International Journal of Plant Production 2 (1), January 2008
ISSN: 1735-6814 (Print), 1735-8043 (Online)
This is a refereed journal and all articles are professionally screened and reviewed.

GUASNR
www.ijpp.info

Impact of spatial-temporal variations of climatic variables on summer maize yield in North China Plain

Dingrong Wu[a,b], Qiang Yu[a,*], Enli Wang[c], Huib Hengsdijk[d]

[a]*Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, P. R. China*
[b]*Graduate School of the Chinese Academy of Sciences, Beijing 100039, P.R. China*
[c]*CSIRO Land and Water, Canberra ACT 2601, Australia*
[d]*Plant Research International, Wageningen University and Research Center, 6700 AA Wageningen, Netherlands*
*Corresponding author. Email: yuq@igsnrr.ac.cn

Accepted 14 October 2007; Published online 25 November 2007.

Abstract

Summer maize (*Zea mays* L.) is one of the dominant crops in the North China Plain (NCP). Its growth is greatly influenced by the spatial-temporal variation of climatic variables, especially solar radiation, temperature and rainfall. The WOFOST (version 7.1) model was applied to evaluate the impact of climatic variability on summer maize yields using historical meteorological data from 1961 to 2000. The model was calibrated and validated using data from field experiments conducted during the period 1998-1999 and simulations were run to analyses the climate impact. Simulated potential yield ranges from 7.7 to 10.0 Mg ha^{-1}, with an increasing trend from south to north, while rainfed yield ranges from 4.3 to 8.1 Mg ha^{-1}, and with an increasing trend from the middle to the north and south of NCP. Gaps between potential and rainfed yields also decreased from the middle to the north and south. The pattern of potential yield was mainly attributed to the distribution of solar radiation and temperature, whereas rainfed yield was mainly influenced by the distribution of rainfall. Interannual variability n of potential yield is small, and was closely related to the variation of solar radiation, while rainfed yield varied greatly, especially in the middle of the plain, where the rainfall is lowest. Combined with consistent research results of winter wheat, results of this study offer scientific basis for policy makers and researchers concerned with the management of food marketing decisions and water resource reallocation.

Keywords: Temporal variability; Spatially variability; Potential yield; rainfed yield; WOFOST

Introduction

Summer maize is one of the main crops in the dominant wheat-maize double cropping system in North China Plain (NCP, 114-121° E, 32-40° N). NCP is the largest and most important agricultural area and known as the ‘Granary of China’ (Figure 1). It covers two metropolises (Beijing and Tianjin) and five provinces (Hebei, Shandong, Henan, Anhui, Jiangsu), with an area of 31.0×10^6 ha, of which 17.95×10^6 ha is arable land, i.e. 18.6% of the national total (Liu et al. 2001). With more than 32% of the maize production in China produced here, maize production in the NCP is an important component for national food security. In the last fifty years, maize yield has been greatly improved, but tends to be stabilized around 6.2 Mg ha^{-1} in recent years (Figure 2). The variable climate, both temporally and spatially, has significant impact on maize production in NCP.

Many researchers studied impact of climate on crop production in NCP. Wang et al. (1992) calculated winter wheat productivity in the NCP by the AEZ (agro-ecological zones) model using averaged climate and soil data, presented an averaged production scenario of the plain. Chen et al. (2004) proposed likely production of winter wheat in the NCP under changed climate and its variability in six single stations. With the support of GIS information and monthly NOAA-AVHRR maximum composite NDVI (Normalized Difference Vegetation Index), a crop growth model was designed to estimate winter wheat yield by Mo et al. (2004). Many others examined relations between crop yields and water consumption at station level (Liu et al., 1998; Zhang et al., 1999).

In contrast to flourishing researches on winter wheat, summer maize remains almost untouched, as its water depression seems not as series as winter wheat because summer maize growth period is the “rainy season” in the NCP. But, as projected by Tao et al (2003), the NCP will faced a general drying of 50 mm in 2021-2030, summer maize will also face water-related challenges in the coming decades. It is reasonable to assume that in the coming future, maize in the NCP will needs irrigation, but now there are few researches concentrated on this problem. Using better-constructed models, Liu et al. (2002) estimated impacts of water stress on summer maize regional productivity. But he was failing to present the variability analyses of potential and rainfed yields.

System approach using crop growth model is an effective way to quantify crop yield and identify its limiting factors. Water limitation can be analyzed from the gap between potential and rainfed yields. Their comparison with actual yield will offer farmers and policy makers instructive references (Rabbinge, 1993) for yield improvement.

Different from previous studies, this study used a process-based model and taking into account explicitly the complex interactions between the atmosphere-soil-crop systems, presents crop potentials and their variability in the whole area in a long period. The main objectives of this paper are (1) to quantify the production potential of summer maize in NCP; (2) to analyse the spatial and temporal variations in maize yield caused by climate variability; (3) to identify areas where yield improvement potential is large; and (4) to discuss the implications of yield variations on future agricultural and resource planning.

Materials and Methods

The model

WOFOST (WOrld FOod STudies) originates from the ‘School of de Wit’ crop growth simulation models and is the first application-oriented models derived from SUCROS model (Bouman et al., 1996).

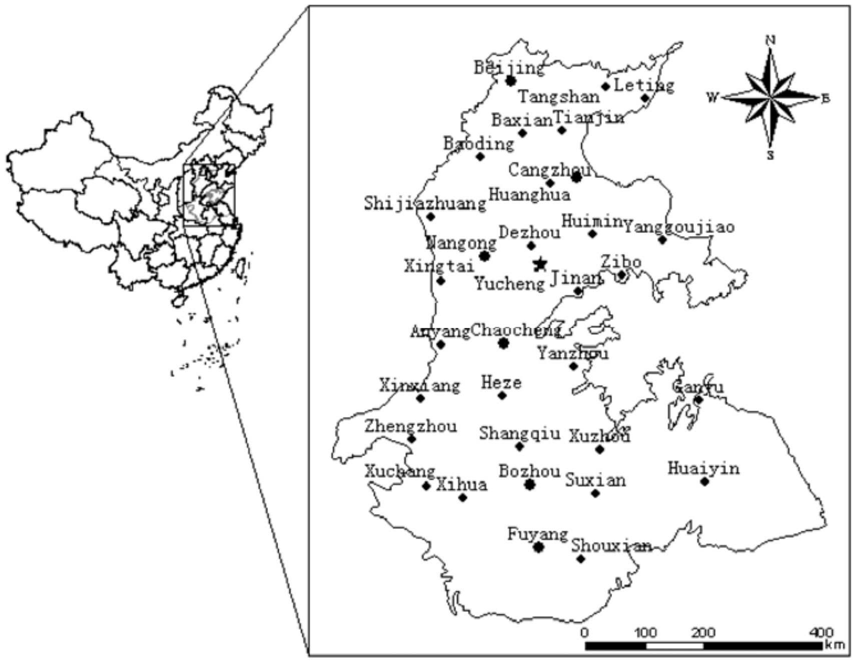

Figure 1. The North China Plain and the locations of meteorological and experimental stations used in this study. ★ represents Yucheng Comprehensive Experimantal Station (YCES), where the model verification experiments were conducted, ◆ represent weather stations, while ● represent selected weather stations for analysis of temporal variation on yield (see section 3.4).

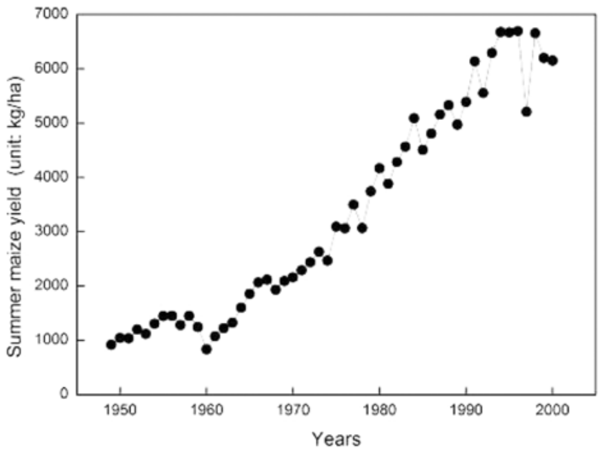

Figure 2. Development of summer maize yields in the NCP. Data were collected from Statistical Bureau of China.

The model simulates daily crop growth rate, based on climate conditions (solar radiation, temperature and rainfall), soil properties (soil depth, water holding capacity and infiltration capacity) and crop characteristics (length of growing cycle, photosynthetic characteristics and partitioning 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 radiation and temperature only, given a set of crop characteristics. In the water-limited production situation the growth rate is limited by shortage of water during at least one part of the growing period. For the water-limited production situation WOFOST keeps track of daily soil water balance taking into account water entering and leaving the rooting zone. Water enters the rooting zone through rainfall taking into account of surface runoff and ponding. Water leaves the rooting zone by soil evaporation, percolation and crop uptake or transpiration. Under sub-optimal water supply transpiration rate is reduced from the potential transpiration rate. This reduces photosynthesis rate proportionally, resulting in reduced growth and yield. Severe drought may result in complete crop failure. In both the potential and water-limited production situations, nutrients are assumed in ample supply while weed, pest and disease control and other crop management are assumed to be optimal (See van Diepen et al. 1989, Supit et al. 1994 and Boogaard et al. 1998 for further details of the model). Figure 3 depicts the crop processes that considered in WOFOST model (Supit et al., 1994).

During last twenty years, WOFOST has been tested extensively against field measurements in various studies under a wide range of growing conditions (Berkout et al. 1988; van Lanen et al. 1992; de Koning et al. 1995; Hengsdijk and Van Keulen 2002; Wu et al., 2005). In this study, WOFOST version 7.1 (Boogaard et al., 1998) was used to simulate summer maize yield and a GIS system was used to map the simulated yield spatially.

Model calibration

The model was calibrated using two years of experimental data from the Yucheng Comprehensive Experimental Station (YCES, 116.60ºE, 36.57ºN, 21.2m a.s.l.), geographically located in the center of NCP (Figure 1). Experiments were carried out in 1998 and 1999, and experimental data in 1998 were used to calibrate the model, while data in 1999 to validate. Summer maize variety Yedan No. 22 was sown with a seed density of 105 kg ha^{-1} in the two years, and pest and diseases were controlled. Soil water content was measured with a neutron probe, made by the Chinese Academy of Sciences, up to 100 cm depth at 10 cm intervals. Additional water was applied by flood irrigation. Detailed site description of the experiment can be found in Lee et al. (2004) and Yu et al. (2002).

An auto-weather station in YCES was used to measure solar radiation, net radiation, air temperature, relative humidity and wind speed at a reference height of 2 m above ground. Rainfall was measured at 8 and 20 o'clock in rainy days 150 m away from experimental site. In this study, irrigation amount was converted and added in weather records as rainfall.

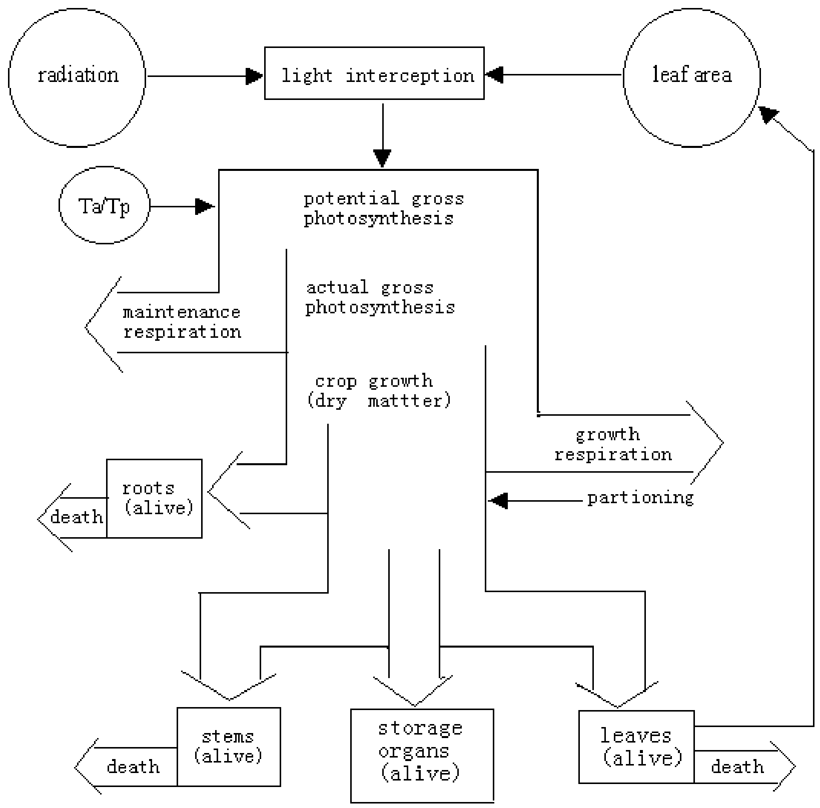

Figure 3. Crop growth processes (T_a and T_b are actual and potential transpiration rate).

Soil physical characteristics including water content at wilting point, field capacity and the saturated hydraulic conductivity were estimated based on a detailed soil analysis from YCES. As WOFOST uses a homogeneous soil layer, available characteristics of 6 soil layers till 150 cm were averaged using the depth of each layer as weighing factor.

Crop data collected include developmental stages, aboveground biomass, leaf area index (LAI), and grain yield. Measurements were taken every 5 days in the growing season. For biomass, maize plants in 5 m^2 were counted and 10 of them were sampled randomly. They were separated into leaf, stem, and seeds. Leaf area index was measured by CID-201 (CID Inc, USA). The grain yields were obtained by harvesting a subplot of 200 m^2. Crop parameters including thermal time requirement for each developmental stage, specific leaf area, and maximum photosynthetic rate and partitioning factors for different organs were calculated based on experimental data from 1998.

Data used in long-term simulation

Climate data

Historical climate data set from 1961 to 2000 for 32 weather stations (Figure 1), evenly distributed in the NCP were obtained from China Meteorological Administration (CMA), which includes daily maximum and minimum air temperature, sunshine duration, vapor pressure, wind speed and rainfall. Currently, most weather stations in China record sunshine hour. To convert sunshine duration to light intensity, the Angstrom formula is used (Frere and Popov 1979):

$$R_1 = R_A(A + B \times nN^{-1})$$

where,

R_1: Incoming daily global solar radiation	[MJ m^{-2} d^{-1}]
R_A: Light intensity received at the limit of the atmosphere	[MJ m^{-2} d^{-1}]
A: Empirical constant	[-]
B: Empirical constant	[-]
n: Actual duration of sunshine	[hr]
N: maximum possible duration of sunshine	[hr]

Based on FAO experience (Frere and Popov 1979), appropriate set of coefficient for *A* and *B* were chosen (using coefficients for the cold/temperate zone). R_A and *N* are latitude relative. An example of values of coefficient of R_A and *N* is presented in Table 1.

The estimated solar radiation matched very well with measured values in the YCES in daily time step. Figure 4 described the agreement between observed and estimated radiation by the slope and the coefficient of determination (R^2) of the regression lines.

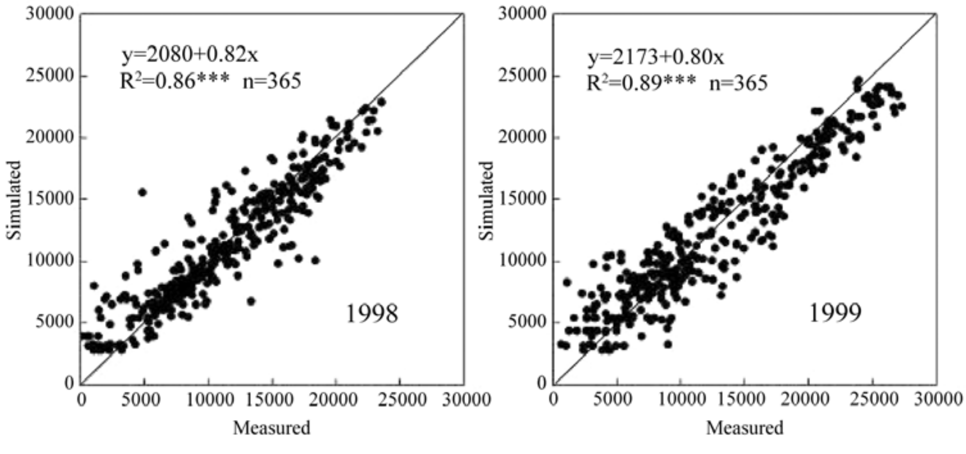

Figure 4. Measured and simulated solar radiation (kJ m^{-2} d^{-1}) in the YCES.

Table 1. Values of coefficient of R_A and N used in Angstrom formula in Dezhou station (37.43ºN).

Months	N (hours)	R_A (MJ m^{-2} d^{-1})
January	10.2	1.76
February	10.9	2.20
March	11.9	3.01
April	13.2	3.37
May	14.0	3.85
June	14.5	4.11
July	14.3	4.03
August	13.6	3.62
September	12.5	2.97
October	11.4	2.43
November	10.6	1.82
December	10.0	1.56

Soil data

For simulation of crop growth under water-limited conditions (specially, in this study, water-limited condition means rainfed condition) a sandy loam soil was used as a uniform soil type, representing the most widely distributed soil type in the NCP (Wang et al., 2001), and its main characteristics were listed in Table 2, which were calculated based on soil sampling in YCES. As initial soil conditions before maize planting varied slightly, soil condition was set as the same the model was validated at the start of the simulations each year. Groundwater table was set at 10.0 m for the entire area, which corresponds with the averaged groundwater table all over the plain.

Table 2. Soil properties of the experimental site at YCES.

Soil textural class	Wilting point v/v	Saturation v/v	Field capacity v/v	Bulk density g/cm	Organic matter mg/kg	Total nitrogen mg/kg	Total phosphor mg/kg	Total potassium mg/kg	pH
Sandy loam	0.11	0.36	0.30	1.376	1.25	0.069	1.21	14.68	8.44

Crop variety and sowing

In the simulations, we assumed that the same maize variety (Yedan No. 22) was used throughout the study area. Sowing dates of maize was based on local crop calendars and ranged from May 30 in the south to June 15 in the north of the NCP. Crop growth stops at physiological maturity as determined by the accumulated temperature.

GIS

A GIS system, together with a database, was used to process and present simulation results. The database stores the time series data of global radiation, accumulated temperature, rainfall, simulated potential and rainfed yields for each location. Point data were interpolated to generate maps for the entire NCP using the Inverse Distance Weighting (IDW) interpolation method (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.

Data analysis

The yearly totals of radiation, temperature and rainfall during maize growing season (Jun. 1 to Sept. 30) at each of the 32 stations were calculated. Averaged values over the 40 years from 1961 to 2000 were presented to show the spatial distribution of those climatic factors. The same calculations were made for simulated potential and rainfed yield, and the differences between potential and rainfed yield. The coefficients of variations of those variables over the 40-year simulation period were calculated for each location. Coefficient of variation is defined as the standard deviation over the mean (×100%). Simulated potential and rainfed yields were compared for 2 representative stations (Chaocheng and Fuyang) to show different impacts of radiation, temperature and rainfall on maize yield in two contract areas. Six stations were selected, along a north-south transect across the NCP at roughly equal distance, to analyze the yield distribution. These stations include Beijing, Huanghua, Nangong, Chaocheng, Bozhou and Fuyang.

Results

Model validation

Performance of the validated model was evaluated by comparing the simulated values and measurements of LAI, biomass of stems, total above ground biomass and the weight of storage organ. In general, the simulated values matched the observed values well (Figure 5). For the independent data of 1999, the model slightly overestimates LAI and biomass except for the leaf and total biomass at the end of the growing season (Figure 5b).

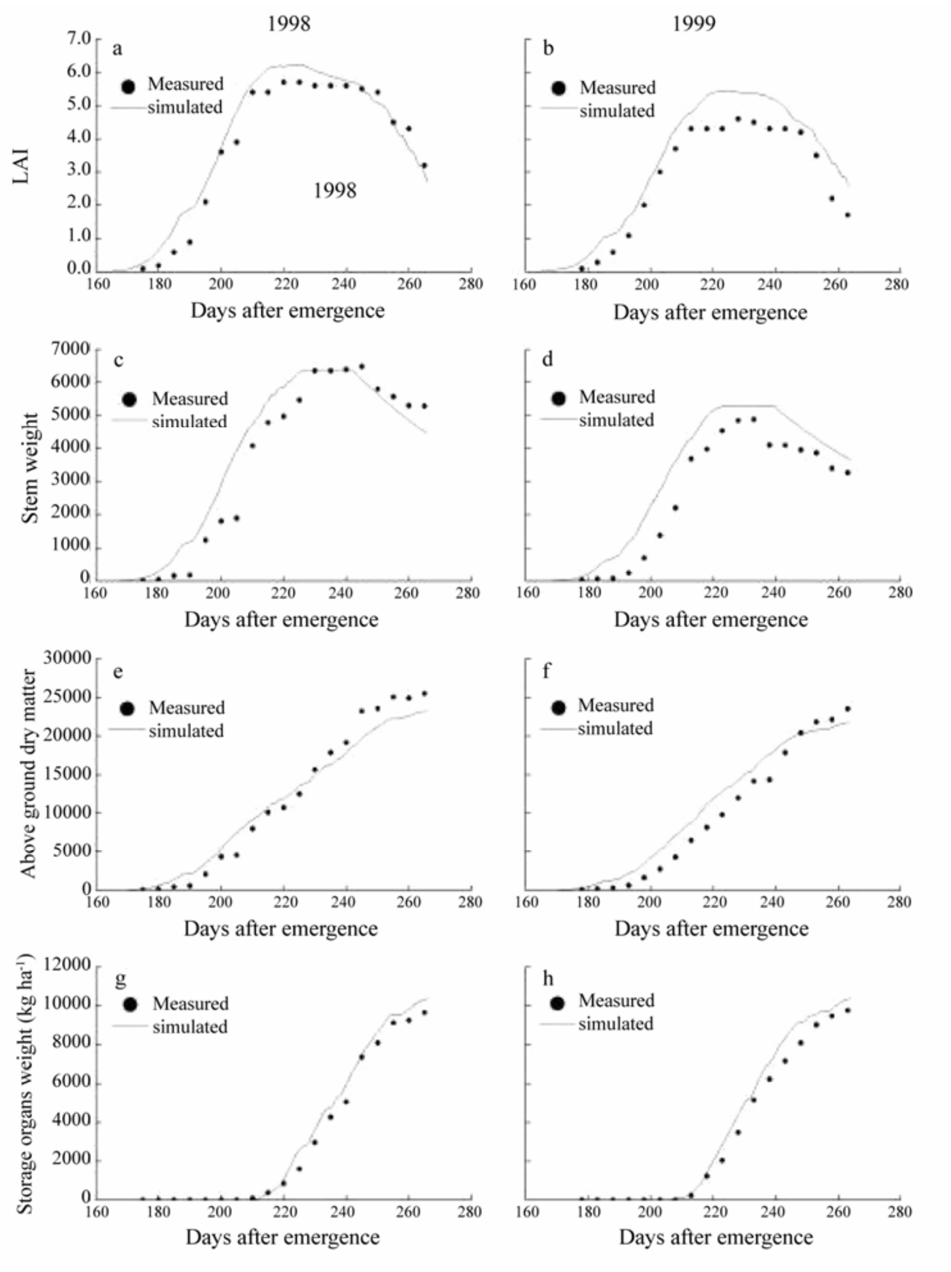

Figure 5. Simulated and measured values of LAI, biomass of stems, total above ground plant parts and the weight of storage organ. Left: comparison with data from 1998, which was used for deriving model parameters. Right: comparison with date from 1999 as independent data.

The end season underestimation of leaf weight was a result of different treatment for dry leaves in the model and in the measurement. In the experiments, dry and drying leaves were collected up and their dry weights were included in leaf dry weight. However, in the model, dry leaves were removed from leaves weight. 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, biomass of stems, total above ground plant parts and the weight of storage organ (Figure 6). Although only two years of data were used to validate the model, the performance of the model for simulating LAI, biomass stems, above ground plant parts and storage organ is considered to be reasonably well, therefore we used the model for long-term simulations.

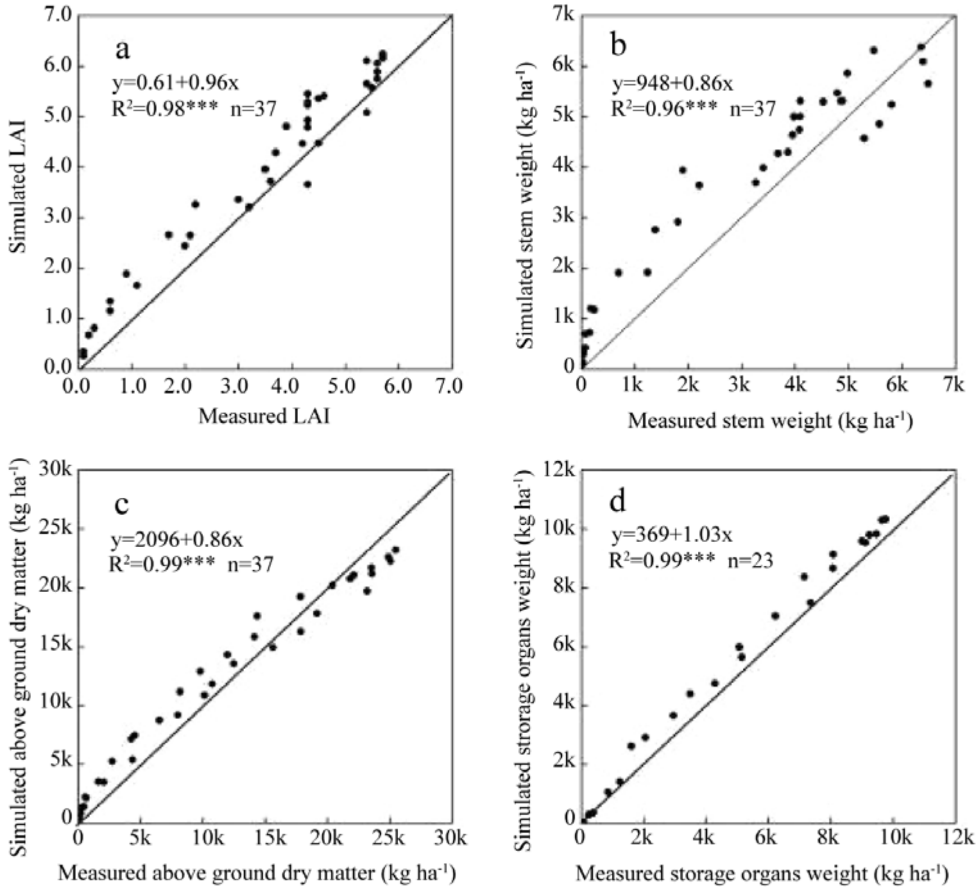

Figure 6. Relationship between observed and simulated values of LAI (a), stems weight, (b) above ground dry matter (c) and storage organ weight (d). Values in 1998 and 1999 were put together. *** Significant at P<0.001.

Spatial variability of climate

Total solar radiation ranged from 1,850 to 2,160 MJ m^{-2} and was higher in the north, duo to the less rainy days. Its inter-annual variation was small (<12) in most part of the plain (Figure 7d). In contrast, cumulative temperature increased from north to south, ranging from 2,780 to 3,170 ^{o}C d, with a low inter-annual variation of lower than 3% (Figure 7e). Growing season rainfall ranged from 325 to 600 mm, with the lowest value found in the middle of the plain, increasing to 450 mm towards north east and to around 600 mm towards south east. Growing season rainfall has very high variability, ranging from 29% in the middle area to more than 50% in the northwest (east of the Taihang Mountains) and 45% in the south.

Simulated potential and rainfed yields

Long-term averaged potential yields in each site vary from 7,700 to 10,000 kg ha^{-1}, with an overall mean of 8,880 kg ha^{-1} (Figure 8a). Generally, it follows a decreasing trend from north to south, due to the lower intercepted solar radiation and shorter crop growth period.

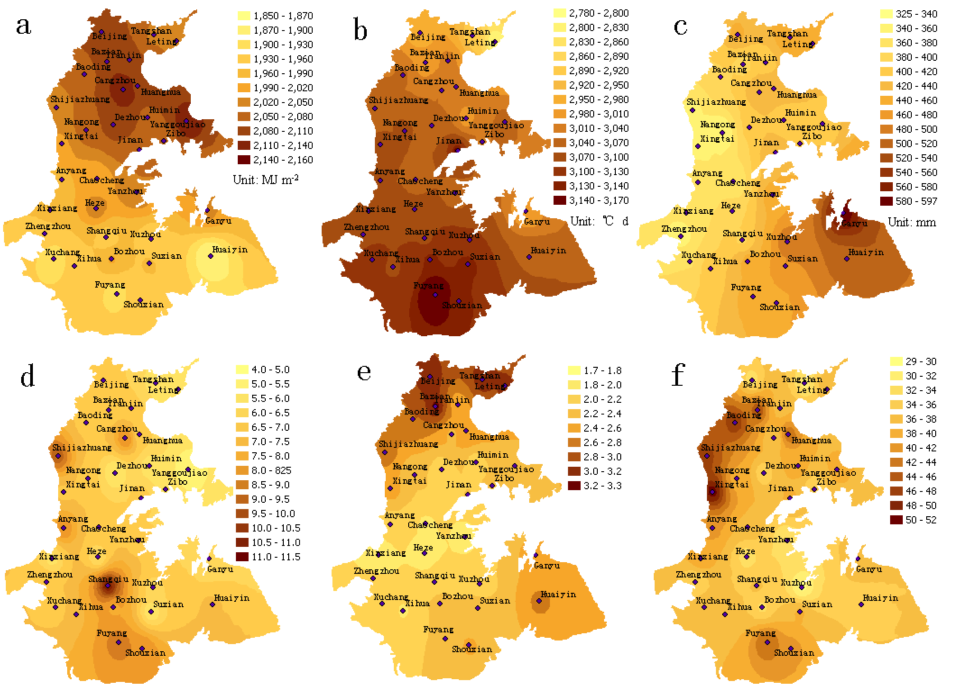

Figure 7. 40 year averaged and variation of total radiation, temperature and rainfall in the maize growing season in North China Plain: (a) total global radiation, (b) cumulative temperature, (c) total rainfall. (d), (e) and (f) indicate the coefficient of variations in global radiation, cumulative temperature and rainfall, respectively.

Rainfed yield varies between 4,320 and 8,090 kg ha^{-1} (Figure 8b), with a regional average of 6,010 kg ha^{-1}. Rainfed yield increases from the regional center to the north and southeast, roughly following the trend of rainfall (Figure 7c).

As actual yield of summer maize through the plain is hard to collect, gap between potential and rainfed yields were used to identify yield improve potential by better water supply. The gap between potential and rainfed yields varied from 1,360 to 4,470 kg ha^{-1}, with the highest value at Zhengzhou, Cangzhou and large part of the Shandong Province (Figure 9). Yield improvement potential is higher in those hotspot areas where the yield gap is high (more than 3,000 kg ha^{-1}) if irrigation water is available. Southern areas like Fuyang have abundant rainfall (rainfall in summer maize season is over 450 mm), the rainfed yield is very close to potential yield. For the entire NCP the mean yield gap between potential and rainfed yields is 2,870 kg ha^{-1}.

Because the model was verified using measurements from the YCES, the long-term simulations for the site are a temporal extrapolation of the experimental findings. Therefore the long terms simulations for the site Dezhou, which locates near the YCES, have the greatest credibility of any of the long-term simulations (Figure 1). Figure 10 is the actual yield, potential yield and rainfed yield in this site from 1961 to 2000. Though actual yield increased very fast in this period, in this site, it is always lower than simulated rainfed and potential yield. Before 1980s, there is a notable trend that rainfed yield increase with decreased potential yield. Gap between actual and potential yield is very large before 1980s because production efficiency of maize cultivars at that time is very low. After 1990s, the gap is relative stable, indicating that the current maize cultivar is well described by the model.

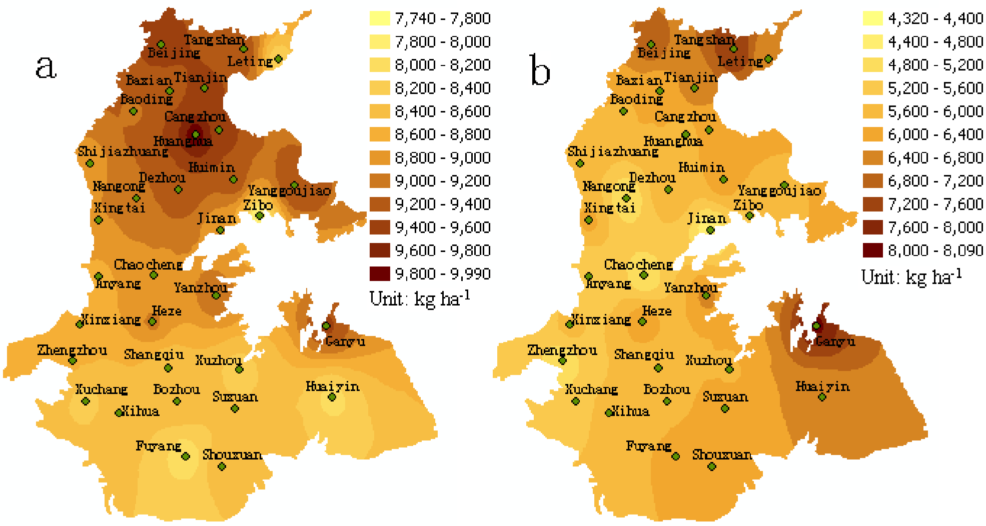

Figure 8. Simulated potential (a) and rainfed (b) yields of summer maize in the North China Plain.

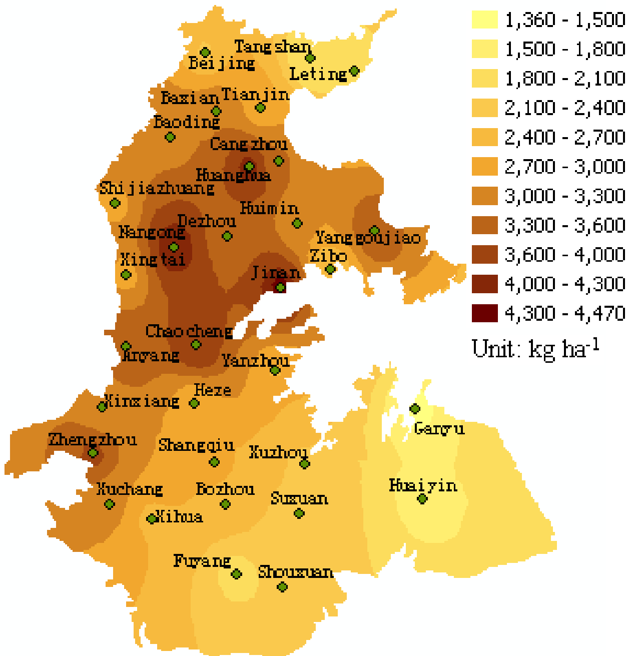

Figure 9. Yield gap between potential and rainfed yield in the NCP.

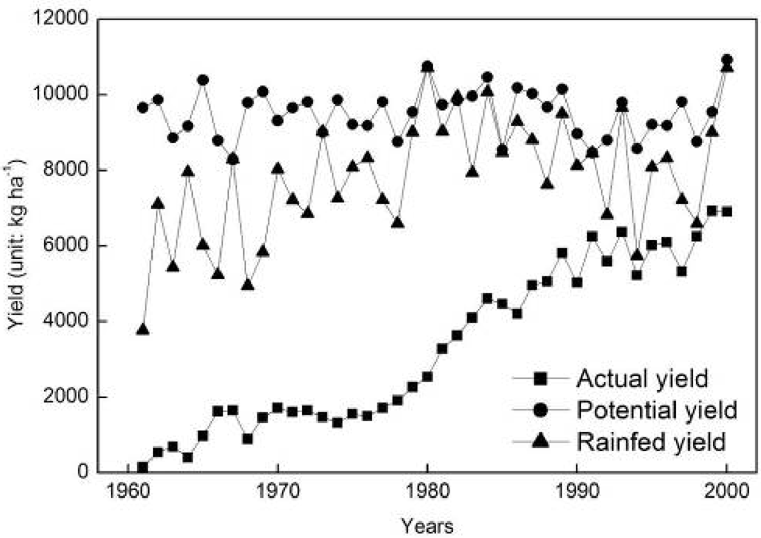

Figure 10. Actual yield, potential yield and rainfed yield in Dezhou from 1961 to 2000.

Interaction between crop yield and rainfall

Figure 11 shows the relationship between potential and rainfed yield at two locations: Chaocheng and Fuyang. Chaocheng is located in the north of NCP with 350 mm rainfall in the maize growing season, while Fuyang is in the south part and has 450 mm growing season rainfall. At Chaocheng, potential yield is relatively constant, while the rainfed yield varies considerably (Figure 11a), implying rainfall variability is the major yield determinant. In contrast, at Fuyang, potential yield varies significantly from year to year and rainfed yield is very similar to potential yield (Figure 11b). This indicates that rainfall is not the limiting factor for yield. Maize yield is limited by the combined effect of solar radiation and temperature, where wetter years will caused yield decrease instead of increase.

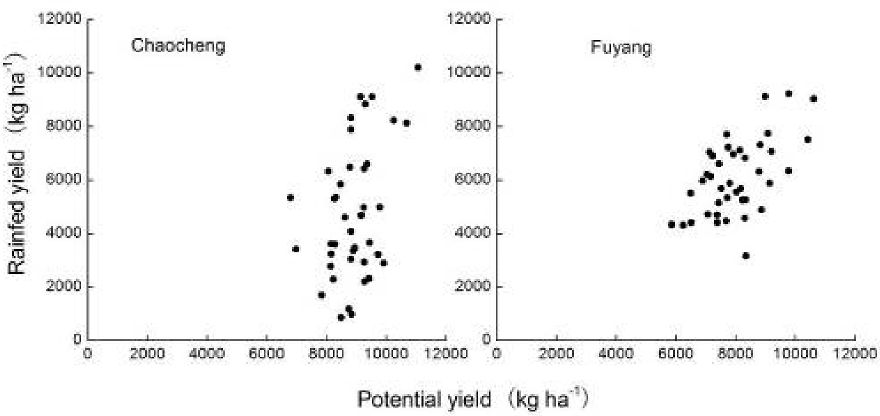

Figure 11. Relationship of simulated potential yield and rainfed yield in Chaocheng and Fuyang from 1961 to 2000.

Temporal variability on maize yield

Figure 12 shows the probability distribution of simulated potential and rainfed yields at six locations along the north-south transect. With decreasing latitude, the distribution line of potential yield moves to the left, indicating decreasing potential yield (Figure 12a). As to the rainfed yield, yield range becomes wider towards the center of the plain (Figure 12b). The range of rainfed yield in Nangong and Chaocheng is quite wide, which means rainfed yield varied greatly and thus rainfall is the most important limiting factor to summer maize growth.

Figure 13 is the coefficient of variation of potential and rainfed yield in the whole plain. Coefficient of variation of potential yield (ranging from 6.3 to 13.7) is much less than that of rainfed yield (varying from 20 to 55), showing the greater impact of rainfall variability. The variation of potential yield is closely related to the variation of solar radiation in summer growing season (Figure 7d). Inter-annual variation of rainfed yield is very big in the middle of the plain, especially in Nangong, Chaocheng and Cangzhou, which are the stations with lowest rainfall.

The rainfall and its variation are similar in the two neighboring locations, Nangong and Shijiazhuang (Figure 7c, f), but the variation of rainfed maize yield is very different (Figure 13). A detailed analysis indicates a relationship between wind speed and rainfed yield. Averaged wind speeds in summer maize growth season in the two stations are 2.42 and 1.52 m s^{-1}, respectively. Higher wind speed at Nangong causes larger water loss from canopy, which may partly explain the higher variability of rainfed yield in Nangong than in Shijiazhuang.

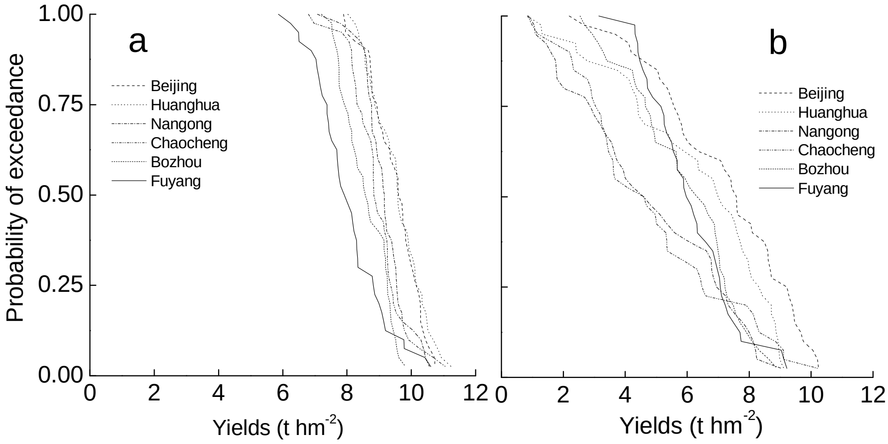

Figure 12. Cumulative distribution of (a) potential yield and (b) water-limited yield of summer maize for six locations in the North China Plain.

Discussion and Conclusions

This paper presented a simulation study based on long term climate records to quantify the potential and rainfed yields of summer maize in the NCP. Areas with big gap between simulated potential and rainfed yields are identified. These areas may have potential to increase maize yield by irrigation if irrigation water is available. The calculated potential/rainfed yield and their spatial distribution are different from the results of Wang et al. (1990), who calculated the maize yield in the NCP by the AEZ (agro-ecological zones) model using averaged climate and soil data. This may be mainly caused by different methods used in the AEZ model and WOFOST model to control the growth season. AEZ method used fixed crop duration, which means higher temperature in the south plain will caused more dry matter, while WOFOST use cumulative temperature, higher temperature means short crop duration and thus less dry matter.

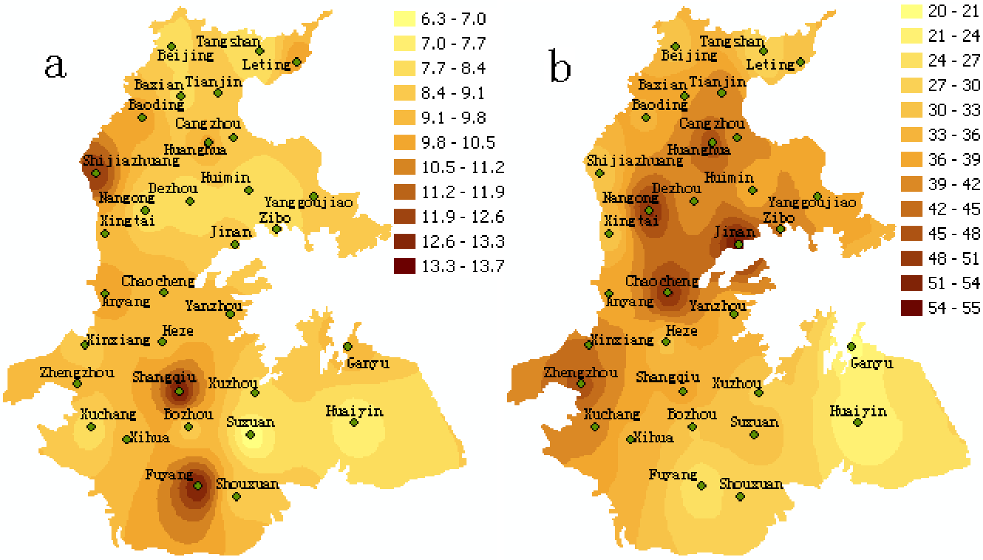

Figure 13. Coefficient of variation of potential (a) and rainfed (b) summer maize yields in the North China Plain (in percentage).

Our results are consistent with that of Liu et al. (2002) but in more detail. Their results also indicated that the middle of the plain had the greatest potential of yield increase by improving water supply. Because they used average climate data, both Wang et al. (1990) and Liu et al (2002) were not able to analyze the impact of climate variability on maize yield. With the support of GIS system, this study depicts potential, rainfed yield and their variability in considerable detail.

The potential yield in the NCP is higher in the north and lower in the south, following a decreasing trend with latitude, with a regional average of 8,880 kg ha^{-1}. Variation of potential yield was mainly caused by the variation of solar radiation in summer maize growth season. Rainfed yield is lower in the middle of the plain and becomes higher in the north and south with a regional average of 6,010 kg ha^{-1}. This pattern was closely related to the distribution of rainfall in the maize growing season. Locations where rainfall is low have higher rainfall variability, thus higher variability of rainfed yield. Yield gap between potential and rainfed yield is 2,870 kg ha^{-1} on regional average, i.e., about 32% of potential yield, and is higher around the center of the plain.

Annual rainfall increases from north to south with decreasing latitude, but in the higher latitude, rainfall is more concentrated in summer. In some places, more than 70% of annual rainfall is falling in the growing season of summer maize (Zhang et al., 1999). For example, Beijing (locates in the north plain) and Chaocheng (locates in the middle plain) have similar annual rainfall of 560 mm and 535 mm, respectively, whereas rainfall in maize growth season is 448 mm and 350 mm, respectively. Therefore, rainfed yield in Chaocheng is much less than in Beijing. As in the southern part of the plain, rainfall is greatly exceeds water demand by maize, thus rainfed yield responded negatively to rainfall in growing season.

In this study, we only considered the impact of spatial and temporal climate variability on the performance of summer maize. The simulations were done using only one soil type. The NCP covers five provinces with various soil types. Different soils have different water holding capacity, which will affect the rainfed maize yield. More detailed analysis requires detailed soil information to address the impact of soil types. However, we think that the results of this paper is representative as the chosen soil type is typical for the NCP, which is located in the alluvial plains of the Yellow river (Chinese National Geographical Map, 1984).

Results of this study have implications for policy makers and researchers concerned with production potential and management of summer maize in the NCP. The study quantifies the potential and limiting factors for improving summer maize yields in the NCP. Results can be further used to quantify the irrigation water requirement to achieve yield potential. Such information can assist in water resource planning linked to agricultural and industrial water use in the north China Plain. Moreover, yield results of this study can be aggregated at regional scale to provide regional maize production levels and variability. Further more, combined with consistent research of winter wheat (Wu et al. 2005), results of this study offer scientific basis for policy makers and researchers concerned with the management of food marketing decisions and water resource reallocation. This is helpful for marketing options, such as forward scales, limits security of supply and stabilize grain price.

Acknowledgements

This work was supported by National Natural Science Foundation of China (Grant No. 40328001).

References

Bechini, L., Ducco, G., Donatelli, M., Stein, A., 2000. Modeling, interpolation and stochastic simulation in space and time of global solar radiation. Agric. Ecosyst. Environ. 81, 29-42

Berkout, J.A.A., Huijgen, J., Azzali, S., Menenti, M., 1988. MARS definition study. Results of the preparatory phase. Main report. Report 17. SC-DLO, Wageningen, the Netherlands.

Boogaard, H.L., van Diepen, C.A., Rötter, R.P., Cabrerav, J.C.M.A., van Laar, H.H., 1998. WOFOST 7.1 User Guide for the WOFOST 7.1 Crop Growth Simulation Model and WOFOST Control Center 1.5. Technical. Document 52, DLO Winand Staring Center, Wageningen, the Netherlands.

Bouman, B.A.M., van Keulen, H., van Laarb, H.H., Rabbinge, R., 1996. The ‘School of de Wit’ crop growth simulation models, A pedigree and historical overview. Agric. Syst. 52, 171-198

Chen, C., Jin, Z.Q., Zheng, Y.F., Liu, J.D., 2004. Assessing the impacts of doubled CO_2 climate change and its variability on winter wheat production in the Huang-Huai-Hai plain of China.. Jiangsu J. Agric Sci. 20, 7-12 (in Chinese with English abstract)

de Koning, G.H.J., van Keulen, H., Rabbinge, R., Janssen, H.,1995. Determination of input and output coefficients of cropping systems in the European Community. Agric. Syst. 48, 485-502

Department of Geography, Northwest Normal University & SinoMap Press, 1984. Chinese National Geographical Map, (in Chinese). SinoMap Press, Beijing PR China, pp 81-82

Fisher, N.I., Lewis, T., Embleton, B.J.J., 1987. Statistical analysis of spherical data. Cambridge University Press. pp 329

Frere, M., Popov, G., 1979. Agrometeorological crop monitoring and forecasting, Plant production and protection. FAO Paper 17. FAO, Rome.

Hengsdijk, H., van Keulen, H., 2002. The effect of temporal variation on inputs and outputs of future-oriented land use systems in West Africa. Agric. Ecosyst. Environ. 91, 245-259

Lee, X.H., Yu, Q., Sun, X.M., Liu, J.D., Min, Q.W., Liu, Y.F., Zhang, X.Z., 2004. Micrometeorological fluxes under the influence of regional and local advection, a revisit. Agric. Forest Meteor. 122, 111-124

Liu CM, Yu JJ, Kendy E ,2001. Groundwater exploitation and its impact on the environment in the North China Plain. Water Int 26, 265-272

Liu, J.D., Yu, Q., Ming, Q.W., Li, S.K., Bi, J.J., 2002. Impacts of water stress on agroclimatic resources of summer maize in Huanghuaihai Plain of China, impact on regional productivity. Resource Science 24, 92-95 (in Chinese with English abstract)

Liu, Y., Teixeira, J.L., Zhang, H.J., Pereira, L.S., 1998. Model validation and crop coefficients for irrigation scheduling in the North China Plain. Agric. Water Manage. 36, 233-246.

Mo, X.G., Lin, Z.H., Li, H.X., Xiang, Y.Q., 2004. Simulation of winter wheat yield and evapotransporation with process-based model and remote sensing data in the Hebei Plain ,in Chinese with English abstract.. Geog. Res. 23, 623-631

Rabbinge R ,1993. The ecological background of food production. In, Chadwick DJ, Marsh J ,eds. Crop protection and sustainable agriculture. Ciba Found Symp. 177, 2–29

Stein, A., Staritsky, I.G., Bouna, J., van Eijnsbergen, A.C., Bregt, A.K., 1991. Simulation of moisture deficits and a real interpolation by universal cokriging. Water Resour Res 27, 1963-1973

Supit, I., Hooijer, A.A., van Diepen, C.A., (eds), 1994. System description of the WOFOST 6.0 Crop Growth Simulation Model. Joint Research Center, Commission of the European Communities. Brussels, Luxembourg

Tao, F.L., Yokozawa, M., Hayashi, Y., Lin, E.D., 2003. Future climate change, the agricultural water cycle, and agricultural production in China. Agric Ecosyst. Environ. 95, 203-215

van Diepen. C.A., Wolf, J., van Keulen, H., Rappoldt, C., 1989. WOFOST, a simulation model of crop production. Soil Use Manage. 5, 16-24

van Lanen, H.A.J., van Diepen, C.A., Reinds, G.J., de Koning, G.H.J., Bulens, J.D., Bregt, A.K., 1992. Physical land evaluation methods and GIS to explore the crop growth potential and its effects within the European Communities. Agric. Syst. 39, 307-328

Wang, E.L., Han, X.L., Qu, M.L., 1992. Climatic and soil productivity of winter wheat and its commercialization ability in Huang-Huai-Hai Plain, in Chinese. Chin. J. Agrometeorol. 13, 10-13

Wang, H.X., Zhang, L., Dawes, W.R., Liu, C.M., 2001. Improving water use efficiency of irrigated crops in the North China Plain-measurements and modeling. Agric. Water Manage. 48, 151-167

Wu, D.R., Yu, Q., Lu, C.H., Hengsdijk, H., 2006. Quantifying production potentials of winter wheat in the North China Plian. European Journal of Agronomy 24, 226-235.

Yu, Q., Liu, Y.F., Liu, J.D., Wang, T.D., 2002. Simulation of leaf photosynthesis of winter wheat on Tibetan Plateau and in North China Plain. Ecol. Model. 155, 205-216

Zhang, H., Wang, X., You, M., Liu, C., 1999. Water – yield relations and water-use efficiency of winter wheat in the North China Plain. Irrig. Sci. 19, 37-45.