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Winter wheat yield potentials and yield gaps in the North China Plain

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ABSTRACT

The North China Plain (NCP) is the most important wheat production area in China, producing about two-thirds of China's total wheat output. To meet the associated increase in China's food demand with the expected growth in its already large population of 1.3 billion and diet changes, wheat production in the NCP needs to increase. Because of the farmland reduction due to urbanization, strategies for increasing wheat production in the NCP should be targeted at increasing current yields. To identify options for increasing wheat yields, we analyzed the yield potentials and yield gaps using the EPIC (Environment Policy Integrated Climate) model, Kriging interpolation techniques, GIS and average farm yields at county level. As most (ca. 82%) of the winter wheat in the NCP is irrigated, it is justified to use potential yield as the benchmark of the yield gap assessment. Wheat potential yields simulated with EPIC using daily weather data from 1960 to 2007 at 43 representative sites varied from 6.6 to 9.1 t ha^{-1} in the NCP, generally increasing from north to south associated with decreasing low temperature stress. Based on the county-level data (2004–2007), the actual wheat yield varied between 2.4 and 7.7 t ha^{-1}, while the yield gap was between 0.6 and 5.3 t ha^{-1} (7–69% of the potential yield) across the NCP and decreased with increase of actual yields (R^2 = 0.82). For the entire region, the weighted average actual yield was 5.7 t ha^{-1}, while the yield gap was 2.7 t ha^{-1} or 32% of the potential yield. Using 80% of the potential yield as an exploitable level, the average actual wheat yield in the NCP could be increased by 1.0 t ha^{-1} or 18%. The results provide an indication of the possibilities to increase wheat yields in the NCP.

1. Introduction

Food security is a major policy concern in China because of its large population of over 1.3 billion that needs to be fed, while arable land resources are limited and decreasing. In 2008, China's farmland area was 121.7 Mha or 0.09 ha per capita, which was 6.5% less than in 1996 due to urban expansion and the conversion to forestland or grassland for ecological conservation. With increasing urbanization and socioeconomic development, China's farmland is expected to further decrease (Fu et al., 2001; Lu et al., 2007), while food demand is expected to increase due to population growth and diet changes. To secure food supply, China must improve the productivity of current arable land, but what are the production potentials of China's farmland in relation to current crop yields? To answer this question the actual and potential or exploitable yields (van Ittersum et al., 2013) needs to be assessed, allowing analysing the yield gap, i.e. the difference between potential (or exploitable) and actual yields. The yield gap concept has been applied in many recent studies (e.g. Shrivastava et al., 1997; Casanova et al., 1999; Bhatia et al., 2008; Lobell et al., 2009; Neumann et al., 2010; Liu et al., 2011) as an indicator for the possibility to increase crop yields in a given region.

Winter wheat (*Triticum aestivum*) is a major staple food crop in China. In 2009, China produced 115 million tonnes of wheat, which was 24% of the total production of food crops including rice, wheat, corn, soybean and potatoes. The North China Plain (NCP) is the most important wheat growing area in China, producing about two-thirds of the total wheat production and thus is a key region in securing national food supply. To increase wheat production in the NCP, the productivity per unit of area must be increased because of the limited scope for expansion of farmland. As elsewhere in China, farmland has decreased during the past decades and is expected to further reduce in the near future as a result of urbanization (Lu and Wang, 2011). As most of the winter wheat area in the NCP is irrigated, the potential yield is a relevant benchmark of the yield gap assessment (see also next section).

Available information from experimental data and the literature indicates that NCP has a potential to increase wheat yield. Results from several crop simulation studies show that potential yields of winter wheat in the NCP vary spatially between 6.4 and 10.2 t ha^{-1} (Wu et al., 2006; Wang et al., 2008, 2010; Chen et al., 2011), which is much higher than the actual yields. However, previous studies mainly focused on the assessment of potential yield, and lacked a systematic and spatial analysis of actual yields and yield gaps at

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county level. To contribute to a better quantitative understanding of the options to increase wheat production in the NCP, we first quantify potential yield of winter wheat using the simulation model EPIC (Williams et al., 1990, 2008). Second, we estimate the yield gap between potential and actual wheat yields at county level.

2. General description of NCP

The NCP (31.9–39.8°N and 112.0–122.5°E) covers the entire Tianjin municipality, the southern part of Beijing municipality, a major part of Hebei, Shandong and Henan provinces, and the northern part of Jiangsu and Anhui provinces (Fig. 1). It comprises about 340 administrative counties with a total population of about 260 M. The total land area is 40.4 Mha, of which 72% is farmland, 14% built-up land, 8% forestland and grassland, and 6% water bodies or no-used land, based on recent land use data interpreted from remote-sensing imagery. Of the total farmland, about 82% had access to irrigation in 2007 according to the available data from local yearbooks. In 2009, NCP produced around 195 Mt of food grains, which is about 40% of the total output in China (estimated based on the statistical data). Winter wheat and summer maize are the most important crops, normally grown in a double crop rotation using irrigation. Due to over-exploitation of groundwater for irrigation, NCP suffers from serious groundwater depletion. Periodically water shortage in the NCP is an important constraint in achieving high crop yields.

Long-term average annual air temperature in the NCP ranges from 10.7 to 16.0 °C, increasing from north to south (Fig. 2a), and average annual precipitation ranges from 562 to 1392 mm, increasing from northwest to southeast (Fig. 2b). Affected by a monsoon climate, above 50% of the annual precipitation (50–60% in the southern part, 60–75% in the middle part and 75–83% in the northern part) is distributed in the rainy season from June to September. Formed on fluvial materials from the Hai River, the Yellow River and the Huai River, prevailing soils have a deep profile and a loamy texture and they are very fertile and suitable for arable farming.

3. Methods and data sources

Yield gap (Y_g) in this study was defined as the difference between potential yield (Y_p) and actual yield (Y_a) of winter wheat, expressed as t ha^{-1} ($Y_g = Y_p - Y_a$) and as percentage of the potential yield ($Y_g/Y_p \times 100$). Both potential yield and actual yield were expressed as fresh weight with a dry mater content of 87% according to Chinese standards for wheat storage. Potential yield refers to the yield a crop can attain when water and nutrients are fully supplied, pests and weeds completely controlled, and farming technique and management are optimized (van Ittersum and Rabbinge, 1997). Actual yield is the yield achieved in a specific year or period with current production techniques and management at farm or regional level. In this study, potential yields of winter wheat were simulated with the EPIC model, and actual yields were collected for each county from the local yearbooks. The study procedure started with testing of the model, followed by simulation of potential yields, estimation of yield gaps and mapping of the results.

3.1. Experimental data and model calibration

EPIC is a simulation model validated and widely used in the USA and in many other countries in the world (Gassman et al., 2005). It has also been tested and used in China for simulating yield and water consumption of different crops (Lu et al., 2003; Liu, 2007; Wang and Li, 2009), wind erosion (Wang et al., 2002), soil organic carbon dynamics (Li et al., 2003; Thomson et al., 2006) and the effects of climate change on crop yields (Chavas et al., 2009). EPIC consists of nine sub-models to simulate major biophysical processes including plant growth and crop yield, nutrient cycling, soil temperature, hydrology, water and wind erosion, and crop and soil management (Williams et al., 1990). The plant growth sub-model simulates daily increase of biomass, light interception, leaf area growth and senescence, nutrient uptake, and partitioning of dry matter among roots, shoots, and grain yield of a crop from planting/emergence to maturity in a daily time step.

Observed data for EPIC calibration and testing were collected from well-controlled field experiments at the Yucheng Comprehensive Experimental Station (36.93°N, 116.63°E) and the Shangqiu Agro-ecosystem Observation Station (34.59°N, 115.58°E) (Fig. 1). Yucheng station has an annual temperature of 13.1 °C and precipitation of 593 mm, and Shangqiu station has an annual temperature of 13.9 °C and precipitation of 708 mm. Soils at both stations are very deep with a similar homogenous loamy texture. For instance, at Yucheng station, the soil is characterized by a texture comprising about 70% silt and 20% sand, bulk density of 1.45 g cm^{-3}, field capacity of 25.6 m m^{-1}, cation exchange capacity of 13.2 cmol kg^{-1}, organic carbon content of 0.32% and pH of 8.4 (mean values for the upper 1 m soil layer).

The observed crop, management and weather data were collected for the growing periods of 2003/2004 and 2004/2005 at Yucheng station, and 2006/2007 at Shangqiu station. The collected data included sowing and harvest dates, leaf area index (LAI), aboveground biomass, grain yield, and farming operation dates (tillage, application of irrigation, fertilizers and pesticides, etc.) as well as daily maximum and minimum air temperature, rainfall, wind speed, relative humidity and sunshine hours. Solar radiation was based on the daily sunshine hours and the Angstrom-Prescott equation (Li et al., 2004; Williams et al., 2008). At both experimental stations, irrigation, fertilizers and pesticides were applied to maintain an optimal condition for winter wheat growth and to control diseases and weeds. Table 1 presents the dates and amounts of fertilization and irrigation during the experimental periods.

The model calibration was conducted in three steps. First, crop parameters were modified based on the observed data from Yucheng station including harvest index (HI), maximum leaf area index, maximum rooting depth, potential heat units from emergence to maturity (PHU),[1] the first and second point on the optimal development curve of leaf area (DLP1, DLP2), and the point when LAI starts to decline (DLAI). Second, the same modified parameters were used to simulate wheat growth for 2003/2004 and 2004/2005 at Yucheng station and for 2006/2007 at Shangqiu station with the observed (daily) weather, soil and management data (Table 1). The simulations started from the sowing date and ended at maturity when the accumulated temperature sum reaches PHU. Finally, the simulated results of LAI, aboveground biomass and grain yield were examined by comparing with the observed data and by regression analyses and the root mean square error (RMSE).

3.2. Data sources and quantification of potential yield in the NCP

Weather data including daily rainfall, minimum and maximum air temperature, relative humidity, wind speed, and sunshine hours (for estimating solar radiation) from 1960 to 2007 were collected for 43 representative meteorological stations in the NCP (Fig. 1) from the China Meteorological Administration. Crop parameters including PHU were based on the calibration results as described

[1] For winter wheat, the PHU is actually the total temperature sum required for maturity after the winter dormancy, as the temperature sum before and during the dormancy is set to 0 in EPIC and recalculated after the dormancy (Williams et al., 2008).

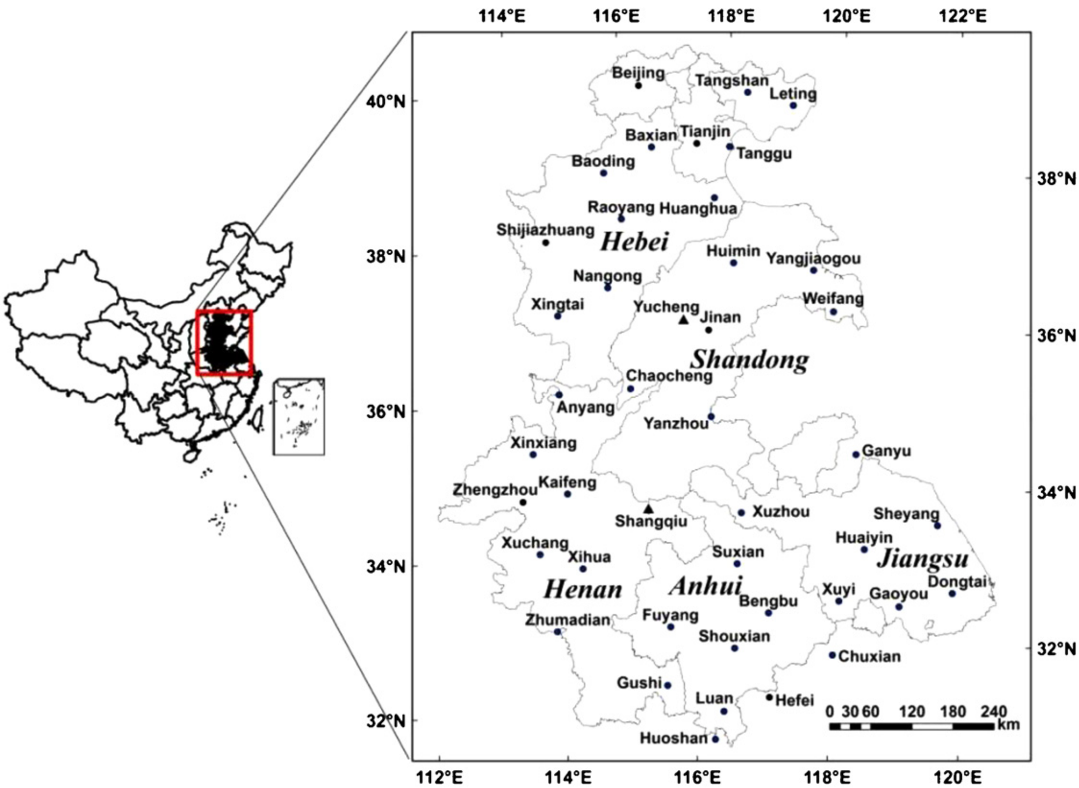

Fig. 1. Location of the North China Plain and the 43 representative meteorological stations.

in Section 4.1. For reasons of simplicity and comparability, it was assumed that the required temperature sum from emergence to maturity, i.e. PHU, was the same for winter wheat throughout the NCP. Sowing/harvest dates vary regionally associated with temperature differences and range from early October/late June in the north to late October/early June in the south of NCP. Based on observation data from wheat yield experiments during 2005–2010 at 36 sites across the NCP (CAESC, 2010; CAESC and WRC-HAAS, 2006, 2008), the sowing date was set at 5th October in the north and 25th October in the south (Table 2). The growing period of winter wheat is expected to end before July in the north and before middle June in the south based on the given PHU. A temperature sum of 100 °C with the base temperature of 0 °C was used to calculate the date of wheat emergence. In addition, a minimum data set for soil profile properties and for crop management was prepared for all sites to meet model requirements, as both factors do not affect simulation results of potential yields.

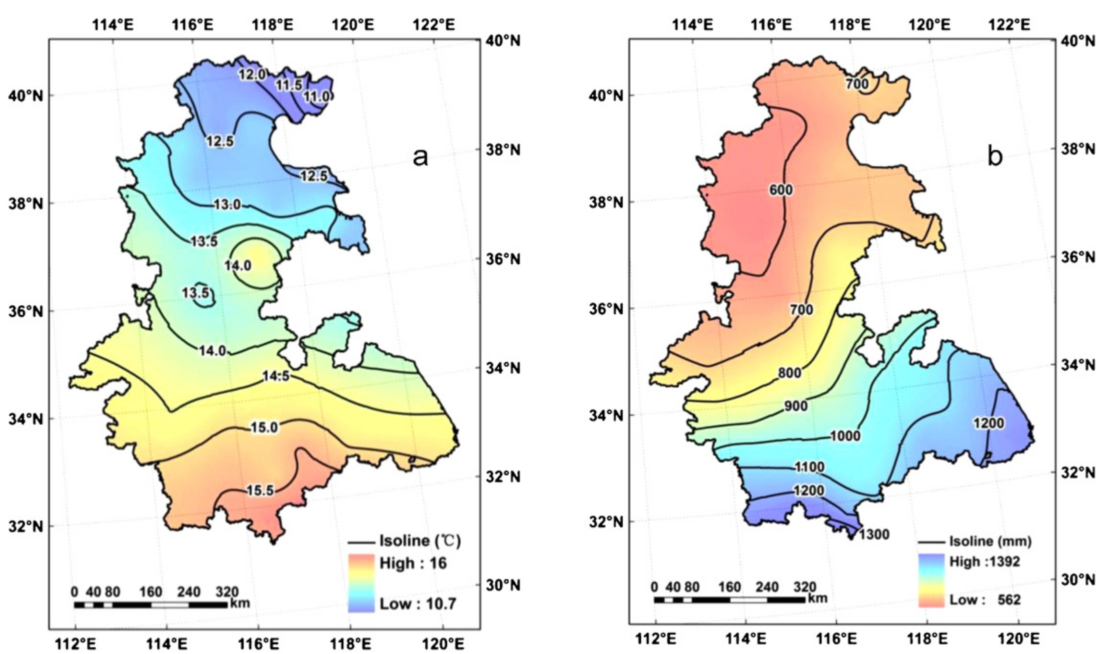

Fig. 2. Spatial distribution of long-term average annual temperature (a) and precipitation (b) from 1960 to 2007.

Table 1
Dates and application amounts of fertilizers and irrigation at Yucheng and Shangqiu stations.

Station	Fertilization		Irrigation	
	Date	Amount (kg/ha)	Date	Amount (mm)
Yucheng	October 13, 2003	142.5 N, 112.5 P, 75 K	March 13, 2004	150
	March 13, 2004	207 N	April 17, 2004	150
	October 8, 2004	187.5 N, 60P, 52.5 K	March 30, 2004	150
	March 30, 2005	84 N, 18 P, 18 K	May 2, 2005	150
Shangqiu	October 15, 2006	90 N, 30 P, 30 K	February 20, 2007	120
	March 23, 2007	45 N, 15 P, 15 K	March 30, 2007	120

Table 2
Assumed sowing dates of winter wheat for different sites in the NCP.

Sowing date	Station
October 5	Bejing, Tangshan, Leting, Baoding, Bazhou, Tianjin, Tanggu
October 8	Shijiazhuang, Raoyang, Huanghua, Xingtai, Nangong, Huimin, Yucheng, Jinan, Yanjiaogou, Weifang
October 10	Anyang, Xinxiang, Zhengzhou, Kaifeng, Chaocheng, Yanzhou
October 15	Xuchang, Xihua, Zhumadian, Shangqiu, Fuyang, Bengbu, Xuzhou, Suxian, Ganyu
October 25	Gushi, Luan, Shouxian, Hefei, Huoshan, Chuxian, Gaoyou, Dongtai, Xuyi, Huaiyin, Sheyang

An EPIC database was built comprising sowing dates, weather, soil and crop management data. The simulations were carried out with water and nutrient in sufficient supply to meet crop demand (determined by the model). Simulations started at the sowing date and stopped at physiological maturity. In the northern part of NCP, temperature conditions are marginally suitable for growing two crops of wheat and maize in one year. In this study, the given wheat sowing dates were based on observation data from experiments at or near the representative stations (Table 2), which are generally comparable to the current practice of winter wheat. The wheat growth duration was determined by the given PHU to obtain a maximum yield regardless of the effect on maize yield in the prevailing wheat–maize double crop rotation. When simulated wheat growing period exceeds the limits for the double crop rotation, summer maize can be grown with an early maturity variety or inter-planted in the wheat field before the harvest as is happening in practice. For each of the stations, simulations of the potential yield were done for 47 years (from October 1960 to June 2007).

3.3. Actual yield data and yield gap estimation

Actual yields were based on statistical data at county level for the period 2004–2007, which were collected from the local yearbooks of Beijing and Tianjin municipalities, and Hebei, Henan, Shandong, Anhui and Jiangsu provinces. Potential yields at the county level were estimated by interpolation and map calculation using ArcGIS 9.3 software based on the simulated results of all sites for the period 2004–2007. First, simulated potential yields of 2004 at 43 sites were interpolated and converted into a grid map using the ordinary Kriging method. Second, in combination with the county map, the potential yields at county level in 2004 were calculated using the tool/command of "zonal statistics as table". Third, the same procedure was applied for the years 2005, 2006 and 2007. Finally, the tables were imported to Microsoft EXCEL to calculate the average potential yields of the four years for each county.

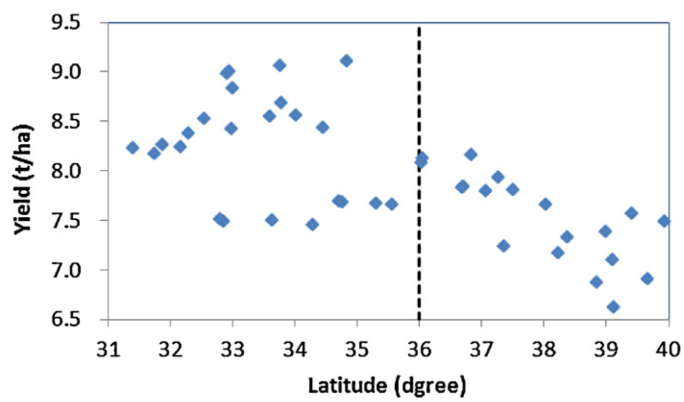

Fig. 3. Variation in average potential wheat yields of 47 years with latitude.

Per county, the average yield gap was calculated using the average potential and actual yields of 2004–2007. For the entire NCP, the yield gap was calculated using the weighted average potential and actual yields (Y_{reg}) calculated with: $Y_{reg} = (Y_i \times SA_i)/\Sigma SA_i$, where Y_i and SA_i are potential or actual yield (t ha^{-1}) and wheat sowing area (ha) in county i, respectively.

3.4. Mapping spatial distribution of wheat yields and yield gaps

A GIS database was built comprising actual wheat yields from 2004 to 2007 for all counties involved, daily weather data and annual potential yields from 1960 to 2007 for the representative meteorological stations, as well as spatial data of land use, soil and administration borders. With this database, the spatial distribution of temperature, precipitation, potential yield and their variations were mapped using the ordinary Kriging method in ArcGIS 9.3. Actual yields and yield gaps were mapped at county level.

Table 3
Calibration results of the EPIC model at two experimental stations in the NCP.

Site	Year	Grain yield (t ha^{-1} in dry matter)		Simulated LAI vs. measured		Simulated biomass vs. measured	
		Measured	Simulated	R^2	RMSE	R^2	RMSE
Yucheng	2003/04	6.94	7.05	0.95	0.84	0.98	1.18
	2004/05	5.70	5.55	0.92	1.48	0.99	1.95
Shangqiu	2006/07	6.97	6.70	0.86	3.60	0.96	2.0

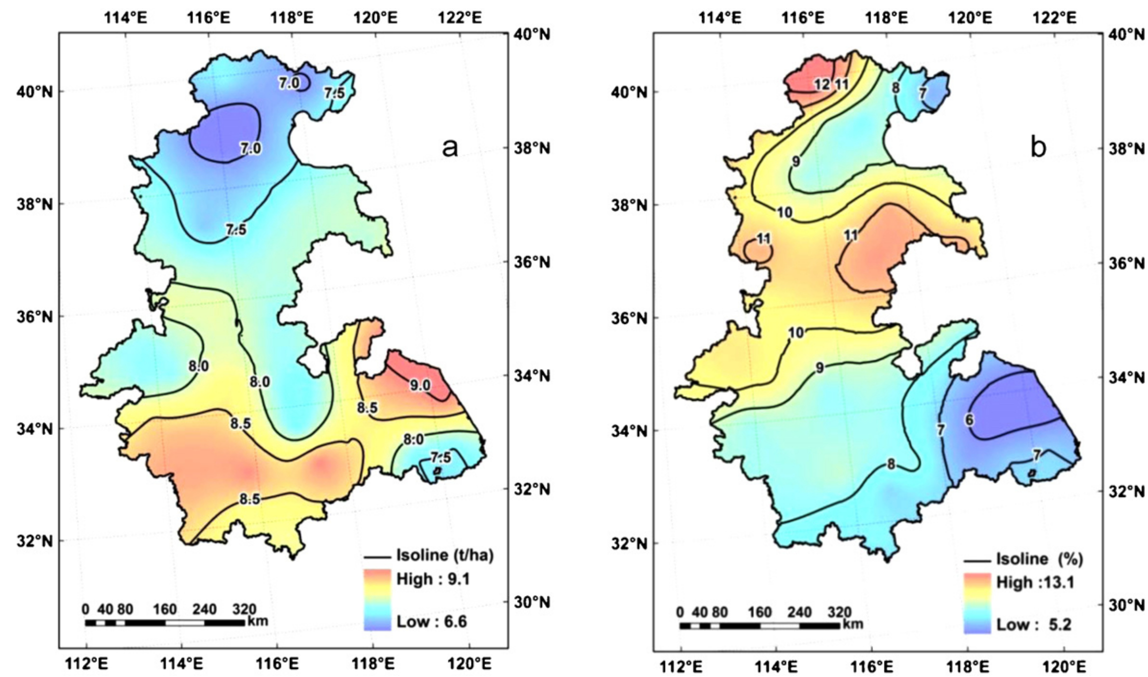

Fig. 4. Spatial distribution of average potential wheat yields (a) and Coefficient of Variation (CV) (b) from 1960 to 2007.

4. Results

4.1. Model calibration results

The PHU for winter wheat calculated by EPIC was 1755 °C based on the observed emergence and maturity dates at Yucheng station, which is representative for the wheat varieties grown in the NCP. Using observed wheat sowing/emergence and maturity dates and daily weather data in 2006 and 2007 at or near each of 36 representative stations (i.e. most stations in Table 2), the PHU calculated with EPIC ranged from 1668 to 1800 °C, while the average was 1758 °C. These estimated values of PHU differed between −5.0 and 2.6% from the above value of 1755 °C. The parameters DLP1, DLP2 and DLAI, which control LAI development, were adjusted to 15.25, 40.95 and 0.55, respectively. HI was adjusted to 0.47, optimal temperature to 16 °C, and maximum rooting depth to 2 m, based on the observed data and literature (Wang et al., 2010). All other crop parameters of winter wheat were as in the original EPIC version 0810.

Simulated LAI, total aboveground biomass and grain yield of winter wheat were used to test the model performance (Table 3). At Yucheng station, simulated LAI and aboveground biomass were highly correlated with measured data (coefficient of determination, R^2 = 0.92–0.99) with the RMSE between 0.8 and 2.0. The model generally simulated wheat growth well in terms of LAI and biomass, but simulated values did not always match with the measured data at all stages of the growing period. For LAI, simulated results fitted well with the observed data during the decreasing in LAI of 2003/2004, and before the leaf area decreased in 2004/2005. Biomass was overestimated during the early stage of development but close to the measured values during the grain-filling stage (in May) of 2003/2004, and it was generally underestimated during the entire growing period of 2004/2005. Simulated grain yields were 1.6% higher and 2.6% lower than the measured yields in 2004 and 2005, respectively. At Shangqiu station, simulated LAI did not match well with the measured values (the measured LAI seemed inaccurate with 2 measured values of 9.7 and 14.6), but simulated biomass fitted better with the RMSE of 2.0 t ha^{-1} (dry matter) (Table 3). The yield at this station was slightly underestimated, i.e. 3.9% lower than measured. In general, the model performance was very good in predicting the grain yield, although the simulated LAI and biomass had some deviations from the measured data.

4.2. Potential yields and the spatiotemporal variation

Long-term average potential yields during 1961–2007 at the 43 sites varied between 6.6 and 9.1 t ha^{-1} (Figs. 3 and 4a), and the temporal variation as indicated by the coefficient of variation (CV) was between 5 and 13% over the NCP (Fig. 4b). For the entire NCP, the weighted average potential yield based on the wheat sowing area in 2007 was 8.0 t ha^{-1}.

Average potential yield showed an increasing trend from north to south in the most of NCP except the humid southern part (Fig. 4a), but the CV showed a decreasing trend from north to south and from west to east (Fig. 4b). In the northern part of NCP (north of 36°N), potential yields varied from 6.6 to 8.2 t ha^{-1}, showing an apparent increasing trend with decreasing latitude (Fig. 3), and the CV was mostly above 10% except in the northeastern part where the CV was much lower (Fig. 4b). In the southern part (south of 36°N), wheat potential yields were between 7.5 and 9.1 t ha^{-1} and showed a weak declining trend with decreasing latitude (Fig. 3). The temporal variation decreased from northwest to southeast in the southern part, with a CV mostly below 9%, much lower than that in the northern part (Fig. 4b).

The regional distribution of potential yields was largely affected by the spatial variation in temperature, particularly the frequency in cold temperature stress (daily air temperature below 0 °C).[2] In NCP particularly in the north, low temperatures in winter and early

[2] In EPIC, two factors are defined and calculated daily to account the effects of temperature stress on crop growth, i.e., the cold temperature reduction factor (FTM, for the dormancy period) and temperature stress factor (TS). For TS, it is defined as a function of RTO, i.e. the difference between daily air temperature and the base temperature to the optimal temperature, calculated with: TS = sin (1.5707 × RTO) when 0.0 < RTO < 2.0, or TS = 0.0 when RTO < 0.0 or RTO > 2.0. For FTM and for details, see Williams et al. (2008).

spring are important stress factors affecting wheat growth, and often cause damage or even death of wheat plants and thus causing yield reduction (Li et al., 2005; Dai et al., 2010; Wang et al., 2011). Because of an increase in annual temperature (Fig. 2a), the duration and severity of low temperature stress gradually decrease from north to south. Statistical results based on the daily weather data showed that the total number of days with temperatures below 0 °C during the winter wheat growing period ranged from 11 days in the south to 88 days in the north. A regression analysis indicated that the potential yield was negatively related to the total number of days with low temperature (R^2 = 0.47).

4.3. Actual yields and yield gaps

Average wheat yield at the county level between 2004 and 2007 ranged from 2.4 to 7.7 t ha^{-1} in the NCP (Fig. 5), while the weighted regional average was 5.7 t ha^{-1}. In 80% of the wheat area, yields were above 5.0 t ha^{-1}, and in 34% of the area mainly in the center of the NCP including southern Hebei, Shandong and northern Henan provinces, yields exceeded 6.0 t ha^{-1}. In 20% of the wheat area yields were between 3.4 and 5.0 t ha^{-1} (except for Haixing County with a yield of 2.4 t ha^{-1}), and this area comprised mainly of the lowland areas in the eastern coastal zone, Cangzhou Prefecture in southeastern Hebei, and some counties in the southern NCP (including southern Henan and Anhui provinces). Generally, the current productivity of winter wheat was much higher in the center than the southern and northern parts of NCP (Fig. 5).

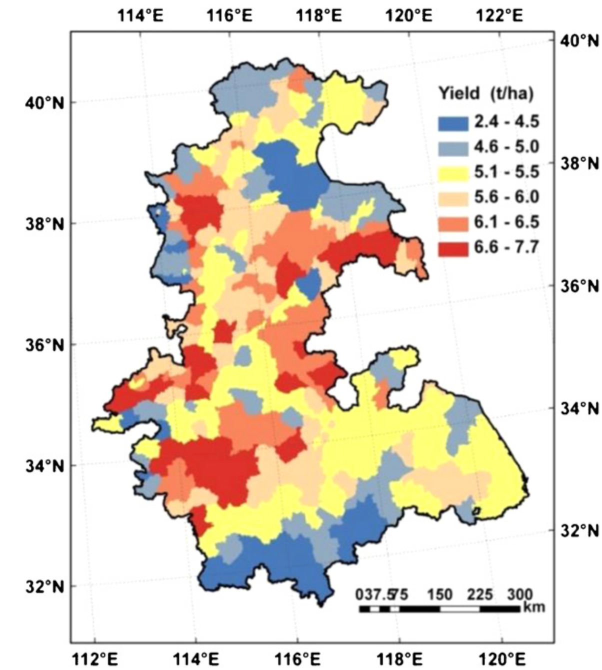

Fig. 5. Spatial distribution of average actual wheat yields during 2004–2007.

Regional variation in actual wheat yield was mainly associated with crop management and soil properties. The center of NCP is traditionally the main wheat production area facilitated by well-developed irrigation systems, good management and high soil quality. In the areas including Cangzhou Prefecture and the coastal areas, low yields were mainly due to adverse effects of soil salinization. In the narrow zone in the southwestern NCP, land comprises not only plain, but also hilly areas where wheat yields are low (less than 4.5 t ha^{-1}) due to inadequate crop management and little irrigation. Most of the irrigated plains are used for growing rice while wheat is mainly grown in the hilly area. Labor shortage as a result of rural labor migration to urban areas or allocated to more profitable vegetable production could also adversely affect the wheat management and thus yields, particularly near urbanized areas such as Beijing, Tianjin, Jinan, Zhengzhou and Tangshan.

Average potential yield during 2004–2007 varied between 7.5 and 8.8 t ha^{-1} across the counties and the weighted regional average was 8.4 t ha^{-1}, 5% higher than the long-term average (see before). The mean yield gap at county level varied between 0.6 and 5.3 t ha^{-1}, i.e. between 7 and 69% of potential yields. The weighted regional average yield gap was 2.7 t ha^{-1} or 32% of the weighted average potential yield. The yield gap differed regionally (Fig. 6): in about 40% of the NCP mainly in Henan, Shandong and Southern Hebei provinces, the yield gap was less than 2.5 t ha^{-1}, or 30% of the potential yield. In 40% of the NCP, the yield gap was between 2.6 and 3.5 t ha^{-1}, or between 30 and 40% of the potential yield. In the rest of NCP mainly in the southwestern part, the yield gap was

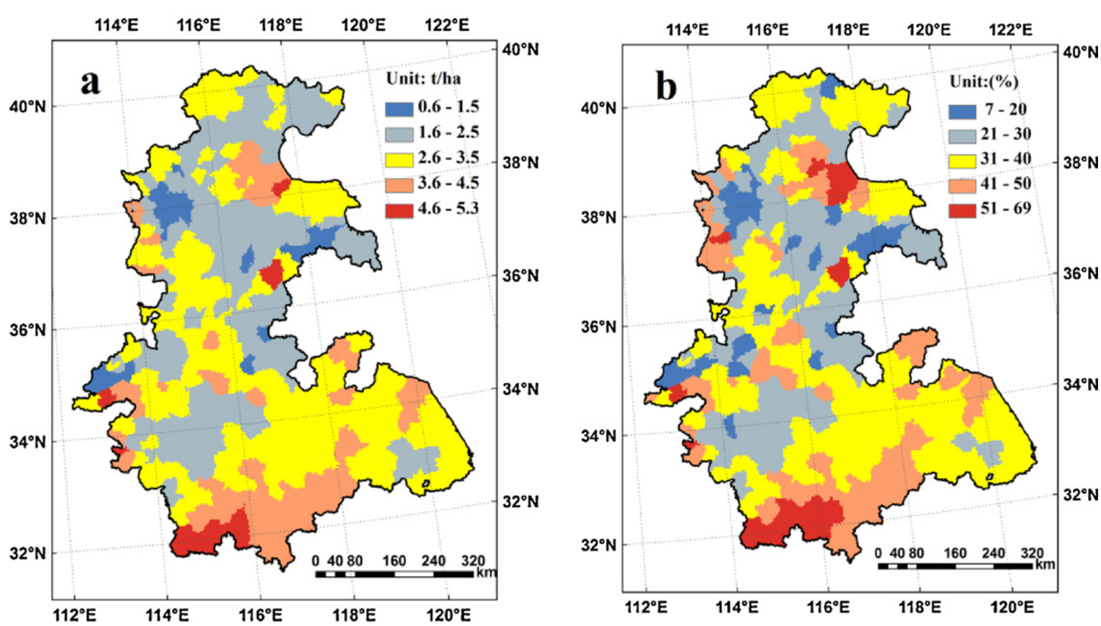

Fig. 6. Spatial distribution of average yield gaps (a: as t ha^{-1} and b: as % of potential yield) during 2004–2007.

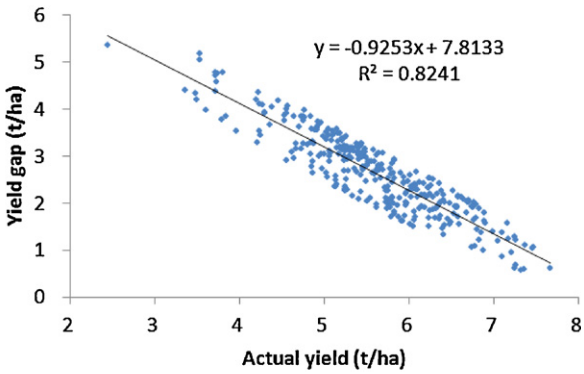

Fig. 7. Relationship between average county-level yield gaps and actual yields during 2004–2007.

large, i.e. between 3.6 and 5.3 t ha^{-1} corresponding with 40–69% of the potential yield, indicating options for increasing current winter wheat yields. Spatial variation in yield gaps was greatly determined by regional distribution of actual yields. Regression analysis of the yield gaps and actual yields using the mean county-level data indicated that both were inversely correlated (Fig. 7, $R^2 = 0.82$). This means that the actual yields explained 82% of the spatial variation. The results imply that NCP areas with low actual wheat yields have a high probability of large yield gaps and large potentials to increase current yields.

5. Discussion and conclusions

Quantitative information on yield potentials and yield gaps is useful for developing strategies to improve crop productivity for securing food supply. This paper presented quantitative analyses on yield potentials and yield gaps of winter wheat and their spatiotemporal variation in the NCP using crop modeling and GIS-based spatial interpolation approaches. Results were presented in various maps to explicitly indicate spatial variation supporting the identification of hot spots, i.e. areas with high potentials to increase current winter wheat yields.

Long-term average potential yields in the NCP varied spatially from 6.6 to 9.1 t ha^{-1}, while the weighted average was 8.0 t ha^{-1} for the entire NCP. Expressed as percentage of the potential yield, the yield gap varied between 7 and 69%, but in a major part of the NCP it was between 20 and 50%. The southern part of NCP with a humid climate had higher yield gaps and thus higher potentials to increase wheat yield (Fig. 4a). For the entire NCP, the potential to increase current yields was 2.7 t ha^{-1} or 47% of the average actual yield (5.7 t ha^{-1}) during 2004–2007. However, the yield increase would be less than 1.0 t ha^{-1} or 18% of the average actual yield, if 80% of the yield potential can be exploited. As Lobell et al. (2009) pointed out by reviewing the magnitude and causes of yield gaps for rice, wheat and maize in major global crop regions, crop yields hardly exceed 80% of their yield potential.

The results suggest that some potential exists to increase wheat production in the NCP, particularly in the areas with high yield gaps, e.g. the humid southern part. To exploit existing yield potentials various strategies are needed. The most important one is to improve the use efficiency of irrigation and fertilizers by good farming practices, such as timely applications of irrigation and fertilizers based on crop requirements and soil conditions (Liang et al., 2011; Liu et al., 2011). Second is to promote farmers to use water-saving techniques such as residue mulching (Wang et al., 2001) and sprinkler irrigation (instead of furrow irrigation) to deal with the increasing water shortages in the NCP. Third is to improve the agro-technical service provision and government support, helping farmers to adjust their crop management and adopt more sustainable farming practices. Last but not least is the development of policies associated with land tenure to stimulate cooperation of individual households or allowing land transfer to merge the very small and fragmented farms (often less than 1 ha) into larger land holdings. The predominant small family farms are generally inefficient in the use of labor and other production factors such as machinery, resulting in low labor productivity and profit. Development of larger scale farming to promote integrated and efficient use of irrigation, machinery and labor resources could alleviate increasing labor shortages in the NCP and other rural areas of China due to migration of rural labor to urban areas.

The results of this study contribute to a better understanding of yield gaps and the potentials to increase winter wheat yields in the NCP. Due to the limited availability of data, the model was validated using data from only two experimental stations located in the center of NCP. Additional validation of the EPIC model with data from two to four other sites (particularly in the north and south of NCP) and for more years, would be worthwhile to provide stronger evidence of the utility of this model in yield gap assessment for this region. In addition, we used the same temperature sum (PHU) in all simulations, not considering changes in wheat varieties. Although the PHU for various wheat varieties grown in the NCP differs generally within a range of 5% of the given value (see Section 4.1), consideration of the variation in wheat varieties would allow a more accurate quantification of potential yields. Furthermore, more detailed farm data could support the validation of results and reveal the causes and factors affecting yield gaps. These additional validations could provide results that are more reliable for policy-makers to support the development of strategies to increase wheat production in the NCP.

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