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Mingxia Huang¹ , Jing Wang^{1,9} , Bin Wang^{2,9} , De Li Liu^{2,3}, Qiang Yu^{4,5,6}, Di He⁷, Na Wang⁸ and Xuebiao Pan¹ 

¹ College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, People's Republic of China

² NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, NSW 2650, Australia

³ Climate Change Research Centre, University of New South Wales, NSW 2052, Australia

⁴ State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Shaanxi 712100, People's Republic of China

⁵ College of Resources and Environment, University of Chinese Academy of Science, Beijing 100049, People's Republic of China

⁶ School of Life Sciences, Faculty of Science, University of Technology Sydney, NSW 2007, Australia

⁷ State Key Laboratory of Severe Weather (LASW), Chinese Academy of Meteorological Sciences, Beijing 100081, People's Republic of China

⁸ Crop Research Institute, Shandong Academy of Agricultural Sciences, Jinan 250100, People's Republic of China

⁹ Authors to whom any correspondence should be addressed.

E-mail: wangj@cau.edu.cn and bin.a.wang@dpi.nsw.gov.au

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Supplementary material for this article is available [online](#)

Abstract

Climate change, with increased temperatures and varied rainfall, poses a great challenge to food security around the world. Appropriately assessing the impacts of climate change on crop productivity and understanding the adaptation potential of agriculture to climate change are urgently needed to help develop effective strategies for future agriculture and to maintain food security. In this study, we studied future maize yield changes under 1.5 °C (2018–2037) and 2 °C (2044–2063) warming scenarios and investigated the adaptation potential across China's Maize Belt by optimizing the sowing date and cultivar using the APSIM-Maize model. In comparison to the baseline scenario, under the 1.5 °C and 2 °C warming scenarios, we found that without adaptation, maize yields would increase in the relatively cool regions with a single-cropping system but decrease in other regions. However, in comparison with the baseline scenario, under the 1.5 °C and 2 °C warming scenarios with adaptation, maize yields would increase by 11.1%–53.9% across the study area. Across the maize belt, compared with the baseline scenario, under warming of 1.5 °C, the potential sowing window would increase by 2–17 d, and under warming of 2 °C, this sowing window would increase by 4–26 d. The optimal sowing window would also be significantly extended in the regions with single-cropping systems by an average of 10 d under the 1.5 °C warming scenario and 12 d under the 2 °C warming scenario. Late-maturing cultivar achieved higher yield than early-middle maturing cultivars in all regions except the north part of Northeast China. Adjusting the sowing date by increasing growth-period precipitation contributed more (44.5%–96.7%) to yield improvements than shifting cultivars (0%–50.8%) and climate change (–53.1% to 23.0%) across all maize planting regions except in the wet southwestern parts of the maize belt. The differences among the maize planting regions in terms of high adaptation potential provide invaluable information for policymakers and stakeholders of maize production to set out optimized agricultural strategies to safeguard the supply of maize.

1. Introduction

Global grain demand is likely to increase further to safeguard food security with the rapidly growing

human population (Regmi and Meade 2013, Keating *et al* 2014, West *et al* 2014, Ehrlich and Harte 2015). However, global climate change poses significant pressure on crop production, especially because rising

temperatures shorten the crop growth period and therefore decrease the accumulation of photosynthetic assimilation (Liu *et al* 2014, Hunt *et al* 2019). Therefore, climate change is a key challenge for increasing harvested grain.

Maize (*Zea mays* L.) is a staple grain and feed crop with the greatest world production (IPCC 2014). China is the second largest maize producer in the world, accounting for 17.7% of the total worldwide maize planting area and 18.6% of worldwide production (FAO 2017). Achieving high maize yields and maintaining maize yield stability are of vital importance in China due to the high demand for maize production for a population of more than 1.3 billion (Huang *et al* 2017). However, the mean annual air temperature in China has increased by 1.2 °C since the 1960s (Piao *et al* 2010, Yu *et al* 2018), which becomes a major obstacle to safeguard the supply of maize due to its negative impacts on maize production (Lobell *et al* 2011, Wang *et al* 2014, Li *et al* 2016, Liang *et al* 2018). Although the impacts of climate change on maize yields depend on local climate conditions, climate warming has decreased maize yields in most maize planting regions of China mainly by shortening the maize growth period (Mo *et al* 2016, Liu *et al* 2017, Chen *et al* 2018, Huang *et al* 2018).

Climate change could have positive impacts on maize production if effective adaptation options are used (Asseng *et al* 2019, Hunt *et al* 2019). Many studies have investigated the impacts of various climate change adaptation options on maize yield and found adjusting sowing date and selecting suitable cultivars were two cost-effective adaptation options (Wang *et al* 2012, Tachie-Obeng *et al* 2013, Zhao *et al* 2015, Abbas *et al* 2017). In general, planting maize cultivars with longer growth periods could compensate for the negative impact of rising temperatures on maize yield (Wang *et al* 2014, Bu *et al* 2015, Huang *et al* 2018). Earlier maize sowing was recommended for adapting to climate change in most maize planting regions in China (Tao and Zhang 2010, Liu *et al* 2013). This approach is recommended because adjusting the sowing date could help reduce the risk of high temperatures and droughts during the key growth stages to maize yields (Rahimi-Moghaddam *et al* 2018).

Temperature is projected to further increase in the future (Harrison *et al* 2014). Therefore, the impacts of future climate change on maize production have been investigated worldwide (Rurinda *et al* 2015). In China, simulation studies have shown that future climate change would further increase maize yields in the northern part of the northeast spring maize planting region due to an elevated CO₂ concentration and more precipitation events (Xiong *et al* 2007, Wang *et al* 2011, Xu *et al* 2014, Liang *et al* 2018), while climate change characterized by rising temperature would decrease maize yields in other maize planting regions mainly by shortening the crop growing period (Xiong *et al* 2007, Tao and Zhang 2011, Lin *et al* 2017, Chen *et al* 2018).

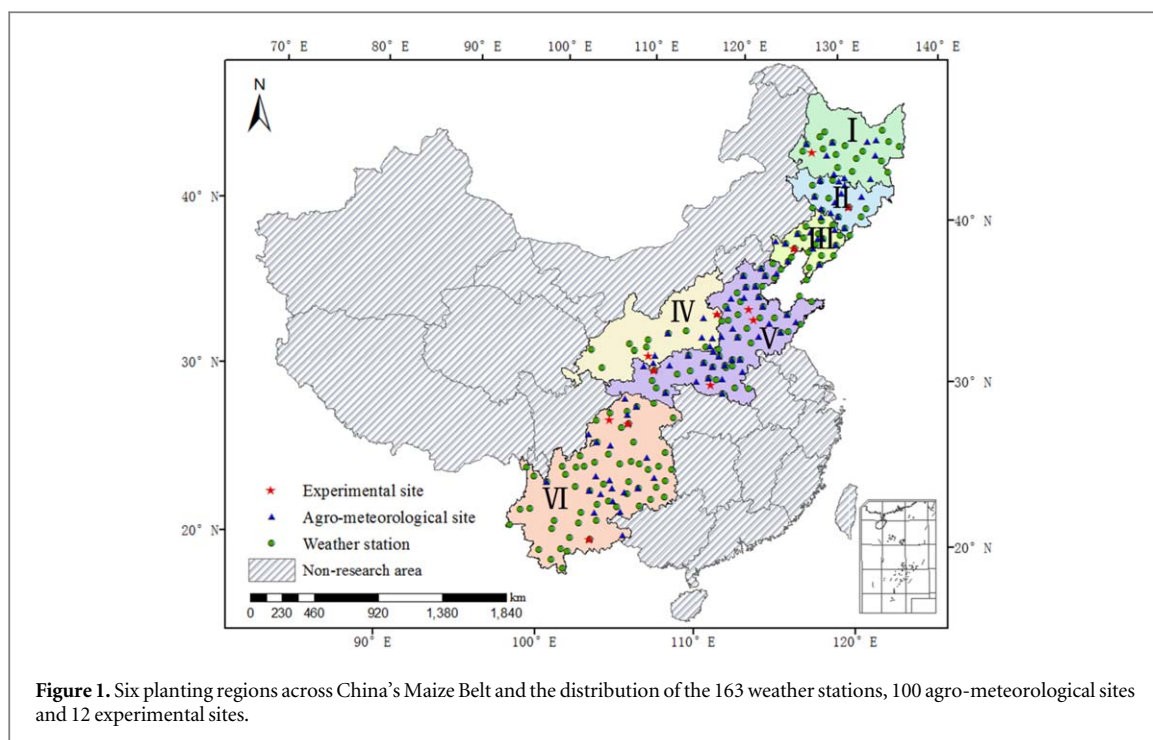
Limited studies in Northeast China and the North China Plain showed that adjusting the sowing date and cultivar shifting could be used to adapt to future climate change (Tao and Zhang 2010, Lin *et al* 2015). However, the adaptation potential of maize production to future climate change, especially under the target warming of within 1.5 °C and 2 °C across the whole maize growing regions of China, has not been investigated. The contrasting climates and cropping systems across the maize belt imply that there could be large regional differences in the adaptation potential of maize production to climate change. Moreover, the relative contribution rates of adjusting sowing dates and shifting cultivars need to be identified to understand the adaptation mechanism of maize production to future warming of 1.5 °C and 2 °C. Overall, understanding the adaptation potential of agriculture to climate change and the adaptation mechanism could help in the development of effective strategies to maintain grain security and design future maize production layouts in China.

The objectives of this study are to (1) explore the impacts of climate change on maize yields under two warming scenarios, (2) determine the optimal sowing windows and suitable cultivars in six maize growing regions of China under baseline and warming scenarios, (3) investigate the adaptation potential of adjusting the sowing date and shifting the cultivar in response to climate change, and (4) identify the relative contribution rates of adjusting the sowing date and shifting the cultivar to yield increases under climate change.

2. Materials and methods

2.1. Study area, historical climate, crop and soil data

China's Maize Belt was divided into six maize planting regions (figure 1) based on geographic location and different cropping systems (table 1). We focused on 163 weather stations with observed climate data in the belt for rainfed maize plantings. Historically observed daily climate data of 163 weather stations from 1980 to 2016 were available from the China Meteorological Administration to drive the maize model and calculate the thermal time of different growing seasons and maize cultivars, including maximum temperature (°C), minimum temperature (°C), precipitation (mm) and sunshine hours (h). Daily solar radiation (MJ m⁻²) was estimated using the Angstrom equation with sunshine hours (Wang *et al* 2015a). Observed phenological data during 1980–2011 by 100 agrometeorological observational sites across China's Maize Belt were used to set the actual maize sowing date and derive the potential sowing window. Observed data on maize cultivar, phenology (e.g. sowing, flowering, and maturity dates), yield and field management practices from 12 experimental sites were used to calibrate and validate the maize model.



These field experiments were conducted across China's Maize Belt to investigate the responses of maize growth and development to sowing date. Detailed information on soil data can be found in supplementary S1 and table S1 is available online at stacks.iop.org/ERL/15/024015/mmedia.

2.2. Future climate change scenarios

Future time series of daily temperature, precipitation and solar radiation data for the study area were statistically downscaled from monthly gridded climate data (with the resolution of $2^\circ \times 2.5^\circ$) obtained from the GISS-E2-H-CC (GE2) global circulation model (GCM), using NWAI-WG downscaling model (Liu and Zuo 2012). The spatial inverse distance-weighted (IDW) interpolation method was used to downscale gridded monthly data to sites, followed by bias-correction using qq-plotting approach by comparing observed and the GCM projected data for the period of 1960–1999. Then, the modified WGEN stochastic weather generator was used to downscale the bias-corrected monthly data to daily data. These climate outputs based on this downscaling approach have been extensively applied in climate change impact studies (Liu *et al* 2014, Anwar *et al* 2015, Wang *et al* 2016, 2017, 2018, Feng *et al* 2019, Yao *et al* 2020). In this study, we selected the GE2 model because it is superior in its ability to capture historical climate for China compared to the ability of other GCMs (Yang *et al* 2019).

To generate warming scenarios of 1.5°C and 2°C , 1986–2005 was set as the baseline period given that 1986–2005 is 0.61°C warmer than the preindustrial period (IPCC 2013, UNFCCC 2015). The 1.5°C and 2°C warming scenarios were derived using 20 year

time slice periods following the methods of previous studies (Gosling *et al* 2017, Leng 2018). Using the 20 year moving mean temperature method, 1.5°C and 2°C warming scenarios, additional warming of 0.89°C and 1.39°C above the baseline were anticipated during 2018–2037 and 2044–2063, respectively, for the GE2 model under representative concentration pathway (RCP) 4.5 (Schleussner *et al* 2016), which represents a moderate greenhouse gas emission scenario which is more closely to meet 1.5°C and 2.0°C target under current socio-economic conditions. Supplementary S2 and table S2 showed projected climate change during the maize growing season.

2.3. Derivation of cultivar parameters in the APSIM-Maize model

The Agricultural Production Systems sIMulator (APSIM) maize model (version 7.7) was used to investigate the future climate change adaptation potential of maize production by adjusting the sowing date and shifting the cultivar. APSIM simulates maize growth, development and yield formation in response to solar radiation, temperature, photoperiod, soil water and nitrogen (Keating *et al* 2003, Holzworth *et al* 2014). Maize phenology is determined by temperature together with photoperiod sensitivity of a given cultivar. Daily aboveground biomass accumulation is calculated by daily solar radiation interception and radiation use efficiency, reduced by soil water and nitrogen stress. Grain yield of maize is determined by grain number, daily grain-filling rate and assimilate re-translocation. Precipitation affects crop biomass accumulation and yields significantly by impacting soil water content in the APSIM. APSIM has been well evaluated and applied in China's Maize Belt and

Table 1. Division of the maize planting regions and cropping systems across China’s Maize Belt.

Region	Location	Cropping system	Growing season	Number of weather station	Number of agro-meteorological site	Number of experimental site
I	Northeast China	Single	1/May–30/September	17	10	1
II	Northeast China	Single	1/May–30/September	12	11	1
III	Northeast China	Single	1/May–30/September	20	13	1
IV	Northwest China	Single	1/May–30/September	9	8	3
V	North China Plain	Double	1/June–30/September	49	36	3
VI	Southwest China	Mixed	1/April–30/September	56	22	3

performed well in capturing the impacts of changes in climate and agronomic management practices on crop growth, development and yield (Liu *et al* 2013, Wang *et al* 2014, Bu *et al* 2015, Dai *et al* 2016). Here, we further evaluated the performance of the APSIM-Maize model in simulating the phenology and yield of maize in terms of different cultivars, sowing dates and regions across China's Maize Belt. The statistical metrics for model evaluation were shown in supplementary S3.

Three representative cultivars at different cultivar maturities (early-, middle- and late-maturing) were selected for each maize planting region to minimize the possible spatial heterogeneity in local cultivars (table 2). For regions I–III, the same representative cultivars were used due to similar cropping system and management options. Genetic parameters for four cultivars used in the APSIM were referenced directly from the literature, and the genetic parameters of the other eight cultivars were derived by model calibration and validation based on experimental field data with 'trial-and-error' method. Genetic parameters for maize phenology were determined by comparing observed and simulated flowering and maturity dates while genetic parameters for maize yields were determined by comparing observed and simulated maize yields. We also referenced the traits of maize cultivars given by breeders to ensure the physiological means of parameters. Experimental field data from the literature were extracted using WebPlotDigitizer software (<https://automeris.io/WebPlotDigitizer/>) from the figures in the literature. To calibrate and validate the APSIM-Maize model, field experimental data were separated into independent calibration and validation data by different sowing dates and years.

2.4. Setting up simulations in APSIM

To evaluate the adaptation potential of maize production to climate change, long-term simulations driven by projected daily climate data including solar radiation, maximum and minimum temperatures and precipitation, for the baseline scenario and 1.5 °C and 2 °C warming scenarios were conducted without any nitrogen stress during the maize growth period under rainfed conditions. Nitrogen fertilizer was applied automatically within 50 cm depth in the soil to keep mineral nitrogen no less than 300 kg ha⁻¹ to avoid of any nitrogen stress. All simulations were conducted under rainfed conditions. For single-cropping maize planting regions (I–IV), the simulation of the first 10 years was discarded as a 'spin up' period to minimize the effect of the initial condition (Teixeira *et al* 2015, Tang *et al* 2019). For the double-cropping system (V–VI), the initial soil water content at the maximal root depth at sowing was reset at 30% and 81% of the plant available water holding capacity for regions V and VI, respectively, according to the observed historical averaged initial soil water content at sowing from agro-meteorological experimental sites.

For all maize planting regions, the maize planting density was set as 67 500 plant ha⁻¹. The planting depth and row spacing were set as 5 cm and 60 cm, respectively. Our study also considered the impact of an increase in CO₂ concentration on maize (supplementary S4). For C₄ crop, the elevated CO₂ concentration mainly affects plant transpiration. Previous study has showed that transpiration efficiency was increased linearly by 37% with CO₂ concentration increasing from 350 to 700 ppm (Lobell *et al* 2015), and therefore we nested this function into APSIM-Maize model.

2.5. Sowing window and cultivar with and without adaptation

In the case of without adaptation options, actual sowing date at each weather station used the average sowing date from historically observed values at each nearest agro-meteorological sites and actual maize cultivar was selected from local typical cultivars in table 2 based on the heat condition at the planting region (supplementary S5 and table S3).

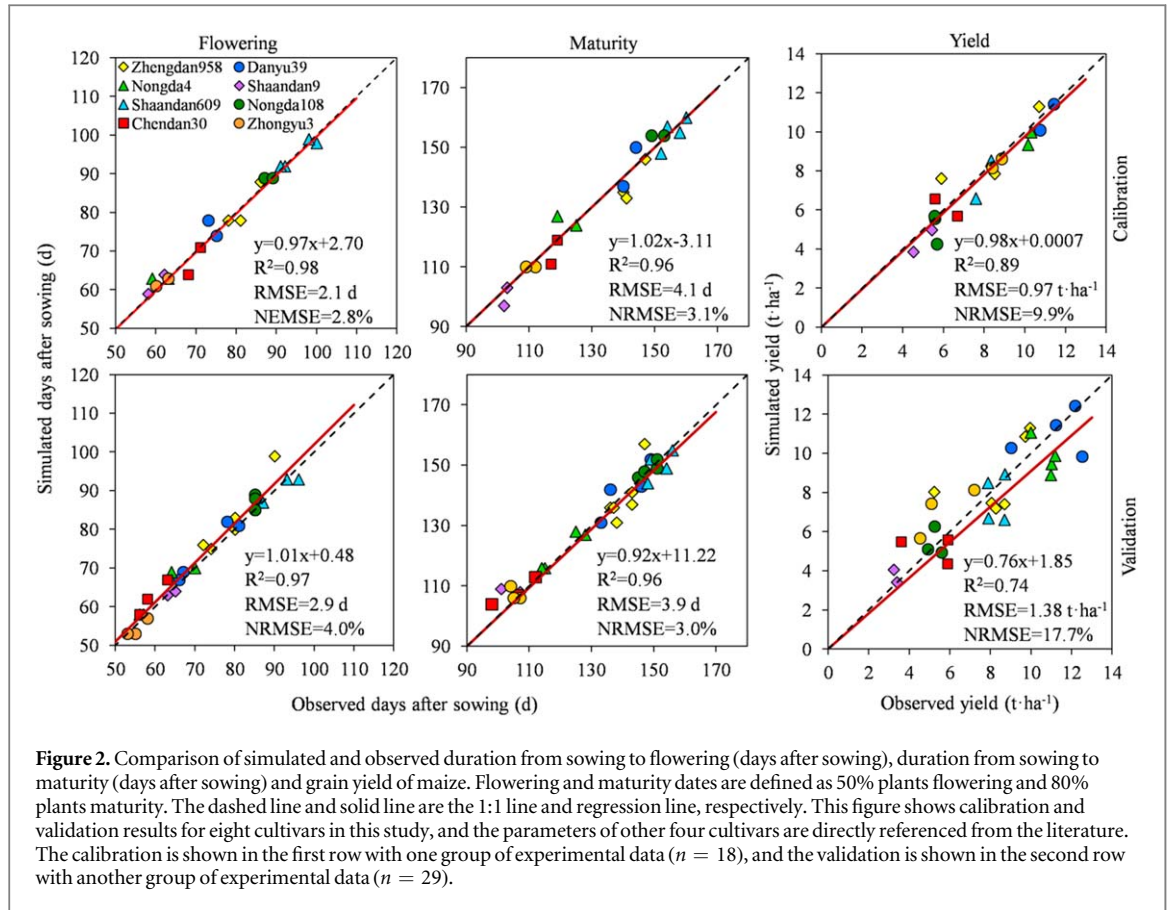
When considering adaptation strategies, the optimal combination of sowing date and maize cultivar was selected from three typical cultivars in table 2 and the sowing date within the potential sowing window for each planting region. The potential sowing window for each region was defined as the period between the earliest and latest planting dates for the early-maturing cultivar at each planting region. The earliest planting date was set as the first day when the five-day moving average of daily average temperature was >8 °C, which is the baseline temperature for maize used in the APSIM-Maize model and is based on a literature review (Sánchez *et al* 2014) in regions I–IV. In region V, with a double-cropping system, the earliest planting date constrained by the harvesting date of the previous crop was set 3 d after harvesting the previous crop recorded in agro-meteorological sites. In region VI, with a mixture of a single-cropping system and a double-cropping system, the earliest planting date was set as the recorded averaged maize planting date from agro-meteorological sites. The latest planting dates in regions I–IV were set as the last day maize could mature before the first frost day calculated as the daily minimum temperature below 0 °C. In regions V–VI, the latest planting date was set as the day maize could mature at 7 d before sowing the next crop. Maize was harvested when one of the following three conditions was achieved: (1) at the physiological maturity date, (2) before the first frost day and (3) 3 d before sowing next season crop.

The optimal sowing window was prescribed as the sowing dates that achieve over 80% of the highest yield within the potential sowing window. Cultivar harvested the highest yield was chosen as the optimal cultivar for a given region.

Table 2. Detailed information on cultivar, cultivar maturity, calibration and validation data, experimental site, and different sources of genetic parameters obtained across six maize planting regions.

Maize planting region	Cultivar	Maturity	Calibration (day/month/year)	Validation (day/month/year)	Observed data for calibration and validation	Experimental site and data source	Genetic parameter source
I–III	Jidan120	E	4/5/1998, 6/5/1999	1/5/2002, 1/5/2004	Flowering and maturity dates, grain yield	Huadian agro-meteorological site, Liu <i>et al</i> (2012)	Liu <i>et al</i> (2012)
	Zhengdan958	M	7/5/2012, 15/5/2013, 15/5/2014	27/4/2012, 17/5/2012, 8/5/2013, 22/5/2013, 8/5/2014, 22/5/2014	Flowering and maturity dates, grain yield	Lindian experimental site, Han <i>et al</i> (2016)	This study
	Danyu39	L	30/4/2012, 30/4/2013	20/4/2012, 10/5/2012, 20/4/2013, 10/5/2013	Flowering and maturity dates, grain yield	Jinzhou experimental site, Cui (2017)	This study
IV	Shaandan9	E	14/6/1990, 19/6/1991	14/6/1992, 19/6/1993	Flowering and maturity dates, grain yield	Wugong agro-meteorological site	This study
	Shaandan609	M	10/4/2012, 10/4/2013	16/4/2012, 28/4/2012, 16/4/2013, 28/4/2013	Flowering and maturity dates, grain yield	Changwu experimental site, Lu <i>et al</i> (2017)	This study
	Nongda108	L	2/5/2003, 28/4/2004, 30/4/2005	2/5/2006, 4/5/2017, 6/5/2008	Flowering and maturity dates, grain yield	Xiyang agro-meteorological site	This study
V	Yunong704	E	28/5/1981	2/6/1982, 6/6/1984	Flowering and maturity dates, grain yield	Nanyang agro-meteorological site, Xiao <i>et al</i> (2016)	Xiao <i>et al</i> (2016)
	Yedan22	M	15/6/1998, 15/6/1999, 15/6/2000, 15/6/2001	15/6/2003, 15/6/2004, 15/6/2005	Flowering and maturity dates, grain yield	Yucheng experimental site, Chen (2009)	Chen (2009)
	Nongda4	L	21/5/2010, 21/5/2012	30/4/2010, 11/6/2010, 30/4/2012, 11/6/2012	Flowering and maturity dates, grain yield	Wuqiao experimental site, Zhu (2013)	This study
VI	Luodan5	E	6/4/2005, 3/5/2006	21/5/2007	Flowering and maturity dates, grain yield	Mengzi agro-meteorological site, Dai <i>et al</i> (2016)	Dai <i>et al</i> (2016)
	Chendan30	M	26/3/2015, 10/4/2015	25/4/2015, 10/5/2015, 25/5/2015	Flowering and maturity dates, grain yield	Nanchong experimental site, Dou <i>et al</i> (2017)	This study
	Zhongyu3	L	5/5/2016, 15/5/2016	25/5/2016, 4/6/2016, 14/6/2016	Flowering and maturity dates, grain yield	Zhongjiang experimental site, Ren <i>et al</i> (2017)	This study

E, M and L represent early-, mid- and late-maturing cultivars, respectively.



2.6. Simulated yield change analyses

There were four types of simulated yield changes (%) in our study compared with that of the baseline scenario: (1) $\Delta Y_{1.5/2.0}$ was the yield change under the 1.5 °C or 2.0 °C warming scenarios compared with baseline, (2) $\Delta Y_{1.5/2.0,s}$ was the yield change caused by climate change from baseline to 1.5 °C or 2.0 °C warming scenarios and the adjusting sowing date, (3) $\Delta Y_{1.5/2.0,c}$ was the yield change caused by climate change from baseline to 1.5 °C or 2.0 °C warming scenarios and the shifting cultivar, and (4) $\Delta Y_{1.5/2.0,s\&c}$ was the yield change when considering climate change from baseline to 1.5 °C or 2.0 °C warming scenarios, changing the sowing date and shifting the cultivar.

$$\Delta Y_{1.5/2.0}(\%) = (Y_{1.5/2.0} - Y_{bl}) / Y_{bl} \times 100 \quad (1)$$

$$\Delta Y_{1.5/2.0,s}(\%) = (Y_{1.5/2.0,s} - Y_{bl}) / Y_{bl} \times 100 \quad (2)$$

$$\Delta Y_{1.5/2.0,c}(\%) = (Y_{1.5/2.0,c} - Y_{bl}) / Y_{bl} \times 100 \quad (3)$$

$$\Delta Y_{1.5/2.0,s\&c}(\%) = (Y_{1.5/2.0,s\&c} - Y_{bl}) / Y_{bl} \times 100, \quad (4)$$

where subscripts s and c represent adjusting sowing date and shifting cultivar, respectively. $Y_{bl/1.5/2.0}$ was the simulated average yield for baseline or under warming of 1.5 °C or 2 °C without adaptation, $Y_{1.5/2.0,s}$ was the simulated yield with the adjusted sowing time alone under warming of 1.5 °C or 2 °C, $Y_{1.5/2.0,c}$ was the simulated yield with the shifted cultivar alone under warming of 1.5 °C or 2 °C, and

$Y_{1.5/2.0,s\&c}$ was the simulated yield with the adjusted sowing date and shifted cultivar under warming of 1.5 °C or 2 °C.

2.7. The relative contribution rate of adjusting the sowing date and shifting the cultivar to yield change

ΔY_s , ΔY_c and $\Delta Y_{s\&c}$ (intermediate variables) were the yield changes that occurred after adjusting the sowing date, shifting the cultivar and combining the adjusted sowing date and shifted cultivar under the 1.5 °C or 2.0 °C warming scenarios compared with the yield under the baseline scenario. The relative contribution rate of climate change ($\Delta R_{1.5/2.0}$), change in sowing date (ΔR_s), change in cultivar (ΔR_c), and combined change in sowing date and cultivar ($\Delta R_{s\&c}$) on yield change was calculated as follows:

$$\Delta Y_s(\%) = (Y_{1.5/2.0,s} - Y_{1.5/2.0}) / Y_{bl} \times 100 \quad (5)$$

$$\Delta Y_c(\%) = (Y_{1.5/2.0,c} - Y_{1.5/2.0}) / Y_{bl} \times 100 \quad (6)$$

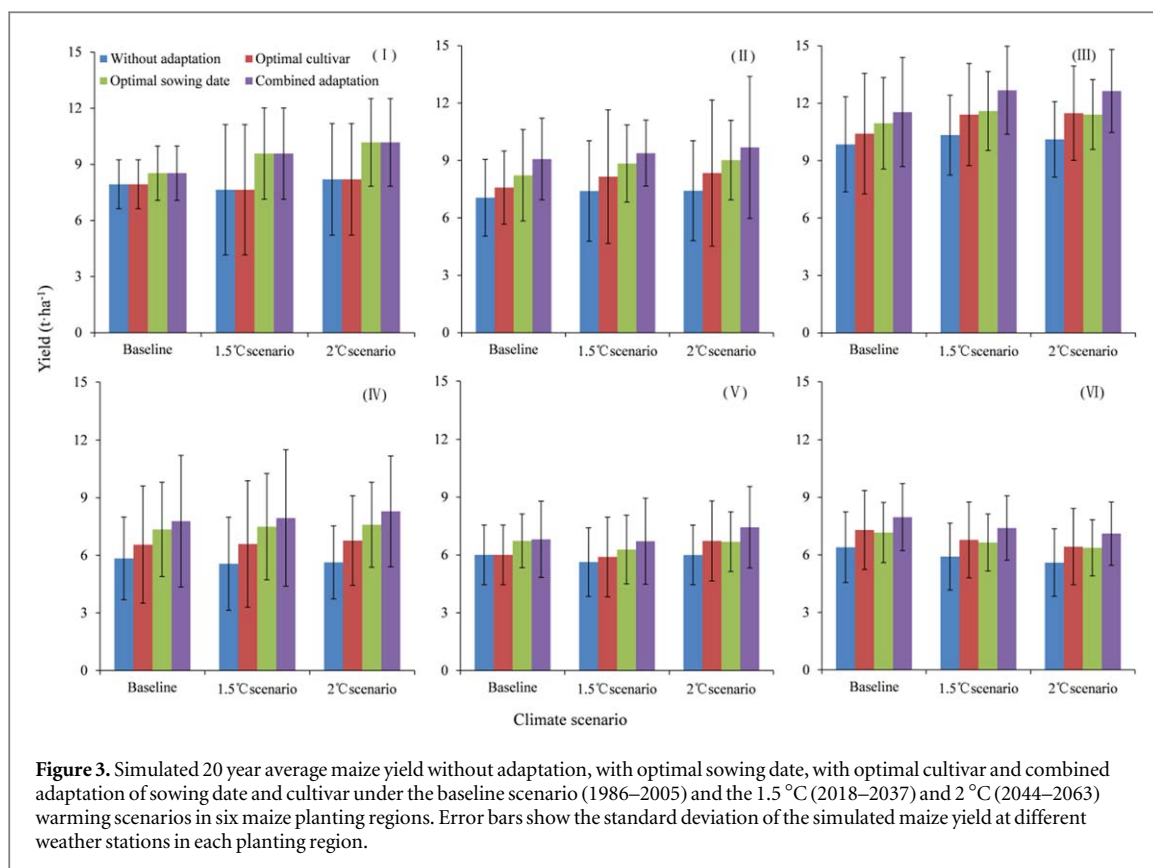
$$\Delta Y_{s\&c}(\%) = (Y_{1.5/2.0,s\&c} - Y_{1.5/2.0}) / Y_{bl} \times 100 \quad (7)$$

$$\Delta R_{1.5/2.0}(\%) = \Delta Y_{1.5/2.0} / \Delta Y_{1.5/2.0,s\&c} \times 100 \quad (8)$$

$$\Delta R_s(\%) = \Delta Y_s / \Delta Y_{1.5/2.0,s\&c} \times 100 \quad (9)$$

$$\Delta R_c(\%) = \Delta Y_c / \Delta Y_{1.5/2.0,s\&c} \times 100 \quad (10)$$

$$\Delta R_{s\&c}(\%) = \Delta Y_{s\&c} / \Delta Y_{1.5/2.0,s\&c} \times 100. \quad (11)$$



3. Results

3.1. Performance of the APSIM-Maize model across China's Maize Belt

Figure 2 shows the comparison of the simulated and observed phenology and yield of maize for eight typical local cultivars across China's Maize Belt. APSIM-Maize simulated the duration from sowing to flowering and from sowing to maturity well with root-mean-square error (RMSE) values of 2.1 and 4.1 d for the calibration period and 2.9 and 3.9 d for the validation period, respectively. The simulated maize yield was in good agreement with the observed maize yield with an R^2 of 0.89 for the calibration and 0.79 for the validation period. For the calibration period, the RMSE was 0.97 t ha^{-1} , the NRMSE was 9.9%; for the validation period, the RMSE was 1.38 t ha^{-1} , and the NRMSE was 17.7%. All cultivar parameters were shown in table S4.

3.2. Future maize yield change under different scenarios

The simulated average rainfed yield without adaptation was $5.8\text{--}10.0 \text{ t ha}^{-1}$ across China's Maize Belt under the baseline climate scenario, with the highest yield in region III and the lowest yield in region IV (figure 3). In comparison with the baseline scenario, without adaptation, warming of 1.5 °C and 2 °C would increase maize yields by 0.9%–4.9% and 2.6%–7.9% in regions I–IV, respectively, and would reduce maize

yields by 6.3%–7.6% and 0.1%–12.5% in regions V–VI, respectively. The factors resulting in yield change varied with region. An increasing CO_2 concentration would lead to maize yield increases in regions I, II and IV (figure 4 and table S5). For region III, the combined increase in growing period precipitation and CO_2 concentration would increase maize yield. However, a decrease in growing period precipitation would decrease maize yield in region V. A decrease in growing period solar radiation and an increase in growing period temperature would decrease maize yield in region VI.

Considering adaptation to climate change through the optimization of the sowing date and cultivar, the simulated average maize yield would increase under all scenarios (figure 3 and table S6). Across China's Maize Belt, simulated average maize yield would increase by 11.1%–53.9%, with the highest increase in regions II and IV and the lowest increase in region VI. Compared with the baseline scenario, under the warming scenarios, only adjusting the sowing date could increase the yield by -0.5% to 40.7%, while only shifting the cultivar could increase the yield by -1.8% to 24.9%.

Contribution rate of 44.5%–96.7% on yield improvement by adjusting the sowing date was higher in comparison with that of shifting the cultivar (0%–50.8%) and climate change (-53.1% to 23.0%) in most maize planting regions, except in regions III and V under warming of 2 °C and in region VI under both warming scenarios

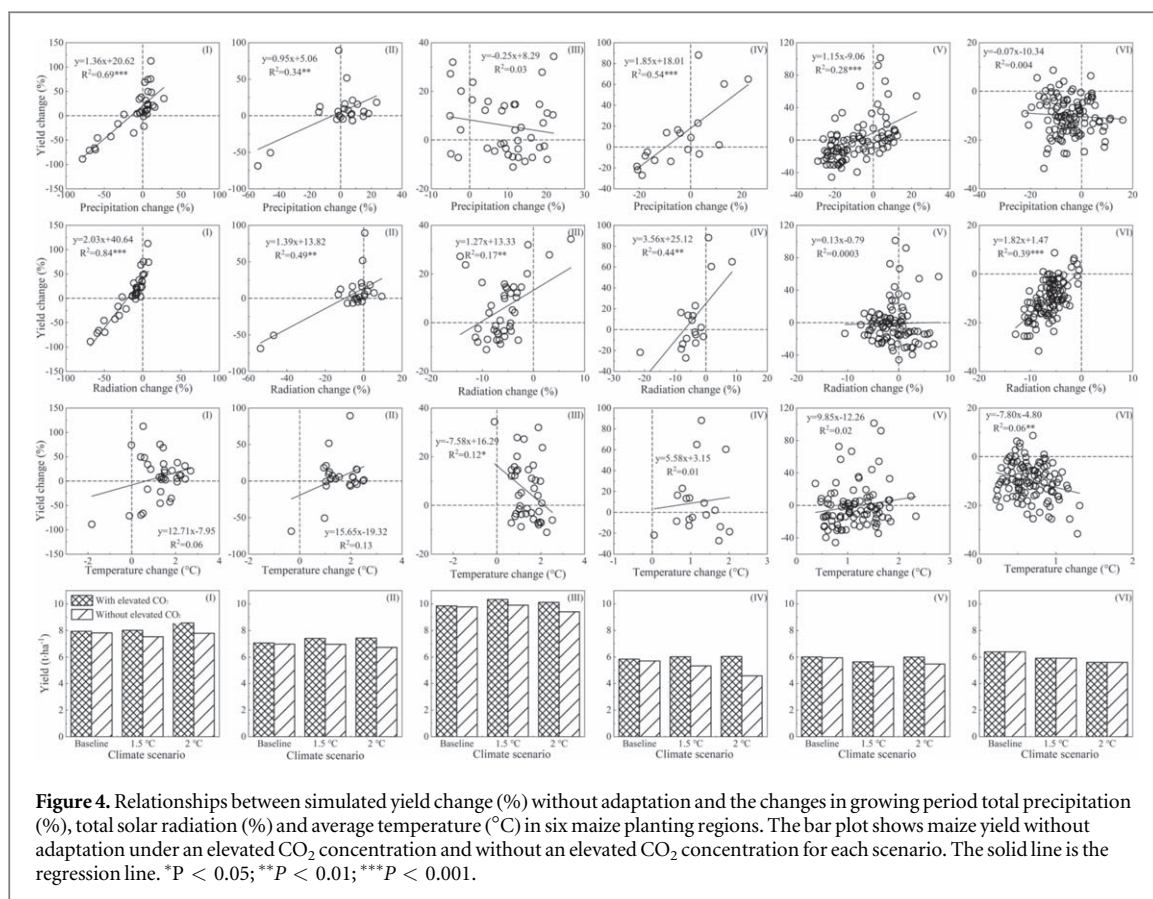


Figure 4. Relationships between simulated yield change (%) without adaptation and the changes in growing period total precipitation (%), total solar radiation (%) and average temperature (°C) in six maize planting regions. The bar plot shows maize yield without adaptation under an elevated CO₂ concentration and without an elevated CO₂ concentration for each scenario. The solid line is the regression line. *P < 0.05; **P < 0.01; ***P < 0.001.

Table 3. The individual and combined contribution rates of climate change, adjusted sowing date and shifting cultivar in different maize planting regions.

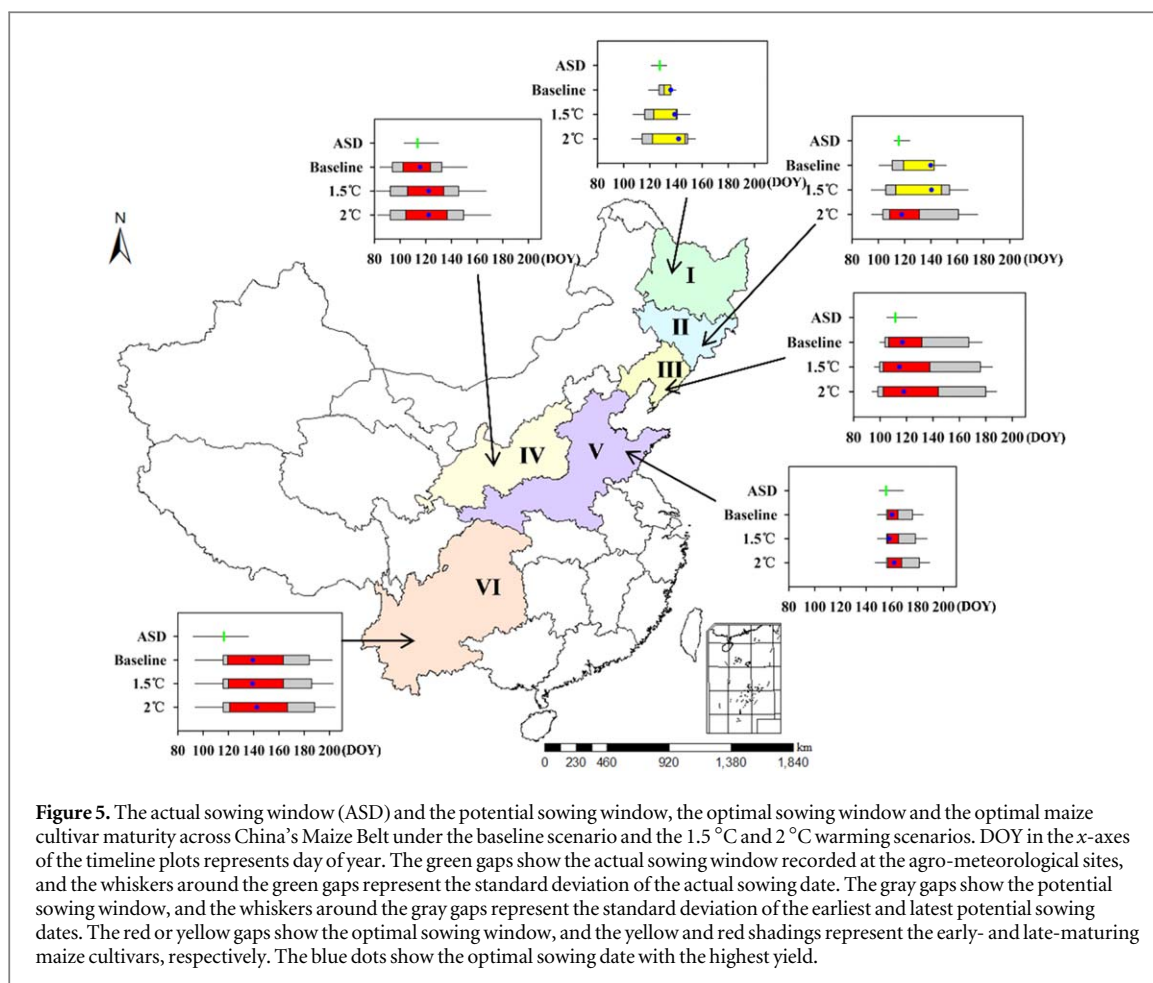
Planting region	Climate change scenario	$\Delta R_{1.5/2.0}$ (%)	ΔR_s (%)	ΔR_c (%)	$\Delta R_{s\&c}$ (%)
I	1.5 °C	3.3	96.7	0	96.7
	2 °C	23.0	77.0	0	77.0
II	1.5 °C	14.9	61.7	32.4	85.1
	2 °C	13.8	60.9	35.0	86.1
III	1.5 °C	17.1	44.5	37.9	82.9
	2 °C	9.3	46.6	49.2	90.7
IV	1.5 °C	6.1	76.3	40.6	93.9
	2 °C	6.3	69.1	39.9	93.7
V	1.5 °C	-53.1	92.0	38.0	153.1
	2 °C	-0.5	47.9	50.8	100.5
VI	1.5 °C	-48.3	73.2	86.7	148.3
	2 °C	-112.7	108.6	117.1	212.7

Note: $\Delta R_{1.5/2.0}$, ΔR_s , ΔR_c and $\Delta R_{s\&c}$ are the relative contribution rates of climate change, change in sowing date, cultivar shift, and combined change in sowing date and cultivar on maize yield change, respectively.

(table 3). Optimal cultivar would not change in region I implying rising heat resource under future scenarios of warming 1.5 °C and 2 °C could still not meet the thermal time required by middle-late maturing cultivars. The contribution rate of shifting the cultivar to yield improvement would increase with climate change in all maize planting regions. The combined effect of sowing date and cultivar shifting was not equal to the sum of their individual impacts in regions II–VI, suggesting an interaction effect between changing the sowing date and shifting the cultivar on maize yield change.

3.3. Potential sowing window, optimal sowing window and cultivar across China’s Maize Belt

Figure 5 shows the potential sowing window, the optimal sowing window and the optimal maize cultivar maturity level across China’s Maize Belt under the baseline scenario and the 1.5 °C and 2 °C warming scenarios. The earliest potential sowing date started in mid-April in regions III and IV, while the latest potential sowing date started in early June in region V under the baseline scenario. The longest potential sowing window was in region VI, with an average of



68 d, while the shortest potential sowing window was only 6 d in region I under the baseline scenario. With climate warming, the earliest potential sowing date advanced for all the maize planting regions except those in regions V and VI, where sowing dates were constrained by the harvest of the previous crop. The latest potential sowing date was delayed for all the maize planting regions. Therefore, the potential sowing window increased by 2–17 d under warming of 1.5 °C and 4–26 d under warming of 2 °C across the maize belt with a higher extension rate in higher latitude regions (e.g. regions I–III). The change in the optimal sowing window under climate change was consistent with the change in the potential sowing window. Significant advances in the start date of the optimal sowing window occurred in region I by 8 d and in region II by 10 d, while the end date of the optimal sowing window was delayed in all the maize planting regions, with a more significant delay in regions I–IV under the warming scenarios compared with under the baseline scenario. Therefore, climate warming would significantly lengthen the optimal sowing window, especially in regions I–IV, by an average of 10 d under warming of 1.5 °C and by 12 d under warming of 2 °C relative to under the baseline scenario. The actual sowing windows in regions I–II and VI occurred slightly earlier than the optimal sowing window, while they were close to the optimal

sowing window in regions III–V. The optimal cultivar maturity level would change from an early-maturing cultivar under the baseline scenario and warming of 1.5 °C to a late-maturing cultivar in region II under warming of 2 °C but would not change with climate change for the early-maturing cultivar in region I and the late-maturing cultivar in other planting regions.

4. Discussion

China's Maize Belt is one of the World's Golden Maize Belts and therefore is significant to securing global food safety. However, maize yield was significantly affected by ongoing climate change. Our simulated results show that climate change would enhance maize yields in regions I–IV mainly due to elevated CO₂ concentrations together with the increase in growing period precipitation. At the same time, future maize yields in regions V–VI would decrease as a result of the decline in precipitation and solar radiation due to warming temperatures accelerating growth phases. These findings are consistent with the results of previous studies in all maize planting regions except Northwest China, where other studies found that future maize yields would decrease (Xiong *et al* 2007, Tao and Zhang 2011, Kang *et al* 2014, Lin *et al* 2017, Liang *et al* 2018). This inconsistency is possibly

because our study considered the impacts of an increase in CO₂ concentration on transpiration efficiency by decreasing stomatal conductance, therefore relieving water stress during the maize growing period in Northwest China (Lobell *et al* 2015, Zhang *et al* 2018).

Optimizing sowing date is recognized as one of most effective adaptation options to address climate change by matching the supply and requirement of crops to climate resources (Kamara *et al* 2009, Tsimba *et al* 2013) and mitigating climate risks such as drought and heat stress (Yang *et al* 2017, Rahimi-Moghaddam *et al* 2018, Tian *et al* 2019). Comparing the current potential sowing window across six regions, regions I and V have shorter sowing windows. This result occurred because region I has a shorter frost-free period, while the maize growing period of region V is constrained by a double-cropping system. With climate change, the future potential sowing window was lengthened because of the advance of the earliest potential sowing date and the delay of the latest sowing date across all six regions, which could provide more opportunities to optimize the sowing date. In addition, the potential sowing window in higher latitude regions would be extended more than that in other regions in our study due to more significant warming in northern China (Piao *et al* 2010), which suggests a large opportunity to adjust the sowing date to adapt to climate change in northern China.

We find that late sowing dates in regions I–II, middle sowing dates in region IV and early sowing dates in regions III and V–VI can have beneficial impacts on maize yield increases because of increased precipitation during longer growing periods (table S7). In contrast, previous studies recommend early sowing dates in regions I–II (Liu *et al* 2013, Bu *et al* 2015, Huang *et al* 2018). This difference is caused by the interaction between the sowing date and cultivar choice. Previous studies used a late-maturing cultivar in these regions and therefore recommended early sowing to obtain a longer growth period. However, we identified early-maturing cultivars suitable in regions I–II due to the shortage of thermal time in higher latitude regions. Late sowing becomes possible under warming scenarios, which could result in addition growth period precipitation. However, testing the adaptive potential of early sowing late-maturing cultivars in regions I–II will be the priority in future work. In contrast, our study recommended late-maturing cultivars in regions III–VI to obtain a longer growing period (table S8), which is consistent with the results of previous studies (Liu *et al* 2013, Bu *et al* 2015, Huang *et al* 2018).

Our study also found that there were significant interactions between sowing date and cultivar on maize yield. For example, the optimal cultivar under the current sowing date in region II is a middle-maturing variety under warming of 1.5 °C (table S9), but the optimal cultivar shifts to an early-maturing variety under an optimal sowing date (figure 5). For regions

IV, late sowing is suitable to the current maize cultivar (figure S1), while middle sowing with the optimal maize cultivar harvested higher yields (figure 5) (Tsimba *et al* 2013). A middle sowing date interacts well with the current maize cultivar in regions V–VI (figure S1), but early sowing with the optimal maize cultivar results in a higher yield (figure 5). Furthermore, in comparison with shifting the cultivar, adjusting the sowing date contributes more in most planting regions except region VI because adjusting the sowing date increases maize yield mainly by increasing growing period precipitation, while this region is not limited by precipitation (Lu *et al* 2017).

Analyzing adaptation potential is helpful for decreasing yield gaps in different planting regions and distinguishing effective adaptation options for future climate change (Guan *et al* 2017, Rahimi-Moghaddam *et al* 2018). Positive adaptation potential indicates that maize yield can be increased by optimizing sowing date and cultivar choices in China under warming of 1.5 °C and 2 °C. However, the lower adaptation potential in regions V–VI than that in the other regions implies that these areas might be vulnerable to future climate change and need to be analyzed further.

The adaptation potential based on our results provides different opportunities and challenges for maize production over maize growing regions. For example, in regions I–III, climate warming lengthens the growing season making it possible to plant maize cultivars with longer growing periods (Liu *et al* 2013, Huang *et al* 2018). For region IV, the high yield of maize is still limited by low growing-season precipitation, although climate change with adaptation would increase maize yields. Therefore, selecting drought- and heat-resistant cultivars should be further studied to improve maize yields. As decreased precipitation and limited growth periods under double-cropping systems are likely to continue reducing yields in region V, improving water use efficiency by adjusting the sowing date and planting late-maturing maize cultivars in spring as well as changing the wheat-maize rotation system to a single-maize cropping system would be feasible adaptation strategies (Zhao *et al* 2018, Sun *et al* 2019). Low solar radiation in region VI could be more severe in the future; thus, breeding new cultivars with higher radiation use efficiency will alleviate the extent of this yield loss. The differences in adaptation potential and adaptation options among different maize planting regions provide useful information for decision makers and growers to optimize maize production layouts and develop effective adaptation strategies under future climate.

However, there were still some uncertainties in our study. We did not consider future cultivars, including rapidly updated higher heat- and drought-resistant cultivars, which may lead to increased adaptation (Singh *et al* 2014, Guan *et al* 2017, Tesfaye *et al* 2017). All simulation assumed under rainfed and no nitrogen stress conditions. There may be nitrogen

fertilization and irrigation interactions with sowing date and cultivar which significantly impact maize yields. However, in China's Maize Belt, the application amounts of nitrogen fertilizer by farmers are always very high (Xu *et al* 2014, Xiao *et al* 2019), which could meet the requirement of maize growth (Chen *et al* 2018). Moreover, irrigation is not used frequently during maize growing season because precipitation concentrates in maize growing season such as regions I–III and V–VI or because there is no available irrigation water resource e.g. in region IV (Wang *et al* 2010, Yin *et al* 2015). Therefore, our assumptions are close to actual production conditions although optimal sowing dates and cultivars may change with different amounts of nitrogen fertilization and irrigation. Simulated maize yields are also sensitive to initial soil water content at sowing especially in the double-cropping regions implying optimal sowing dates and cultivars would change with initial soil water content. In addition, our study used a relatively optimistic climate change scenario because international efforts have been implemented to mitigate climate warming to realize the target of warming within 1.5 °C and 2 °C according to the Paris Agreement (UNFCCC 2015). Climate change would decrease maize yields more significantly under the more pessimistic climate change scenarios than under other scenarios (Xiong *et al* 2007, Tao and Zhang 2011). However, the design of this study based on limited scenarios and a single model could provide feasible guidance for more climate change impact assessments with multiple global climate models and multiple crop models (Araya *et al* 2015, Wang *et al* 2015b, Rahman *et al* 2018, Yang *et al* 2019).

5. Conclusion

Our study explored the impacts of future climate change on maize yield and investigated the adaptation potential across China's Maize Belt by optimizing the sowing date and cultivar with the validated APSIM-Maize model under warming 1.5 °C and 2 °C scenarios. Adaptation is necessary as maize yield declined in region V–VI without adaptation. With adaptation maize production keeps stable for increasing yield under temperature limited warming 2 °C. Adjusting sowing date increased more yield than shifting cultivar in regions I–V, and shifting cultivar produced more in region VI. The late sowing in regions I–II, the middle sowing in region IV and the early sowing in regions III and V–VI coupling with current early-maturing cultivar in regions I and later-maturing cultivar in other regions produced higher yields.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID iDs

Mingxia Huang  <https://orcid.org/0000-0002-2040-9490>

Jing Wang  <https://orcid.org/0000-0002-7960-0396>

Bin Wang  <https://orcid.org/0000-0002-6422-5802>

Xuebiao Pan  <https://orcid.org/0000-0002-9527-8982>

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