Influence of Climate Change on Winter Wheat Growth in North China During 1950-2000*

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ABSTRACT

The crop model World Food Studies (WOFOST) was tuned and validated with meteorological as well as winter wheat growth and yield data at 24 stations in 5 provinces of North China from 1997 to 2003. The parameterization obtained by the tuning was then used to model the impacts of climate change on winter wheat growth for all stations using long-term weather data from 1950 to 2000. Two simulations were made, one with all meteorological data (rainfed) and the other without water stress (potential). The results indicate that the flowering and maturity dates occurred 3.3 and 3 days earlier in the 1990s than that in the 1960s due to a 0.65°C temperature increase. The simulated rainfed yields show that the average drought induced yields (potential minus rainfed yields) have decreased by 9.7% over the last 50 years. This is to be compared with a 0.02% decrease in yield if the precipitation limit is lifted. Although the precipitation during the growing season has decreased over the last 50 years, the drought effects on the rainfed yields remained to be practically unchanged as the spring precipitation did not decrease markedly.

Key words: crop growth model, World Food Studies (WOFOST), climate change, winter wheat, North China

1. Introduction

Chinese agriculture has undergone tremendous structural changes over the last decades. The average staple crop productivity has doubled in 25 yr while the population increased by 25 % [China Statistical Yearbook (CSY), 2003]. Winter wheat is one of China's most important staple food crops, with a total farming area of nearly 24 million hectares and a production exceeding 92 million ton in 2002 (CSY, 2003). Although China has been the world′s largest wheat producer since 1983 (FAOSTAT, 2004), the export has only exceeded the import since 2001 (CSY, 2003) or 2003 (FAOSTAT, 2004). Following the World Trade Organization agreements, China's decreasing import tariffs are likely to raise the demand for land-intensive cultivation, e.g., wheat, for the domestic market (FAO, 2002).

Winter wheat growth and productivity are influenced by weather, especially temperature and precipitation which determine both phenological development and growth rates (Bauer et al., 1984). Furthermore, Chinese agriculture is strongly affected by the East Asian monsoon system. In the north this often causes low temperature, regional and large-scale droughts while the south faces floods, high temperature, continuous rain, severe floods, and hail storms. These disasters frequently have adverse effects on agriculture. As a result the winter wheat production fluctuates interannually with varying meteorological conditions (e.g., Tao et al., 2004).

In addition to interannual variabilities, regional climate in China is undergoing a change. The average annual temperature for China as a whole has increased by 0.5-0.7 °C (Wang et al., 2004) while the total precipitation has decreased (Zhai et al., 1999) over the last 50 years. Moreover, during the period 1990 to 2100 the global surface air temperature is projected to increase by 1.4 to 5.8°C as a result of increasing concentrations of atmospheric carbon dioxide and other greenhouse gases (IPCC, 2001). Consequently the regional climate will also be affected (Ding and Ren, 2005; Qian et al., 2005).

To assess the possible impacts of climate

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variability and change on crop production, crop models have been extensively applied during the recent decades (Riha et al., 1996; Dai, 1997; Lin et al., 1997; Zhang and Wang, 1998; Hulme et al., 1999; Mavromatis and Jones, 1999; Lal et al., 1999; Alexandrov and Hoogenboom, 2000; Xiong et al., 2001). While many studies in China have focused on rice production (e.g., Ge et al., 2002), relatively few have dealt with wheat. Recently, Wu (2003) conducted an experiment for two years (2000-2001) at Yucheng Experiment Station (36°57′N, 116°36′E), Shandong Province. He retrieved a series of parameters for World Food Studies (WOFOST) model which must be changed according to different winter wheat cultivars, soil types, and climate condition. This model will also be used in this study.

Climate change will doubtless have impacts on the agricultural productivity and operations in the future. It is therefore important to investigate how agriculture has responded to historic climate change over the last 50 years. Climate consists of various variables such as temperature, precipitation, wind speed, and solar radiation. It is the combined effect of all the climatic variables that have the impact on yields. To understand the relative role played by each climatic variable, a tool to separate the influences of each climatic variable is needed. A crop model that simulates crop growth influenced by climate provides an effective means for this purpose. The aim of this paper is to tune and validate the WOFOST model with observations from North China, then to assess the influence of climate change in winter wheat in 5 provinces of North China in the latest 50 years. Particularly, the role played by precipitation will be identified.

2. Material and methods

2.1 *Study area*

Shandong, Hebei, Shanxi, Shaanxi, and Henan Provinces are the major winter wheat-growing regions on the North China Plain. The total arable area is 40.9 million hectares, of which 13.8 million was used for wheat in 2000 (CSY, 2001). The region encloses temperate, semi-humid and monsoon-controlled climatic zones with an annual mean temperature of 11.2-14.4°C. Summers are rainy and hot (monthly mean temperature ranges from 22 to 28°C) whereas winters are dry and cold (monthly mean temperature ranges from -10 to 1°C). The total annual precipitation generally ranges from 400 to 1000 mm (China Meteorological Administration, 2000) depending on circulation patterns and topographic features. For example, that strong East Asian monsoons bring colder winters (Tao et al., 2004), dust storms, and droughts are common in springtime. Moreover, frequent hail and dry-hot winds damage crops in May and June.

The winter wheat region in northern China is divided into 24 ecological regions based on climate, soils, land use, and current agriculture practices (China Meteorological Administration, 2000). Hence 24 stations, one representative of each region were selected and winter wheat growth and yields were simulated for these stations (Table 1).

2.2 *The WOFOST model*

WOFOST model belongs to a family of models developed by the school of C.T. de Wit in Wageningen, the Netherlands. The model originated in the framework of interdisciplinary studies on world food security and on the potential world food production. The latest version 7.1.2 issued in 2002 is available as freeware on the internet. Supit et al. (1994) and Boogaard et al. (1998) described the model in detail. WOFOST is developed to simulate the effect of cultivar, planting density, weather, soil water, and nitrogen on crop growth, development, and yield. The model has been used for crop growth monitoring (Lanen et al., 1992), potential yield forecasting on regional and national scales (Rötter, 1993; Wolf, 1993), as well as for climate change scenarios (van Diepen et al., 1987; Wolf and van Diepen, 1991; Wolf, 1993). Furthermore, the model has been applied in different climatic regions (Wolf et al., 1989; Savin et al., 2001), including northern China (Wu, 2003).

2.3 *Input data required by the model*

The input data to run WOFOST include weather, crop characteristics, and soil data.

The meteorological data required to estimate

Table 1. Characteristics of the 24 stations in North China winter wheat region

Station	Province	Longitude (°E)	Latitude (°N)	Annual mean temperature (°C)	Annual total rainfall (mm)	Cropping
Dezhou	Shandong	116.19	37.52	13.2	656.5	Single crop
Huimin	Shandong	117.32	37.30	12.5	568.5	Single crop
Tai′an	Shandong	117.09	36.10	12.8	681.3	Single crop
Zibo	Shandong	118.00	36.50	13.2	615.0	Single crop
Weifang	Shandong	119.05	36.42	12.5	588.3	Double crops
Heze	Shandong	115.26	35.15	13.7	624.7	Single crop
Jining	Shandong	116.35	35.26	13.6	660.1	Single crop
Juxian	Shandong	118.50	35.35	12.25	754.5	Single crop
Zhuozhou	Hebei	115.58	39.29	12.3	571.9	Single crop
Tangshan	Hebei	118.09	39.40	11.5	610.3	Single crop
Shijiazhuang	Hebei	115.00	38.31	13.4	517.0	Single crop
Nangong	Hebei	115.23	37.22	9.5	202.1	Single crop
Hejian	Hebei	116.05	38.27	12.9	604.9	Single crop
Fenyang	Shanxi	111.47	37.15	9.1	46.15	Single crop
Yuncheng	Shanxi	111.01	35.02	14.0	529.5	Single crop
Changzhi	Shanxi	113.04	36.03	9.9	534.0	Single crop
Xunyi	Shaanxi	108.18	35.10	9.5	590.2	Double crops
Hancheng	Shaanxi	110.27	35.28	14.0	529.5	Single crop
Shangzhou	Shaanxi	109.58	33.52	12.8	668.5	Single crop
Chenggu	Shaanxi	107.20	33.10	14.3	852.6	Single crop
Tangyin	Henan	114.21	35.56	14.2	558.8	Double crops
Ruzhou	Henan	112.50	34.11	12.1	816.1	Single crop
Qixian	Henan	114.47	34.32	14.2	637.1	Single crop
Xinyang	Henan	114.05	32.07	15.3	1105.7	Single crop

wheat growth and yields include daily values of maximum, minimum and mean air temperature, precipitation, early morning vapour pressure, mean wind speed at 2 m above ground, and solar radiation at the surface. Daily weather data for 70% of the stations were provided by China Meteorological Administration during the period 1950 to 2003. For the other meteorological stations where daily weather data from 1950 to 2003 were unavailable, it was obtained from nearby weather stations within 30-40 km distance. All weather data have been quality controlled. Missing values have been replaced with the long-term daily averages from a neighbouring station which has been adjusted according to the difference of two stations.

There are 17 genetic parameters of the model which strongly influence the simulated winter wheat growth. These parameters are either chosen following Wu (2003) or tuned (8 of 17 parameters) within the reasonable range to force the modelled results to approach the observed ones.

WOFOST model also requires soil physical characteristics, such as water retention, hydraulic conductivity, and workability for calculating the daily soil water balance. The available water content is estimated from the textural class of the predominant soil. The other soil input data were obtained from the Second Soil Survey (China Soil Survey Office, 1995).

2.4 *Tuning and validation of the model*

The model was tuned by changing the genetic parameters. The observations for year 2000 or 2001 were used in the tuning process. The validation period for the model was 1997-1999 and 2001-2003 for Huimin, Nangong, Xinyang, Shangzhou, Xunyi, and Beijing Stations, and 1997-2000 and 2002-2003 for the remaining 18 stations, including flowering and maturity dates and yields for all the 24 stations.

2.5 *Simulated impacts of climatic variables*

Changes in all meteorological variables used by the model will have an impact on the growth. Two simulations are made, one showing the total effects of all climatic variables and the other the effects excluding that from precipitation. The difference of the two would give information about the importance of precipitation for the growth in relation to other climatic variables.

3. Result and discussion

3.1 *Tuning and validation*

WOFOST model was tuned for Huimin, Nangong, Xinyang, Shangzhou, Xunyi, and Beijing in 2000. The other stations were adjusted to 2001 when the weather conditions were closer to normal and relatively few climate disasters occurred. The soil parameters were set for each station according to previous studies (China Soil Survey Office, 1995). The genetic parameters for winter wheat were tuned through simulations since these data were not available for most stations. These parameters were changed to get close agreement between the simulated and observed growth stages and yields. When the simulated flowering and maturity dates agreed within 10% and the yields within 15% range of the observed values at same time, the genetic parameters were set and considered to be reasonable. If not, the genetic parameters were further adjusted until the simulated results were within the 10% or 15% range for the observed date and yield respectively. To aid the comparison of simulated results with observed information for tuning the model (Fig.1), the following statistics are computed: correlation coefficients (R), bias, relative bias, mean square error (MSE), and relative MSE. Table 2 shows these statistics when the tuning process is finished and the parameters are determined.

The simulated dates are on average 1.2 days and 0.03 days earlier than the observed for flowering and maturity respectively. Furthermore, the systematic error is small. The simulated yields agree well with the observed, only 2% bias. The determined parameters tend to overestimate the yield in most stations, which

Table 2. Analysis of model output and observation for winter wheat

	R	n (number)	Bias	Relative bias	MSE	Relative MSE
Flowering	0.80	104	-1.2 days	0.01	4.2 days	0.04
Maturity	0.79	107	0.0 days	0	3.9 days	0.02
Yield	0.90	56	17.5 kg hm^{-2}	0.02	495.9 kg hm^{-2}	0.10

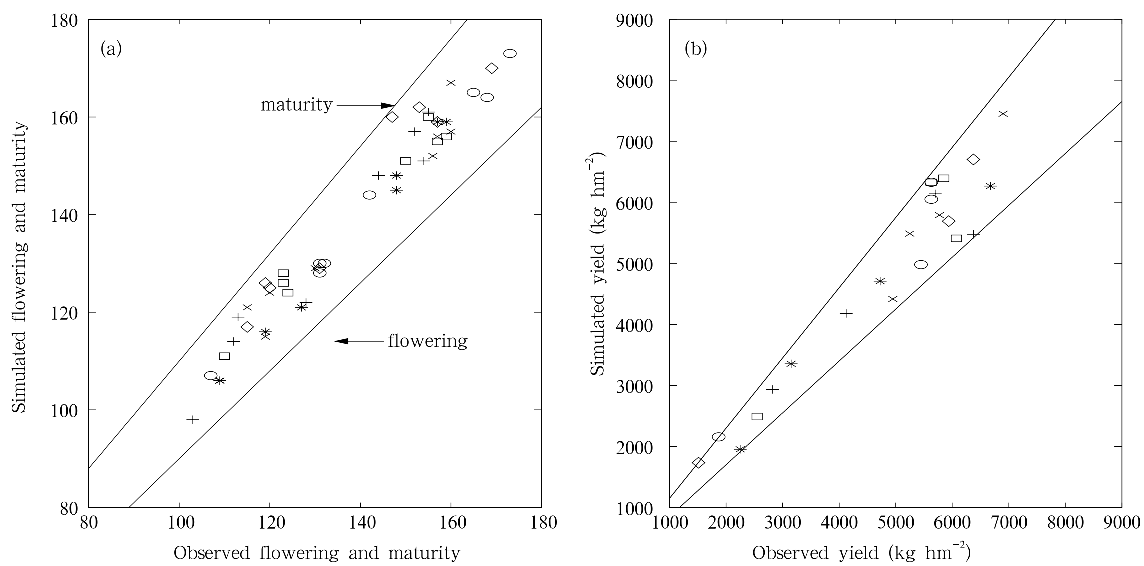

Fig.1. Simulated growth stages and yields of winter wheat compared with observations for tuning the model for 24 stations in North China.

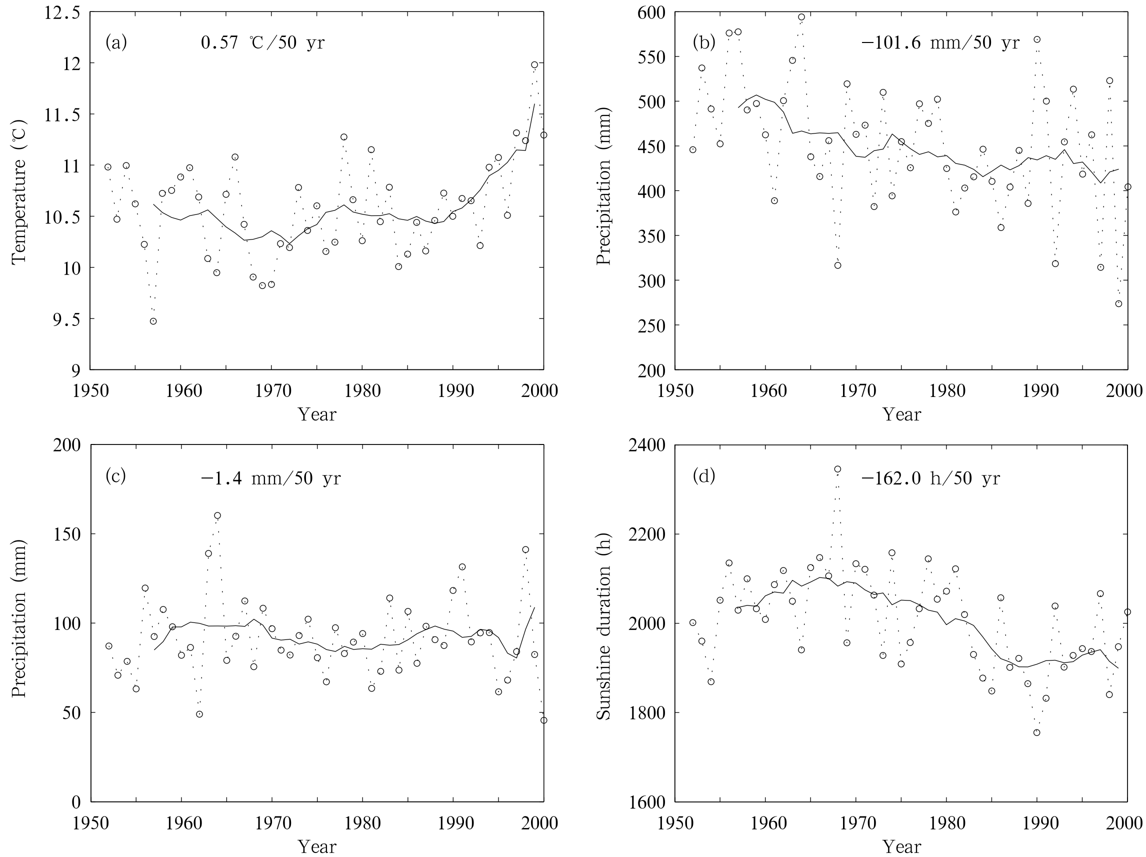

Fig.2. Variability of temperature (a), precipitation (b), precipitation in spring (March-May (c)), and sunshine duration during the growing season (October-June (d)) of winter wheat in North China from 1950 to 2000. The dashed line shows the interannual variability while the solid line displays the 10-yr moving average.

may be considered to account influences by factors such as pest or disease incidences that are not represented by the model. Furthermore, WOFOST, as other crop growth models, has some shortcomings which caused the differences between simulations and observations. For example, WOFOST treated some aspects simply and used a simple formula instead of a complex one to simplify input. And WOFOST model also disregards dry matter transportation from leaves and stems to seeds during grouting of winter wheat. Death of winter wheat induced by low temperature was not calculated by WOFOST during winter. As a result, all these reasons can make the deviation in the observed values and simulated yields.

3.2 *Climate change in growing season*

Climate change during the growing season is firstly assessed before the simulated impact of climate change on winter wheat growth is evaluated. The growing season for winter wheat in North China is assumed from October to June. The regional climate variables in North China were made from these 24 stations.

Four most important climatic variables are potted in Fig.2, and the trends are indicated in the figures over the last 50 years. The mean temperature during the growing season in the last 50 years shown in Fig.2a has a fairly great annual fluctuation and an increasing trend that follows that of the annual mean temperature over whole China (National Climate Center, 2000). The decadal mean temperature (Table 3) increased from 10.4°C (1960s) to 11.0°C (1990s).

Depending on the precipitation amounts in northern China, droughts often occur on a regional scale and seriously influence winter wheat yields. Between 1950 and 2000 precipitation decreased by 101.6 mm/50 yr (17.0%) in the growing season (Fig.2b). For example, the total precipitation declined gradually from 464 mm to 421 mm in the 1960s and 1980s, respectively. In the 1990s the decadal average precipitation during the growing season was 418 mm, which is equal to a decrease of 17.0% compared to the 1950s.

Since droughts in North China generally occur in spring, we have paid extra attention to precipitation changes in March through May. Figure 2c illustrates how spring precipitation has decreased with a rate of -0.3 mm/10 yr, which is much smaller than that of the whole growing season. However, spring precipitation in the 1970s and 1990s was less than that in 1960s and 1980s, and 2000 was the driest year of all 50 years, triggering a number of large scale droughts (National Climate Center, 2000).

There are three main ways in which radiation is important for plant life (Jones, 2000). Firstly, some of the solar radiation absorbed by winter wheat is used for the synthesis of energy-rich chemical bonds and reduced carbon compounds. Secondly, radiation is the major mode of energy exchange between the wheat plant and the aerial environment. Thirdly, the amount and spectral distribution of short wave radiation regulate crop growth and development. Sunshine duration is often used as an indicator of solar radiation. The amount of sunshine duration has decreased by 30.2 h/10 yr during the growing season across the North China Plain (Fig.2d). In the 1980s and 1990s, the sunshine duration decreased by 173.2 h/10 yr and 154.9 h/10 yr compared to that in the 1960s. The decreasing of sunshine duration will have adverse effects on winter wheat growth, which we will see in the following section.

3.3 *Simulated influence of climate change on the growth and yields*

Using the parameters determined by the tuning of the model, observed flowering and maturity dates, yields and long-term weather data, simulations were made for all 24 stations in North China from 1950 to 2000. It is assumed that there is no change in winter wheat variety or agricultural management. In that way the growth and yields can only be influenced by climate. The simulated potential yields are affected mainly by temperature and radiation, while the rainfed yields are also determined by the actual rain. The difference between the potential and rainfed yields indicates the role played by the precipitation relative to other climatic variables.

3.3.1 *Impact on the growth*

Temperature influences plant growth and development through their effects on stomatal opening and rate of physiological processes. High temperature can speed up the biochemical reactions and increase transpiration losses. A rise in temperature leads to increased accumulation of degree-days, hence growth and development rates boost, resulting in

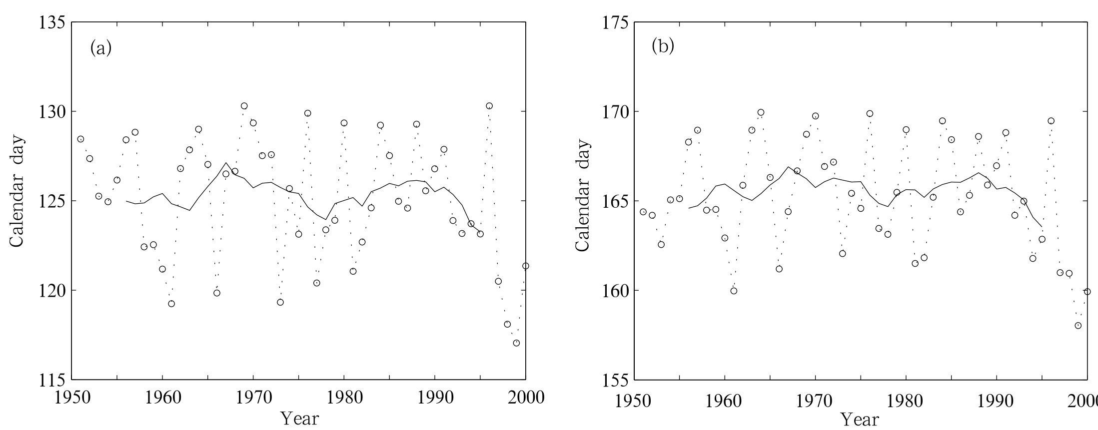

Fig.3. Simulated flowering (a) and maturity (b) dates for winter wheat in North China from 1950 to 2000. (The dashed line shows the interannual variability while the solid line displays the 10-yr moving average.)

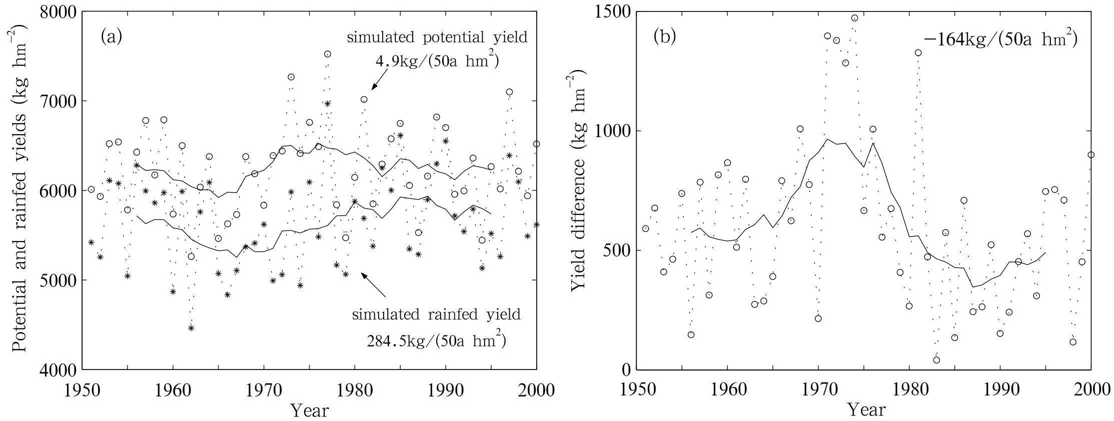

Fig.4. (a) Simulated potential and rainfed winter wheat yields and (b) difference yield of potential yield minus rainfed yield in North China from 1950 to 2000. (The dashed line shows the interannual variability while the solid line displays the 10-yr moving average.)

Table 3. The mean climate and simulated potential yields in North China

	1950s	1960s	1970s	1980s	1990s
Mean temperature during growing season (°C)	10.6	10.4	10.5	10.5	11.0
Sunshine duration in growing season (h)	2020.8	2100.9	2043.8	1929.7	1946.0
Precipitation in growing season (mm)	503.4	463.7	453.9	421.4	418.3
Precipitation in spring (mm)	88.8	101.4	87.6	93.3	84.6
Simulated potential yield (kg hm^{-2})	6269.7	5938.9	6473.5	6374.8	6180.8
Simulated water limited yield (kg hm^{-2})	5688.9	5371.3	5562.2	5930.7	5655.4

Growing season = October−June, Spring =March−May

a reduction of phenophase duration. Figure 3 shows the growth dates over the last 50 years in North China. The duration of flowering and maturity clearly reduced in the 1990s as well as the flowering and maturity dates occurred 3.3 days and 3 days earlier than that in the 1960s due to a 0.65°C temperature increase. These results are in agreement with Sainia and Nanda (1987) and Dhiman et al. (1985), who found that the flowering and maturity dates reduced by about 5 days and 4 days under 1°C temperature increase in Northwest India.

3.3.2 *Influence on yields*

In order to separate the role of precipitation change from other climatic variables, the differences between the simulated potential and water limited yields are examined.

In WOFOST the modeled potential yields are influenced mainly by temperature and sunshine duration. The simulated potential yields were the lowest in the 1960s with 5938 kg hm^{-2} , which coincided with the lowest decadal mean temperature during growing season, 10.35°C. The sunshine duration was relatively high, 2101 h. This indicates that the low temperature was the main reason for the small potential yield in the 1960s. The highest potential yield cropped up in the 1970s with 6474 kg hm^{-2}, corresponding to a good cooperation between relatively high mean air temperature and the sunniest decade with 2044 sunshine hours. Of course, the temperature distribution is an important reason for yield. For example, the same mean temperature with warm winter and cool summer was feasible for winter wheat to increase yield. In the 1990s the potential yield was lower than that in the two previous decades, in part due to shortage of sunshine, 1946 h, the highest average decadal temperature. The increasing mean temperature caused a decade with shorter growing periods (Fig.4) which lowered the potential yield. In combination with the simulated annual anthesis and maturity dates, a negative trend of 2.7 and 2.6 days respectively in the 1990s is evident compared with the 1980s. Similar to others (e.g., Southworth et al., 2002), we found that a shorter growing season is inherently detrimental since there is less time for photosynthesis and accumulation of biomass and hence potential yield.

The rainfed yields are influenced by temperature, radiation and rain since non-irrigated agriculture is affected frequently by spring drought in North China. The drought effect on yields (the potential minus rainfed yields) was 606 kg hm^{-2} during the 50 years, equal to 9.7% of the potential yield (Fig.4). The most serious drought in 1974 led to a decrease of 23% of the potential yield. Furthermore, the drought effect was in general serious in the 1970s with a 14% decrease of the potential yield, due to relatively low spring precipitation relative to other decades. On the other hand, the combination of rain and growth stage also plays an important role. For example, rain shortage during the tasseling, flowering, and filling periods will have more negative effects on the yield than during other growth stages. Although the total precipitation during the growing season decreased, it seems that the drought effect on rainfed yield did not change seriously owing to a stable spring precipitation over the 50 yr period.

4. Conclusions and discussions

The WOFOST model was tuned and validated to fit the observed flowering and maturity periods as well as yields in 5 provinces from 1997 to 2003. Most simulated growth dates and yields agree within a ±15% range of the observed data, with a slight tendency to overestimate yields. The modelled trends in winter wheat yield and growth are in agreement with the observed values from 24 stations. The results demonstrate that WOFOST model predicts potential winter wheat yields and growth reasonably well in North China under current climatic conditions.

By assuming constant winter wheat varieties and agricultural practices, the impacts of climate on winter wheat growth and yields over the last 50 years were simulated. Two simulations were made to identify the role played by the precipitation in relation to other climatic variables. The simulated results show that the winter wheat growing period has reduced by 1.8% owing to a temperature increase of 0.65°C. Moreover, the flowering and maturity dates occurred 3.3 days and 3 days earlier in the 1990s than those in the 1960s. The drought has a great effect on potential yield from year to year. On the average, the negative effect is 9.7% of the potential yield. While the potential yield decreased only by 0.02% and rainfed yield increased by 0.07% for 50 years. Although the precipitation during the growing season has decreased over the five decades, the rainfed yields were only slightly affected as spring precipitation did not decrease markedly. This points out the importance of the spring precipitation for winter wheat production in North China.

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