The Influence of Climate Change on Winter Wheat during 2012–2100 under A2 and A1B Scenarios in China

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Abstract

By assuming constant winter wheat varieties and agricultural practices in China, the influence of climate change on winter wheat is simulated using the corrected future climate projections under SRES A2 and A1B scenarios from 2012 to 2100, respectively. The results indicate that the growth of winter wheat would be strongly influenced by climate change in future. The average flowering and maturity dates of winter wheat would advance by 26 and 27 days under scenario A2, and by 23 and 24 days respectively under scenario A1B from 2012 to 2100. The simulated potential productivity of winter wheat shows a decrease of 14.3% and 12.5% for scenarios A2 and A1B respectively without the fertilization effect of CO₂, while an increase of 1.3% and 0.6% with the fertilization effect of CO₂. Additionally, for northern China, the simulated potential productivity would markedly decrease under both scenarios, independent with the fertilization effect of CO₂, which indicates that the current planted winter wheat would be more vulnerable than that in southern China. The most likely reason is the current winter wheat varieties in northern China are winter varieties or strong winter varieties, which need some days of low temperature for dormancy. While in southern China, the winter wheat is spring or half winter varieties and can grow slowly during winter, thus, they would be affected slightly when winter temperature increases. The results of this study may have important implications for adaptation measures.

Keywords: climate change; A2 and A1B scenarios; WOFOST; winter wheat; China

1 Introduction

At present, 40% of the Earth’s land surface is managed for cropland and pasture. In developing countries, nearly 70% of people live in rural areas where agriculture is the largest supporter of livelihoods. Being a large developing country, China has a total population about 1.3 billion, and the food production is 546.5 billion kg [NBSC, 2011]. Up to now, agriculture is still the most important industry for China. Winter wheat is one of China’s most important staple food crops, with a total farming area of nearly 24.3 million hm² and a production exceeding 115.2 billion kg in 2010 [NBSC, 2011].

The interannual, monthly and daily distributions of climate variables (e.g., temperature, radiation, precipitation, and wind speed) affect a number of physical, chemical and biological processes that drive the crop productivity. The meridional distribution of crop is a function of the current climate, as well as of pho-
to period. The total seasonal precipitation and the spatial variability are both of major importance to crops. Short-term natural extremes, such as droughts, floods, and interannual and decade climate variations, such as the El Niño Southern Oscillation (ENSO), all have important effects on crops. In China, winter wheat growth and productivity are also strongly influenced by climate, especially temperature and precipitation which determine both phenological development and growth rates. Specifically, Chinese agriculture is strongly affected by the East Asian monsoon. In the north it often causes low temperature, regional and large-scale droughts, while floods, hail storms, and high temperatures in the south. As a result, the winter wheat productivity fluctuates interannually with varying meteorological conditions.

In addition to interannual variability, regional climate in China is undergoing a change. The average annual temperature for China as a whole shows an increasing trend of 0.29°C per 10 years, while the total precipitation has changed slightly from 1961 to 2011 [CMA, 2011]. Moreover, for the period 1990–2100 the global surface air temperature is projected to increase by 1.1–6.4°C as a result of increasing concentrations of atmospheric CO$_2$ and other greenhouse gases [IPCC, 2007]. Consequently the regional climate in China will also be affected [Ding et al., 2007a]. It is expected that agriculture will be affected greatly by climate change.

To assess possible impacts of climate change on crop productivity, crop models have been extensively applied during recent decades. While many studies for China have focused on rice yield [Yao et al., 2007; Xiong et al., 2005; 2010], relatively few have dealt with wheat in different regions of China using future projections. Wu et al. [2003] conducted a 2-year experiment (2000–2001) at Yucheng experiment station (116°36'E, 36°57'N), Shandong province. He retrieved a series of parameters for WOFOST (World Food Studies) model which must be changed according to different winter wheat cultivars, soil types and climate condition. This setup of the model have been used to assess the impact of the past climate change on winter wheat in China [Song et al., 2006] and will also be used in this study.

The objective of this paper is to use the validated crop model, WOFOST, together with five general circulation models (GCMs) under SRES A2 and A1B scenarios, to assess possible influence of the future climate change on winter wheat growth and productivity in China. This will be done spatially and temporally between temperate, semi-humid region, and warm-humid climate regions of China from 2012 to 2100. Particularly, the different influences of climate change on productivity of winter wheat will be identified in different climate regions. By excluding the effects of precipitation, this study focuses on the climatic effects of temperature increasing and provides insights for future agricultural decision making.

2 Material and methods

2.1 Study area

Winter wheat are planted in Shandong, Hebei, Shanxi, Shaanxi, and Henan provinces in northern China as well as in Jiangsu, Anhui, Hubei, Sichuan, Chongqing, Guizhou, Yunnan provinces in southern China. In northern China, the winter wheat region has an annual mean temperature of 11.2–14.4°C, summer is rainy and hot (monthly mean temperatures range from 22 to 28°C) whereas winter is dry and cold (monthly mean temperatures range from –10 to 1°C). The total annual precipitation generally ranges from 400 to 1,000 mm [CMA, 2000] depending on circulation patterns and topographic features. While in southern China, most of the winter wheat region encloses warm and humid monsoon-controlled climatic zones. Winter temperature (December to next February) is higher than that in northern China with 0–5°C, and summer is hot with mean temperature at 25–28°C. The annual precipitation is around 800–1,500 mm which is much more than that in northern China.

The winter wheat region in China is divided into 50 ecological regions based on climate, soils, land use, and current agriculture practices [CMA, 2000]. Hence 50 stations, one representative for each region are selected (Fig. 1). The stations locate from 33° to 42°N belong to northern China, others belong to southern China. In northern China, the current winter wheat varieties are winter varieties or strong winter varieties,
2.2 The WOFOST model

WOFOST 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. 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 productivity. The model has been used for crop growth monitoring, potential productivity forecasting on regional and national scales, as well as future impact of climate change. Furthermore, the model has been applied in different climatic regions, including China [Song et al., 2005; 2006; Wu et al., 2003].

The WOFOST model describes phenological development, growth and productivity formation, a crop from emergency till maturity on the basis of crop genetic properties and environmental conditions. The model simulates dry matter accumulation of a crop as a function of temperature irradiation, and crop characteristics with 1-day step. The basis for calculating dry matter productivity is the rate of gross CO$_2$ assimilation of the canopy. This rate depends on the solar radiation absorbed by the canopy. From the absorbed radiation and the photosynthetic characteristics of individual leave, the daily rate of CO$_2$ assimilation of crop is calculated. Part of the carbohydrates is used to provide for the maintenance of the exiting live biomass. The remains are converted into structure matter.

A crop growth simulation model also has to keep track of the soil moisture content to determine when and what degree a crop is exposed to water stress. This can be done with the aid of a water balance, which compares for a given period, incoming water in the rooted surface soil with outgoing water and quantifies the difference between the two as a change in the amount of soil moisture stored. Since this work focuses on the potential productivity without water stress, this part of the model is not used.

2.3 Data and methods

SRES A2 and A1B scenarios are selected in this study, which represent a high emission level and a middle emission level. CO$_2$ concentration increases gradually from $380 \times 10^3$ to $836 \times 10^3$ from 2000 to 2100 for A2 scenario, and from $380 \times 10^3$ to $703 \times 10^3$ for A1B scenario [IPCC, 2007a]. Simulations of five GCMs are chosen from the IPCC Data Distribution Centre (http://www.ipcc-data.org/), which are identified to be capable in realistically modeling climate in East Asia despite their systematic errors [Ding et al., 2007b; Jiang et al., 2004]. These five GCMs are listed in Table 1.

<table>
<thead>
<tr>
<th>Model name</th>
<th>Resolution (number of grids)</th>
<th>Simulation period</th>
<th>Country/Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFDL CM2.1</td>
<td>144×90</td>
<td>1861–2100</td>
<td>USA/GFDL</td>
</tr>
<tr>
<td>MPI ECHAM5</td>
<td>192×96</td>
<td>1860–2100</td>
<td>Germany/MPI</td>
</tr>
<tr>
<td>MRI CGCM2.3.2a</td>
<td>128×64</td>
<td>1901–2100</td>
<td>Japan/MRI</td>
</tr>
<tr>
<td>NCAR CCSM3.0</td>
<td>256×128</td>
<td>1870–2100</td>
<td>USA/NCAR</td>
</tr>
<tr>
<td>UKMO HADCM3</td>
<td>96×73</td>
<td>1860–2100</td>
<td>UK/UKMO</td>
</tr>
</tbody>
</table>

Weather is a direct factor affecting crop growth. Winter wheat assessments are related to the weather data of climate model projections besides the crop model itself. The crop model requires weather data at site level as input for simulating productivity, so it is necessary to transform weather data from grid level into corresponding data of site level. The simple method of transformation is used with the nearest grid data as the site data for every station.

The systematic errors are brought due to different geographical situation between the sites and grids.
in the process of transformation. The difference of topography (elevation) can influence climate. This influence in turn affects crop growth and productivity. It is also necessary for impact assessments to identify and correct the errors. One possible approach is to add difference between the simulated monthly baselines (1961–1990) and the monthly observations provided by the China Meteorological Administration to the simulated future monthly data of the corresponding month. Then the corrected projections are supposed to simulate the impact of climate change on the growth and productivity of winter wheat.

3 Results and analysis

3.1 Tuning and validation of WOFOST

WOFOST is tuned for 28 stations in 2000 and the other 22 stations are adjusted to 2001 when the weather conditions are close to normal and relatively few climate disasters occurred. The soil parameters are set for each station according to previous studies [CSSO, 1995]. The genetic parameters for winter wheat are tuned through simulations since these data are not available for most stations. Then the crop model is validated using the observations during 1998–1999 and 2001–2003 for 28 stations as well as 1998–2000 and 2002–2003 for the remaining 22 stations. The results demonstrate that the model is skillful in predicting the winter wheat growth and productivity in China (for a more detailed description of the tuning and validating of WOFOST, see Song et al. [2006]).

3.2 Climate change in growing season during 2012–2100

The winter wheat grows normally from October to next June in northern China and from November to next May in southern China. The temperature of the growing season is shown in Figure 2 for scenarios A2 and A1B provided by the five GCMs during 2012–2100.

![Figure 2](image)

**Figure 2** Temperature projections during the growing season of winter wheat in China from 2012 to 2100 provided by GCMs for (a) A2 scenario, and (b) A1B scenario (dotted line: interannual variability; solid line: 10-year moving average)

The temperature of the growing season has a large interannual variability and an average increase of 4.4°C and 3.9°C for scenarios A2 and A1B respectively during 2012–2100. Slight difference is found among the trends of temperature in different regions of winter wheat. For scenario A2, the average temperature is projected to increase by 3.8–4.6°C, with great increase in Hebei, Shanxi, northern Shandong as well as western Yunnan by 4.3–4.6°C, and in other regions by 3.8–4.3°C. For scenario A1B, the increase in the average projected temperature is lower than that for scenario A2. The projected temperature is higher by 3.8–4.4°C than the baseline in southern China, and 3.5–3.8°C in most regions of northern China. These results are similar to Ding et al. [2007b] who pointed out that the annual temperature is projected to increase by...
5.5°C and 3.4°C for scenarios A2 and B2 respectively over China.

3.3 Simulated influence of climate change on winter wheat

Using the parameters determined by the tuning of the model and corrected projections of these five GCMs, simulations of winter wheat growth and productivity are made for all 50 stations from 2012 to 2100. Firstly, five simulated flowering, maturity as well as productivity of winter wheat are obtained from the crop model based on the outputs of the five GCMs. Secondly, the average simulated flowering, maturity and productivity from these five simulations are calculated. It is assumed that there is no change in winter wheat variety and agricultural management. The way only the climate effects on the growth and productivity is considered.

3.3.1 Climate impacts on the growth of winter wheat

Temperature influences crop growth and development through their effects on stomata opening and rate of physiological processes. High temperature can speed up the biochemical reactions and increase transpiration losses. A rise in temperature leads to increase accumulation of degree days, hence growth and development rates boost, resulting in a shortened phenophase. The simulated results show that the duration of flowering and maturity of winter wheat are clearly reduced during 2012–2100 due to the increasing temperature. For A2 scenario, the average simulated flowering as well as maturity dates would take place 26 days and 27 days earlier, while for A1B scenario the average simulated flowering and maturity would advance by 23 days and 24 days (Table 2). In another words, the flowering and maturity of winter wheat would be 5.9 days and 6.1 days earlier under 1°C warming. These results are in agreement with Sainia and Nanda [1987] and Dhiman et al. [1985], who found that the flowering and maturity dates are advanced by about 4–5 days under 1°C temperature increase in Northwestern India. Of course, the warming also influences the thermal condition and the northern growing border of winter wheat [Yang et al., 2011; Liu et al., 2011].

<table>
<thead>
<tr>
<th>Climate change/Impact</th>
<th>2012–2100</th>
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</thead>
<tbody>
<tr>
<td>Temperature change during the growing season</td>
<td></td>
</tr>
<tr>
<td>4.4°C</td>
<td>3.9°C</td>
</tr>
<tr>
<td>Precipitation change during the growing season</td>
<td></td>
</tr>
<tr>
<td>160 mm</td>
<td>80 mm</td>
</tr>
<tr>
<td>Simulated flowering change</td>
<td></td>
</tr>
<tr>
<td>26 days earlier</td>
<td>23 days earlier</td>
</tr>
<tr>
<td>Simulated maturity change</td>
<td></td>
</tr>
<tr>
<td>27 days earlier</td>
<td>24 days earlier</td>
</tr>
<tr>
<td>Simulated potential productivity change without CO₂ fertilization effect in whole winter wheat region</td>
<td></td>
</tr>
<tr>
<td>−14.3%</td>
<td>−12.5%</td>
</tr>
<tr>
<td>Simulated potential productivity change with CO₂ fertilization effect in whole winter wheat region</td>
<td></td>
</tr>
<tr>
<td>1.3%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Simulated potential productivity change without CO₂ fertilization effect in northern winter wheat region</td>
<td></td>
</tr>
<tr>
<td>−23% to −15%</td>
<td>−25% to −10%</td>
</tr>
<tr>
<td>Simulated potential productivity change with CO₂ fertilization effect in northern winter wheat region</td>
<td></td>
</tr>
<tr>
<td>−20% to 0</td>
<td>−24% to 0</td>
</tr>
</tbody>
</table>

3.3.2 Climate impacts on potential productivity of winter wheat

The effects of climate change on winter wheat include not only the changing climate itself, but also the increasing CO₂ concentration in the atmosphere. Two cases are considered, one with the effects of the changing climate only (without fertilization effect of CO₂), and another with the effects of the both changing climate and CO₂ concentration (with fertilization effect of CO₂).

(1) The case without fertilization effect of CO₂.

Under A2 scenario, the potential productivity would
decrease by 17.9% over northern China (Fig. 3b) on average. Further, it would decrease by over 20% in the regions including Hebei, Shandong, Shaanxi as well as Henan (Fig. 3a). All the 24 stations in northern China would have statistically significant negative trends at the 95% confidence level according to the Mann-Kendall test. For southern China, the potential productivity would decrease by 9.6%, the reduction is over 15% in most parts of Sichuan, while it is projected to increase slightly in southern Zhejiang and Anhui. The majority of the stations (20 out of 26) have negative trends in potential productivity, with 16 stations statistically significant at the 95% confidence level.

Under A1B scenario, the potential productivity is simulated to decrease by 15.1% and 6.5% for northern China and southern China, respectively (Fig. 3d). It would decrease by over 15% for most parts of northern China, in contrast to less than 10% decrease in most parts of southern China. Furthermore, there are 21 of 24 stations (88%) with statistically significant negative trends at the 95% confidence level in northern China, and 13 of 26 (50%) stations with the same statistically significant negative trends in southern China. As a whole, the reduction in the productivity under A1B scenario is less than that under A2 scenario. A possible reason is that the temperature increase of the growing season under A2 scenario is higher than that under A1B scenario.

According the simulation, future climate change would have a negative effect on the potential productivity of winter wheat for most parts of China. Furthermore, the influence over northern China seems to be more serious than that over southern China under both A2 and A1B scenarios. The simulated decrease-

![Figure 3](image-url)  
**Figure 3** Spatial distribution of trends in simulated average potential productivity of winter wheat for (a) A2 and (c) A1B scenarios, temporal distribution of simulated average potential productivity of winter wheat in northern (b) and southern (d) China from 2012 to 2100 without fertilization effect of CO₂ (dotted line: interannual variability; solid line: 10-year moving average)
ing productivity is due to shorter growing induced by the increasing temperature. In combination with the simulated annual anthesis and maturity dates, a negative trend of more than 20 days was evident. Similar to Southworth et al. [2002], we found that the shortened growing of winter wheat is inherently detrimental to potential productivity, since there is less time for photosynthesis and accumulation of biomass.

(2) The case with fertilization effect of CO$_2$. Although the net CO$_2$ fixation rate is often close to CO$_2$ saturation in C$_4$ plants, photosynthesis in C$_3$ plants (for example winter wheat) tends to increase continuously with increasing CO$_2$ above $350 \times 10^{-6}$. This is partly because CO$_2$ inhibits photo-respiratory loss by competing with O$_2$ and shifting rubisco function towards carboxylation. Figure 4 shows these effects on potential productivity of winter wheat for A2 and A1B scenarios. It indicates that the simulated potential productivity would decrease in most parts of northern China and west part of southern China. Moreover, in Hebei province, the potential productivity is projected to decrease by over 10%, while to increase by 0–10% in east part of southern China for A2 scenario (Fig. 4a). The same trends are simulated for A1B scenario (Fig. 4b). On average, the potential productivity is projected to increase slightly by 1.3% as well as 0.6% for A2 and A1B scenarios respectively with fertilization effect of CO$_2$ during 2000–2100.

![Figure 4](image_url)

**Figure 4** Spatial distribution of trends in simulated average potential productivity of winter wheat for (a) A2, and (b) A1B scenarios from 2012 to 2100 with the fertilization effect of CO$_2$.

4 Conclusions and discussion

The temperature is projected to increase over the winter wheat regions in China during 2012–2100. The growth of winter wheat in China would be strongly influenced by the increasing in temperature. As an example, the average flowering and maturity of winter wheat would advance by 26 days and 27 days from 2012 to 2100 respectively under scenario A2, as well as by 23 days and 24 days under scenario A1B. The simulated potential productivity of winter wheat show an average decrease of 14.3% and 12.5% respectively under A2 and A1B scenarios without the fertilization effect of CO$_2$, while it show an increase of 1.3% and 0.6% under scenarios A2 and A1B respectively with the fertilization effect of CO$_2$. Additionally, for northern China, the simulated potential productivity is projected to decrease markedly under both scenarios, whether the fertilization effect of CO$_2$ is considered or not, which indicates that the current planted winter wheat is more vulnerable in northern China than that in southern China facing future climate change.

A possible problem associated with the projected warming is the current winter wheat varieties planted in northern China are winter varieties or strong winter varieties, which need some days of low temperature for winter dormancy. When the temperature, especially the winter temperature, is increasing, the winter varieties and strong winter varieties of winter wheat
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cannot have enough time for dormancy. For instance, winter temperature is projected to increase by 4.7°C under A2 scenario over northern China, and by 4.2°C under A1B scenario during 2012–2100, which means that winter temperature during the second half of the 21st century would be above 0°C and be 3°C and 2°C at the end of the 21st century under A2 and A1B scenarios respectively. As a result, the dormancy of winter wheat would be influenced strongly. While in southern China, the winter wheat is spring or half winter varieties and they can grow slowly during winter. They are slightly affected when winter temperature increases. Thus, winter wheat planted in northern China would be more vulnerable than that in southern China.

Our results are in line with earlier findings of crops response to climate change in China. Yao et al. [2007] found without CO₂ fertilization effect on crops, the future climate change would have a negative impact on rice productivity in China under B2 scenario, while positive effects considering CO₂ fertilization. Xiong et al. [2007] also pointed out that without the CO₂ fertilization effect, China's maize productivity would suffer from a negative effect under both A2 and B2 scenarios, while with the CO₂ fertilization effect taken into account, productivity is projected to increase for rain-fed maize but decrease for irrigated maize using CERES-Maize model. The IPCC [2007] indicated that in mid- to high-latitude regions, moderate to medium local increases in temperature (1–3°C), across a range of CO₂ concentrations and rainfall changes, can have small beneficial impacts on the main cereal crops, while further warming would have increasingly negative impacts. For temperature increases over 3°C, average impacts are stressful to all crops and to all regions.

The growing season of winter wheat from 2012 to 2100 would be shortened under scenarios A2 and A1B. As a result, it would be possible that there are longer growing season for other crops planted after winter wheat maturity. For example, three crops would have enough time to grow in one year in southern China, and there is possible more time for another crop growth in northern China. In this case, the agricultural practices would change tremendously. The results of this study may have important implications for choosing adaptation measures.

Like most studies on effects of climate change on agriculture using crop models, there are several sources of uncertainties and limitations in this study, including a number of simplifications and limitations of WOFOST [Wu et al., 2003], large discrepancies in GCM projections, and the assumed strength of CO₂ fertilization. Furthermore, the impacts of weeds, diseases and insect pests on crop growth, development and final productivity formation are assumed to be controlled. All these ideal conditions would cause the negative effect of climate change on winter wheat productivity underestimated. The crop model simulates the current range of agricultural technologies available in China, and it does not include potential technologies improvements. Nevertheless, the use of the crop model and the climate change scenarios does allow us to make a first assessment on the impacts of future climate change on growth and productivity of the winter wheat in China.

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References


