The Effects of Climate Change on Maize Yield Potential over the Last 50 Years: A Case Study of Hebei Province, China

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Abstract: Studies on the impacts of climate change on crop yield are of great importance for ensuring food security. This study evaluated the impacts of climate change on summer maize yield potential for 1970 to 2019 for the low plain area of Hebei Province using a Hybrid Maize model applied to daily meteorological data. The effects of solar radiation, temperature, and precipitation on potential changes to maize grain yield were evaluated. Two climate scenarios were set to assess the relative contributions solar radiation and temperature changes on maize yield. The results showed a decline in maize yield potential of 7.5% from 14.6 t/hm^2 in the 1970s to 13.5 t/hm^2 in the 2010s, whereas solar radiation decreased by 6.6% from 2,007 MJ / m^2 to 1,874 MJ / m^2. There was an increasing trend in average temperature, with rates of 0.21 °C/10a and 0.44 °C/10a before and after maize silking, respectively, which resulted in shortening of the pre-silking and post-silking growth periods by 0.61 days/10a and 1.89 days/10a, respectively. The results showed no effect of rainfall on yield potential, whereas solar radiation and temperature showed significant positive correlations with yield potential. Scenario analysis showed that climate warming was responsible for 80.3% of the decrease in yield potential, far exceeding the contribution of solar radiation of 17.1% during the same period. The results of this study suggest that climate change may have a serious impact on crop yield potential in the low plains of Hebei Province.

1 INTRODUCTION

The role of climate change in food security challenges has increasingly attracted widespread attention (Yang et al., 2010; Lobell et al., 1980). The climate of the North China Plain has undergone significant changes since the 1970s (Wang et al., 2010), with a rate of warming exceeding national and Northern Hemisphere averages (Tan et al., 2009), whereas solar radiation intensity has generally declined during the same period (Li et al., 2012). Some studies have concluded that changes to maize yield in the North China Plain from the 1980s to the present can be attributed to a decline in solar radiation (Wang et al., 2014; Jia et al., 2020). Among the many studies on climate change since 1960s, Meng et al. (2020) evaluated the impacts on changes in solar radiation on maize production, showing that solar dimming has affected maize yield potential over the past 50 years. However, other studies have attributed changes in maize yield potential to warming under climate change, and not to decreasing radiation (Challinor et al., 2014; Schelenker and Lobell, 2010). Although there has been a lot of attention on the potential impacts of solar radiation and climate warming on crop yields, quantitative studies remain limited. Recent studies attributed the 17% drop in the yield potential of maize in the North China Plain from the 1960s to 2015 to a decline in solar radiation (Meng et al, 2020), whereas the 27% increase in the maize yield potential in the United States of America (USA) Corn Belt from 1984 to 2013 has been attributed to solar brightening (Tollenaar and Aguilera, 1992). The conflicting views on the reasons for changes in maize yield potential reflect the complex effects of climate change on crop growth and development among different regions. A targeted evaluation of the impact of climate change on maize yields of specific regions

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can be of great significance for sustainable agricultural production under climate change.

The Hybrid-Maize model is a corn growth model released by the University of Nebraska-Lincoln (Yang et al., 2004). This model was developed as a hybrid between existing generalized crop models such as the INTERCOM model and maize-specific models such as the CERES-Maize model (Yang et al., 2004; 2006). This Hybrid-Maize model is able to simulate both long-term and current season maize growth development and yield (Yang et al., 2006), and has been used in many studies to evaluate maize yield potential (Liu et al., 2008; Hou et al., 2013; Liu et al., 2015a), resilience of difference maize varieties (Li et al., 2016; Yang et al., 2017), ecological differences (Liu et al., 2015b; Bai and You, 2018), and the effects of agronomic management, such as irrigation and cultivation (Grassini et al., 2010; Bai et al., 2010). The model showed good performance when applied to the North China Plain, requiring model parameters such as growing degree-day (GDD), plant density, and sowing dates of suitable varieties to be well calibrated, and it was found that the yield potential of maize under different climatic conditions could be simulated (Bai, 2009).

The low-lying plain area of the North China Plain is an important summer maize producing area in China, with its maize output accounting for ~7% of the national total. The significant changes in climate of this region over the past few years (Shao et al., 2016) have emphasized the need to analyze the impact of climate change on the yield potential of maize in this region. Such a study can reveal the drivers of changes in maize yield potential and the impacts of climate change on food security. The aim of the present study was to apply the Hybrid-Maize model to analyze and explain changes in maize yield potential in the low plains of Hebei Province over the past 50 years. The results of the present study can provide support for sustainable agricultural production in the region under climate change.

2 STUDY AREA, MATERIALS, AND METHODS

2.1 The Study Area

The low plain area of Hebei Province occupies the central and southern parts of Hebei Province, mainly including the cities of Xingtai, Handan, Hengshui, and Cangzhou. A wheat and maize rotation system is the dominant cropping system in the region. Shenzhou County, Hengshui City, in the center of the study area, has a warm and semi-humid monsoon climate with an annual average temperature of 13.4 °C, annual precipitation of 481.7 mm, 200 annual frost-free days, 2,563 hours of annual total sunshine, total solar radiation of ~5,300 MJ/m^2, and an annual average wind speed of 2.1 m/s.

2.2 Maize Yield Model

The meteorological data for Shenzhou, Hebei Province used in the present study were obtained from the China Meteorological Agency. These data included daily maximum, minimum, and average temperature, precipitation, average wind speed, average relative humidity, and sunshine hours.

The Hybrid-Maize model requires daily solar radiation, temperature, Growing Degree Days (GDD) for different maize varieties, sowing date, and sowing density. The present study analyzed data for the Zhengdan 958 maize variety with a GDD set at 1,680 °C to ensure comparability of simulated maize yield potential for different years (Meng et al., 2020). The sowing date and plant density in the simulation were set to June 10 and 60 × 10^3 plants/ha, respectively. Maize yield, accumulated solar radiation, and average temperature before and after maize flowering of each year were simulated to analyze potential changes to maize yield potential.

2.3 Maize Yield Simulation

The Hybrid-Maize model simulation results were imported into Microsoft Excel 2007 for statistical analyses and graphing. Linear regression was used to analyze trends in stimulated grain yield potential, solar radiation, temperature, and precipitation from 1970 to 2019.

Two climate scenarios were established within simulation by the Hybrid-Maize model: (1) Scenario 1 represented a scenario of constant solar radiation and measured temperature data from 1970-2019; however, daily solar radiation was set to the value in 1970 to assess the effect of temperature on maize yield. (2) Scenario 2 represented a scenario of constant temperature and measured solar radiation; however, daily temperatures were set to those of 1970 to assess the effect of radiation on changes to yield. The contributions rates (CR) of temperature and radiation to changes in maize yield potential were calculated as:

$$CR_T = Y_{temp} / Y_{actual} \times 100\% \quad (1)$$

$$CR_R = Y_{radiation} / Y_{actual} \times 100\% \quad (2)$$

where Y_{temp} and $Y_{radiation}$ are the changes in yield potential resulting from changes in temperature and radiation, respectively, and Yactual is the change in yield potential resulting from climate change.

3 RESULTS

3.1 Impact of Climate Change on Summer Maize Yield Potential over the Last 50 Years

As shown in Figure 1, there was a fluctuating downward trend in summer maize yield from 1970 to 2019. The ten-year average summer maize yields for 1970-1979, 1980-1989, 1990-1999, 2000-2009, and 2010-2019 were 14.6, 15.3, 13.7, 13.6, and 13.5 t/hm2, respectively, showing a slight increasing trend in 1970-1990, followed by a rapidly decreasing trend in 1990-2000. Summer maize yield from 1970-1979 exceeded that in 2010-2019 by 7.5%. The results indicated a significant impact of climate change on the yield potential of summer maize in the low plains of Hebei Province, with a particularly obvious decline in yield potential since 1990 (Figure 1).

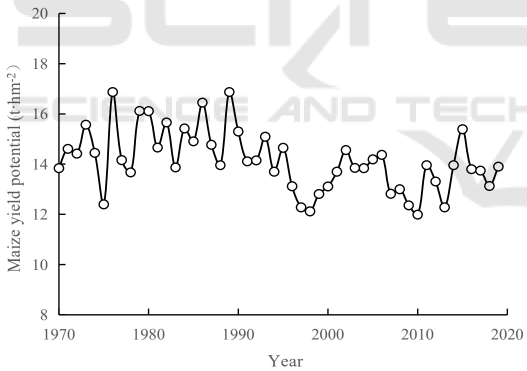

Figure 1: Changes in summer maize yield potential in the low plains of Hebei Province from 1970 to 2019.

3.2 The Effects of Climate Change on Maize Yield Potential

3.2.1 The Impacts of Solar Radiation on Maize Yield Potential during the Growth Period

There was a decreasing trend in total solar radiation during the summer maize growth period from 1970 to 2019 (Figure 2A). Ten-year average total solar radiation decreased by 6.6% from 2,007 Mj/m^2 in 1970-1979 to 1,874 Mj/m^2 in 2010-2019. The yield potential of summer maize decreased by 0.67 t/hm^2 for every 100 Mj/m^2 decrease in total solar radiation (Figure 2B). This result suggested the decrease in total solar radiation has had a significant impact on maize yield potential over the last 50 years.

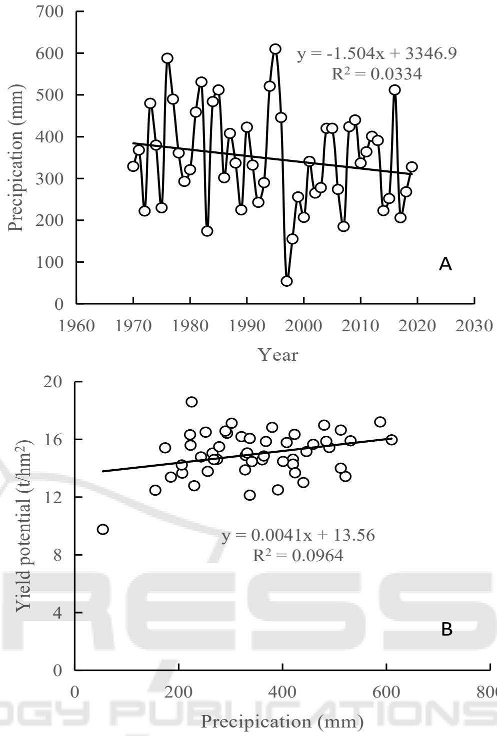

Figure 2: Variation in total solar radiation during the growth period of maize (A) and its impact on yield potential (B) in the low plains of Hebei Province from 1970 to 2019.

3.2.2 The Effects of Temperature Variation on the Yield of Summer Maize during the Growth Period

As shown in Figure 3A & B, there were significant increases in the maximum, minimum, and average temperature during the summer maize growth season. There were also significant increases in average temperature before and after silking 0.21 ℃/10a and 0.44 ℃/10a, over the last 50 years, respectively (Figure 3C). The increases in temperature had significant impacts on the maize growth and development process, mainly manifested as an accelerated and shortened maize growth process. There were significant decreases in the lengths of maize over the pre-silk and post-silk growth stages of 0.61 d/10a and 1.89 d/10a, respectively (Figure 3D).

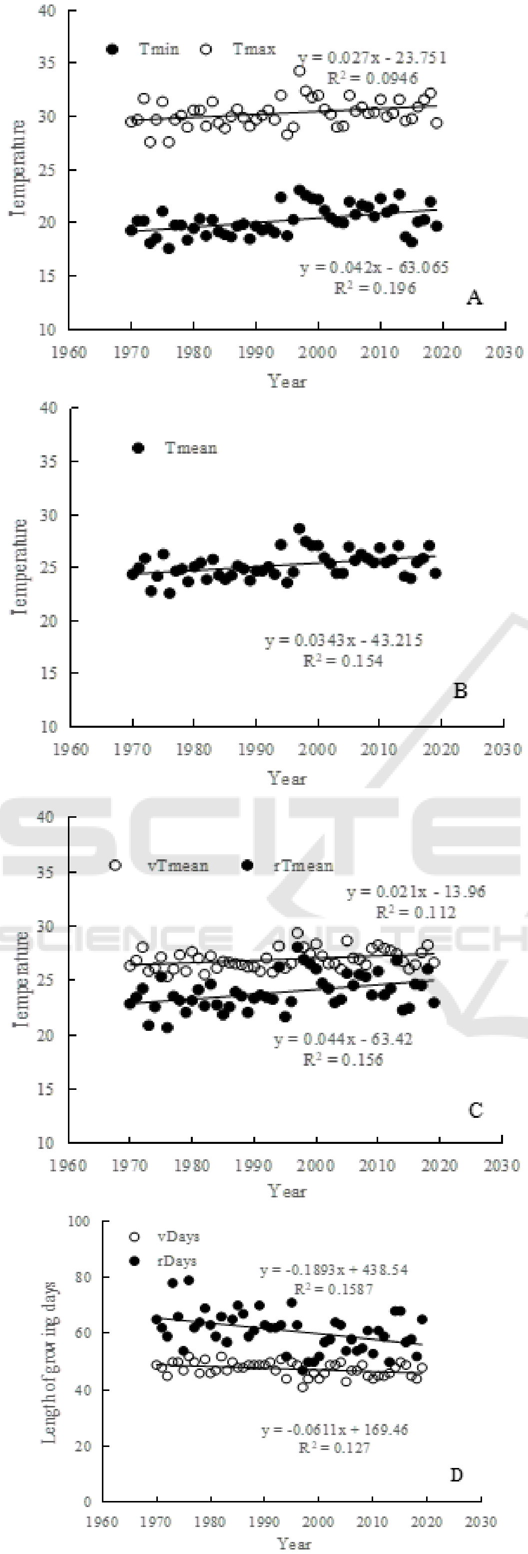

Figure 3: Changes in the maximum (A), minimum (B), and the average temperature (C) and the average lengths of pre- and post-silking maize over the growth period (D) in the low plains of Hebei Province from 1970 to 2019.

Further study showed significant inverse linear relationships between simulated yield potential of summer maize and maximum (A), minimum (B), and average temperature from maize emergence to silking (C) and from silking to maturity (D) (Figure 4). The yield potential of summer maize decreased by 0.713 t/hm^2 and 0.597 t/hm^2 for every 1 ℃ increase in maximum and minimum temperature, respectively, whereas the yield of maize decreased by 0.828 t/hm^2 and 0.569 t/hm^2 for every 1 ℃ increase in temperature from emergence to silking and from silking to maturity, respectively.

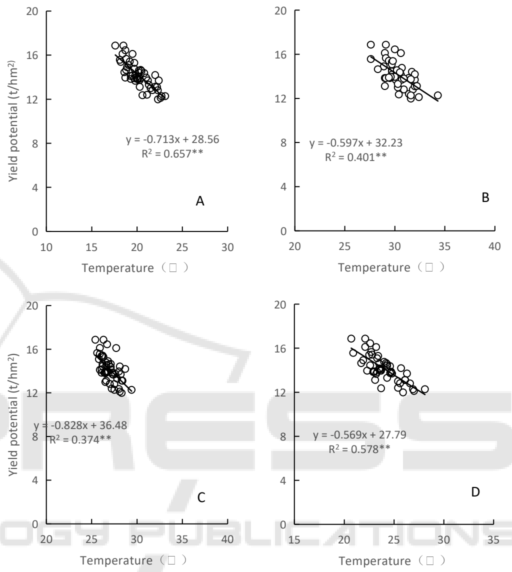

Figure 4: The effect of temperature on maize yield potential in the low plains of Hebei Province from 1970 to 2019 (A minimum temperature; B maximum temperature; C average temperature from emergence to silking stage; D average temperature from silking to maturity stage).

3.2.3 Impact of Climate Change on Rainfall and Yield Potential of Summer Maize

Rainfall over the summer maize growth period over the last 50 years has ranged from 83 to 618 mm (average of 353.7 mm) with a large yearly variation (coefficient of variation of 34.0%). There was a downward trend in overall rainfall (Figure 5A). There was no significant correlation between rainfall during the summer maize growth period and maize yield potential over the last 50 years (Figure 5B), indicating that rainfall was not the main driver of changes to maize yield potential.

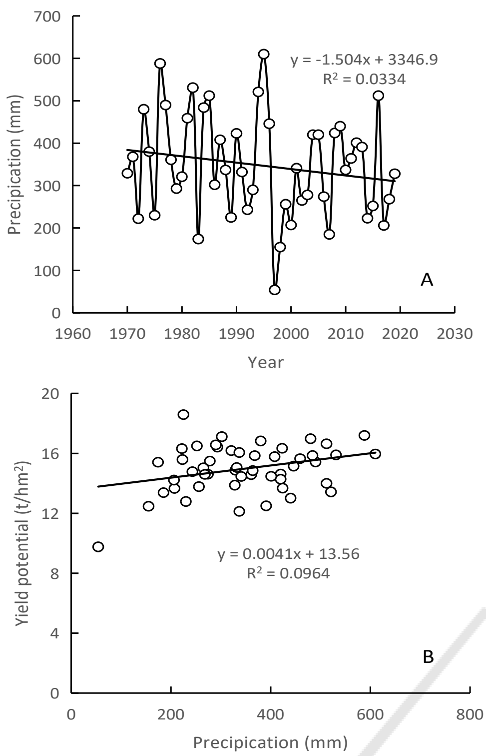

Figure 5: precipitation (A) and the effect of rainfall on maize yield potential (B) during the maize growth period in the low plains of Hebei Province from 1970 to 2019.

3.3 Scenario Analysis

The results of scenario analysis showed a decline in simulated maize yield potential under constant radiation by 0.306 t/hm^2/10a, whereas that under a constant temperature decreased by 0.065 t/hm^2/10a. The relative contributions of temperature rising to the yield potential decreasing was 80.3%, higher than the reduction caused by solar radiation of 17.1%. The increase in temperature significantly affected maize yield potential over the last 50 years.

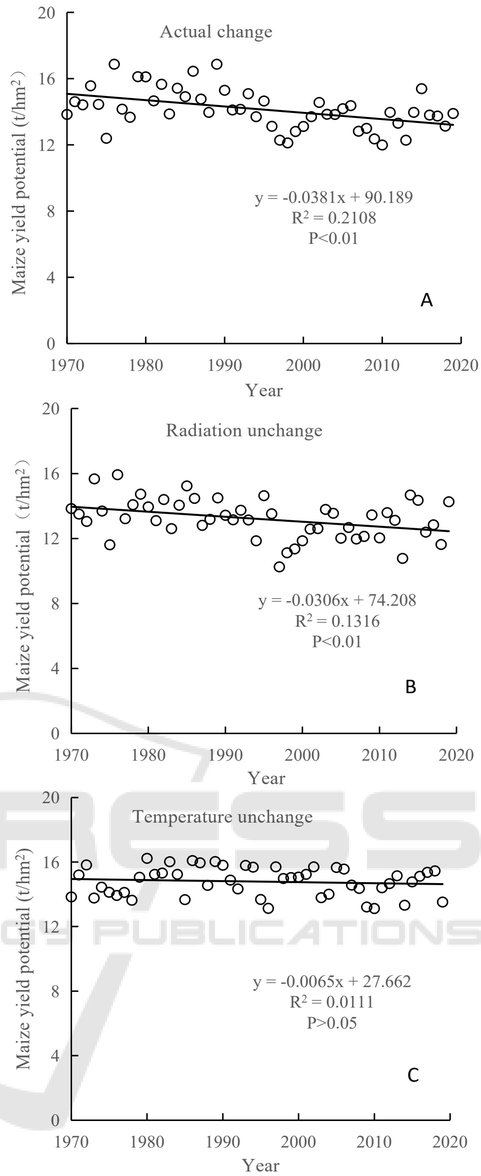

Figure 6: Maize yield potential in the low plains of Hebei Province from 1970 to 2019 under actual climate change (A), constant radiation (B), and constant temperature (C).

4 DISCUSSION AND CONCLUSIONS

Changes to the climate over the last 50 years have had a significant impact on the yield potential of summer maize in the low plains of Hebei Province, with yield potential showing a fluctuating downward trend at a rate of 9.2%, exceeding the reduction in global average maize yield of 3.8% (Lobell and Burke, 2008), but lower that of 19% of the North China Plain

(Liu et al., 2015a). This result was consistent with the results of other studies applying the Hybrid-Maize model in the Xingtai (Wang et al., 2014) and Luancheng (Jia et al., 2020) areas in the piedmont plains of Hebei Province and the North China Plain (Du et al., 2017). The results of the present study showed a decline in the yield potential of summer maize at a rate of 0.381 t/hm^2/10a from 1970 to 2019, lower than the average rate of decline of 0.689 t/hm^2/10a in Henan Province (1961-2010) (Yu and Ma, 2015) and 0.84 t/hm^2/10a decline in Huanghuaihai (1962-2006) (Huang and Liu, 2011). The differences in the rates of decline of maize yield potential among different studies can be related to differences in time series and spatial location of meteorological data used.

The results of the present study showed that the main meteorological factors affecting the yield potential of summer maize were changes in total solar radiation and the increase in temperature during the growth period, with relative contributions to the total decrease in maize yield of 17.6% and 80.3%, respectively. High temperature during the maize growth period was the main factor decreasing potential maize yield, contributing 80.3% to the loss in yield, far exceeding that in Xingtai (Wang et al., 2014) and Luancheng (Jia et al., 2020) of 30% and 20%, respectively, and showing that climate change can greatly affect maize yield potential.

The durations and timings of various growth phases have a large impact on maize yield (Wang et al., 2014). Average temperature increased by about 1.7℃ over the past 50 years, with the temperatures before and after maize silking increasing by 1.05 ℃ and 2.2 ℃ on average, respectively. The trend of increasing warming resulted in early flowering and maturity (Xiao et al., 2015) and a shortening of the maize growth period, and particularly reproductive growth, which in turn reduced the duration available for carbohydrates to transfer to maize yield, thereby reducing maize yield potential (Tao and Zhang, 2010; Challinor et al., 2014). The results showed that the durations of the summer maize growth, silking, and silking-harvest periods were shortened by ~2.5 d/10a (Figure 7), 0.61 d/10a, and 1.89 d/10a, respectively. The reduction in the maize growth period due to a warming climate may be the primary driver of the decline in maize potential yield in this region.

The reduction in solar radiation was an additional factor affecting the yield potential of maize in this area. A previous study identified average reductions in total solar radiation during the maize growth period of > 10%/10a and 3.3%/10a for the 2010s and 1970s, respectively (Zhang, 2013). Yang et al. (2018) identified a decrease in total solar radiation in the maize growing season from 2011 to 2015 of 16.2% compared to that from 1961 to 1980. Many factors can impact the intensity of solar radiation, among which the decrease in solar radiation may be related to the increase in the concentration of atmospheric particulate matter in the air (Ruckstuhl et al., 2008). The study by Meng et al. (Meng et al., 2020) suggested that the reduction in total solar radiation during the summer maize growth period in the North China Plain may be related to the increase of atmospheric PM2.5 concentration. Every 10 ug/m^3 increase in PM2.5 results in a reduction in radiation and total solar radiation during the maize growth period of 55 MJ/m^2 and 17%, respectively. The reduction in total solar radiation affected maize photosynthesis and reduced the synthesis of carbohydrate synthesis, thereby constituting another main driver of the decrease in maize yield potential.

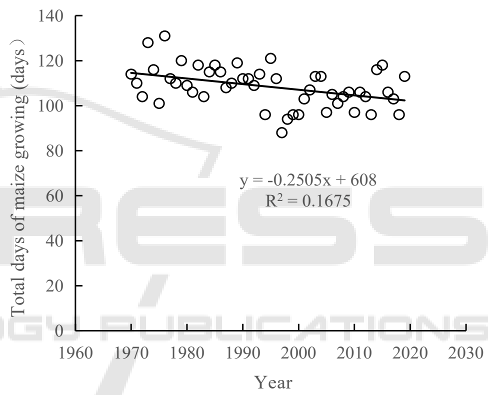

Figure 7: Variation in the summer maize growth period in the low plains of Hebei Province from 1970 to 2019 as simulated by the Hybrid-Maize mode.

In 1970-1990, the solar radiation had the trend of slightly increasing, which lead to the maize yield potential slightly increased. Then in 1990-2000, the continuous temperature rising and solar dimming happened in those years significantly decreased the maize grain yield. Scenario analysis showed that 80.3 % of the reduction in summer maize yield potential over the past 50 years can be attributed to increased temperature, and an additional 17.1% to decreased solar radiation. Climate warming was the main factor affecting the reduction in maize potential yield. This result was consistent with those of relevant international studies (Challinor et al., 2014; Schelenker and Lobell, 2010), but inconsistent with many domestic studies (Meng et al., 2020; Yang et al., 2018). The present study was limited by using data from a single weather station. Therefore, further research is needed to identify the factors with greater impacts on maize productivity at larger scales.

Measures that can be taken to mitigate the climate warming-induced reduction in maize yield potential include selection of maize varieties with longer growth periods, adjustment of sowing dates and densities, and improvement of agronomic measures such as tillage, fertilization, and irrigation (Tollenaar and Aguilera, 1992; Li et al., 2016; Yang et al., 2017; Liu et al., 2015a). The use of maize varieties with longer growth periods can prolong the maize post-flowering stage and increase the filling stage, thereby increasing maize yield (Tao and Zhang, 2010; Wheeler et al., 2000; Zhang et al., 2008). In addition, optimization of management measures such as tillage, fertilization and irrigation, suitable sowing date, and density (Liu et al., 2015a; Li et al., 2016) are mature and feasible technical solutions for reducing the impact of climate change on maize yield.

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