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Short Communication

Dominant sources of uncertainty in simulating maize adaptation under future climate scenarios in China

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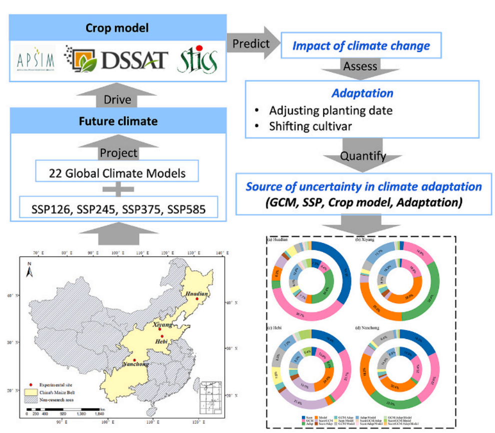
HIGHLIGHTS

- Multi-source climate data drive three crop models to assess adaptation uncertainty.
- Direction and magnitude of yield change varied with climate and crop model.
- Adjusting planting date and shifting cultivar would have high adaptation potential.
- Dominant source of uncertainty depended on adaptation type used.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The potential of climate adaptation has been widely investigated with a climate-crop modeling approach. Although different sources of uncertainty in projected crop yields have been quantified in climate change impact assessments, uncertainty in simulating the crop adaptation to future climate has not been fully assessed.

OBJECTIVE: The objective of this study was to determine the uncertainty in simulating maize adaptation to future climate change with two adaptation options (adjusting planting date and shifting cultivars) at four contrasting sites across China's Maize Belt.

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METHODS: Maize yield with adaptation was simulated using three crop models (APSIM, DSSAT-CERES, and STICS) driven by 22 global climate models (GCMs) under four emission scenarios of future societal development pathway (SSP126, SSP245, SSP370, and SSP585) during two periods (2040–2069 and 2070–2099).
RESULTS AND CONCLUSIONS: We found that late planting had a greater potential to cope with climate change at most study sites. However, all sites required new cultivars with increased thermal time requirements. Under optimum management options at the four study sites, rainfed maize yields were likely to increase by 1.9%–68.3% compared with yields obtained without adaptation. For the adaptation simulation using adjusted planting date alone, GCM was the major source of uncertainty, accounting for 22.9%–36.7% of the total uncertainty at all sites except a high-altitude site where changing planting time was the major source of uncertainty (32.4%). For the adaptation simulation using shifting cultivar alone, crop model was the dominant source of uncertainty, accounting for 24.0%–38.0% of the total uncertainty at all sites except a high-latitude site where shifting cultivar was the major source of uncertainty (34.0%). These findings demonstrated that adaptation options have great potential for increasing maize yields, and the major source of uncertainty depends on study sites and adaptation type used.
SIGNIFICANCE: The results of this study advance the understanding of the dominant sources of uncertainty in crop yield under different climate adaptations, thereby improving our confidence in assessments of future climate impact on maize yields determined by different adaptation strategies.

1. Introduction

Climate warming, with increased frequency and intensity of extreme climate events, is projected to severely threaten crop production. Maize (*Zea mays* L.) is a staple grain and feed crop with the greatest production in the world (IPCC, 2014). Maize yields have been negatively impacted by climate change. For example, Lobell et al. (2011) reported that global average maize yield has been reduced by 3.8% due to historical climate change. In the future, projected global maize yield will be reduced by 7.4% for each degree-Celsius increase in mean air temperature (Zhao et al., 2017). China is the second largest maize producer in the world, and climate change is projected to decrease rainfed maize yield by up to 24% in 2010–2099 compared with 1976–2005 in the absence of adaptation (Lv et al., 2019). Meanwhile, the world's cropland area has been shrinking due to rapid urban expansion (van Vliet et al., 2017). However, global population is projected to exceed 9.7 billion by 2050 (UN_DESA, 2017), resulting in growing food demand. This imbalance between food supply and demand threatens global food security. Increasing yield per hectare is an important means to combat the food crisis, especially with regard to cereal crops. Ongoing climate change, shrinking area of the world's cropland, and increasing demand for food from a soaring world population have raised an urgent need for adaptation to climate change to maintain high maize yields in the future.

Various adaptation options, including adjusting planting dates, shifting cultivars, increasing planting densities, optimizing irrigation applications and fertilizer rates, have been widely used in adapting to climate change (Guan et al., 2017). Among the adaptation options, adjusting planting dates and shifting cultivars have been recognized as two of the most effective adaptation options. They could increase crop yields by making full use of climate resources, and avoid the high-risk periods of heat and drought stress (Guan et al., 2017; Rahimi-Moghaddam et al., 2018; Huang et al., 2020). Data from field experiments showed that shifting cultivars and advancing planting date could prolong the maize growth period by 6.5 days in China during 1981–2009, thereby compensating for the negative impact of rising temperatures on the length of the maize growth period (Tao et al., 2014). Our previous study found that optimizing planting date and selecting appropriate cultivars could result in 11.1%–53.9% increases in maize yield across China's Maize belt under the 1.5 °C and 2 °C warming scenarios (Huang et al., 2020). In the central US's Maize Belt, optimizing planting date could have increased maize yield by 6.6% during 1980–2015 (Baum et al., 2020). In a semiarid environment in Pakistan, optimizing planting date and suitable cultivar could increase maize yield by 0.6–1.1 t·ha^{-1} during the 2040–2070 period relative to the 1981–2010 period due to avoiding the high risk window of extreme temperature (Rahimi-Moghaddam et al., 2018).

Although climate change adaptation is recognized to have great potential for improving maize yield, there is still large uncertainty in simulating yield responses to adaptation options based on climate-crop modeling due to the selection of global climate models (GCMs), emission scenarios, crop models, and gradients of adaptation options (Kassie et al., 2015; Guan et al., 2017). Kassie et al. (2015) found that a medium-maturing maize cultivar could achieve higher yields compared with an early-maturing maize cultivar under one GCM, but shifting cultivars was not effective in improving maize yield under other GCMs. Additionally, large uncertainties exist in projecting optimal planting dates under different GCMs, as well as under different emission scenarios (Waongo et al., 2015; Wang et al., 2018a). Moreover, the contribution of adaptation options to crop yields varies with the crop models used for simulation (Guan et al., 2017). However, assessing the main sources of uncertainty in simulating the potential of different climate change adaptations have not been conducted despite many studies have investigated the uncertainty in simulating climate change impacts without adaptation (Asseng et al., 2013; Wang et al., 2020; Müller et al., 2021). An understanding of the sources of uncertainty in simulating climate change adaptation is essential for improving our confidence in assessing the impacts of climate change, and to put forward efficient adaptation strategies for policy-makers and stakeholders.

In this study, we selected four representative sites from China's Maize Belt as a case study region. We first tested the performance of three different maize models in simulating phenology and yields. Then, the effects of climate change on yields under different adaptation options were simulated by the calibrated models driven by multiple GCMs from the Coupled Model Inter-comparison Project Phase 6 (CMIP6) under different emission scenarios. Our specific objectives were to (1) quantify future climate change at the study sites; (2) assess the impacts of future climate change on maize yield with three crop models; (3) investigate the potential of different adaptation options to cope with the impacts of climate change on maize yield; (4) identify the dominant source of uncertainty in simulating adaptation of maize to future climate change.

2. Materials and methods

2.1. Study site, crop, and soil data

Four sites (Huadian, Xiyang, Hebi, and Nanchong) with contrasting climates and cropping systems were selected to represent major rainfed maize planting regions of China's Maize Belt (between 23°–48°N, Fig. S1 and Table S1). Huadian, Xiyang, and Hebi have a temperate monsoon climate, while Nanchong has a subtropical monsoon climate. The single maize cropping system is popular at Huadian and Xiyang where the maize growing season runs from May to September (Table S1). In contrast, the widely used cropping system at Hebi is the wheat-maize rotation, and the wheat-maize relay intercropping system is used at Nanchong. The maize growing season is June to September at Hebi and April to September at Nanchong. For the maize growing seasons in 1961–2010, Huadian, Xiyang, Hebi, and Nanchong had mean rainfall amounts of 610, 444, 414, and 796 mm, respectively, mean temperature of 18.4, 21.3, 25.0, and 24.3 °C, and mean solar radiation of 18.4, 19.6, 18.8, and 16.3 MJ·m^{-2}·d^{-1} (Table S1).

Observed maize planting dates during 1980–2011 at four agro-meteorological sites were used to set the actual maize planting date. Observed phenology (e.g., planting, flowering, and maturity dates), yield, and field management practices were obtained from field experimental sites and agro-meteorological sites and used to calibrate the maize models (Tables S2-S3). Detailed soil and climate types for each site are shown in Table S1. Field experimental data at Nanchong were extracted from tables or figures in the published literature using WebPlotDigitizer software (https://automeris.io/WebPlotDigitizer/). Field experimental data at Huadian, Xiyang, and Hebi were obtained from agro-meteorological sites (Text S1). Soil data at each site were obtained from the China Soil Scientific Database (Table S4).

2.2. Historical and future climate data

Historically observed daily maximum and minimum air temperatures (°C), rainfall (mm), and sunshine hours (h) during 1961 to 2010 were available from the China Meteorological Administration (CMA). Daily solar radiation (MJ·m^{-2}·d^{-1}) was derived from sunshine hours using the Angstrom equation (Wang et al., 2015a). To cover a wide range of climate projections, 22 GCMs from CMIP6 under four emission scenarios of future Shared Socio-Economic pathways (SSP126, SSP245, SSP370, and SSP585) were used in this study (Table S5). CMIP6 has been improved in the projection of climate features such as extreme temperature and precipitation compared with CMIP5 (Fan et al., 2020; Wyser et al., 2020; Xin et al., 2020). Projected daily maximum and minimum temperatures (°C), rainfall (mm), and solar radiation (MJ·m^{-2}·d^{-1}) for each study site from 1961 to 2100 were statistically downscaled from monthly gridded climate data simulated by the 22 GCMs under the four emission scenarios (Text S2).

2.3. Crop models and parameterization

Three process-based crop models (APSIM, DSSAT-CERES, and STICS) were used in this study (Tables S6–S7, Text S3). These models performed well in capturing the impacts of climate change and agronomic management practices on maize growth, development, and yield formation over the world under current climate conditions (Jégo et al., 2011; Gaydon et al., 2017; Yakoub et al., 2017).

At each study site, the genetic parameters of one representative cultivar used for the three models were determined based on field experimental data using a trial-and-error method (Table S8). Calibration and validation results showed that the three models with adjusted genetic parameters (Tables S9–S11) performed well in simulating phenology, with root mean square error (RMSE, Text S4) of less than 4.6 days for both flowering and maturity dates. The three models also performed well in simulating yield, with R^2 more than 0.98 and RMSE less than 1.5 t·ha^{-1} (Figs. S2 and S3).

2.4. Long-term simulation setup

Simulations were conducted for the baseline period (1980–2009), the 2050s (2040–2069), and the 2080s (2070–2099). To compare the simulations under the baseline, the 2050s, and the 2080s, we used all climate projection data downscaled by multiple GCMs from CMIP6. Maize varieties (Tables S9-S11) and agronomic management settings following the records from agro-meteorological sites were kept unchanged during the simulation periods (Table S12). Specifically, we reset initial soil water and nitrogen content before planting date of each year to avoid carry-over effects from previous season and focus on the climate change impact only during maize growing season (Asseng et al., 2011; Wang et al., 2020). We did not consider the impacts of initial soil water conditions on maize yield in this study. The initial soil water content before planting was reset to 40% of plant available water holding capacity (PAWC) at Huadian, 30% of PAWC at Xiyang and Hebi, and 81% of PAWC at Nanchong each year.

Maize planting density was set as 67,500 plants·ha^{-1}, with a planting depth of 5 cm and row spacing of 60 cm. 180 kg·N·ha^{-1} was applied at planting. Maize was harvested at one of the following times: (1) at physiological maturity, (2) before the first frost day for a single-cropping system (e.g., Huadian and Xiyang), (3) three days before planting the next season crop for a double cropping system (e.g., Hebi and Nanchong). Annual atmospheric CO_2 concentrations were used as inputs for each crop model (Text S5) (Xiao et al., 2020).

2.5. Adaptation by adjusting planting date and shifting cultivars

The adaptation potentials of adjusting planting date and shifting cultivars to future climate change were simulated separately. For example, the representative cultivar at each site was used when simulating the adaptation potential of adjusting planting date, while the historical average planting date recorded at each site was used when simulating the adaptation potential of shifting cultivars. For adjusting planting date, the earliest planting date in a single crop system (Huadian and Xiyang) was set as the first day when the five-day moving average of daily minimum temperature was >8 °C (the base temperature for maize, (Sanchez et al., 2014)). The earliest planting date was set three days after the wheat crop was harvested at Hebi. At Nanchong, the earliest planting date was set as the actual normal planting date recorded at the agro-meteorological site. Ten planting dates were set (beginning with the earliest planting date) with an interval of five days at Huadian, Xiyang, and Nanchong, while at Hebi only five planting dates with an interval of three days were set due to the short maize planting window (Table S13). The adaptation of shifting cultivars to climate change was simulated and evaluated by using adapted cultivars. Adapted cultivars had thermal time to maturity that increased by increments of 10% of the total thermal time required to reach maturity based on the normal representative maize cultivar used at each site. Thus, seven adapted cultivars were used for all sites except for Hebi where five adapted cultivars were used due to the short maize growing season (Tables S14–16). Text S6 shows the calculation of climate change impact and adaptation potential, and Text S7 shows the quantification of the different sources of uncertainty.

3. Results

3.1. Projected climate change

We first determined the projected changes of climate variables during the maize growing season using the ensemble of 22 GCMs under the four emission scenarios at the four study sites (Fig. 1). Mean temperature, rainfall, and solar radiation were projected to increase in both the 2050s and the 2080s compared with the baseline under all scenarios except the SSP370 emission scenario. All GCMs projected higher temperature under higher emission scenarios for all four sites. Mean temperature was projected to increase by 2.1 °C and 3.1 °C, respectively, in the 2050s and 2080s compared with the baseline across emission scenarios and GCMs. Moreover, higher variations of mean temperature changes were found under higher emission scenarios, as indicated by larger ranges of box plot whiskers. Similarly, growing season rainfall was projected to increase by 12.4% and 18.1% in the 2050s and the 2080s, respectively, compared with the baseline across emission scenarios and GCMs. The higher emission scenarios projected more rainfall than the lower emission scenarios at all four sites. Unlike the changes in temperature and rainfall, projected changes in growing season solar

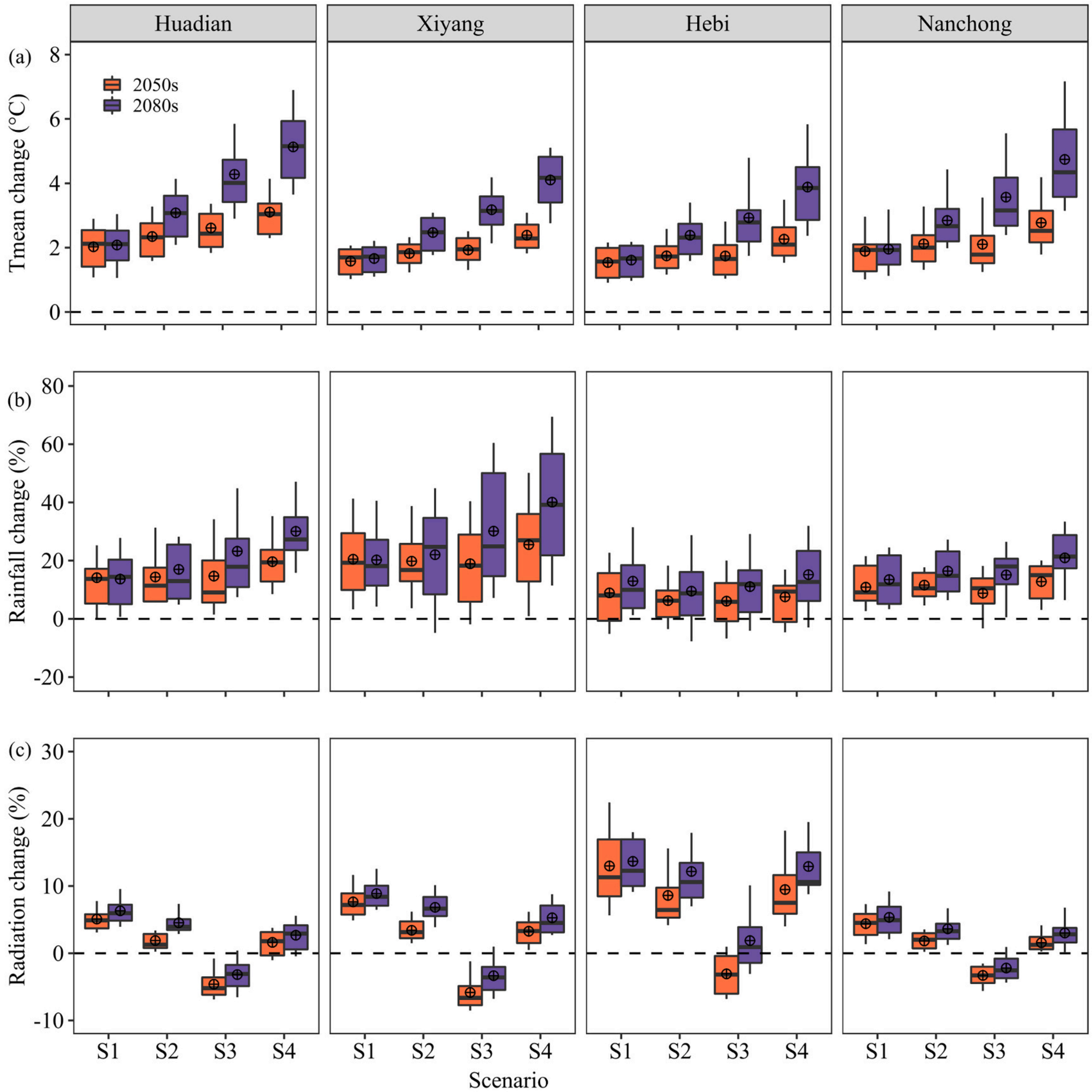

Fig. 1. Projected changes of climate variables during the maize growing season at four study sites in China's Maize Belt. a: projected mean temperature change (°C). b: projected rainfall change (%). c: projected solar radiation change (%). Projections were for the 2050s (2040–2069) and the 2080s (2070–2099) compared with the baseline (1980–2009). S1: SSP126, S2: SSP245, S3: SSP370, and S4: SSP585. Box boundaries indicate the 25th and 75th percentiles across 22 GCMs, and whiskers below and above the box indicate the 10th and 90th percentiles. The black lines and crosshairs within each box indicate the median and mean, respectively.

radiation did not show a consistent trend with emission scenarios. In the 2050s and 2080s, solar radiation was projected to decrease by 3.8% and 1.2% under the SSP370 scenario, but would increase by 5.3% and 7.6% under the other three scenarios.

3.2. Projected maize yield change

Next, we evaluated the impacts of climate change on maize yield simulated by three crop models (APSIM, DSSAT-CERES, and STICS). The projected rainfed yield changes under four emission scenarios are shown in Fig. 2. In general, there were large changes in projected maize yields at all four sites. Mean projected yield changes at Huadian, Xiyang, Hebi, and Nanchong were − 9.2%, 4.5%, 2.1%, and − 10.8%, respectively, in the 2050s, and − 16.8%, 5.6%, −0.9%, and − 13.1% in the 2080s across scenarios, GCMs, and crop models. There were larger projected yield decreases under higher emission scenarios (SSP370 and SSP585) than lower emission scenarios (SSP126 and SSP245) at Huadian, Hebi, and Nanchong. At Xiyang, there were large differences in projected yield change directions among the crop models. Specifically, maize yield was projected to increase by APSIM and STICS, but maize yield was projected to decrease by DSSAT-CERES at Xiyang.

To determine the key meteorological factors impacting maize yield in each model, we assessed the relationship between climatic variables (growth period temperature, rainfall, solar radiation, and yearly CO_2 concentration) and maize yield change (Fig. S4 and Table S1). In particular, rainfall and CO_2 concentration were the key factors resulting in the increase of maize yield for all three crop models. In contrast, rising temperature would reduce maize yields at most sites for most crop models, except at Huadian and Xiyang with STICS. Generally, the three models exhibited a consistent pattern in simulating climate change impacts.

3.3. Variation of adaptation potential by adjusting planting date and shifting cultivar

Given the projected yield loss in the future due to climate change, the adaptation by adjusting planting date (Fig. 3) and shifting cultivar (Fig. 4) was expected to improve maize yield in China's Maize Belt. By adjusting planting date, the single-crop planting regions (Huadian and Xiyang) would have larger adaptation potential than the double-crop

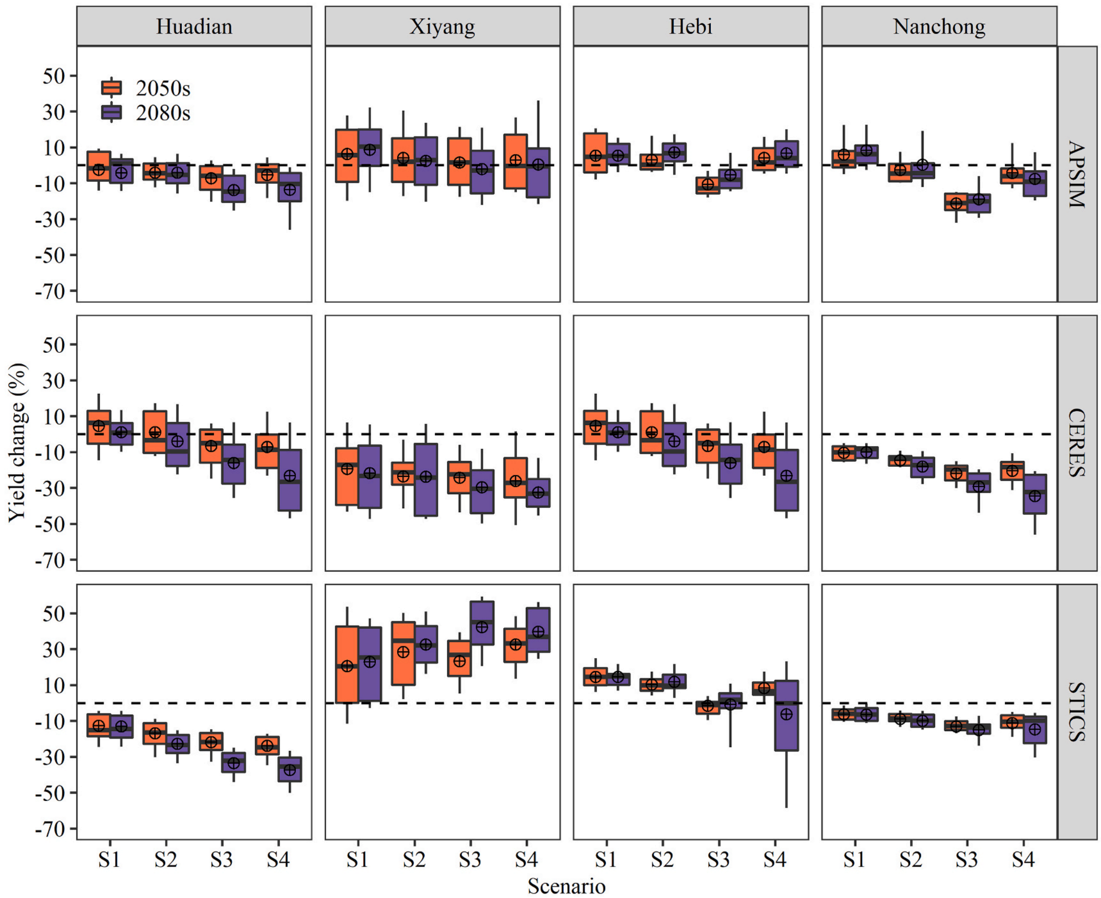

Fig. 2. Projected maize yield changes (%) at four study sites in China's Maize Belt. The yield change was projected by three crop models (APSIM, DSSAT-CERES, and STICS) driven by 22 GCMs and four emission scenarios (S1: SSP126, S2: SSP245, S3: SSP370, and S4: SSP585) in the 2050s (2040–2069) and the 2080s (2070–2099) compared with the baseline (1980–2009). Box boundaries indicate the 25th and 75th percentiles across 22 GCMs, and whiskers below and above the box indicate the 10th and 90th percentiles. The black lines and crosshairs within each box indicate the median and mean, respectively.

planting regions (Hebi and Nanchong). In particular, the model ensemble yield would increase by 11.2% at Huadian and 44.7% at Xiyang in the 2050s, and by 9.6% and 40.4%, respectively, in the 2080s. The model ensemble yields would only increase by 8.9% at Hebi and 2.2% at Nanchong in the 2050s, and by 16.3% and 1.9%, respectively, in the 2080s. The yield increase rate was higher under lower emission scenarios than under higher emission scenarios for the single-crop planting regions. DSSAT-CERES simulated a higher variation of projected maize yield than the other two models.

Shifting cultivar would increase maize yield significantly at all sites (Fig. 4). Specifically, model ensemble yield would increase by 59.9% at Huadian, 22.6% at Xiyang, and 30.2% at Nanchong in the 2050s, and by 68.3%, 33.8%, and 21.8%, respectively, in the 2080s. However, yield would increase only by 10.3% in the 2050s and 18.1% in the 2080s at Hebi. Similar to what was observed when planting date was adjusted, DSSAT-CERES simulated higher variation of projected maize yield than the other models in simulating adaptation potential of shifting cultivar.

Moreover, different crop models projected similar optimum planting dates, although the optimum planting dates varied among study sites (Fig. S5). Late planting was recommended at Huadian, Xiyang, and Nanchong, but early planting would result in greater yield at Hebi. However, different crop models projected contrasting cultivars (Fig. S6). DSSAT-CERES recommended later maturing cultivars than the other two models. Overall, adjusting planting date (Fig. S7) or shifting cultivar (Fig. S8) could maintain and even boost maize yields at the four sites under most emission scenarios. However, high adaptation potential was also accompanied by large yield variation, suggesting large uncertainty in simulating adaptation of maize to climate change.

3.4. Sources of uncertainty in simulating climate adaptation

We assessed the contributions of emission scenarios, GCMs, crop models, gradients of adaptation options, and their interactions to the total uncertainty in simulating adaptation of maize at each site (Fig. 5). In simulating the adaptation of adjusting planting date, GCMs were the major source of uncertainty at Huadian, Hebi, and Nanchong, with contribution rates of 36.7%, 23.1%, and 22.9%, respectively. At Xiyang, gradient of planting date was the largest source of uncertainty (32.4%). In simulating the adaptation of shifting cultivar, crop model was the largest source of uncertainty, accounting for 38.0%, 24.0%, and 30.4% of the total uncertainty at Xiyang, Hebi, and Nanchong, respectively. At Huadian, shifting cultivar contributed the largest uncertainty (34.0%) in simulated maize yield. The interaction of crop model and gradient of adaptation options at Huadian, GCMs at Xiyang, interaction of scenarios and GCMs at Hebi, and GCMs at Nanchong were also the important sources of uncertainty.

4. Discussion

4.1. Future climate change impacts on maize yield

In this study, we assessed the impact of future climate change on maize yield with three crop models using an ensemble of 22 GCMs under four different emission scenarios from CMIP6 at four contrasting sites across China's Maize Belt. Our results showed that maize yields at Huadian and Nanchong would decrease consistently among GCMs, crop models, and emission scenarios due to shortened maize growth period as

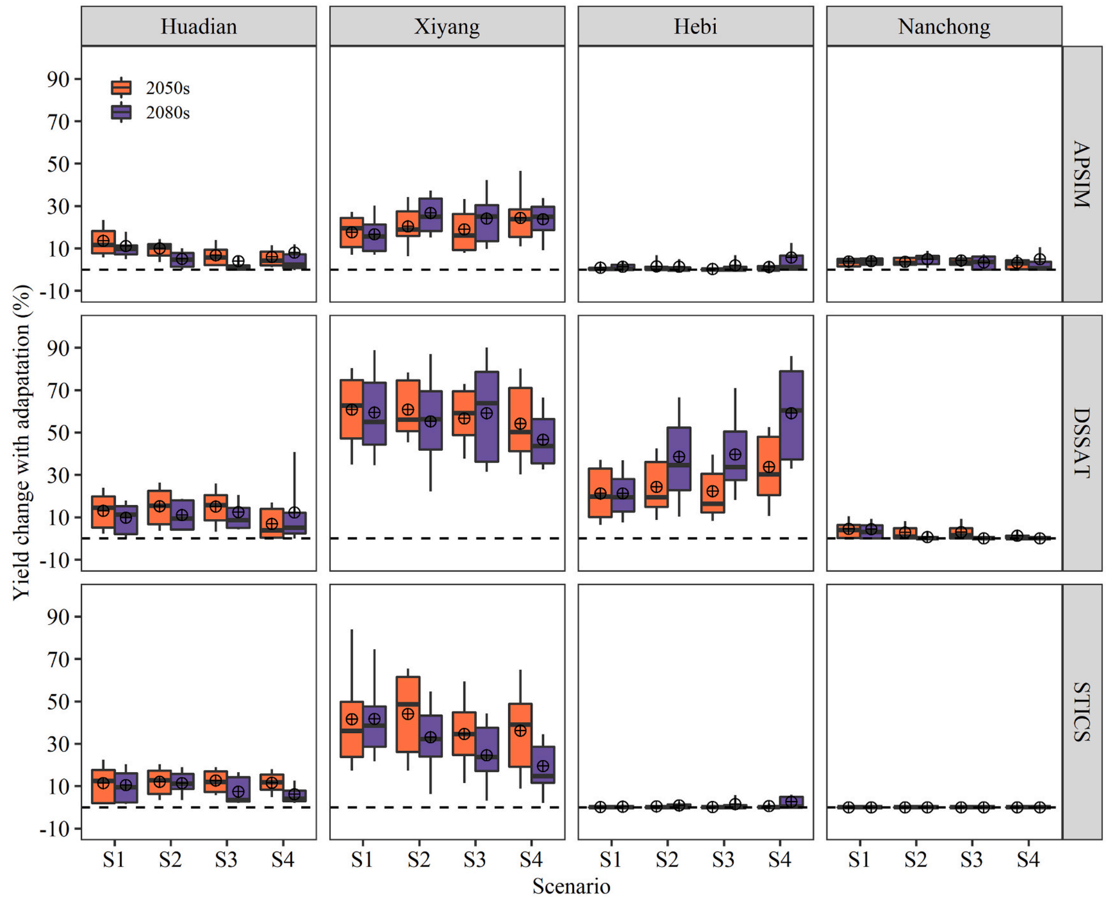

Fig. 3. Yield change from normal to optimum planting dates at four study sites across China's Maize Belt. The yield change was projected by three models (APSIM, DSSAT-CERES, and STICS) and 22 GCMs under four emission scenarios (S1: SSP126, S2: SSP245, S3: SSP 370, and S4: SSP585) in the 2050s (2040–2069) and the 2080s (2070–2099). Box boundaries indicate the 25th and 75th percentiles across 22 GCMs, and whiskers below and above the box indicate the 10th and 90th percentiles. The black lines and crosshairs within each box indicate the median and mean, respectively.

a result of rising temperatures (Figs. 2 and S4). The results were consistent with a previous study using CERES-Maize driven by one GCM under different emission scenarios released by CMIP5 (Tao and Zhang, 2010). Maize yields at Hebi increased under the two low emission scenarios (SSP126 and SSP245) as a result of increased growth period rainfall, but decreased under the two high emission scenarios (SSP370 and SSP585) due to rising temperature. Lin et al. (2017) also found that maize yield would decrease under a high emission scenario with a greater temperature increase. However, at Xiyang, different crop models projected varied yield change direction regardless of emission scenarios and time period; e.g., increase for STICS, decrease for DSSAT-CERES, and no significant change for APSIM (Fig. 2). Guan et al. (2017) also found different results with different crop models in projecting sorghum yield in West Africa. The difference in simulated yield change among models is likely due to the differences in how crop models simulate the responses of maize growth and development to rising temperature (Asseng et al., 2013; Bassu et al., 2014).

4.2. Climate change adaptation potential across China's Maize Belt

We found adjusting planting date and shifting cultivar could boost maize yields at the four study sites. Similar results were reported in China's Maize Belt under warming 1.5 and 2 °C scenarios (Huang et al., 2020; Zhang et al., 2020). This was mainly a result of adaptations not only offsetting the negative impacts of climate change on maize (Table S17), but also a result of adaptations making full use of the positive impacts on maize growth of lengthening growing season due to climate warming (Rahimi-Moghaddam et al., 2018; Lv et al., 2019; Jiang et al., 2021). Adjusting planting date and shifting cultivar would increase yield more at high-latitude sites. This finding was consistent with the results reported by Zhang et al. (2020) that showed that adjusting planting date and changing cultivar would result in higher maize yield in China's Northwestern area. Our results showed that yield increases due to shifting cultivar (10.3%–68.3%) were similar to yield increases reported in previous studies (Zhao et al., 2015; Lv et al., 2019). In contrast, adjusting planting date would increase maize yield by 1.9%–44.7%, which is higher than reported by Zhang et al. (2020). This difference is likely because we optimized maize planting date for each site instead of using a fixed optimum planting date at a regional scale.

4.3. Uncertainty due to adjusting planting date

The variation of GCMs, emission scenarios, crop models, and adaptation options could result in great uncertainty in projecting crop yields. Previous studies mainly focused on the uncertainty in simulating climate change impacts on maize yield without adaptation (Asseng et al., 2013; Parkes et al., 2019). There have been only a few studies reporting uncertainties for projecting maize yield changes with adaptation (Waongo et al., 2015; Guan et al., 2017), but none of them quantified uncertainties from climate adaptations. In this study, we found there was a large uncertainty in simulating climate change adaptation (Figs. 3 and 4), regardless of the adaptation options.

We found that GCM was identified as a major source of uncertainty in simulating adaptation of adjusting planting date at Huadian, Hebi, and Nanchong. The large uncertainty from GCMs was associated with large variation in simulated growth period rainfall among the GCMs (Fig. S9a)

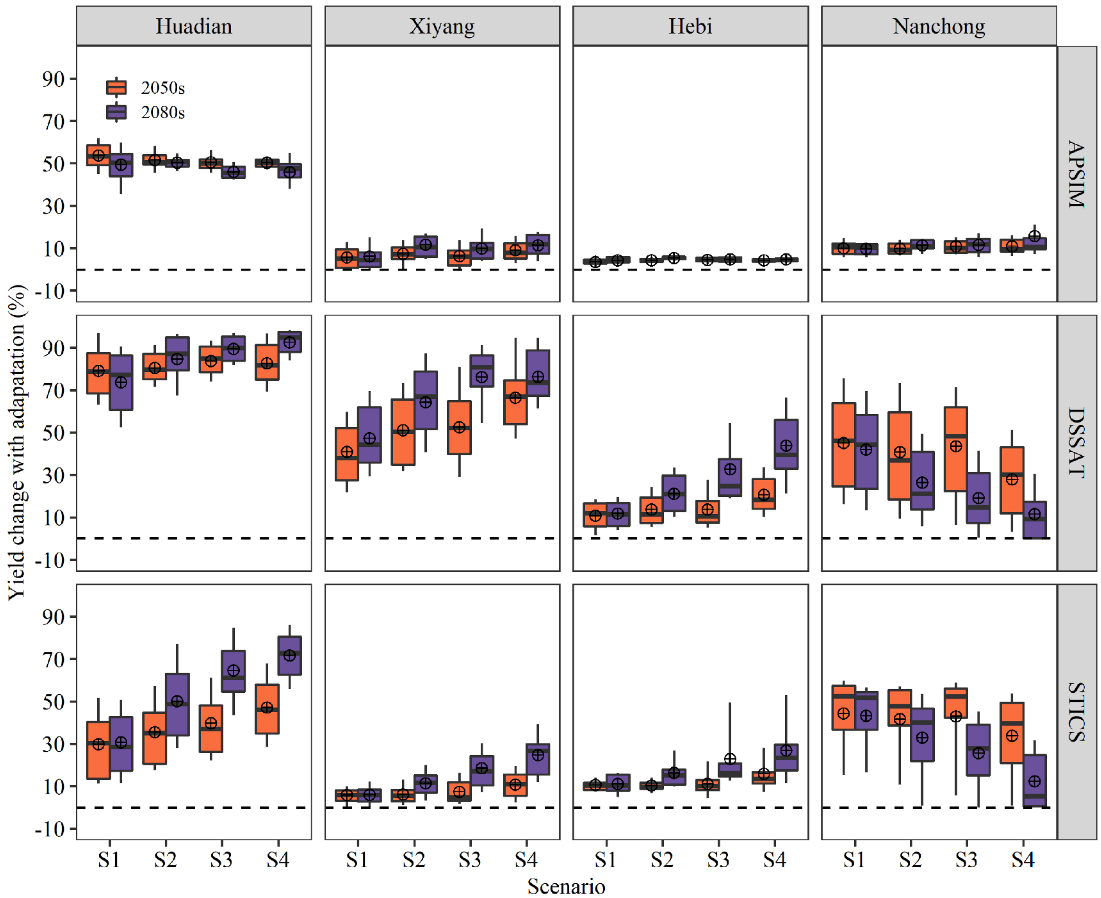

Fig. 4. Yield change from the actual cultivar to the cultivar with optimum thermal time at four study sites across China's Maize Belt. Yield change was projected by three crop models (APSIM, DSSAT-CERES, and STICS) driven by 22 GCMs under four emission scenarios (S1: SSP126, S2: SSP245, S3: SSP370, and S4: SSP585) in the 2050s (2040–2069) and the 2080s (2070–2099). Box boundaries indicate the 25th and 75th percentiles across 22 GCMs, and whiskers below and above the box indicate the 10th and 90th percentiles. The black lines and crosshairs within each box indicate the median and mean, respectively.

that had a great impact on projected maize yields (Fig. S7). Similar results have been reported in other climate impact assessment studies that did not consider adaptation options. Wang et al. (2020) found that GCM was the dominant uncertainty source in projecting Australia's wheat yield due to large variations in GCM-projected rainfall changes. However, it is worth noting that varied planting date was the primary source of total uncertainty at a high-altitude site Xiyang (Table S1). This was likely related to large difference in growing season temperature and rainfall across different planting dates (Fig. S9a and b). These results among sites suggest that the source of uncertainty in simulating adaptation potential of adjusting planting date depends on the local climate.

4.4. Uncertainty due to shifting cultivar

Our study found that crop model was the major source of uncertainty in simulating adaptation potential due to shifting cultivar at Xiyang, Hebi, and Nanchong. This was mainly due to differences in how physiological processes are modeled with different model structures used in the crop models, especially the response of maize development to temperature. Wang et al. (2015b, 2018b) found that there were large differences in simulating maize development in response to temperature among the crop models used widely over the world. We found that the response of maize yield to shifting cultivar has a large variance among crop models (Fig. 4). Similar results were reported by Bassu et al. (2014) who showed that different maize models had high uncertainty in simulating maturity date under high-temperature conditions. Improving the temperature response function by considering cardinal temperatures with clear biological meanings is likely to reduce uncertainty of yield simulation. For example, improving temperature response functions used in wheat models could reduce grain yield simulation error by 19%–50% (Wang et al., 2017). However, changing cultivar was the dominate source of uncertainty at a high-latitude site Huadian. We found this was because there are large differences in the total solar radiation of maize growth period across different cultivars (Fig. S10c). Similar to adjusting planting date, the dominant source of uncertainty in simulating adaptation potential of shifting cultivar also depends on the local climate.

4.5. Study limitations

Although a large amount of simulation work was conducted in our study, there are still some limitations. First, we only used three crop models to assess climate change impacts. A multi-model intercomparison showed that the ensemble mean from 23 models performed better in simulating climate change impacts on maize yields than any individual model (Bassu et al., 2014). More crop models are still needed to increase our confidence in simulating maize adaptation to climate change. Second, parameterization methods can also affect the projected yield (Tao et al., 2018). He et al. (2017) showed that different parameterization methods could achieve similar simulation accuracy with different sets of parameters. However, different genetic parameters are likely to cause differences in simulated yields under future climate change (Xiong et al., 2019). Third, our study only changed the thermal time in simulating the adaptation of shifting cultivar. Other important cultivar traits related to yield formation, such as grain filling rate and radiation use efficiency, were not included. It is thus necessary to investigate the potential of other cultivar genetic parameters to increase

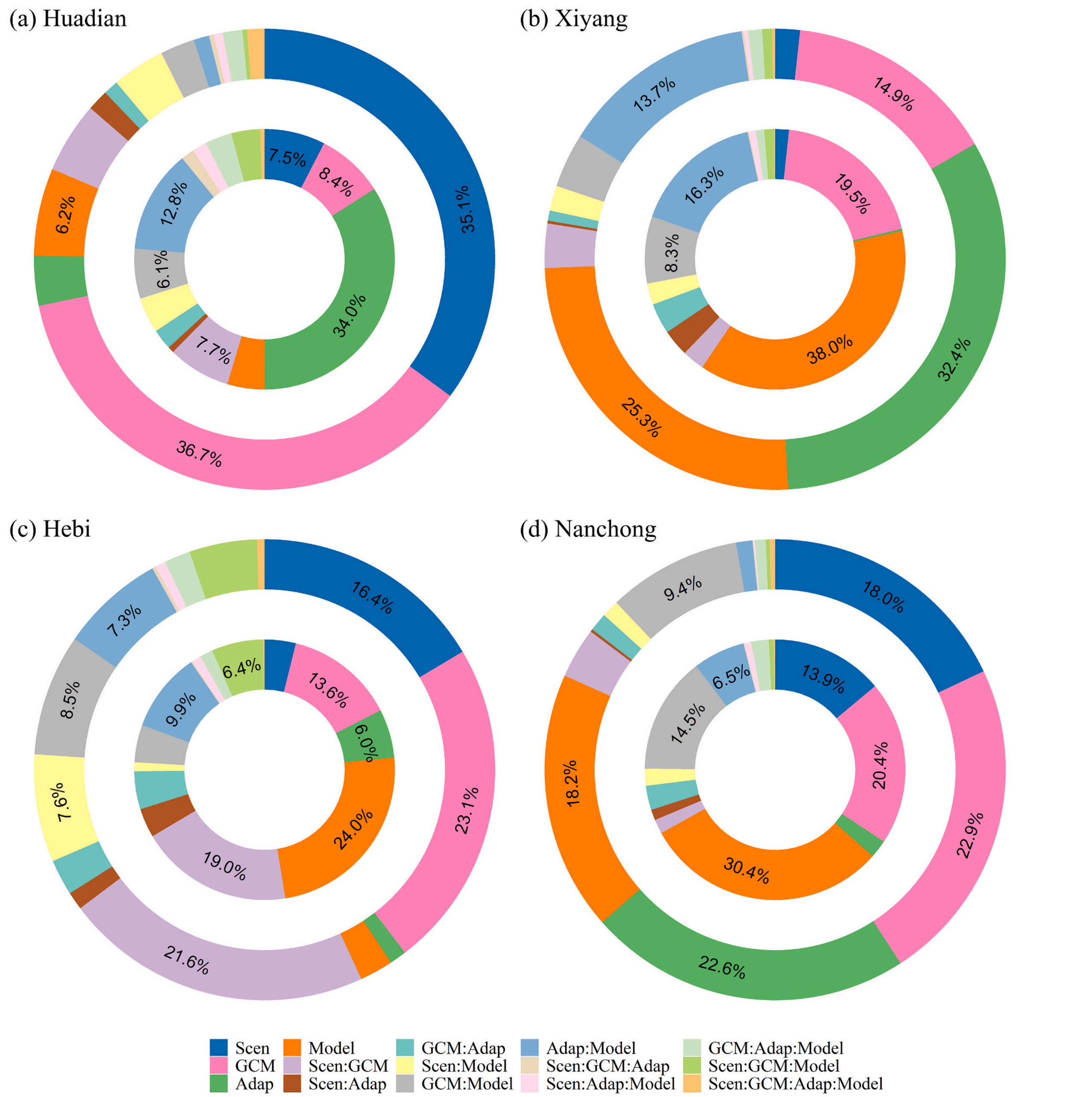

Fig. 5. Proportion of uncertainty in simulating adaptation of maize to climate change at four typical sites across China's Maize Belt. The sources of uncertainty were separated into scenarios (Scen, e.g., SSP126, SSP245, SSP370, and SSP585), GCMs, gradients of adaptation options (Adap), crop models (Model, e.g., APSIM, DSSAT-CERES, and STICS), and their interactions. The outer circle represents the uncertainty based on adjusting planting date; the inner circle represents the uncertainty based on shifting cultivar.

maize yield under climate change. In addition, other adaptation options such as changing planting density, irrigation, and fertilization rates were not considered in this study due to the computational burden (Ma et al., 2008).

5. Conclusions

There were no consistent results regarding the impacts of climate change on maize yield given that different crop models were used in this study. In other words, the direction and magnitude of yield change without adaptation options were specific to site, emission scenario, and crop model. When considering adaptation options, all three crop models identified that late planting would produce higher yields for the three sites with a longer planting window under future climate, while early planting was more appropriate for Hebi. All crop models showed that the cultivar with a greater thermal time requirement would result in higher yield under future climate. For the first time, we found that the dominant source of uncertainty in climate adaptation depended on adaptation type used. We advanced our understanding regarding the major source of uncertainty in crop yield when considering different climate adaptations. These findings are expected to provide new insights for assessing the potential of climate adaptation strategies with the climate-crop modeling approach.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103411.

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