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Quantifying production potentials of winter wheat in the North China Plain

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Abstract

The North China Plain (NCP) is one of the major winter wheat (*Triticum aestivum* L.) producing areas in China. Current wheat yields in the NCP stabilize around 5 Mg ha^{-1} while the demand for wheat in China is growing due to the increase in population and the change in diet. Since options for area expansion of winter wheat are limited, the production per unit of area need to be increased. The objective of this study is to quantify the production potential of winter wheat in the NCP taking into account the spatial and temporal variability caused by climate. We use a calibrated crop growth simulation model to quantify wheat yields for potential and water-limited production situations using 40 years of weather data from 32 meteorological stations in the NCP. Simulation results are linked to a Geographic Information System (GIS) facilitating their presentation and contributing to the identification of hotspots for interventions aimed at yield improvements. In the northern part of the NCP, average simulated potential yields of winter wheat go up to 9.7 Mg ha^{-1}, while average water-limited yields only reach 3 Mg ha^{-1}. In the southern part of the NCP, both average potential and water-limited yields are about 7.5 Mg ha^{-1}. Rainfall is the limiting factor to winter wheat yields in the northern part of the NCP, while in the southern part, the joint effect of low radiation and high temperature are major limiting factors. Temporal variation in potential yields throughout the NCP is low in contrast with the temporal variation in water-limited yields, which is especially great in the northern part. The study calls for the collection of location-specific and disaggregated irrigated and rainfed wheat yield statistics in the NCP facilitating the identification of hotspots for improvement of current wheat yields.

Keywords: Temporal variability; Spatial variability; Potential yield; Water-limited yield; WOFOST

1. Introduction

The North China Plain (NCP), located between 114–121°E and 32–40°N is the largest and most important agricultural area of China and also known as the 'Granary of China' (Fig. 1). It covers two metropolises (Beijing and Tianjin) and five provinces (Anhui, Hebei, Henan, Jiangsu, Shandong), with an area of 31 million ha of which 17.95 million ha is used for agriculture, which is 18.6% of the total agricultural area in China (Liu et al., 2001). In 2003, 51, 32 and 31% of the wheat, maize and cotton produced in China, respectively, came from the NCP, which is also a major production area for soybean and peanut.

Wheat and maize are the most important crops in the NCP, usually grown in a double cropping system of winter wheat followed by maize in the summer (Zhang et al., 2003). Annual rainfall varies between 480 mm in the north and 850 mm in the south of the NCP. Rainfall during the growing season of winter wheat ranges between 90 and 300 mm, which is much less than the estimated crop water requirements, especially in the northern plain (Zhang et al., 1999). In large parts of the NCP, supplemental irrigation with ground or surface water is used in winter wheat production. However, excessive use of groundwater for irrigation purposes is causing the decline of groundwater tables (Jia and Liu, 2002). In addition, the availability of surface water from the Yellow River decreases due to lower rainfall and heavy extraction upstream for irrigation and other purposes (Xu, 2002).

Winter wheat yields in the NCP showed a steady increase between the 1970s and late-1990s, but in recent years average yields tend to stabilize around 5 Mg ha^{-1} (Fig. 2). However, the demand for wheat in China is rising due to the rapidly growing population that needs to be fed. In addition, living standards of the Chinese population increase, resulting in a greater share of wheat (products) in the human diet and fueling the demand for

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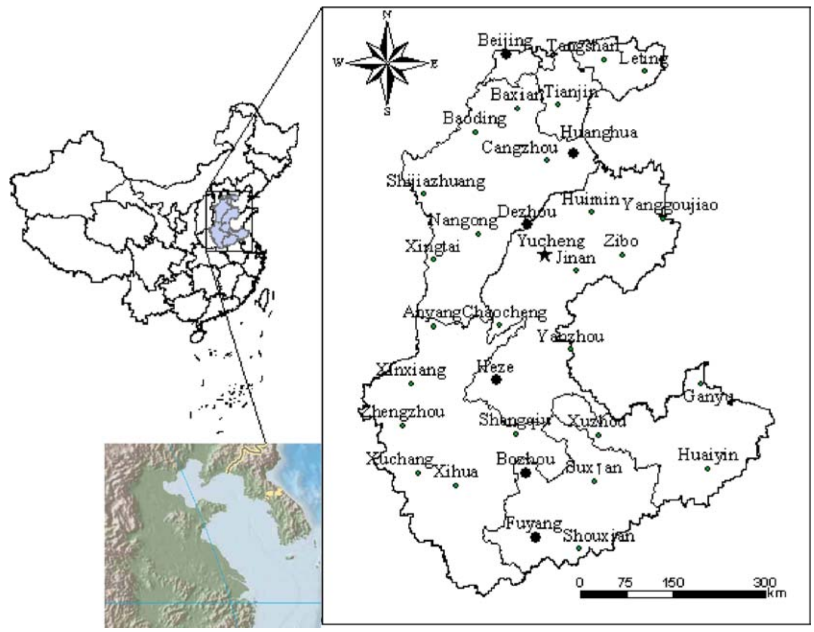

Fig. 1. The North China Plain and the locations of meteorological and experimental stations used in this study: (⋆) represents Yucheng Comprehensive Station, (●) represent weather stations, while (●) represent selected weather stations for analysis of temporal variation on yield (Section 3.4).

wheat further (Heilig, 1999). Therefore, wheat production in the NCP is important for maintaining national food security.

The production of wheat can be increased by increasing the production per unit of area or by expansion of the area cropped with wheat. The latter option is difficult to achieve as competition for land with urban areas is already strong and most likely further increases in the future, while other areas are less suitable for agricultural production due to poor soil fertility or roughness of the landscape. The best strategy seems, therefore, to aim at increasing wheat productivity.

In this study we explore the production potentials of winter wheat in the NCP using a crop growth simulation model linked to a Geographic Information System (GIS). The analysis provides us with information on where and what the possibilities are to increase current productivity levels of winter wheat in the NCP. The study contributes to the identification of limiting factors for improving winter wheat yields in the NCP. Results can be linked to location-specific information on water availability to develop strategies for investments in irrigation infrastructure.

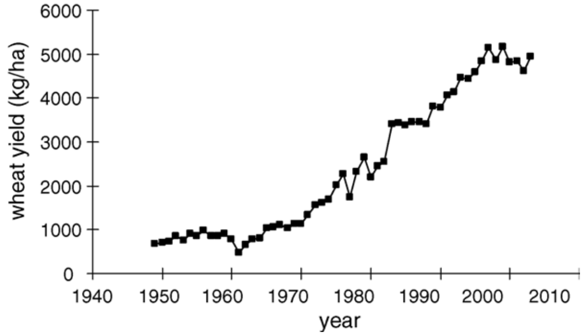

Fig. 2. Development of winter wheat yields in the North China Plain.

The objectives of this study are to (1) quantify the production potential of winter wheat, (2) identify the spatial and temporal variability caused by climate in winter wheat yields, (3) contribute to the identification of hotspots for yield improvement of winter wheat, and (4) contribute to the identification of limiting climatic factors for yield improvement in different part of the NCP.

To realize these objectives a dynamic crop growth simulation model developed by the World Food Studies, WOFOST, version 7.1 has been used (Boogaard et al., 1998). Simulated crop yields are linked to a GIS facilitating the mapping of crop growth potentials in NCP and contribute to the identification of hotspots for intervention aimed at increasing current yield levels of winter wheat. In the following section, WOFOST and used data are described. Subsequently, results are presented beginning with the calibration procedure of WOFOST for prevailing conditions in the NCP followed by a characterization of the spatial and temporal climate variability in the NCP. Subsequently, simulated wheat yields and their variability for different production situations are presented. In Section 4, limitations of the study are discussed and implications of the results for policy makers and researchers indicated.

2. WOFOST model and used data

2.1. The model

WOFOST originates from the ‘School of de Wit’ crop growth simulation models (Bouman et al., 1996) and has been applied in various locations for different purposes (e.g. Berkout et al., 1988; Van Lanen et al., 1992; De Koning et al., 1995; Hengsdijk and Van Keulen, 2002). The model simulates daily crop growth rate, based on soil properties (i.e. soil depth, water holding capacity and infiltration capacity), climate conditions (i.e. solar radiation, temperature and distribution of rainfall) and crop characteristics (i.e. length of growing cycle, photosynthetic characteristics and distribution of dry matter over plant parts).

The model is able to simulate two distinct production situations (Bouman et al., 1996). In the potential production situation the crop growth rate is determined by climate conditions only, i.e. radiation and temperature, given a set of crop characteristics. In the water-limited production situation the growth rate is limited by shortage of water during at least a part of the growing period. For the water-limited production situation WOFOST keeps track of a daily water balance taking into account water entering and leaving the rooting zone. Water enters the rooting zone through rainfall while soil specific non-infiltrating fractions are taken into account. The infiltrated fraction is added to the soil water, while the non-infiltrated fraction is stored on the soil surface first and may subsequently infiltrate while it may be subject to evaporation and/or runoff. Water leaves the rooting zone by soil evaporation, percolation and crop uptake used for transpiration. Under sub-optimal water supply the transpiration rate is reduced. This reduces photosynthesis rate proportionally, resulting in reduced growth and yields. Severe drought may result in complete crop failure.

In both the potential and water-limited production situation, nutrients are in ample supply while weed, pest and disease control and other crop management are optimal for the simulated yield levels. See Van Diepen et al. (1989), Supit et al. (1994) and Boogaard et al. (1998) for other details of the model.

2.2. Climate data

Historical data from 32 weather stations evenly distributed in the NCP were available (Fig. 1). The data included daily maximum and minimum air temperature, sunshine duration, vapor pressure, wind speed and rainfall, which were available for the period 1961–2000. Sunshine duration was converted into solar radiation using the Ångström–Prescott equation (Supit et al., 1994). Estimated solar radiation matched well measured values in Yucheng Comprehensive Experimental Station (YCES), 116.60°E, 36.57°N, 21.2 m a.s.l. located in the centre of NCP (Fig. 1).

2.3. Soil data

For simulation of crop growth under water-limited conditions the characteristics of a sandy loam soil were used as the predominant and most widely distributed soil type in the NCP (Wang et al., 2001). Specific soil characteristics required for WOFOST such as field capacity, wilting point and hydraulic conductivity were based on a detailed soil analysis from YCES (Table 1). As WOFOST uses a homogeneous soil layer, available characteristics of six soil layers till 150 cm were averaged using the depth of each layer as weighing factor. At the start of the simulations, the groundwater table was set at 3.0 m for the entire area, which corresponds with the groundwater table at sowing of winter wheat in YCES.

Table 1
Soil properties of the experimental site at Yucheng Comprehensive Experimental Station

Soil texture	Sandy loam
Wilting point (v/v)	0.07
Saturation (v/v)	0.30
Field capacity (v/v)	0.24
Bulk density (g/cm^3)	1.43
Organic matter (mg/kg)	1.25
Total nitrogen (mg/kg)	0.069
Total phosphor (mg/kg)	1.21
Total potassium (mg/kg)	14.68
pH	8.44

2.4. Crop data

In the simulations, we assumed that the same winter wheat variety (Jining No. 142) was used throughout the study area. Sowing dates of winter wheat were based on local crop calendars and ranged from 5 October in the north to 11 November in the south of the NCP. Crop growth stops at physiological maturity as determined by accumulated temperature.

2.5. GIS

A GIS database was developed and used to process and present simulation results. The database contained information from the meteorological stations and model output. In detail, it includes global radiation, accumulated temperature, rainfall, potential and rainfed yields, their temporal variability, and the gap between potential and rainfed yield. Using this database, point data were interpolated to generate maps for the entire NCP. The inverse distance weighting (IDW) interpolation method was used. In this method, a neighborhood about the interpolated point is identified and a weighted average is taken of the observed values within this neighborhood. The weights are a decreasing function of distance (Fisher et al., 1987). Generated maps were stratified at equal intervals according to the interpolated values at each grid.

When applying a simulation model to problems on regional scale, two methods can be used: simulate first and then interpolate results on a grid (‘calculate first, interpolate later’, CI), or interpolate first inputs on a grid and then calculate model outputs at grid nodes (‘interpolate first, calculate later’, IC). Stein et al. (1991) and Bechini et al. (2000) showed that CI resulted in smaller mean squared differences between predicted and observed values than IC, mainly because more variables were interpolated in the IC procedure thus increasing the error in model application. In this study CI was used.

3. Results

3.1. Model calibration

We calibrated the WOFOST model using experimental field data from YCES. The 2-years winter wheat experiment from 1999 to 2001 had two treatments, i.e. one in which irrigation water was supplied maintaining soil at 70–80% of field capacity, and the other was rainfed. The first treatment was used for calibrating WOFOST under potential production situations, and the later for water-limited situations.

In the experiment, leaf area and biomass of 10 randomly selected plants were measured every 5 days from emergence to maturity, except during the winter period. In addition, daily minimum and maximum temperature, global radiation, vapor pressure, wind speed and precipitation were measured.

The major crop-specific parameters that were modified in the calibration procedure included accumulated temperature determining the phenological development, leaf area index at emergence, specific leaf area, maximum assimilation rate, harvest index, and light-use efficiency.

Simulated LAI, total biomass and dry matter of storage organs were used to calibrate model parameters (Fig. 3). In general, simulated results matched well with the measured parameters in the calibration procedure. Simulated LAI was close to the observed LAI till May, 180 days after sowing. Then, simulated LAI overestimated observed LAI due to the damage of the leaves caused by hot and dry winds prevailing in May, and causing the death of leaves in a very short period. Therefore, total biomass was some-

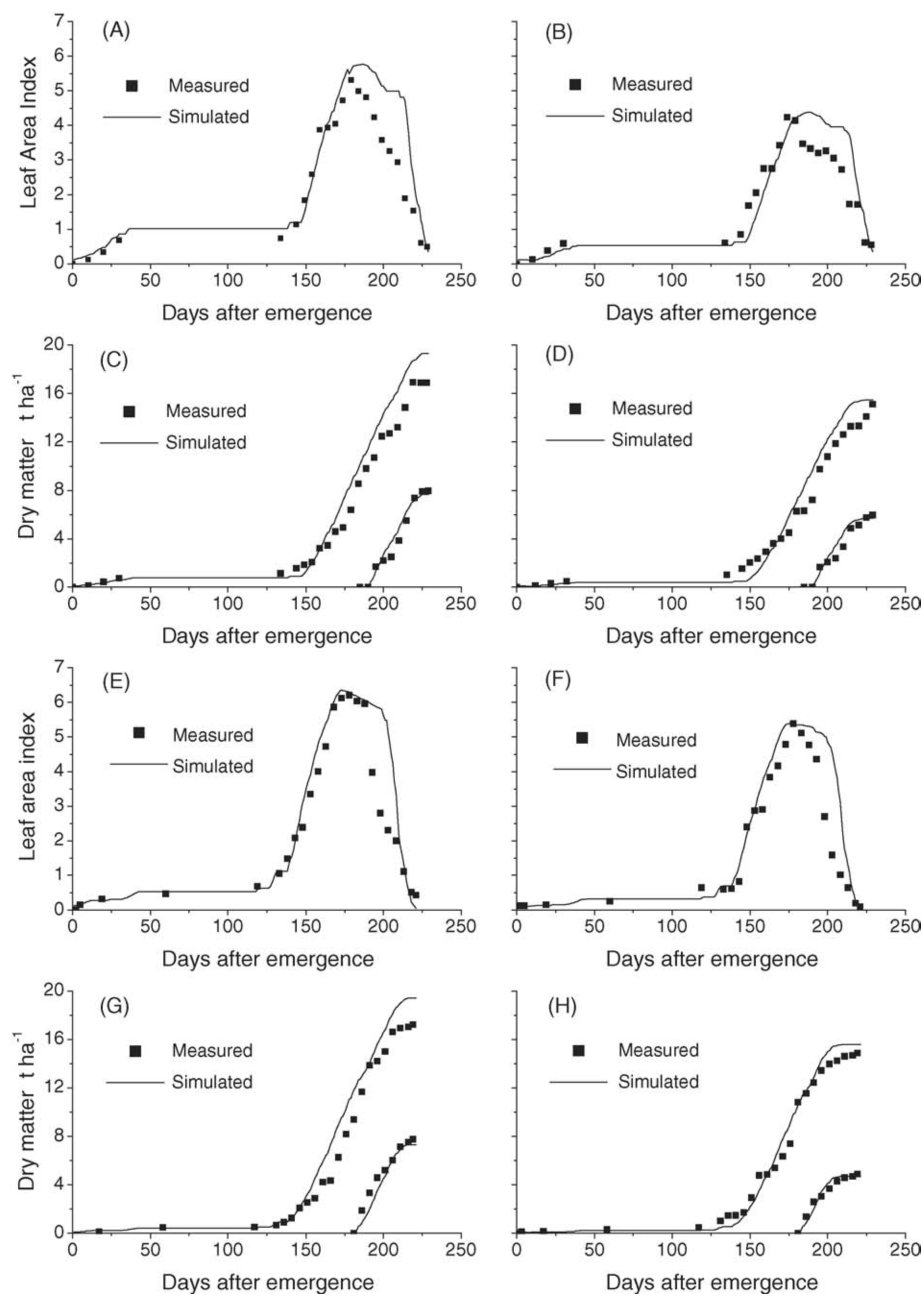

Fig. 3. Calibration results of WOFOST using experimental data from Yucheng Comprehensive Station. On the left-hand side simulated and measured values for the potential production situation while on the right-hand side for the water-limited production situation. (A)–(D) refer to the calibration using experimental data from the growing season 1999–2000, and (E)–(H) refer to the validation using data from the 2000–2001 growing season. In (C), (D), (G) and (H), both the total biomass and grain dry matter are plotted.

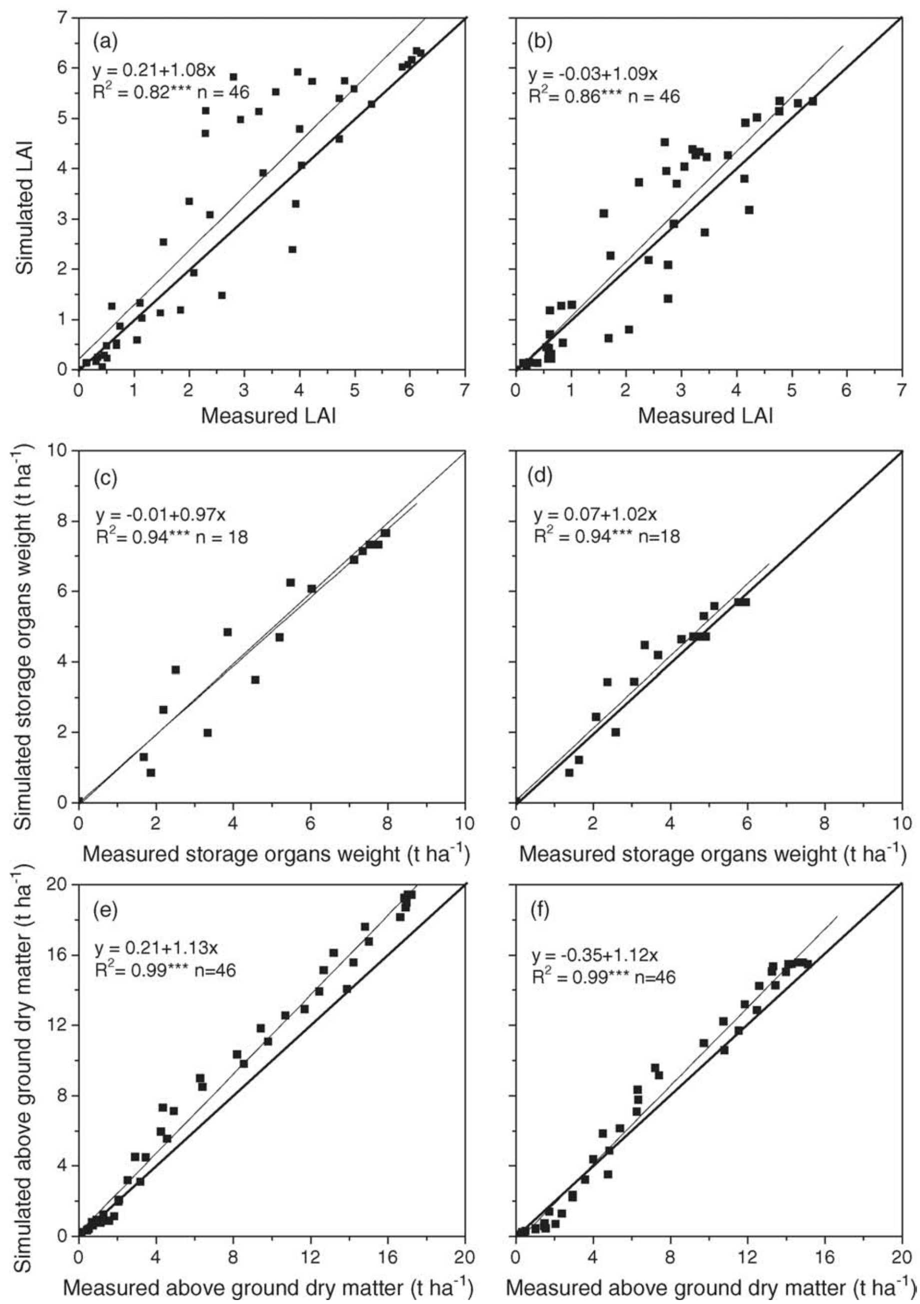

Fig. 4. Relationship between observed and simulated values of LAI, total biomass and grain dry matter under potential ((a), (c) and (e)) and water-limited ((b), (d) and (f)) production situation. ***Significant at $p < 0.001$.

what overestimated but simulation of grain dry matter showed a good fit. Agreement between observed and simulated values is also described by the slope and the coefficient of determination (R^2) of the regression lines between simulated and observed values for LAI, total biomass and grain dry matter (Fig. 4).

3.2. Spatial and temporal variability of climate

First, spatial and temporal variability of global radiation, accumulated temperature and rainfall in the NCP during the winter wheat growth season (1 October–10 June in the next year) is analyzed (Fig. 5). Global radiation varies between 2500 and 3000 MJ m^{-2} d^{-1} and shows low variability between years, i.e. the coefficient of variation varies between 0.035 and 0.077. Radiation is higher in the north of the NCP, thanks to the lower rainfall and latitude, i.e. less cloudy days and more sunshine hours per day in the growing season, respectively.

Accumulated temperature in the winter wheat season increases from 1730 °C d in the north to 2710 °C d in the south of the NCP. Temporal variability is greater in the north and north-west of the NCP, i.e. East of the Taihang Mountains, but the coefficients of variation are similar to those found for radiation.

Rainfall increases from less than 100 mm in the north to 340 mm in the south of the NCP. The coefficients of

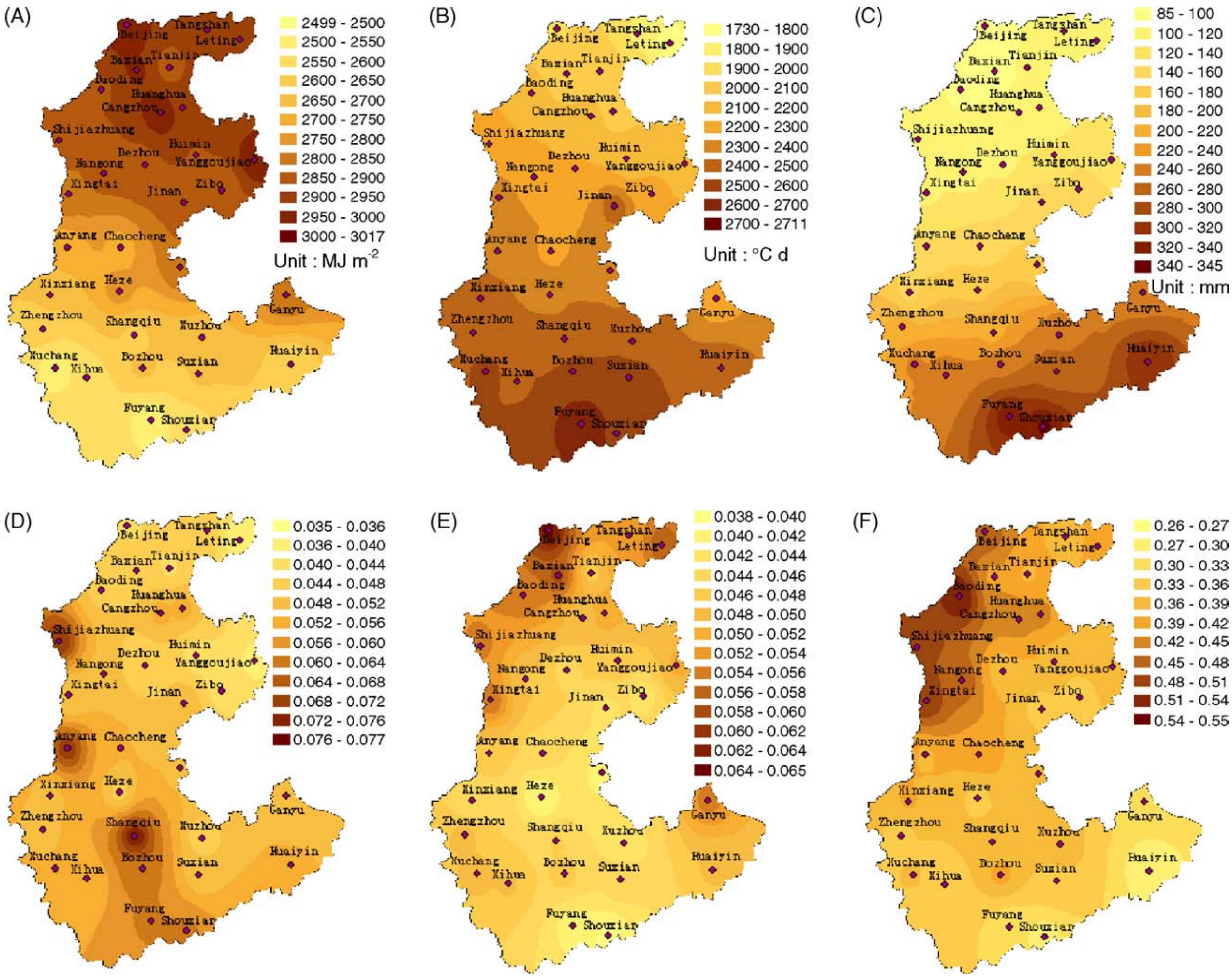

Fig. 5. (A) Global radiation, (B) accumulated temperature and (C) rainfall in the winter wheat growing season of the NCP. (D)–(F) indicate the coefficient of variations in global radiation, accumulated radiation and rainfall, respectively.

variation for rainfall are much greater than for radiation and accumulated temperature, i.e. they vary between 0.27 and 0.55.

3.3. Spatial variation in potential and water-limited yields

Long-term average potential yields vary from 7.4 to 9.8 Mg ha^{-1} in the NCP, with an overall mean of 8.2 Mg ha^{-1} for the entire NCP (Fig. 6). Generally, potential yields decrease from north to south, due to lower radiation and the shorter growing season caused by higher temperatures in the south. Along the same latitude, potential yields increase with longitude from west to east, as it is cooler near the coast, which extends the growth duration of winter wheat. Meteorological station Leting has the highest potential yield, thanks to the long growing season and high solar radiation. In several years, potential yields reach 10.0 Mg ha^{-1}. Near Shouxian, the southmost meteorological station, lowest potential yields are attained, i.e. they are often less than 5.0 Mg ha^{-1}.

Long-term average water-limited yields in the NCP vary between 3.0 and 7.7 Mg ha^{-1}, with an overall mean of 5.0 Mg ha^{-1} and a coefficient of variation of 0.27. In contrast with potential yields, water-limited yields increase from north to south similar to the trend in rainfall.

The yield gap between potential and water-limited yields varies between 0.5 Mg ha^{-1} in the south and 5.4 Mg ha^{-1} in the north of the NCP (Fig. 7). These yield gaps indicate yield loss due to water stress and suggest potentials to increase yields by improving water supply, such as in Cangzhou in the northern part of the NCP where the yield gap is greatest. In the southern part of the NCP, for example Fuyang and Shouxian, yield gaps are much smaller and, therefore, the possibilities to increase yields by improving water supply are limited. For the entire NCP the mean yield gap between potential and water-limited yields is 3.2 Mg ha^{-1}.

3.4. Temporal variability in potential and water-limited yields

In the potential production situation variability in yield performance is associated with temporal variation in radiation and temperature, while in the water-limited situation also the variation in rainfall is important. Here, we analyze the consequences of temporal variability for winter wheat yields in both

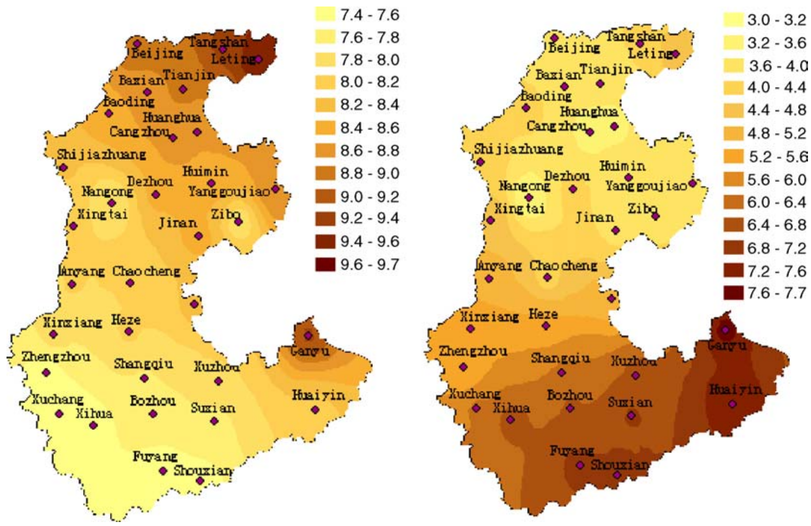

Fig. 6. On the left-hand side the simulated potential yields of winter wheat, and on the right-hand side the winter wheat yields under water-limited conditions in the NCP (in Mg ha^{-1}).

the potential and water-limited production situation. Based on 40 years of weather data, simulated winter wheat yields from six selected locations, which roughly represent a north–south cross-section of the NCP, namely Beijing, Huanghua, Dezhou, Heze, Bozhou and Fuyang were analyzed in detail (Fig. 1).

Cumulative probabilities of potential yields in the six locations show the same slope indicating that temporal variability in radiation and temperature is similar throughout the NCP (Fig. 8). The range of potential winter wheat yields, i.e. between 5.8 and 11.0 Mg ha^{-1} (Fig. 8A), is smaller than for water-limited yields in the six locations which vary between 1.0 and 9.0 Mg ha^{-1} (Fig. 8B). Variability in radiation and temperature has only little effect on the variation of potential yields in the NCP, while

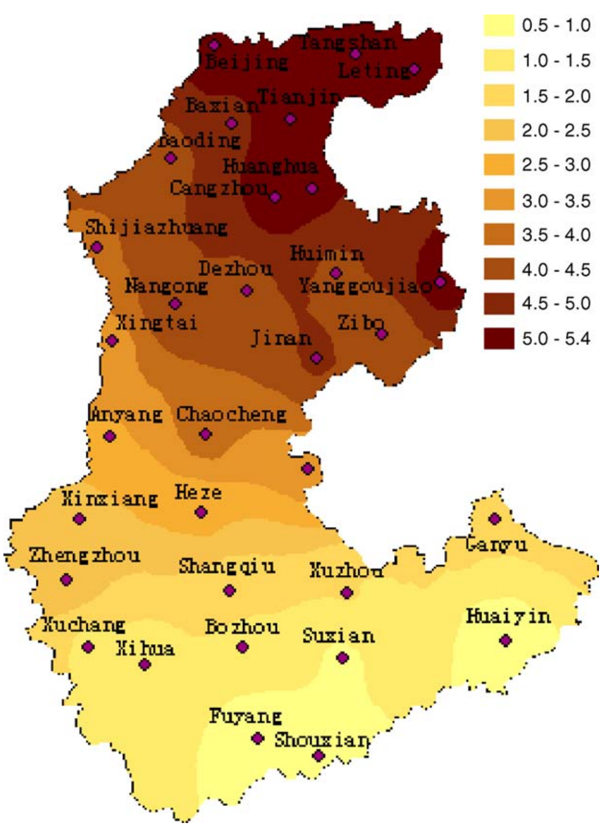

Fig. 7. Yield gaps between potential and water-limited yields in the NCP (in Mg ha^{-1}).

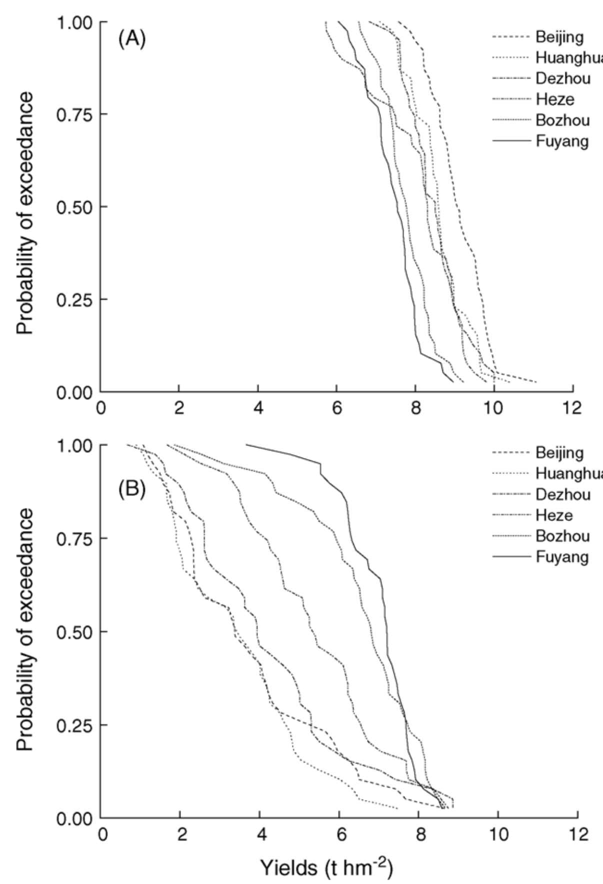

Fig. 8. Cumulative distribution of (A) potential yield and (B) water-limited yield of winter wheat for six locations in the NCP.

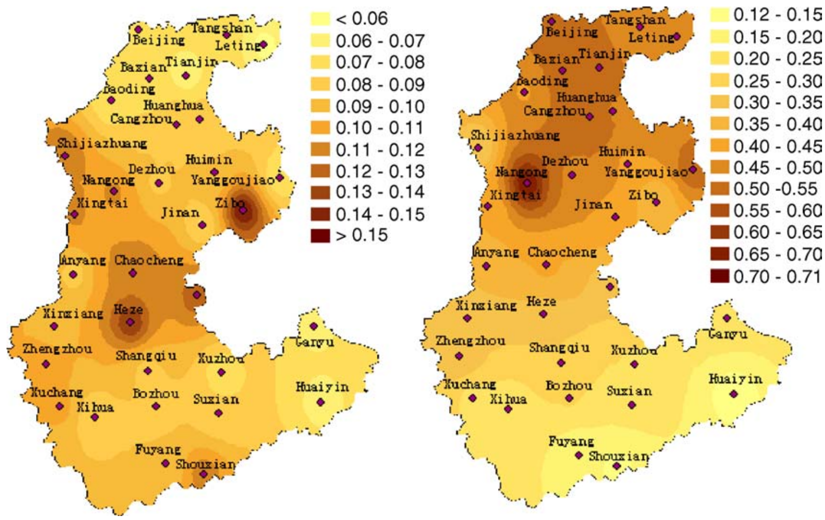

Fig. 9. On the left-hand side, the coefficient of variation of potential winter wheat yields, and on the right-hand side the coefficient of variation of water-limited winter wheat yields in the NCP.

rainfall variability has a much greater impact on the variation in water-limited yields. Different slopes of the cumulative probabilities of water-limited yields indicate that temporal variation in yields differs throughout the NCP. In the northern part of the NCP, such as Beijing, the range of water-limited yields is wide and the probabilities are evenly distributed. The amount of rainfall in Beijing varies greatly with almost the same probability. High variation in rainfall together with average low rainfall in the northern part of the NCP limit wheat productivity with a fairly high probability.

Water-limited yields in the southern part of the NCP, such as Fuyang show less variation as indicated by the steep slope of the cumulative distribution of yield (Fig. 8B). Probability is low that here yields will greatly reduced by unfavorable rainfall pattern. Variation in rainfall has little effect on the performance of winter wheat. Instead, wheat growth is mainly determined by the joint effect of radiation and temperature as also indicated by the yield gap between simulated potential and water-limited yields (Fig. 7).

In the NCP, coefficients of variation of potential winter wheat yields vary between 0.06 and 0.15, much less than those for water-limited yields, which vary between 0.12 and 0.70. Around Zibo and Heze variability in potential yields is highest. Variability in water-limited yields is especially high around Nangong and Cangzhou, which have extreme low average annual rainfall. Only a little change in rainfall will have a great effect on yields in both locations as yields are severely limited by water as shown in the yield gap analysis (Fig. 7).

Wind speed affects water-limited yields because it determines water loss through crop canopy transpiration and soil evaporation. In Nangong and Shijiazhuang, rainfall and its variation are similar (Fig. 5), but variability in water-limited yields is highly different, i.e. it is much higher near Nangong (Fig. 9). Average wind speed during the winter wheat growing season in Nangong is $1\,m\,s^{-1}$ higher than in Shijiazhuang, i.e. 2.87 and $1.84\,m\,s^{-1}$, respectively. Higher wind speed causes large water loss from the crop canopy in Nangong, which partly may explain the higher variability of rainfed yield in Nangong than in Shijiazhuang.

4. Discussion and conclusions

This paper presents a crop growth simulation study to quantify the potential and water-limited yields of winter wheat in the NCP. Climate-related temporal and spatial variability in yield performance is simulated using long-term daily weather data from various meteorological stations spread evenly throughout the NCP. Based on the simulated potential and water-limited yields, yield gaps have been identified. Different from studies calculating crop potentials using statistical regression models (Liu et al., 1998, 1999) is that in this study a process-based model has been used taking into account explicitly the complex interactions between the atmosphere–soil–crop systems.

WOFOST performed well in the calibration procedure of this study. One limitation of the model is that it does not account for the effects of possible cold and heat stress during the growing season, while these are major meteorological phenomena in the NCP. Extreme low temperatures during the winter period may endanger the survival of winter wheat seedlings especially in the northern NCP, while high maximum temperatures during earlier summer may jeopardize seed filling. Another limitation of WOFOST is that it is based on one soil layer. However, characteristics of the alluvial soils in the NCP are quite uniform throughout the soil profile and, therefore, we expect that rainfed yields are not much affected by this simplification.

The NCP covers five huge provinces, in which climate, soils and management may vary considerably. We have taken into account the effects of climate-related spatial and temporal variability on the performance of winter wheat. The fact that we used only one soil type may be a limitation of this study, since rainfed yields in contrast to potential yields may be affected by location-specific soil water characteristics. In a follow-up study also effects of spatial variability in soil characteristics will receive proper attention, enabling to evaluate the consequences in more detail. However, we think that general conclusions of this paper will stand as the NCP is located in the alluvial plains of the Yellow River with only little variation in soil characteristics affecting rainfed yields (Chinese National Geographical Map, 1984).

Average long-term simulated potential yields in the northern part of the NCP go up to 9.7 Mg ha^{-1}, while average water-limited yields only reach 3 Mg ha^{-1}. In the southern part of the NCP both potential and water-limited yields are on average about 7.5 Mg ha^{-1}. Average losses due to water stress are about 40% of the potential yield in the whole plain, but vary considerably throughout the NCP. Temporal variation in potential yields throughout the NCP is low in contrast with that in water-limited yields, which is especially great in the northern part due to high inter-annual variation in rainfall. In the northern part of the NCP, rainfall is the limiting factor to winter wheat yields, while in the southern part the joint effect of radiation and temperature are major limiting factors. Results indicate options to increase water-limited yields in the northern part of the NCP through improving drought tolerance in wheat varieties, or through supplying irrigation water.

Results of this study have various implications for policy makers and researchers concerned with management of winter wheat in the NCP. In the northern part, an adequate water supply is key for improving yield levels. The yield gap analysis is useful for identification of where and to what extent yields can be improved when irrigation water is available. However, the NCP faces increasing water scarcity and the amount of water available for agriculture is likely to decrease in the future (Varis and Vakkilainen, 2001). Therefore, strategies to improve the use efficiency of existing water resources in agriculture are urgently needed (Wang et al., 2001). Albersen et al. (2000) evaluated agricultural production in China using the AEZ (agro-ecological zones) model, and they draw a similar conclusion, i.e. North China has great potential to increase agricultural productivity by improving water supply. In the southern part of the NCP, water-limited yields are close to potential yields, but both are still much higher than current average yields in the NCP. Here, improvements in crop management, such as nutrient, pest and disease management are most likely limiting further yield increase and will need to have priority to increase current yields.

Unfortunately, location-specific and disaggregated statistics for current irrigated and rainfed winter wheat yields are not readily available for the NCP which hampers the identification of hotspots for yield improvement. To fully appreciate and exploit the obtained results in this study such statistics are urgently needed. Therefore, this simulation study calls for the collection of location-specific and disaggregated wheat yield statistics in the NCP so that policymakers and researchers are better able to identify hotspots for improvement of current winter wheat yields.

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