CERES-Maize model-based simulation of climate change impacts on maize yields and potential adaptive measures in Heilongjiang Province, China

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Abstract

BACKGROUND: Climate change would cause negative impacts on future agricultural production and food security. Adaptive measures should be taken to mitigate the adverse effects. The objectives of this study were to simulate the potential effects of climate change on maize yields in Heilongjiang Province and to evaluate two selected typical household-level autonomous adaptive measures (cultivar changes and planting time adjustments) for mitigating the risks of climate change based on the CERES-Maize model.

RESULTS: The results showed that flowering duration and maturity duration of maize would be shortened in the future climate and thus maize yield would reduce by 11–46% during 2011–2099 relative to 1981–2010. Increased CO₂ concentration would not benefit maize production significantly. However, substituting local cultivars with later-maturing ones and delaying the planting date could increase yields as the climate changes.

CONCLUSION: The results provide insight regarding the likely impacts of climate change on maize yields and the efficacy of selected adaptive measures by presenting evidence-based implications and mitigation strategies for the potential negative impacts of future climate change.

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Keywords: climate change impacts; adaptive measures; CERES-Maize model; Heilongjiang Province

INTRODUCTION

Agriculture is one of the most sensitive systems to climate change.^{1–3} Climate change, especially increases in atmospheric carbon dioxide (CO₂) concentrations, will result in increasing global temperatures and change current rainfall patterns. These changes could cause direct and indirect consequences for future agricultural production and food security.^{4–7} Considering the socio-economic importance of agriculture and food security, it is essential to assess how future climate change will affect crop yields. Adaptation is an important factor that will shape the severity of the impacts of climate change on food production in the future.^{8,9} Thus the relative potential of adaptation strategies should be developed and evaluated for coping with climate risk.

In China, maize is grown as a staple grain crop and fodder and an industrial raw material owing to its large production potential. In 2012 the total maize production and planting area in China were 205.6 million tons and 35.0 million hectares respectively.¹⁰ Northeast China (NEC), where the famous Golden Maize Belt of China is located, is an important commodity grain production base accounting for almost one-third of the nation's total maize production and planting area. As a geographical part of NEC, Heilongjiang Province accounted for 41.9% of the total maize production in NEC and 14.0% of that in China in 2012.¹⁰ Thus maize here plays an important role in the regional food security. Similarly

to other crops, maize growth and development are very sensitive to climate change.^{11,12} Therefore it is important to understand how maize production will be affected by climate change in Heilongjiang Province and which adaptive measures should be considered to mitigate the possible negative impacts or to benefit crop production under climate change.

Various methods have been used to explore the interactions between climate change and crop production and to assess adaptation measures. Physically based, plot-specific crop models, whose input parameters have physical meaning and represent the environmental and varietal variability, have been widely used to explore the potential impacts of climate change on food production and to evaluate adaptation options.¹³ Many researchers have combined point-based maize models with climate data that were derived from General Circulation Models (GCMs) or Regional Circulation Models (RCMs) to assess the potential impacts of

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climate change on maize production.^{4,14–17} The Decision Support System for Agrotechnology Transfer (DSSAT) is a comprehensive decision support system¹⁸ that includes the CERES-Maize (Crop-Environment Resource Synthesis, Maize) model.¹⁹ The CERES-Maize model is one of the most popular process-based maize models and has been extensively employed to evaluate the effects of climate and managerial practices on maize production across the world. In addition, the CERES-Maize model has undergone rigorous evaluation across a wide range of different climates and soil conditions in China.^{17,20–25} Many researchers have used the CERES-Maize model to assess the potential responses of maize to expected climate changes in China. Among these researchers, Wang and Lin²⁶ and Lin *et al.*²⁷ conducted earlier studies regarding the prediction of Chinese maize production based on the CERES-Maize model. Recently, Xiong *et al.*¹⁷ used the CERES-Maize model v3.5 with the regional climate model RCM-PRECIS to assess the effects of climate change on maize production in China under SRES (Special Report on Emission Scenarios)²⁸ A2 and B2 scenarios. In addition, Guo *et al.*²⁰ used the CERES-Maize model v4.0 with the HadCM3 global climate model to explore the effects of climate change on maize yields and water use efficiencies across the North China Plain under the SRES B2A scenario. Tao and Zhang²² used the CERES-Maize model v4.0 to simulate maize production for representative stations in China with global mean temperature increases of 1, 2 and 3 °C respectively.

However, few studies assessed and quantified the effectiveness of different adaptive strategies to provide farmers and policy-makers with explicit guidance. Furthermore, many of the previous studies were conducted at a national level²² or at a regional level²⁰ with a very limited number of stations, which could not provide detailed simulations of the climate impacts and efficacy of adaptive measures for the large study region. In contrast, provincial-scale studies could provide higher-resolution data by using more study stations and thus enhance understanding of the climate impacts and adaptations. Wang *et al.*²³ conducted a provincial-scale study using the CERES-Maize (DSSAT) v4.0 model and six SRES scenarios in Jilin, the neighboring province of Heilongjiang. Nevertheless, no systematic provincial-level simulation with the CERES-Maize model has been conducted in Heilongjiang Province, in which maize production would be more sensitive to climate change owing to its higher latitude.

In this study we assessed the potential impacts of climate change on yields of rain-fed maize during three periods, 2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2099), relative to the baseline (1981–2010) and evaluated the potential mediating efficiencies of two selected household-level autonomous adaptation options based on the recently developed CERES-Maize (DSSAT) v4.5 model and by using four Representative Concentration Pathways (RCPs)^{29,30} that were the state-of-the-art climate scenario set in Heilongjiang Province, China.

MATERIALS AND METHODS

Study area and stations

Heilongjiang Province (43° 25′–53° 33′ N, 121° 11′–135° 05′ E) is located in the northernmost region of China at relatively high latitude and is one of the most sensitive regions to climate change.³¹ In the last 46 years, Heilongjiang Province has experienced a significant warming trend, with an annual temperature increase of 2.1 °C.³² Generally, the climate of this region is dominated by the continental-monsoon climate regime, with an annual precipitation that varies from 400 to 650 mm. Most of the precipitation

in this region occurs in the summer and autumn, which coincides with the growth period of maize and benefits its growth and development.³¹ The relative abundance of rainfall during the growing season ensures that precipitation is not the main restricting factor for maize growth. Instead, high temperatures and precipitation during the growing season, obvious seasonal differences, fertile soils that are rich in organic matter, and a vast alluvial flat plain make Heilongjiang Province one of the most important areas for commercial crop production in China.

Study stations here were selected from the Agrometeorological Experimental Stations (AESs) where maize growth and yield observations were available. In addition, these selected AESs met the following criteria: they (1) were located in primary maize production areas, (2) had representative maize cultivars that were cultivated for at least three years, (3) had good managerial records for the representative cultivars and (4) were located near weather stations to obtain weather observation records. Overall, we selected nine stations. Figure 1 shows the geographical locations of these stations, which follow an uneven distribution. Most of the stations are located in the southern vast plain, which corresponds to the main maize cultivation area.

Climate scenario and climate model

Climate scenarios reflect plausible future climate conditions that have been constructed to investigate the potential consequences of anthropogenic climate change and natural climate variability.³³ Many earlier assessments of the impacts of climate change on crops were based on the Special Report on SRES scenarios that was used in the Third and the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). However, these SRES scenarios did not account for policy actions that would mitigate climate change.^{29,34}

Recently, the Fifth Assessment Report of the IPCC adopted a new scenario set that contains greenhouse gas (GHG) emissions and concentrations that are referred to as RCPs. These RCPs are named based on their relative radiative forcing (W m^{-2}) at the end of the 21st century as RCP2.6, RCP4.5, RCP6.0 and RCP8.5. RCP2.6 is a mitigation scenario leading to a very low forcing level, RCP4.5 and RCP6.0 are both medium stabilization scenarios and RCP8.5 is a scenario with very high GHG emissions.^{29,35} The corresponding CO₂ emissions and concentrations of the four RCPs in the future are indicated in Figs 2(a) and 2(b) respectively.

The four RCPs, which cover a wide range of future emission and climate scenarios as illustrated in Fig. 2, were used as inputs for HadGEM2-ES³⁶ to compute the climate projections in this study. HadGEM2-ES is a coupled atmospheric/ocean general circulation model that was used in the fifth phase of the Coupled Model Intercomparison Project (CMIP5).³⁷ In view of the coarse spatial resolution and uncertainty of climate modelling, the HadGEM2-ES output data were downscaled to a $0.5^\circ \times 0.5^\circ$ grid with a daily temporal resolution and simultaneously bias-corrected using the quantile mapping method³⁸ before they were used as inputs to run the crop model.

CERES-Maize crop model

The CERES-Maize model embedded in DSSAT was selected to simulate maize yield in Heilongjiang Province, since it is one of the oldest, most advanced and most widely used crop simulation models.³⁹ This model is cultivar-specific and site-specific and operates on a daily time step. In addition, the model can simulate the development of roots and shoots, the growth and senescence of leaves and stems, biomass accumulation and the growth

Figure 1. Geographical locations of selected maize stations in Heilongjiang Province.

Figure 2. Global CO₂ (a) emission and (b) concentration under different RCP scenarios.

of maize grains as a function of the weather and soil conditions, cropping management practices and cultivar characteristics (Fig. 3).^{18,19} Thus it can be used to simulate the impacts of weather, soil water, soil nitrogen dynamics and some management strategies on maize growth and yield. Since its release,¹⁹ the CERES-Maize model has been applied widely in different regions of the world at various scales from field to regional or national level.⁴⁰

Here we used the most recent version CERES-Maize (DSSAT) v4.5 to assess the potential impacts of future climate change and two adaptive measures on maize production in Heilongjiang Province.

Compared with the previous version CERES-Maize (DSSAT) v4.0, the newly developed one made some improvements in bug fixes and also owned new capabilities of modeling effects of organic matter on soil, reading atmospheric CO₂ from external file, etc., all of which would elevate its performance for simulating crop growth and development.⁴¹

Input data for CERES-Maize model

The basic input data required by the CERES-Maize model include daily weather data, soil data, crop management data and

Figure 3. Overview of structure of CERES-Maize (DSSAT) v4.5 model.¹⁸

cultivar-specific genetic coefficients. Additional details regarding data requirement, data sources and data processing are provided below.

Weather data. The daily maximum and minimum air temperature, precipitation and solar radiation data at each station are used as the basic inputs for setting up weather files in the CERES-Maize model. The daily observed weather data (maximum and minimum air temperatures, precipitation and hours of sunshine) of the 1981–2010 baseline that was used for calibrating and validating the CERES-Maize model were obtained from the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn>). The observed weather data for five selected stations (Fuyu, Harbin, Hailun, Jiamusi and Tailai) were collected from the local meteorological stations that were located at the same sites, while the weather data for the other four stations (Boli, Jixian, Qinggang, Wuchang) were filled using the data from the closest meteorological stations. The daily solar radiation data that are required by the model were not available. Thus the data were calculated at the station level using the Ångström equation,⁴² which is based on latitude and daily sunshine hours. The projected weather data for baseline, 2020s, 2050s and 2080s under the four different RCPs were derived from the GCM-HadGEM2-ES model. In addition, the weather data were bias-corrected and downscaled to a high resolution with a $0.5^\circ \times 0.5^\circ$ grid that was provided by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) of

Potsdam Institute for Climate Impact Research. Each of the study stations used the weather data from the nearest grid to simulate the maize yields of the baseline and future periods.

Soil data. The crop model requires soil data to describe soil characteristics for each study station. The required soil data include soil classification, color, slope, drainage class and the characteristics of each soil layer, which include soil mechanical composition, organic content, bulk density, pH value in water, cation exchange capacity and total nitrogen. These data were extracted from the Chinese Soil Genus Records.⁴³

Crop observation and management data. The records of maize phenology, grain yields and management practices for the nine study stations between 1981 and 2009 were provided by the National Meteorological Centre of China, which collected these data from the local AESs. These records were used to define the required parameters (maize cultivar, row spacing, seeding density, seeding depth, fertilizer information, date of planting, date of harvest, etc.) of the CERES-Maize model. Based on the observed data of maize planting, flowering and maturity dates, the maize flowering duration (from planting to flowering) and maturity duration (from planting to maturity) were calculated. The phenology duration and grain yield data were used to calibrate and validate the CERES-Maize model. The records of maize grain yields, weeds, extreme climate events, plant diseases and insect

Table 1. Description of genetic coefficients used by CERES-Maize

Coefficient	Description of genetic coefficient	Unit
P1	Thermal time from seedling emergence to the end of the juvenile phase (above a base temperature of 8 °C) during which the plant is not responsive to changes in photoperiod	°C days
P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h)	days
P5	Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C)	°C days
G2	Maximum possible number of kernels per plant	–
G3	Kernel-filling rate during the linear grain-filling stage and under optimum conditions	mg day ⁻¹
PHINT	Phyllochron interval: the interval in thermal time between successive leaf tip appearances	°C days

pests were used to determine the representative maize cultivar for each study station.

Genetic coefficients. In the DSSAT model, the genetic coefficients are defined as sets of parameters that describe the interactions between crop genotype and environment. In addition, these coefficients characterize the differences in crop development, growth and yield among the cultivars.⁴⁴

Six genetic coefficients are used by the CERES-Maize model to characterize or define one maize cultivar. Table 1 provides the definitions of the six genetic parameters. Four of the parameters (P1, P2, P5 and PHINT) control the timing of the phenological stages, while the other two parameters (G2 and G3) characterize the potential yield under optimal conditions.

Genetic coefficients can be directly measured in field experiments or estimated from observed data.⁴⁵ However, the process of measuring genetic coefficients in the field is time-consuming and expensive and may be restricted to specific regions. In DSSAT, the GLUE (Generalized Likelihood Uncertainty Estimation) Coefficient Estimator module was designed to estimate genotype-specific coefficients for all included crop models,⁴⁶ such as the CERES-Maize model. The main feature of this method is that it is relatively fast and cheap. Thus, in this study, the GLUE module was used with the multi-year observed cultivar data to determine the genetic coefficients of a certain maize cultivar.

Calibration and validation of CERES-Maize model

All crop models must be calibrated and validated for the environment of interest to obtain robust results. For model calibration, the genetic coefficients of each maize cultivar are determined by adjusting parameters until the simulated values agree well with the observed values.⁴⁷ Model validation determines the ability of the calibrated model to simulate the characteristics of a separate data set.⁴⁸

Before model calibration and validation, the representative maize cultivars should be selected. Not all maize cultivars should be used in the impact assessment and adaptive measure simulations. The selected cultivars must be continually cultivated for at least three years at the same site. In addition, the selected

cultivars should have stable yields without any records of disease, weeds, extreme climate events or other stress conditions during the calibration and validation years.

The observed records for each representative cultivar from one year without environmental stress were selected for the genetic coefficient calibration using the GLUE Coefficient Estimator module. In addition, the records of two or three additional years were used for model validation. Information about the stations, representative cultivars and calibration and validation years is presented in Table 2.

The coincidence between the simulated and observed growth durations and grain yields could be measured using the normalized root mean square error (NRMSE), which is calculated by the equation

$$\text{NRMSE} = \left[\sum_{i=1}^n (S_i - O_i) / n \right]^{1/2} \times (1/\bar{O}_i) \quad (1)$$

In addition, the degree that each simulated value deviates from the corresponding observed value can be evaluated by calculating the percentage of predicted deviation (PD) using the equation

$$\text{PD}_i = (S_i - O_i) / O_i \quad (2)$$

Here S_i and O_i refer to the simulated and observed values for the studied variables respectively (e.g. maize flowering duration, maturity duration and grain yield), $\bar{O}_i$ is the mean of the observed values, n is the number of comparisons and i is each observation. The simulation is considered perfect when the NRMSE is less than 10%, good if the NRMSE is greater than 10% and less than 20%, fair if the NRMSE is greater than 20% and less than 30%, and poor if the NRMSE is greater than 30%.⁴⁹ A negative deviation indicates an under-prediction, while a positive deviation indicates an over-prediction.⁵⁰ The closer the values of NRMSE and PD to zero, the better the model simulates the observed parameters. The simulated and observed data of maize flowering duration, maturity duration and grain yield were compared in this study.

Model application

To assess the impacts of future climate change on maize production, the commonly used 'dumb farmer' method⁵¹ was employed. This method assumes that all variables other than weather and atmospheric CO₂ concentration, such as soil, cultivar and management practices, are held constant to simulate the impacts of climate change on maize production.

The assessment results of the climate change impacts were obtained by comparing the CERES-Maize model outputs over three periods (2020s, 2050s and 2080s) under four RCPs with the corresponding values of the baseline. To understand the impacts of increasing atmospheric CO₂ concentrations on maize yields, we ran the crop model for all stations using the baseline CO₂ concentration of 363 ppm. This concentration was derived from the NOAA Mauna Loa CO₂ Database (<http://co2now.org/>). Next we ran the model using future CO₂ concentrations under the four RCP scenarios in the 2080s period. This period was used because the predicted CO₂ concentrations were relative high compared with those of other periods among most RCP scenarios (Fig. 2(b) and Table 3).

To mitigate the negative impacts of climate change on maize production, two of the most commonly used household-level autonomous adaptation measures (replacing the local cultivars

Table 2. Characteristics of sites selected for calibration and validation of crop model and projection of rice yield

Site	Longitude (E)	Latitude (N)	Altitude (m)	Maize cultivar	Type of maturity	Years
Boli	130° 35'	45° 45'	220.5	4zao6	Early	2005*, 2007–2009
Fuyu	124° 29'	47° 48'	162.7	Longdan1	Late	2000*, 2001, 2002
Harbin	126° 46'	45° 45'	142.3	4dan19-H	Late	2003*, 2004, 2005
Hailun	126° 58'	47° 26'	239.4	Haiyu6	Medium	2005, 2006, 2007*
Jiamusi	130° 17'	46° 49'	81.2	Dongnong248	Mid-late	2005, 2006*, 2008
Jixian	131° 07'	46° 44'	102.3	Hei221	Medium	2006*, 2007, 2008
Qinggang	126° 06'	46° 41'	207.4	4dan19-Q	Late	2003*, 2004, 2007
Tailai	123° 25'	46° 24'	150.5	4dan19-T	Late	2003, 2006*, 2008
Wuchang	127° 09'	44° 54'	194.6	Moji	Mid-late	1999, 2002, 2003*

*The observed records of these years were used for calibrating the crop model.

Table 3. Projected changes in annual average temperature and precipitation in study area relative to baseline (1981–2010) and CO₂ concentration

Scenario	Temperature increase (°C)			Precipitation increase (%)			CO ₂ (ppm) ^a		
	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
RCP2.6	1.5	2.0	2.3	6.8	11.1	14.4	418	440	429
RCP4.5	1.5	3.0	3.8	8.2	8.7	12.9	424	495	523
RCP6.0	1.3	2.7	4.1	0.1	2.3	16.0	420	497	612
RCP8.5	1.5	4.1	7.0	7.2	12.9	23.7	436	578	804

^a Source: <http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=download>.

and changing the planting dates) were selected to simulate their potential efficacy for offsetting climate risk.

With regard to switching the maize cultivars, we replaced the local early- or medium-maturing maize cultivars with late-maturing cultivars that have a longer growing season and relatively higher production. This new cultivar was introduced from another study station.

For shifting the planting date, we advanced the planting date in the simulations by 15, 10 and 5 days and compared the results with the current planting date for each station. In this way, we assessed how altering the planting date could increase maize yields. According to the results of the impact assessment mentioned above, maize production would suffer the most serious failure in the 2080s period. Therefore this period was selected to simulate maize yields in this experiment. The simulated maize yields before and after adjusting the planting dates were compared with each other to evaluate the efficiency of this adaptive measure.

RESULTS

Climate change scenarios of temperature and precipitation

The average changes in temperature and precipitation of the study area under different RCP scenarios are shown in Table 3. It was obvious that the temperature would significantly increase with elevated CO₂ concentrations in the future. The annual average temperature was projected to increase by 1.5, 2.0 and 2.3 °C for the 2020s, 2050s and 2080s periods respectively relative to the baseline period under the RCP2.6 scenario. Under the RCP4.5 scenario, the annual average temperature was expected to increase by 1.5, 3.0 and 3.8 °C in the 2020s, 2050s and 2080s periods respectively. The trend of annual average temperature under the RCP6.0 scenario was similar to that under RCP4.5. However, the annual average temperature under the RCP8.5 scenario was the highest

among all scenarios, with an increase of 7.0 °C during the 2080s period relative to the baseline period.

In addition, the annual average precipitation was projected to show an increasing trend with time under different scenarios. The annual precipitation would increase by 6.8, 11.1 and 14.4% in the 2020s, 2050s and 2080s periods respectively relative to the base period under the RCP2.6 scenario. However, under the RCP8.5 scenario, the annual average precipitation was expected to increase the most among all RCPs, with increases of 7.2, 12.9 and 23.7% in the 2020s, 2050s and 2080s periods respectively.

Performance of CERES-Maize model

A comparative analysis showed that a close correspondence occurred between the observed and simulated flowering duration and the biological yield of all selected maize cultivars under the various agricultural management strategies and soil conditions (Fig. 4). The NRMSE was low for the two selected parameters. The lower NRMSE value (5.5%) was obtained for flowering duration and the higher NRMSE value (10.8%) was obtained for grain yield. According to the $\pm 15\%$ PD criteria, the model accurately predicted both parameters (Fig. 4). After validating the CERES-Maize model, the ultimately defined genetic coefficients of all cultivars that were used for simulating the maize yield were obtained (Table 4).

Climate change impact simulation

Impacts on maize phenology

The flowering duration and maturity duration were two important phenological stages in the CERES-Maize model. The modeling results showed that the durations of flowering and maturity would be shortened by 3–27 and 7–60 days respectively relative to the baseline conditions when considering the different cultivars, periods and RCP scenarios (Tables 5 and 6). The most serious

Figure 4. Comparison of simulated and observed (a) flowering durations and (b) yields. The full line is the 1:1 reference line and the broken lines show the percentage of PD with $\pm 15\%$.

Table 4. Calculated genetic coefficients of maize cultivars

Cultivar	P1	P2	P5	G2	G3	PHINT
4zao6	159	0.19	671	983	16.4	57.1
Longdan1	240	0.93	708	475	12.4	46.1
Haiyu6	161	0.67	712	553	13.8	46.8
4dan19-H	225	0.62	739	670	14.8	55.3
Dongnong248	201	0.41	717	491	11.6	44.5
Hei221	196	0.81	716	680	14.7	58.8
4dan19-Q	196	0.82	724	458	10.2	58.2
4dan19-T	254	0.20	723	772	15.0	45.7
Moji	209	0.85	708	625	13.3	40.6

decreases in the flowering and maturity durations occurred under the RCP8.5 scenario, with decreases of 5–27 and 15–59 days respectively. This trend was the opposite for the RCP2.6 scenario. The shorter numbers of days for both durations under the RCP6.0 scenario were similar to the durations under the RCP4.5 scenario.

When considering the time series at all study sites, the average days of growing duration (from planting to maturity) decreased with time under all RCP scenarios except the RCP2.6 scenario. Under the RCP2.6 scenario, the shortest maize growing duration occurred during the 2050s period.

In addition, the growing duration varied with the cultivars used at the different sites. The 4zao6 cultivar at the Boli station had the shortest maturity durations while the 4dan19-T cultivar at the Tailai station had the longest in all periods and RCP scenarios (Table 6). In addition, the Haiyu6 cultivar at the Hailun station had the largest decrease (38%) in maturity duration relative to the current conditions under the RCP8.5 scenario during the 2080s period.

Impacts on maize yields

By comparing the maize yield results under future climate conditions with those under the baseline, we obtained insight regarding the changes in maize yields induced by climate changes when the maize cultivars, soil conditions and management practices were held constant. The changes in average maize yields without incorporating the CO₂ fertilization effects are presented in Fig. 5. The average maize yields decreased significantly (11–46%) for all periods and RCP scenarios. Under all RCP scenarios, the decreasing

yield trend continued with time. Thus the lowest decrease would occur in the 2020s period and the highest in the 2080s period, with decreases of 11–14 and 17–46% respectively. The losses from the current maize yields were projected to be 11–17, 10–32, 14–34 and 14–46% for the RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios respectively. Among all RCPs, the most serious impact of climate change on maize yield occurred under the RCP8.5 scenario, with decreases of 14, 24 and 46% for the 2020s, 2050s and 2080s respectively.

From the perspective of the stations, not all stations would face yield reductions in the future climate scenarios (Table 7). During the 2020s, the Fuyu, Jiamusi and Jixian stations would have 3–15% greater maize yields. The predicted grain yields ranged from –61% (for the Haiyu6 cultivar at the Hailun station in the 2080s under the RCP8.5 scenario) to +15% (for the Longdan1 cultivar at the Fuyu station in the 2020s under the RCP2.6 scenario) relative to the baseline conditions of the different cultivars, periods and scenarios (Table 7). The highest predicted maize yield (8293 kg ha⁻¹) occurred for the 4dan19-T cultivar at the Tailai station in the 2020s under the RCP 2.6 scenario. In addition, the lowest predicted maize yield (2459 kg ha⁻¹) occurred for the 4dan19-Q cultivar at the Qinggang station in the 2080s under the RCP8.5 scenario (Table 7). Generally, early- and medium-maturing cultivars have lower maize grain yields. In addition, the long-season cultivars generally show smaller changes in grain yield relative to the medium- and short-season cultivars (Table 7).

When the CO₂ fertilization effects were considered in the 2080s, the margin of the yield decrease was reduced by 1.6–3.7% owing to the increased yield that resulted from the increased atmospheric CO₂ concentration (Table 8). In this case, the maize yields could increase by 959, 1958, 2207 and 2173 kg ha⁻¹ on average for the RCP2.6, RCP4.5, RCP6.0 and RCP8.5 scenarios respectively relative to the simulations that did not consider the CO₂ fertilization effect.

Adaptive measures simulation

The results presented above indicated that the 4dan19-T cultivar at the Tailai station would have high grain yields owing to its long growth period in the future climate conditions (Tables 6 and 7). Thus we selected this cultivar to replace the shorter-season cultivars 4zao6 at the Boli station and Haiyu6 at the Hailun station, which were predicted to suffer higher yield reductions in the future

Table 5. Changes in maize flowering duration (days) under future climate scenarios compared with baseline

Station	BS ^a	RCP2.6			RCP4.5			RCP6.0			RCP8.5		
		2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
Boli	81	-5	-8	-8	-4	-9	-14	-6	-10	-13	-7	-12	-20
Fuyu	92	-4	-9	-7	-4	-11	-15	-5	-10	-15	-5	-13	-21
Hailun	81	-5	-9	-8	-5	-10	-14	-5	-10	-14	-6	-13	-20
Harbin	90	-6	-10	-9	-6	-12	-16	-3	-9	-19	-7	-14	-27
Jiamusi	78	-3	-7	-7	-3	-8	-13	-3	-8	-13	-5	-10	-18
Jixian	89	-5	-9	-9	-5	-11	-15	-5	-11	-15	-7	-13	-22
Qinggang	90	-5	-9	-8	-6	-12	-15	-6	-11	-14	-6	-13	-21
Tailai	99	-7	-11	-9	-5	-14	-17	-5	-13	-17	-8	-15	-24
Wuchang	91	-6	-10	-8	-6	-11	-15	-7	-12	-15	-7	-14	-22

^a Flowering duration under baseline (days).**Table 6.** Changes in maize maturity duration (days) under future climate scenarios compared with baseline

Station	BS ^a	RCP2.6			RCP4.5			RCP6.0			RCP8.5		
		2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
Boli	151	-20	-29	-26	-19	-34	-43	-18	-34	-43	-26	-38	-54
Fuyu	164	-10	-20	-15	-9	-31	-45	-13	-28	-43	-15	-35	-56
Hailun	159	-15	-26	-22	-14	-36	-47	-16	-34	-46	-19	-40	-59
Harbin	162	-21	-31	-28	-18	-39	-47	-15	-30	-5	-24	-41	-59
Jiamusi	152	-8	-21	-18	-8	-28	-43	-7	-27	-44	-16	-35	-56
Jixian	164	-15	-25	-22	-13	-35	-47	-14	-34	-48	-23	-40	-60
Qinggang	161	-19	-29	-26	-16	-38	-46	-18	-35	-45	-22	-41	-57
Tailai	169	-13	-22	-18	-10	-36	-45	-14	-33	-45	-17	-35	-57
Wuchang	156	-23	-30	-26	-21	-35	-42	-20	-34	-41	-24	-39	-54

^a Maturity duration under baseline (days). **Figure 5.** Changes in mean maize yields under future climate scenarios compared with baseline.

climate scenarios (Table 7). When the 4dan19-T cultivar was transplanted at the Boli station under the future scenarios, the maize yield increased by 35–39, 28–42 and 3–35% for the 2020s, 2050s and 2080s periods respectively relative to the early-maturing cultivar 4zao6 (Fig. 6(a)). When the 4dan19-T cultivar was introduced at the Hailun station to replace the middle-maturing cultivar Haiyu6, the potential yield increases were 8–19, 11–28 and 6–23% for the 2020s, 2050s and 2080s periods respectively (Fig. 6(b)).

The simulation results from shifting the maize planting dates indicated that delaying the planting date by 5–15 days at most stations could result in yield increases of 1–27% relative to using the present planting dates in the 2080s period (Fig. 7). If the planting dates were advanced by 5–15 days, the maize yields would decrease by 4–16%. Nevertheless, advancing the planting date did not always lead to lower maize yields. Advancing the planting date by 5–10 days at the Boli station under the RCP4.5, RCP6.0 and RCP8.5 scenarios resulted in a yield increase. In general, delaying the planting date by 5–15 days increased the maize yields by an average of 6%.

DISCUSSION

Crop model validation

The crop model accuracy is determined by the degree of goodness-of-fit between the observed and simulated values of specific parameters. According to the NRMSE description by Rinaldi *et al.*,⁴⁹ the calibrated CERES-Maize model showed robust ability to simulate the flowering durations (NRMSE = 5.5%) and the grain yields (NRMSE = 10.8%) in the model validation process. In addition, the low percentage of predicted deviations (PD < ±15%) for all parameters confirmed that the CERES-Maize model performed well when simulating the phenological stages and the yields of the maize crop. Therefore this model is a reliable tool for climate change impact studies in Heilongjiang Province.

Table 7. Changes in maize yield (%) under future climate scenarios compared with baseline

Station	BS ^a	RCP2.6			RCP4.5			RCP6.0			RCP8.5		
		2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
Boli	7513	-13	-16	-14	-4	-9	-14	-6	-10	-13	-7	-12	-20
Fuyu	5484	11	9	15	-4	-11	-15	-5	-10	-15	-5	-13	-21
Hailun	6764	-13	-22	-18	-5	-10	-14	-5	-10	-14	-6	-13	-20
Harbin	7239	0	-1	3	-6	-12	-16	-3	-9	-19	-7	-14	-27
Jiamusi	5742	11	2	5	-3	-8	-13	-3	-8	-13	-5	-10	-18
Jixian	6509	5	4	7	-5	-11	-15	-5	-11	-15	-7	-13	-22
Qinggang	5800	-12	-23	-13	-6	-12	-15	-6	-11	-14	-6	-13	-21
Tailai	7371	-5	1	12	-5	-14	-17	-5	-13	-17	-8	-15	-24
Wuchang	7718	-14	-20	-17	-6	-11	-15	-7	-12	-15	-7	-14	-22

^a Yield under baseline (kg ha⁻¹).

Table 8. Changes in mean maize yield (%) under future climate scenarios in 2080s with and without CO₂ fertilization effect, and resulting values of fertilization effect

CO ₂ fertilization effect	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Without	-1.7	-27.0	-27.5	-47.1
With	-0.1	-23.8	-23.8	-43.5
Effect ^a	1.6	3.3	3.7	3.6

^a Obtained by calculating the difference between the results with and without CO₂ fertilization effect.

Impacts assessment

All future climate scenarios indicated a general tendency toward shorter flowering and maturity durations for all maize cultivars. When the CO₂ fertilization effects were not considered, the predicted grain yields of maize gradually decreased across all RCP scenarios. The projected decreasing trend of rain-fed maize production over time in this study agreed with those of Lin *et al.*²⁷ and Xiong *et al.*,¹⁷ who adopted SRES A2 and B2 scenarios, but the decreasing rate of maize yield was greater than them. For these studies, the most important causative factors for rain-fed crop yield reduction are increasing temperature and decreasing precipitation.^{52,53} However, in view of the current sufficient water condition and the large precipitation increases that were projected

by the HadGCM2-ES model under the RCP scenarios (Table 3), the water deficits may be slight or even not exist in many agricultural regions. Consequently, based on the applied scenarios, the increase in air temperature was the main factor that led to maize yield reductions in Heilongjiang Province. Elevated temperatures could accelerate the development of maize, resulting in earlier maturation and less time for the formation and accumulation of dry matter.^{54–56} Thus yield reductions would occur under the future warming climate conditions, while the decreasing rate of maize yield could be understood by the way that the temperature increase in Heilongjiang Province would be potentially greater than the national average level.

When the elevated CO₂ concentration was considered in the simulation for the 2080s period, the CO₂ fertilization effect on rain-fed maize was not as significant as that on irrigated rice and wheat simulated by Lin *et al.*²⁷ based on the CERES family models. Additionally, the amplitude of rain-fed maize reduction decreased slightly more than that of Xiong *et al.*¹⁷ and Wang *et al.*,²³ in which the rain-fed maize may suffer water limitations. All these differences could be reasonably interpreted by two aspects. Firstly, photosynthesis in C3 plants (e.g. rice and wheat) usually increases in response to elevated CO₂,⁵⁷ whereas photosynthesis of maize, a C4 plant, is almost CO₂-saturated at current atmospheric CO₂ concentrations owing to a C4-specific photosynthetic pathway, a CO₂-concentrating pump.⁵⁸ Therefore increased CO₂ would directly generate great benefits on the photosynthesis of

Figure 6. Changes in maize yields with 4dan19 cultivar at (a) Boli and (b) Hailun stations.

Figure 7. Maize yields on changed planting dates under different RCP scenarios at (a) Boli, (b) Fuyu, (c) Hailun, (d) Harbin, (e) Jiamusi, (f) Jixian, (g) Qinggang, (h) Tailai and (i) Wuchang stations.

rice and wheat, but little on that of maize. Secondly, elevated CO_2 could decrease stomatal conductance, which may reduce transpiration in favor of delaying the onset of drought stress.⁵⁹ It appears that the CO_2 fertilization effect on maize would only be reflected when water is a limiting factor, because the CO_2 effect on stomatal conductance may conserve soil water and increase drought tolerance. When both of the above aspects were considered, it was not difficult to understand that the CO_2 fertilization effect on maize in this study was less than that on irrigated rice and wheat and that on maize under water stress condition. Thus the CO_2 fertilization effect was too slight to offset the maize yield reduction at the end of the century in Heilongjiang Province.

Taken together, the maize production in Heilongjiang Province would suffer more negative effects from future climate change under RCP scenarios than the national average production under SRES scenarios. Therefore it was necessary to take adaptive measures to cope with the future climate conditions for ensuring food security.

Adaptation evaluation

Considering the apparent negative impact of climate change on maize yields, it is important to assess adaptive options in response to climate change, because efficient adaptive options could compensate some detrimental impacts. In this case, we found that, when the original cultivars were replaced by the late-maturing and high-yielding cultivar under the same climate and soil conditions, the maize yields increased significantly. This result potentially occurred because climate warming can extend the length of the potential growing season,³¹ and the late-maturing cultivar was able to use the heat from the warmer climate more

efficiently.²³ Therefore this cultivar had a longer growth season and thus had higher yields than the cultivar with early maturation. Wang *et al.*²³ pointed out that the simulated maize production was greater when a maize cultivar with a longer growth period from southwest China was used to replace the local cultivar in Jilin Province. This adaptive measure was also true of other crops such as rice⁶⁰ and wheat.⁶¹ Although the late-maturing cultivar could increase yields, the increasing yield margin would decline with time owing to the high temperatures (Fig. 6). Thus more benefits will result from the development of new crop cultivars that are high-temperature-tolerant with higher thermal requirements.¹¹

In addition, changing the planting dates is another economic and feasible method for alleviating the adverse effects of climate change.¹¹ Our simulation results indicated that, in general, delaying the planting dates of the maize cultivars by 5–15 days would result in grain yield increases. This result potentially occurred because the delayed planting dates would allow the maize crop to avoid thermal stress during its key developmental stages.^{11,23,62} The changed trend of maize production with the changed planting dates was similar to that of Jin *et al.*⁶³ However, Alexandrov and Hoogenboom⁶¹ reported that advancing the planting date of maize would increase maize yields in Athens. Additionally, Sultana *et al.*⁶⁴ found that delaying planting dates would result in increased wheat yield in Pakistan. These results suggested that the proper change of planting dates for key developmental stages of crops to avoid thermal stress would vary with crop species, planting zones and future climate conditions.

It was thus evident that replacing the local cultivar by cultivars with longer growth periods and delaying the planting dates could be considered as two feasible adaptation strategies for reducing

the negative impacts of climate change on maize production in Heilongjiang Province, and, based on the results of this study, changing cultivars may be more efficient than changing planting dates at the end of this century (Figs 6 and 7). In addition, Jin *et al.*⁶³ stated that, by replacing cultivars and changing planting dates at the same time, maize production would gain more benefit than from adopting only one of the two adaptive measures. The efficiency of this integrative adaptation option needs further exploration in Heilongjiang Province.

STUDY UNCERTAINTIES AND LIMITATIONS

Estimates of the impacts of climate change on crop production that are based on crop models are plagued with uncertainties and limitations.

First, key uncertainties in crop production projections result from possible climate changes (GCM uncertainty). Different climate models can generate different climate scenarios.⁶⁵ Since the findings in this study were based on bias-corrected HadGEM2-ES climate data, the crop production responses obtained using non-bias-corrected climate data or from other GCMs potentially may differ from our results. Second, although the CERES-Maize model has been widely employed, uncertainties and limitations can be derived from the crop model and its parametrizations.²² The model could not simulate the impacts of all of the important environmental and management factors on crop growth and production, including insect pests, weeds and diseases. Third, the CERES-Maize model characterizes a specific maize cultivar using six genetic coefficients. Thus the model could only describe the main properties of the cultivar rather than all its traits. The simplified coefficients would constrain the ability of the CERES-Maize model to simulate all maize cultivar characteristics. Finally, we adopted the 'dumb farmer' approach to assess the impacts of future climate changes. This means that changes in soil, cultivar and management practices and effects of technology improvements were not considered in these simulations owing to the lack of sufficient data and reasonable methodology. The implication of ignoring autonomous and planned adaptations in impact assessments would be an underestimation of the future maize yield and thus an overestimate of negative impacts of climate change.

CONCLUSIONS

Future climate change would negatively affect maize production in the main cultivated areas of Heilongjiang Province during this century under different RCP scenarios. The increased CO₂ concentrations would not significantly increase the grain yields as the climate changed, because maize is a C4 crop and the precipitation would not be in deficit. Thus the increasing temperature would be the main climatic factor influencing maize production. However, switching the local maize cultivars and planting dates could mitigate the adverse impacts of elevated temperature. Replacing early- and mid-maturing cultivars with late-maturing cultivars could result in higher maize yields owing to the increased growth period. In addition, delaying the planting dates was an effective adaptation option for avoiding thermal stress during the key developmental stages of maize. Further research on the efficacy of breeding new crop cultivars and integrating the two adaptations simulated in this study is needed in order to mitigate the climate change impacts. These results could provide insights for farmers and policy-makers regarding the likely impacts of climate

change on maize production and the potential effective adaptations in Heilongjiang Province.

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