suggested that they were not suitable for rainfed winter wheat. The dashed line is the 1:1 line and the black solid line is the linear trend line. The trend line is close to the 1:1 line. The simulated yields and the statistical yields are quite comparable, as indicated by a highly significant *F*-test (the *P* value is higher than 99%) and high r^2 value (0.73). The slope is not significantly different from 1, while the intercept is not significantly different from 0. The difference between the simulated and statistical provincial average yields is generally within 10% of the statistical averages (Table 3). The statistical tests indicate good performance of the GEPIC model in simulating crop yields for rainfed winter wheat.

Results and discussion

Irrigation depth and the role of irrigation for winter wheat yield in different regions

Information on the amount of irrigation water applied (or irrigation depth) is important for quantifying the contribution of irrigation to yield. It is also the basis for studying the impacts of changes in irrigation on the regional and national food production. Spatial maps of annual irrigation depth have not been available on the national scale with high resolution for winter wheat prior to this study. The GEPIC model is used to simulate the annual irrigation depth for irrigated winter wheat.

For each homogenous simulation unit, the first simulation was conducted with an assumption of sufficient irrigation, holding other factors unchanged. GEPIC determined the annual irrigation depth (I_0) with which no water stress occurred during the growth period. Yield was simulated under the sufficient irrigation condition. If the ratio of the simulated yield to the statistical yield fell in a practical range (90–110%), it was assumed that the annual irrigation depth equals I_0. Otherwise, the annual irrigation depth was adjusted

Table 3 Provincial averages of crop yield, ET and CWP

Region/province	Rain-fed winter wheat						Irrigated winter wheat					
	Area (ha)	Y_{sta} (kg ha^{-1})	Y_{sim} (kg ha^{-1})	Diff[a] (%)	ET (mm)	CWP (kg m^{-3})	Area (ha)	Y_{sta} (kg ha^{-1})	Y_{sim} (kg ha^{-1})	ET (mm)	CWP (kg m^{-3})	Irrigation (mm)
NCP provinces	*1897833*	*2585*	*2430*	*–6.0*	*316*	*0.77*	*15076880*	*4429*	*4512*	*377*	*1.20*	*133*
Beijing	676	1336	1366	2.3	208	0.66	143986	4548	4682	346	1.35	255
Tianjin	16	1240	1161	–6.4	244	0.48	135562	3391	3300	300	1.10	184
Hebei	60739	956	1016	6.3	157	0.65	2872018	4737	4711	331	1.42	216
Henan	815073	2565	2318	–9.6	278	0.83	4607538	4511	4507	371	1.21	104
Shandong	303357	2252	2094	–7.0	254	0.83	3811299	4682	4816	344	1.40	133
Anhui	504124	2680	2568	–4.2	412	0.62	1730729	3385	3505	466	0.75	92
Jiangsu	213848	3372	3418	1.4	372	0.92	1775748	4260	4615	459	1.01	97
Northwest provinces	*1741907*	*1145*	*1220*	*6.6*	*266*	*0.46*	*2644380*	*2236*	*2299*	*378*	*0.61*	*157*
Gansu	687681	966	1116	15.6	246	0.45	233863	1563	1579	304	0.52	189
Shaanxi	697304	1225	1303	6.4	300	0.43	1252027	2832	2954	425	0.70	137
Ningxia	38050	1099	987	–10.2	226	0.44	17237	1974	1859	358	0.52	180
Xinjiang							499920	4135	3930	360	1.09	395
Shanxi	318872	1359	1291	–5.0	241	0.54	641333	3066	3085	329	0.94	103
Southwest provinces	*1799547*	*1951*	*2006*	*2.9*	*388*	*0.52*	*2385361*	*2804*	*2844*	*432*	*0.66*	*108*
Chongqing	338823	2117	2126	0.4	375	0.57	242007	2528	2624	425	0.62	140
Guangxi	4790	892	973	9.1	258	0.38	19930	1281	1319	285	0.46	140
Guizhou	544128	1422	1524	7.2	399	0.38	204106	1666	1925	432	0.45	84
Sichuan	641655	2571	2685	4.4	420	0.64	1297701	3483	3561	455	0.78	91
Yunnan	270092	1353	1234	–8.8	309	0.40	620688	1916	1781	391	0.46	138
Xizang	59	1436	1559	8.6	280	0.56	929	3372	3365	427	0.79	181
Southeast provinces	*445628*	*2206*	*2212*	*0.3*	*393*	*0.56*	*1064864*	*2710*	*2807*	*455*	*0.62*	*101*
Shanghai	1051	2995	2812	–6.1	290	0.97	60742	3435	3839	378	1.02	60
Zhejiang	24969	2296	2254	–1.8	416	0.54	168157	2936	3018	487	0.62	110
Jiangxi	11672	1426	1548	8.6	378	0.41	41202	1544	1567	438	0.36	14
Hubei	378791	2260	2273	0.6	394	0.58	650883	2792	2882	467	0.62	122
Hunan	25033	1711	1620	–5.3	376	0.43	98205	1925	1997	405	0.49	38
Fujian	2270	1377	1574	14.3	369	0.43	32024	2432	2489	422	0.59	0
Guangdong	1842	2048	1861	–9.1	303	0.62	13651	2607	2347	340	0.69	0

[a] *Diff* is defined as $(Y_{sim} - Y_{sta})/Y_{sta} \times 100\%$

by a step length (10 mm), and the crop yield was simulated with the new annual irrigation depth. This process continued until the ratio fell in the practical range. When the ratio was higher than 110%, which was the dominant case, the annual irrigation depth was decreased stepwise. In case the ratio was smaller than 90%, the irrigation depth was increased stepwise. All the grids were simulated with this procedure. The national map indicating the simulated annual irrigation depth is shown in Fig. 3.

In Hebei, Beijing, Tianjin, Shandong and Henan provinces, the five relatively dry provinces in the NCP provinces, annual precipitation is variable, ranging from 300 to 1,000 mm with an average of 480 mm (Zhang and You 1996). A majority of the rainfall (70% of annual precipitation) is concentrated in the period from July to September (Wang et al. 2000). Rainfall during the winter wheat growing season ranges from 100 to 180 mm, which can only meet approximately 25–40% of crop water requirements (defined as the potential crop water consumption without any water stress) over the wheat growing season (October–June) (Li et al. 2005). The yield of rainfed winter wheat was generally lower than 2,500 kg ha^{-1}, and it varied greatly among provinces, ranging from less than 1,000 kg ha^{-1} in Hebei to 2,565 kg ha^{-1} in Henan (Table 3). In these five provinces, supplemental irrigation is a key to guarantee high and stable crop yields. For example, in Hebei province, annual irrigation depth was between 150 and 300 mm (Fig. 3), and yield could be increased by a factor of four. On provincial average, irrigation depth was 28–74% of total ET for irrigated winter wheat in these five provinces (Table 3). The yields were increased by 76–396% under irrigated conditions compared to that under rainfed conditions.

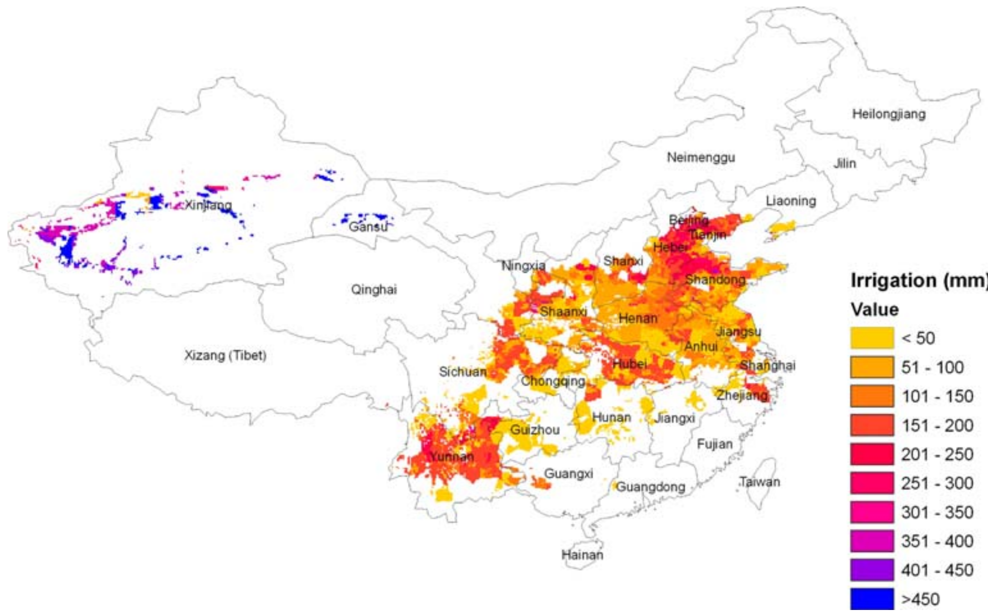


Fig. 3 Map of simulated irrigation depth for winter wheat (2000)

In Anhui and Jiangsu, the two relatively wet provinces in the NCP provinces, annual precipitation was higher than 800 mm (Leemans and Cramer 1991). The high precipitation provided favourable moisture conditions for rainfed agriculture. However, supplemental irrigation during dry spells could further improve crop yield of winter wheat. Annual irrigation depth was generally less than 100 mm in these two provinces (Fig. 3). Irrigation depth was only approximately 20% of ET, and the yields of irrigated winter wheat were about 26% higher than those of the rainfed winter wheat (Table 3).

In the Northwest provinces, high evaporation and low precipitation make irrigation vital for winter wheat production. In Xinjiang province, rainfed winter wheat production is not possible due to the low annual average precipitation of 145 mm (Shi and Lu 2001). However, its sufficient sunlight and radiation resources give the province a potential for high-yielding winter wheat when irrigation is applied. The current winter wheat yield level of over 4,000 kg ha^{-1} was achieved with full irrigation (>400 mm) (Fig. 3). Except for Xinjiang, irrigation was about 31–62% of ET in other Northwest provinces, and the yields were increased by 62–126% under irrigated conditions compared to those under rainfed conditions (Table 3).

In most of the Southeast provinces, precipitation was higher than 1,200 mm. Precipitation could meet the water requirement for winter wheat during its growing period. The simulation shows that there was no irrigation applied. However, based on the statistical data, irrigated winter wheat still existed in some places. This is because winter wheat was generally planted in the winter period in the paddy ‘‘irrigated’’ field, where rice was planted during summer. Supplemental irrigation might be applied at the start of the wheat growth cycle in autumn to give the young seedlings good conditions for germinating and emergence (personal communication, H. van Velthuizen). Because irrigation was not applied during crop growth period, it is not surprising that the simulated annual irrigation depth was zero. On provincial average, irrigation was generally less than 25% of ET. The difference was small between irrigated and rainfed winter wheat yields. Winter wheat yields under irrigated conditions were only increased by 8–28% compared to those under rainfed conditions. Overall, in the Southeast region, water is not a main constraint. Instead, the warm climate conditions were not suitable for winter wheat, leading to relatively low yield, even with irrigation.

In the Southwest provinces, precipitation ranged from 600 to 1,800 mm in the major winter wheat producing areas. Irrigation was 19–49% of ET on provincial average (Table 3). Supplemental irrigation was mostly applied in Sichuan, Chongqing and Yunnan. The yields of irrigated winter wheat were not substantially higher than that of rainfed winter wheat, with amounts ranging from 17 to 44% at the provincial level (Table 3). In most part of this region, constraints due to soil depth, soil fertility and terrain slope were severe for crop growth (Fischer et al. 2002).

CWP under rainfed and irrigated conditions

CWP was calculated based on the simulated yield and ET for rainfed and irrigated winter wheat, respectively.

The results showed that under rainfed conditions, winter wheat had CWP values generally in the range of 0.20–1.20 kg m^{-3}. Relatively higher CWP values were found in the high-yielding rainfed winter wheat belt, mainly the provinces in the NCP, and Hubei, Chongqing and Sichuan provinces (Fig. 4). This belt had the most favourable climate conditions for rainfed winter wheat in China (Fischer et al. 2002). In Jiangsu province, the average annual precipitation varied from 850 to 1,200 mm in the major wheat producing areas (Leemans and Cramer 1991). High precipitation was an important reason for the high CWP values under rainfed conditions.

North of the high-yielding rainfed winter wheat belt, the low precipitation and low temperature seriously limit winter wheat production. South of this belt, the high temperature poses constraints to winter wheat production. The high temperature together with plentiful precipitation leads to high evapotranspiration, while yield is low. The lowest values of CWP were seen in Guangxi and Guizhou provinces where soil depth, soil fertility and terrain slope were not suitable for winter wheat (Fig. 4, Table 3).

The effects of supplemental irrigation on CWP varied significantly among regions (Figs. 4, 5). The NCP provinces stood out to be the region with the most significant improvement in CWP under irrigated conditions. On average, CWP under irrigated conditions was appropriately 56% higher than that under rainfed conditions. The Northwest provinces and the Southwest provinces could improve CWP by 33 and 27%, respectively. In the Southeast provinces CWP for irrigated winter wheat was only 10% higher on average than that for rainfed winter wheat. These provinces generally received high precipitation during the winter wheat growing period. The irrigation did not increase crop yield much, but the actual ET increased substantially (Table 3).

The role of supplemental irrigation is further specified in Fig. 6. In the regions with annual precipitation less than 600 mm, e.g. in Xinjiang, winter wheat generally could not achieve economic yields with rainfall alone. Therefore full irrigation was required. Rainfed winter wheat was generally feasible when annual precipitation was higher than 600 mm (Fig. 6). However, supplemental irrigation can increase crop yield. ICWP was mostly high between 600 and 1,000 mm isohyets (Fig. 6). Large parts of the NCP provinces were located between the isohyets, and had ICWP higher than 1 kg m^{-3}. The significant increase in yield with less significant increase in ET resulted in high ICWP values. In the regions receiving more than 1,000 mm annual precipitation, ICWP was generally small. Most parts of Southeast and Southwest provinces had ICWP values below 0.5 kg m^{-3}. In these provinces, an increase in irrigation may not significantly improve crop yield, but may lead to much higher evapotranspiration.

In the precipitation-rich Southwest and Southeast provinces, irrigated winter wheat is planted in some areas despite the small increase in crop yield. This is because water is not a scarce resource in these provinces. The opportunity cost of irrigation is relatively low. As long as irrigation can increase yield and

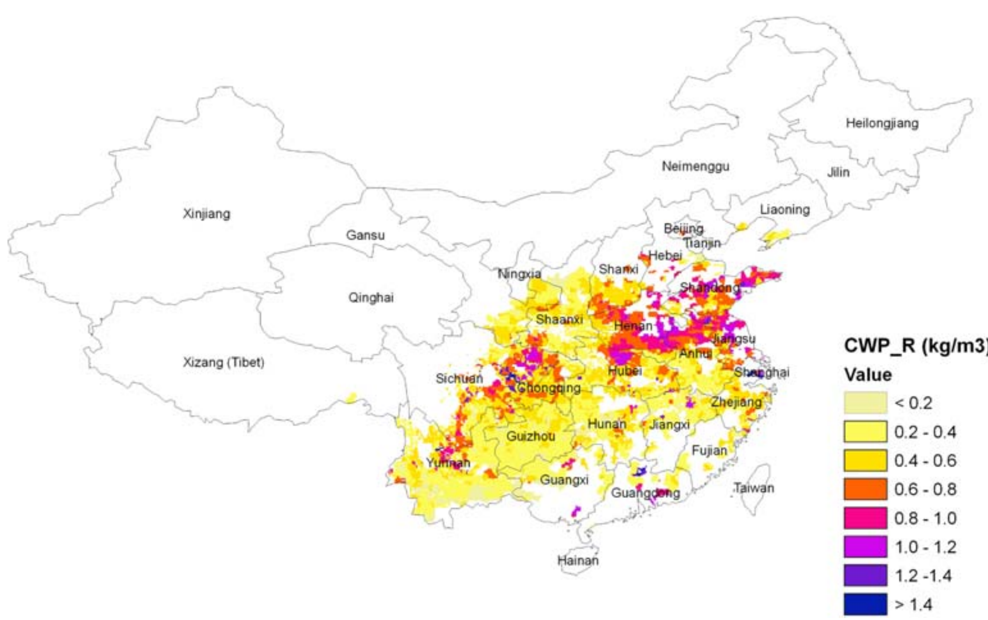


Fig. 4 Simulated crop water productivity for rainfed winter wheat in 2000

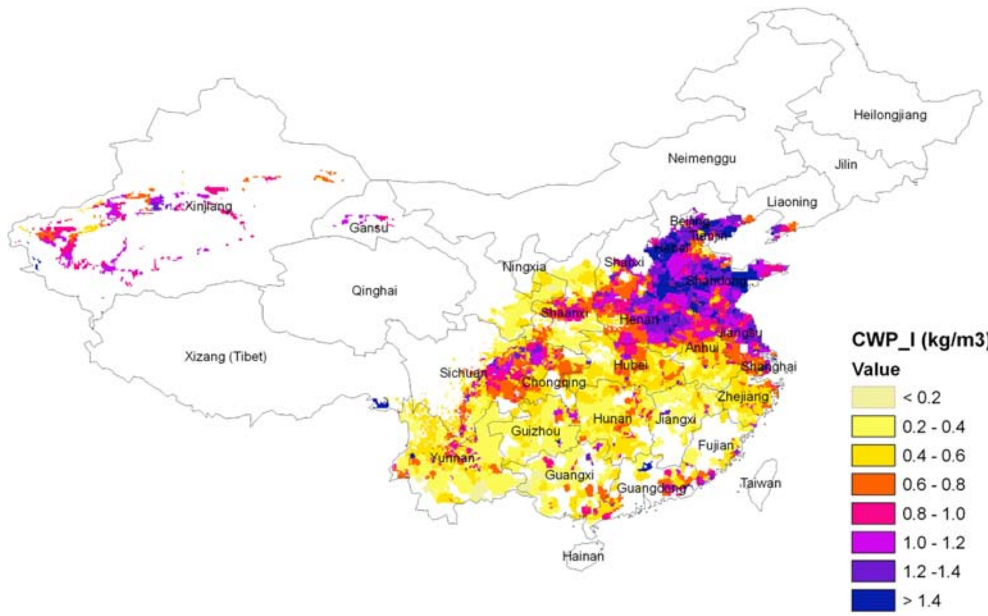


Fig. 5 Simulated crop water productivity for irrigated winter wheat in 2000

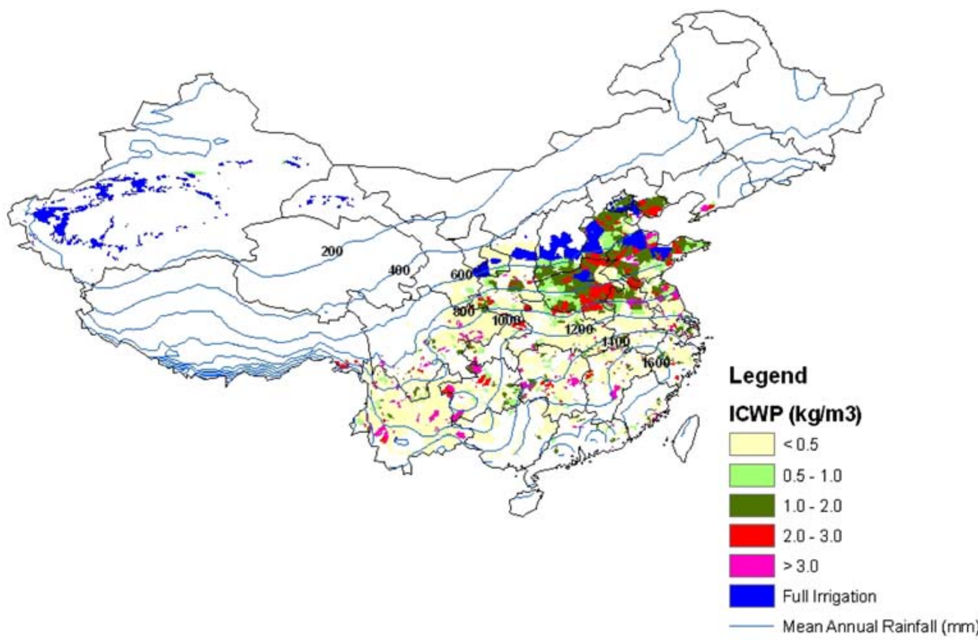


Fig. 6 Simulated irrigation crop water productivity (*ICWP*) for winter wheat in 2000

income, farmers will irrigate, regardless of whether irrigation could result in high CWP. In contrast, in water-scarce provinces, e.g. those in NCP and Northwest regions, competitive uses exist among agriculture and other sectors. The opportunity cost of irrigation is high. Efficient allocation of the precious water among different sectors is of importance for both regional economic development and food production. Achieving high values of CWP, especially high ICWP, has to be considered an important objective in agricultural water management.

Comparison of CWP in this study with others reported

The simulated CWP values in this study are compared with those reported in the literature (Table 4). To exclude extreme values, the CWP range in this study is determined by taking the 5 and 95 percentiles of the cumulative frequency distribution.

In this study, CWP for irrigated winter wheat was between 0.40 and 1.51 kg m^{-3} in the NCP provinces (Table 4). The CWP values from Zhu et al. (1994) fell

Table 4 Documented results of CWP in China

Crop	Regioin/ stations	Reference	CWP-range[a] (kg m^{-3})	Mean (kg m^{-3})	SD (kg m^{-3})	Minimum (kg m^{-3})	Maximum (kg m^{-3})
Irrigated winter wheat	North China plain	This study	0.40–1.51	1.19	0.36	0.18	2.20
Irrigated winter wheat	North China plain	Zhang et al. (1999)	1.18–1.40				
Irrigated winter wheat	North China plain	Jin et al. (1999)	1.49–2.30				
Irrigated winter wheat	North China plain	Zhu et al. (1994)	1.48				
Rain-fed winter wheat	Hebei province	This study	0.20–0.87	0.65	0.23	0.18	0.91
Rain-fed winter wheat	Hebei province	Mo et al. (2005)	0.05–0.83				
Irrigated winter wheat	Hebei province	This study	0.68–1.63	1.42	0.32	0.18	2.20
Irrigated winter wheat	Hebei province	Mo et al. (2005)	1.23–1.58				
Winter wheat	Hebei province	McVicar et al. (2002)	0.12–2.15				
Rain-fed winter wheat	Beijing city	This study	0.60–0.73	0.66	0.05	0.68	0.81
Irrigated winter wheat	Beijing city	This study	0.89–1.60	1.30	0.21	0.69	1.80
Winter wheat	Beijing city	Zhang et al. (1998)	0.93–1.55				
Irrigated winter wheat	Changwu station	This study		0.76			
Irrigated winter wheat	Changwu station	Li et al. (2000)	0.65–1.21				
Irrigated winter wheat	Changwu station	Kang et al. (2002)	0.77–1.46				
Irrigated winter wheat	Luancheng station	This study		1.37			
Irrigated winter wheat	Luancheng station	Zhang et al. (2004)	1.01–1.61				
Irrigated winter wheat	Luancheng station	Zhang et al. (2003)	1.28–1.82				
Irrigated winter wheat	Luancheng station	Wang et al. (2001)	1.08–1.28				

[a] Defined as the 5 and 95 percentile of the entire range for "this study"

in the same range. Zhang et al. (1999) gave a similar upper limit, 1.40, while Jin et al. (1999) reported one of 2.30. Compared to the data reported, the lower limit of CWP in our study is relatively small. The reason is that our study covers the entire NCP provinces, whereas most others dealt with some specific sites.

In Hebei province, an important winter wheat producing province in China, the simulated upper and lower values of CWP under irrigated conditions were 0.68 and 1.63, respectively (Table 4). These are both in the range reported by McVicar et al. (2002) for the same province. The simulated CWP of rainfed winter wheat ranged between 0.20 and 0.87 kg m^{-3}. The results compare well with Mo et al. (2005) for the Hebei province (Table 4).

Impacts of irrigation reduction on winter wheat production and policy implications

Irrigated winter wheat production is the largest water user in the NCP (Shi and Lu 2001; Xu et al. 2005). The excessive water consumption has led to a series of environmental problems including a drop in the regional groundwater table at an alarming rate (Liu and He 1996; Wang et al. 2001). For example, Shijiazhuang, the capital city of Hebei province, has experienced an annual decline in the shallow groundwater table by 1.0–1.2 m since the 1990s (Xu et al. 2005). With the rapid economic development in the region, the water demand by industries and domestic users will continuously put pressure on irrigation water supply. The serious environmental problems caused by excessive water withdrawal have called for urgent measures to halt the trend. Given the fact that irrigated winter wheat is the major water user of the region, reducing the irrigation for winter wheat would be an option to alleviate water stress (Xu et al. 2005; Shi and Lu 2001).

With the help of the GEPIC model the impacts of alternative irrigation reductions on winter wheat production are quantified. Two scenarios were proposed to assess the impacts of changes in irrigation water supply for winter wheat in the NCP provinces on regional and national wheat production.

Scenario I (S1)

Irrigation depth of winter wheat is reduced by 5–25% in the NCP provinces, while the irrigated area of winter wheat remains unchanged. The simulation is based on the assumption that the reduction of the irrigation depth is evenly distributed in each grid where irrigation is applied in the NCP provinces. This scenario leads to a reduction of irrigation water by 5–25% in the region.

Scenario II (S2)

Irrigated winter wheat area is reduced by 5–25% in the NCP provinces, and it is replaced by rainfed winter wheat area. By assuming an even distribution of the replaced irrigated area, this scenario will result in 5–25% of irrigation water reduction in the NCP provinces.

For both the scenarios, it is assumed that spring wheat sown area and its yield remain unchanged.

Under S1, when irrigation reduction is less than 20%, each percentage (1%) reduction will lead to 0.41% reduction of wheat production in the NCP provinces, or 0.17% of wheat production reduction in China. When the irrigation reduction surpasses 20%, each percentage reduction will lead to 1% of wheat production reduction in the NCP provinces, or 0.42% reduction of wheat production in China (Fig. 7). This is mainly because the impacts of irrigation reduction on yield depend upon the severity of water stress of the crop. A significant change in the production reduction rate when the irrigation reduction is over 20% indicates a water stress threshold, above which wheat yield will be seriously affected. The results suggest the importance for controlling the irrigation depth reduction rate below 20% to prevent significant wheat production losses.

Under S2, each percentage irrigation reduction will lead to 0.44% of wheat production reduction in the NCP provinces, or 0.18% of wheat production reduction in China (Fig. 7). This reduction rate remains unchanged over the range considered. The production reduction is due to the yield difference between irrigated and rainfed winter wheat in the NCP provinces.

S1 and S2 have similar effects on wheat production when the irrigation reduction rate is below 20% (see Fig. 7). When irrigation reduction is above this percentage, S2 outweighs S1. This indicates that depending on the magnitude of irrigation reduction, different measures may be taken to optimize water allocation and food production. For water savings of up to 20% irrigation water, there is no large difference between S1 and S2 for the production. If more irrigation is planned to be reduced, S2 will be more efficient than S1 since S2 reduces wheat production less with the same water saving.

Within the NCP, the Haihe River Basin is the most water stressed area. The basin primarily includes Hebei and two mega cities, Beijing and Tianjin. With only 1.0% of China's water resources and some 3.3% of China's total areas, the Haihe River Basin accounts for about 10% of the national population, 15% of China's industrial production, and 10% of the total agricultural output (Yang and Zehnder 2002). However, water scarcity has imposed an increasing constraint to the economic development in the region (Yang and Zehnder 2005). Based on the most authoritative projection by the Chinese Academy of Engineering and the Chinese Academy of Sciences, water demand will increase by 1.38 and 1.15 billion m^3, respectively, in the industrial and domestic sectors in the Haihe River Basin in the first decade of the twenty first century (Pan and Zhang 2001). This increased water demand could be met by a reduction of irrigation water supply by 20%, which represents a release of 2.66 billion m^3 of water from irrigation. The GEPIC simulation suggests that this will lead to about 3.5% reduction of the national wheat production, either by implementing deficit irrigation (S1) or by changing irrigated winter wheat into rainfed winter wheat. In other words, the projected water demand increment in the industrial and domestic sectors in the Haihe River Basin may be compensated with a relatively small percentage decrease in wheat production in the country.

Conclusion

The GEPIC model provides a systematic way to estimate crop yield, crop water productivity and irrigation for winter wheat across regions with relatively high spatial resolution. It is also capable of simulating the impacts of changing water situation on wheat production, and thus can be a useful tool for supporting policy making in integrated water resources management in

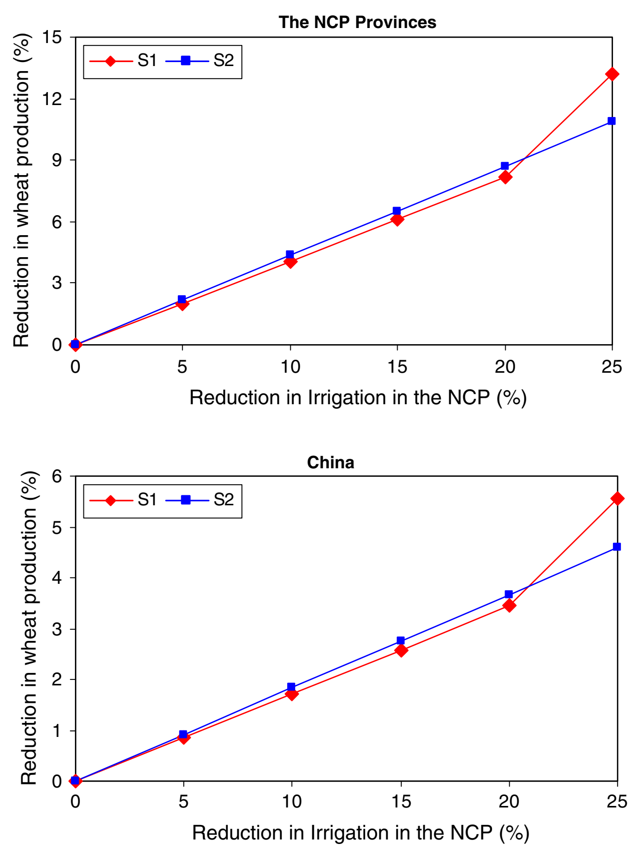


Fig. 7 Relations between reduction in irrigation in the NCP and reduction in wheat production

China as well as in other countries and regions in the world.

Irrigation has played an important role to improve CWP in the NCP and the Northwest provinces. The simulation results showed that, in the NCP provinces, CWP under irrigated conditions was 56% higher than that under rainfed conditions. However, the intensification of water stress has raised a need to consider alternatives for irrigating winter wheat. Water savings are possible by either reducing irrigation water supply or by reducing heavily irrigated areas by those using less irrigation. Up to 20% of reduction of irrigation water supply, simulations provide very similar results for both scenarios. However, above 20% reduction, the replacement of irrigated by rainfed areas causes a lower loss of production with the same amounts of irrigation water reduction.

It needs to be pointed out that the analysis of trade-offs in the two scenarios in this study is far from comprehensive. First, the reduction in irrigation depth or irrigated area may likely occur in the areas where irrigation is less important in improving winter wheat yield. The irrigation depth in these areas is likely small. In this case, the effects of a given percentage reduction in irrigation depth or irrigated area on the national winter wheat production would be less significant than that simulated here. However, the amount of irrigation water saving would also be smaller. Second, the automatic irrigation and fertilization option may lead to an overestimation of crop yields and CWP by assuming that local farmers have perfect knowledge in water and fertilizer management. The timing of irrigation and fertilization can affect crop yields and CWP and therefore requires further analysis. To do this, further detailed input data on water and fertilizer management is necessary for each county. Third, when comparing the benefits and costs of different scenarios, many additional factors also need to be considered, typically farmers' income, rural employment, social stability, food security, and the environmental impact of irrigation, etc. A comprehensive assessment integrating economic and social issues is necessary for the future research to better understand the pros and cons of different scenarios.

The accuracy of the GEPIC outputs largely depends on the quality of the input data. Although the validation has shown that GEPIC generally performed well in simulating crop yield and CWP in China, large discrepancies still existed between the simulated and statistical values in many counties. The errors in the inputs and the assumptions made in this study partly contributed to the errors of the outputs. For example, the estimation of the nitrogen fertilizer rate per hectare is extremely rough, and may lead to large fertilizer input errors. The default crop parameters cannot exactly reflect the crop characteristics in China. The assumption that the farmers optimize the use of water and nitrogen is also far from the reality. Apart from water and nutrient, some other factors like pest and diseases may also pose constraints to crop growth. Although EPIC has a generic pest component for simulating insect and disease damage and a weed competition component, the function is difficult to apply on a national scale due to the lack of the necessary information. Access to the more detailed datasets will improve the accuracy of the simulation results.

In this study, we estimate the irrigation depth indirectly by comparing simulated and statistical yield data. This method is based on the assumption that all the inputs like soil parameters, fertilizer application rates, crop calendar are accurate. The results can be affected by the uncertainty of these inputs. Besides, other factors such as pest and disease infestations can influence crop yield. We did not integrate the effects of these factors. This may lead to underestimation of irrigation depth. However, as long as the data base on these factors is weak, the possibility of uncertainties reduction remains limited.

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