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Thermal Time Requirements for Maize Growth in Northeast China and Their Effects on Yield and Water Supply under Climate Change Conditions

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Abstract: Northeast China (NEC) is a region sensitive to climate change. However, the adoption of long-season maize cultivars in NEC has caused a substantial yield increase under climate change conditions. It is important to determine whether such cultivar adoptions are effective throughout the whole NEC to sustainably increase grain yield. In this study, phenological observations and meteorological data at six sites from 1981 to 2018 were used to detect thermal time (TT) trends during the maize growing period. TT, as a parameter for measuring changes in maize cultivars, was used in the crop simulation model CERES-Maize to examine the variations in maize yield produced with different cultivar \times climate combinations in different decades. In NEC, both TTs from emergence to anthesis and from anthesis to physiological maturity showed significant increasing trends from 1981 to 2018. Simulation results for humid areas revealed that adopting longer-season cultivars during 2000–2018 caused yield increases, ranging from 6.3% to 13.3%, compared with the 1980s. However, for stations in semi-humid areas, maize grain yield showed a decrease or a small increase (from -12.7% to 8.0%) when longer-season cultivars were adopted during 2000-2018. For semi-humid areas, decreasing trends in the ratios of rainfed yield to no water-stress yield ($Y_{rainfed}/Y_{no water-stress}$) and lower $Y_{rainfed}/Y_{no water-stress}$ values during 2000–2018 indicated a growing sensitivity of maize production to water, which was attributed to changes in TT and precipitation. Our results indicate that, for the semi-humid area, maize yield was limited by water after introducing cultivars with higher TT requirement under climate change conditions. Therefore, securing food supplies will depend on increases in water-use efficiency levels and other adaptive strategies, such as varietal diversification, drought-resistant varieties, conservation tillage and irrigation.

Keywords: climate change; crop simulation model CERES-Maize; thermal time; water scarcity; grain yield

1. Introduction

Northeast China (NEC) (Heilongjiang, Jilin and Liaoning provinces) is the most important and largest rain-fed maize production region in China, and the grain production of maize in NEC accounts for 30% of the nation's total [1,2]. Generally, the maize growing season in NEC extends from May to September, and maize production has mainly been conducted under rain-fed conditions. From 1961 to 2017, NEC has experienced a warming trend in surface average air temperature equal to 0.31 °C per decade, which is higher than the average value of all of China during the same period, and the value of the whole world during the past 50 years [3]. This indicates that NEC is a region sensitive to climate change [3]. In addition, annual total precipitation and rainfall days experienced decreasing trends of 0.52% per decade and 2.44 days per decade, respectively. Consequently, drought



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). risk is a main limiting factor of maize production in NEC [2]. Moreover, most areas in NEC show future drying trends during the middle and late maize growth stages (from June to September) [4].

Progressive climate change is expected to negatively affect agricultural production [5–7]. If maize genotypes and management practices are fixed, then climate change (warmer temperatures and a decrease or seasonal redistribution of precipitation) induces reductions in crop season duration, and thus, yield (warmer climates accelerate crop development and reduce the length of the growing period) [8–11]. However, the actual yields in NEC showed a tendency to increase by 1.27 metric tons (t) per hectare (ha) per decade from 1961 to 2010 [12]. The negative effects of climate warming on maize yield appear to have been reversed by changing the sowing date and adopting longer-season cultivars in NEC [2,13]. Baum's results confirmed that changes in cultivar relative maturity or sowing date across the landscape can mitigate anticipated climate impacts [14].

Additionally, modern breeding has increased ear fertility and grain-filling rate, as well as delayed leaf senescence, without modifying the net photosynthetic rate [15,16]. Specifically, the adoption of longer-season cultivars caused a substantial increase in maize yield from 6.5% to 43.7% during 1981–2007 in NEC [1,13]. In addition, for each extra day of the extended growing season, the spring maize grain yield increased by 75.2 kg/ha [13]. However, the longer growth period of these maize cultivars also results in a greater water requirement [9].

In the Chinese Maize Belt, the sensitivity of maize production to water has increased, and water scarcity in China remains a serious problem [9]. In midwestern USA, lengthening the maize maturation time is not a widespread climate change-related adaptive strategy, and hybrid maturation times were shorter in fact in the majority of the region during 2000–2017 owing to production-related factors, such as decreasing grain drying costs and labor constraints [17]. In Europe, shorter-maturing oat varieties have been preferred in response to climate change because of concerns about late-season droughts [18]. Thus, in areas prone to precipitation shortages or heat stresses, shortening the hybrid maturation period may be a risk-averse strategy [17]. However, in China, would the adoption of longer-season cultivars be an effective strategy for the whole NEC to sustainably increase grain yield? Would this increase the susceptibility of yields to water scarcity and adverse weather in NEC?

In this study, we focused on the relationship between the increased demand for water and water availability during maize production in NEC. The CERES-Maize model has proven to be an effective tool to estimate maize production under many kinds of environment [19–22]. Therefore, we used the CERES-Maize model to simulate rainfed yields and no water-stress yields of different cultivars planted under different climatic conditions, which would help to address the problem that how to increase maize yields sustainably in NEC. On the basis of the precipitation requirement (446–460 mm) during the maize growing season to meet yield potential without irrigation, the NEC was divided into two areas, humid (450 mm \leq precipitation during maize growing season < 600 mm) and semi-humid (300 mm \leq precipitation during maize growing season < 450 mm). The objectives of this study were to (i) identify changes in the thermal requirements of maize cultivars and (ii) quantify the effects of cultivar shifts on maize yield and water available over the past 38 years in NEC.

2. Materials and Methods

2.1. Study Sites

In this study, six agrometeorological experimental stations for maize in northeast China (NEC) were selected on the basis of their representative climate and the completeness of the phonological data from 1981 to 2018. The sites were Tailai (46.4° N, 123.42° E) and Bayan (46.08° N, 127.35° E) in Heilongjiang province, Baicheng (45.63° N, 122.83° E) and Dunhua (43.37° N, 128.2° E) in Jinlin province, and Fuxin (42.07° N, 121.75° E) and Changtu



(42.78° N, 124.12° E) in Liaoning province (Figure 1). These sites are also members of the national meteorological networks of the China Meteorological Administration.

Figure 1. The locations selected for simulation of maize yield in Northeast China (NEC). Solid circles indicate locations used for simulating yield (names are shown in regular font). Lines show provincial boundaries. Province names are in italics. The left figure is a map of China that indicates the location of NEC.

2.2. Climatic, Biological and Soil Data

Climatic data, including the daily mean, maximum and minimum temperatures, daily sunshine hours and daily precipitation, were collected from 1980 to 2018 at each station. Sunshine duration was converted into daily solar radiation using the Ångström formula [23,24]. The experimental data on maize phenology (sowing, emergence, anthesis and physiological maturity dates) were obtained from local agrometeorological experimental stations in NEC. For each station and each year, the accumulated thermal times (TTs) (expressed in degree days above a base temperature of 8 °C) from emergence to anthesis and from anthesis to physiological maturity were calculated. The soil data used in this study included soil texture, bulk density, saturated volumetric water content, drained upper limit and field water capacity in different soil layers. These data were also obtained from the agrometeorological experimental stations.

2.3. Crop Modeling and Simulation

The CERES-Maize model simulates maize yield under both rainfed and no water-stress conditions [25,26]. The model has performed well in a variety of regions in China [27–29]. In this study, we relied on a calibrated model from a prior report [28]. To simulate grain yield, the CERES-Maize model requires the input of daily solar radiation, maximum and minimum temperatures and precipitation. Other model inputs included the date of planting and plant population density. In this study, the real sowing dates for varieties used in the 1980s and 2000–2018, as well as plant population densities (44,800 plants/ha at all stations), were used in the simulations for both rainfed and no water-stress maize with varieties from the 1980s and 2000–2018. The change in atmospheric CO_2 level since the 1980s was not taken into account in the simulation. For each station, model parameter TT from seedling emergence to the end of the juvenile phase (P1, expressed in degree days above a base temperature of 8 °C) was calibrated by comparing the simulated anthesis date with the observed date using the trial-and-error method. In the simulation, the P1 values averaged during the 1980s and 2000–2018 for each station were used as parameter values

(Table 1). In addition, averages of TTs from anthesis to physiology maturity during the 1980s and 2000–2018 were used as TTs from silking to physiological maturity (P5, expressed in degree days above a base temperature of $8 \,^{\circ}$ C) for the crop model simulation (Table 1).

Table 1. Parameters P1 and P5 in the CERES-Maize model during the 1980s and 2000–2018 for the six stations.

| Time | Parameter | Fuxin | Changtu | Baicheng | Dunhua | Tailai | Bayan |
|-----------|-----------|-------|---------|----------|--------|--------|-------|
| 1980s | P1 | 310 | 310 | 265 | 200 | 240 | 220 |
| | P5 | 780 | 762 | 664 | 459 | 637 | 572 |
| 2000s | P1 | 320 | 335 | 295 | 315 | 290 | 270 |
| | P5 | 795 | 809 | 760 | 545 | 721 | 621 |
| 2011-2018 | Р1 | 320 | 335 | 300 | 315 | 290 | 270 |
| | Р5 | 821 | 858 | 810 | 565 | 726 | 641 |

We used the CERES-Maize model to relate yield outcomes to weather realizations using a scenario in which varieties were constant. Thus, the same varieties used by farmers in the 1980s were used throughout the simulation. For the model simulation, grain yield under climate conditions during the 1980s, 2000s and 2011–2018 was the average of a 10-year or 8-year simulation incorporating weather data from 1981–1990, 2001–2010 and 2011–2018, respectively. $Y_{no water stress}$ simulations assumed that water inputs were non-limiting to eliminate the effects of water stresses on the simulated maize yield. Planting density, sowing depth and nutrient inputs (N, *p* and K were applied at 90, 60 and 46 kg/ha, respectively) were kept constant throughout the simulated years 1981–2018.

2.4. Data Analysis

A linear regression analysis was used to detect trends in TT from emergence to anthesis and from anthesis to physiological maturity. The slope of the linear regression line against time was evaluated using a *t*-test at the 95% or 99% confidence level. The following equations were used to examine the percentage of yield variation owing to the change of both varieties and climate.

$$PV1 = \frac{\text{grain yield of 2000s' varieties * 2000s' climate-grain yield of 1980s' varieties * 1980s' climate}{\text{grain yield of 1980s' varieties * 1980s' climate}}$$
(1)

$$PV2 = \frac{\text{grain yield of 2011-2018 varieties * 2011-2018 climate-grain yield of 1980s' varieties * 1980s' climate}{\text{grain yield of 1980s' varieties * 1980s' climate}}$$
(2)

The following equations were used to examine the percentage of yield variation owing to the change of climate.

$$PV3 = \frac{\text{grain yield of } 2011-2018 \text{ varieties } * 2011-2018 \text{ climate-grain yield of } 1980\text{s' varieties } * 2011-2018 \text{ climate}}{\text{grain yield of } 2011-2018 \text{ varieties } * 2011-2018 \text{ climate}}$$
(3)

 $PV4 = \frac{\text{grain yield of 2000s' varieties * 2000s' climate-grain yield of 1980s' varieties * 2000s' climate}{\text{grain yield of 2000s' varieties * 2000s' climate}}$ (4)

3. Results

3.1. Environmental Conditions and Trends in Thermal Time (TT) during the Maize Growing Period

The six stations selected in this study represent six different climatic regions, classified by average temperature and total precipitation during the maize growing season, representing regions with precipitation levels between 300 and 450 mm (semi-humid) and between 450 and 600 mm (humid) that have temperatures in the 16.0 to 22.0 °C range. More detailed information on the climate of each site is provided in Figure 2a,b and Table 2. The average temperature and total precipitation are presented using box plots, in which the box contains the middle 50% of the data, and the upper and lower edges of the box indicate the 75th and 25th percentiles of the data set, respectively. The median value is indicated by a horizontal line in the box. The upper and bottom lines of the diagram represent the values between the 10th and 90th percentiles, respectively.



Figure 2. Total precipitation (**a**) and average temperature (**b**) during maize growing season from 1981 to 2018 for the Dunhua, Bayan, Tailai, Baicheng, Chuangtu and Fuxin stations.

Table 2. The climatic regions classified by average temperature (T_{ave}) and total precipitation (p) during the maize growing season from 1981 to 2018 in Northeast China.

| | Dunhua | Bayan | Tailai | Baicheng | Changtu | Fuxin |
|----------------|-----------|-----------|-----------|-----------|-----------|-----------|
| T_{ave} (°C) | 16.0–17.5 | 17.6–19.5 | 19.0–20.5 | 19.0–20.5 | 19.6–21.0 | 20.6–22.0 |
| p (mm) | 451–600 | 451–600 | 300–450 | 300–450 | 451–600 | 300–450 |

Both thermal times (TTs) from emergence to anthesis and from anthesis to physiological maturity had similar increasing trends from 1981 to 2018. The TT from anthesis to physiological maturity had a larger magnitude than the TT from emergence to anthesis, with increases ranging from 18.9 to 52.0 °C days per decade for stations during the 1981 to 2018 period (Figure 3a–f). Therefore, the TT from anthesis to physiological maturity was 41–146 °C days greater by 2011–2018 than it was in the 1980s, which is equivalent to a 5–23% increase in the TT. Five of six stations, except Fuxin, experienced significant increases in the TTs from emergence to anthesis and from anthesis to physiological maturity. In Fuxin, the trend did not differ significantly from zero (Figure 3a).



Figure 3. Time series of the thermal times during the vegetative (open boxes) and reproductive (open circles) periods of maize at Fuxin (**a**), Changtu (**b**), Baicheng (**c**), Dunhua (**d**), Tailai (**e**), and Bayan (**f**) sites in Northeast China (NEC) from 1981 to 2018. Straight lines represent the linear regression lines against years. ** p < 0.01 and * p < 0.05.

3.2. Effects of Varietal Change on Maize Yield

Simulating the maize yields of 2000–2018 using the CERES-Maize model with varieties from the humid region stations (Changtu, Dunhua and Bayan) produced increases of 6.3–13.3% (Figure 4a,c,e calculated by Equations (1) and (2)) compared with varieties from the 1980s because the cultivars had higher TT requirements. For the semi-humid region stations (Fuxin, Baicheng and Tailai), compared with 1980s varieties, the maize yields of the 2000–2018 varieties ranged from -12.7% to 8.0% (Figure 4b,d,f, calculated by Equations (1) and (2)), although cultivars with higher TTs were used in maize production.



Figure 4. Simulated combined effects of variety (varieties planted in the 1980s and 2000–2018) and climate (climate in the 1980s and 2000–2018) on grain yields in humid region (**a**,**c**,**e**) and semi-humid region (**b**,**d**,**f**) stations. Error bars indicate standard deviations.

Maize yield of the 1980s varieties in the humid region stations decreased 9.6–35.7% (Figure 4a,c,e, calculated by Equation (3)) owing to climate change from the 1980s to 2011–2018. Similarly, if maize varieties had not changed since the 1980s, then the maize yields in the 2000s for the humid region stations would decrease 5.4–35.5% (Figure 4a,c,e, calculated by Equation (4)) compared with the maize yields of the 2000s varieties. For the semi-humid region stations, if maize varieties did not change since the 1980s, then maize yields in 2011–2018 would decrease 7.8–20.6% (Figure 4b,d,f, calculated by Equation (3))

compared with the maize yields of the 2011–2018 varieties. Additionally, if maize varieties did not change since the 1980s, then maize yields in the 2000s would decrease 1.8–11.0% compared with the maize yields of the 2000s varieties (Figure 4b,d,f, calculated by Equation (4)).

3.3. Rainfed Maize Yield Compared with No Water-Stress Maize Yield

To determine whether the gaps between no water-stress and rainfed maize yields in the humid and semi-humid regions are increasing, the ratios of rainfed yield to no water-stress yield ($Y_{rainfed}/Y_{no water-stress}$) were calculated for five combinations of three kinds of varieties and three climatic periods (Figure 5a–f). For the humid region stations, $Y_{rainfed}/Y_{no water-stress}$ was between 0.72 and 0.99 when varieties used in the 1980s were combined with climates from the 1980s. In the 2000s and 2011–2018, $Y_{rainfed}/Y_{no water-stress}$ remained constant (for Changtu) or decreased to 0.82–0.88 (Figure 5a,c,e). For the semihumid region stations, $Y_{rainfed}/Y_{no water-stress}$ was lower (0.72–0.79) than in humid region stations when varieties used in the 1980s were combined with climates from the 1980s. In the 2000s and 2011–2018, $Y_{rainfed}/Y_{no water-stress}$ decreased to 0.57–0.68 (Figure 5b,d,f).

 $Y_{\text{rainfed}}/Y_{\text{no water-stress}}$ when the 1980s varieties were combined with 2000s or 2011–2018 climates increased compared with $Y_{\text{rainfed}}/Y_{\text{no water-stress}}$ during the 2000s and 2011–2018 at all the region stations (Figure 5a–f). The increasing magnitude (0.11–0.20) for semi-humid region stations (Baicheng and Tailai) was greater than that (0.06–0.15) for humid region stations.

3.4. Correlating Thermal Time (TT) and Precipitation

Because at the semi-humid region stations (Fuxin, Baicheng and Tailai), compared with 1980s varieties, maize yields of the 2000s and 2011–2018 varieties decreased, to investigate correlations between TT and precipitation during the 1980s, 2000s and 2011–2018 for Fuxin, Baicheng and Tailai stations, accumulated TTs since maize emergence and the corresponding total precipitation were presented in Figure 6. For these three stations, the numbers of growing days (from emergence to physiological maturity) during the 2000s and 2011–2018 increased (2–20 d) compared with during the 1980s, whereas the available water decreased. The average rainfall for each day dropped from 2.8, 3.0 and 2.8 mm/day to 2.6, 1.8 and 2.1 mm/day for Fuxin, Baicheng and Tailai, respectively.



Figure 5. Ratios of simulated rainfed yield to no water-stress yield for combinations of variety (varieties planted in the 1980s and 2000–2018) and climate (climate in the 1980s and 2000–2018) for humid region (**a**,**c**,**e**) and semi-humid region (**b**,**d**,**f**) stations. Error bars indicate standard deviations.



Figure 6. The correlations between thermal time and precipitation during the 1980s and 2000–2018 at Fuxin (**A**), Baicheng (**B**), and Tailai (**C**) stations. The emergence dates at the Fuxin, Tailai and Baicheng stations were 12 May, 17 May and 19 May, respectively, which were averaged using the observed data. Thermal time from emergence (E) to physiological maturity (PM) showed as horizontal lines.

4. Discussion

To determine whether cultivar selection (adoption of cultivars with higher thermal time requirements) is a sustainable strategy to maintain or increase maize yield in northeast China (NEC), we divided the NEC into two areas to analyze the thermal time (TT) requirements for maize growth and their effects on yield and water supply under climate change conditions. Switching to late maturing cultivars may have increased the grain yield by 6.5–43.7% during 1981–2007 in NEC [2,13]. In this study, simulation results for humid areas indicated that the adoption of longer-season cultivars during the 2000s and 2011–2018 caused increases in yield ranging from 6.3% to 13.3% compared with the 1980s, which indicated a shift towards planting higher-yielding cultivars in these areas to take advantage of the resulting growing season extension and that water is not a limiting factor. The cultivars adopted during the 2000s and 2011–2018 have higher TT requirements, especially for the grain fill (calculated as the TT from flowering to maturity) period (Figure 3), which increases the length of time devoted to yield accumulation. Sacks and Kucharik [30] found a lengthening of the maize reproductive period from 1981 to 2005, which was attributed to the use of longer-season cultivars. Thus, the cultivars adopted during the 2000s and 2011–2018 more efficiently used the growing season in these areas. In the USA, an average lengthening of the grain filling period by 0.37 days per year has occurred as a result of variety renewal [31]. Moreover, statistical analyses suggest that a longer grain-filling period accounts for roughly one-quarter of the yield increase trend by promoting kernel dry matter accumulation [31].

Climate change induced reductions in crop duration, and thus, yield may be reversed by the planting of varieties that require more time to mature [1,13]. This was verified in humid areas of NEC, in which the longer growth periods of longer-maturing varieties also resulted in a greater water requirement. Whereas the study on water requirement of oat in north and northeast China indicated that the crop water requirement and irrigation demand presenting decreasing trends over past decades [32]. In fact, precipitation levels in 62% of NEC failed to meet the demands of longer-maturing varieties (445–460 mm during the maize growing season) [9]. Our studies confirmed these results. We found that for semi-humid areas, grain yield decreased or slightly increased (from-12.7% to 8.0%) when longer-season cultivars were adopted during the 2000s and 2011–2018. Compared with rainfed maize growing in semi-humid areas of NEC, winter wheat planted in north China showed an improved yield level and yield stability, which might be attributed to the development of agricultural technology (including irrigation) and breeding [33].

Generally, drought events caused maize yield reductions when they occurred later in the season (10–22%) or in the early season (5–17%) [34]. The decreasing rainfall (Figure 6) and the increasing demand for water are the main reasons for yield variations during the 2000s and 2011–2018 in semi-humid areas. Moreover, the decreasing yields during the 2000s and 2011–2018 may be attributed to the decreasing rainfall per day during the maize growing season. Undoubtedly, the adoption of longer-season cultivars contributed to maintaining the maize yield's stability because maize yield decreased (from 1.8% to 35.7%) if varieties were not changed since the 1980s (Figure 4). As water resources become increasingly scarce, especially under climate change conditions, increasing maize yields in semi-humid areas should not only depend on cultivar selection but also on increasing water-use efficiency [35,36]. The dry matter accumulation after silking and kernel weight are the key factors to increase water-use efficiency [37]. Other adaptive strategies can be adopted by farmers to cope with drought, including varietal diversification, drought-resistant varieties, soil tillage and irrigation [38]

During the past years, adaptation strategies against drought have been implemented in NEC [39]. The adoption of more than one maize variety (varietal diversification) was regarded as an effective way to mitigate the negative effects caused by drought and increase the maize yield stability, since different maize varieties vary in resilience to drought and hybrid maturity (longer maturity hybrids or shorter maturity hybrids), and households usually have several fields to grow maize. Furthermore, farmers that used more than one variety often adopted drought resistant varieties. In areas prone to precipitation shortages, shortening the hybrid maturity may be a risk-averse strategy [17,34]. If farmers used more than one variety, the maize yield was about 150 kg/ha higher than farmers who only planted one variety [38].

Generally, the genetic improvement in maize yield is associated with increased stress tolerance [40]. Drought tolerant hybrids consistently had 3–6% lower seasonal ET than conventional hybrids under water-limited conditions and less water extraction for drought tolerant hybrids were found during the vegetable stage [41]. Farmers that adopted drought resistant varieties had higher maize yield under dry conditions compared to that without using drought resistant varieties [42]. The adoption of drought resistant varieties led to maize yield increase by about 220 kg/ha [38]. For semi-humid areas of NEC, the potential for further maize yield improvement through increasing drought stress tolerance is very large, not only because of the frequent occurrence of drought [2], but also due to the larger yield gap between no water-stress and rainfed maize yields (Figure 5b,d,f).

The positive effects of conservation tillage and deep loosening tillage have been supported by many studies [38,43,44]. Conservation tillage was referred to tillage used in spring instead of rotary tillage, which mainly includes ploughing and no tillage. Tillage in autumn can help to improve soil water holding content capacity and reduce soil evaporation in spring [45]. The adoption of conservation tillage led to maize yield increase by 438–459 kg/ha [38]. However, less than 20% of farmers in NEC used either conservation tillage or deep loosening tillage in maize production. Whether the households have higher soil quality and whether they can receive technical support are two factors that affect the application of tillage practices [38].

Generally, irrigation is the most efficient adaptation measure to mitigate drought effects [7,46] In NEC, irrigation includes dibbling irrigation used to cope with drought in spring and irrigation adopted in both summer and autumn. Dibbling irrigation (seeding with irrigation to the seeds) is a traditional practice in NEC which is widely used in spring before maize sowing [38].Maize yield was highly correlated with the soil moisture content during planting date [47] and dibbling irrigation is an effective measure to adjust sowing soil moisture content. Therefore, dibbling irrigation can cope with drought by improving both water use efficiency and maize seeding emergence ratio [47,48]. Irrigation in summer and autumn can mitigate the negative effects of drought; the adoption of irrigation in summer and autumn led to maize yield increase by 419–435 and 444–463 kg/ha, respectively [38]. However, the irrigation systems in NEC are not well developed; less than 25% of farmers have irrigation access in maize production [49]. Therefore, the development of more efficient irrigation systems should be given high priority in semi-humid areas of NEC.

The $Y_{rainfed}/Y_{no water-stress}$ ratio represents the gap between no water-stress and rainfed maize yields. A lower $Y_{rainfed}/Y_{no water-stress}$ value indicates a greater water scarcity for maize to obtain its potential yield. For semi-humid region stations, both the decreasing trend in $Y_{rainfed}/Y_{no water-stress}$ and its lower values during the 2000s and 2011–2018 (Figure 5) indicated a growing sensitivity of maize production to water, as reported by Meng et al. [9] who use a hybrid-maize model to examine the gap between irrigated and rainfed maize yields of Chinese maize belt. The decrease in $Y_{rainfed}/Y_{no water-stress}$ is partly related to reductions in precipitation (Figure 6) and to increased evaporative demands in warmer climates. Precipitation becomes the dominant climatic factor driving maize yield variations when the growing season precipitation is less than ~400 mm [50]. The gap between rainfed and no water-stress yields substantially increased from 25% in the 1980s to 35% in the 2000s and 2011–2018 at semi-humid region stations, which manifested the changing correlations between TT and precipitation. Gao et al. [51] also reported that the projected increase in annual precipitation did not always keep pace with the rising temperature to sufficiently support the cropping systems in North China under both the RCP4.5 and RCP8.5 scenarios. A larger gap between rainfed and no water-stress yields also suggests that new adaption measures, other than a shift to longer-maturing varieties,

are needed. In fact, factors other than thermal availability appear to more strongly impact farmer decision-making [17]. Under climate change conditions, new hybrids with drought-tolerant qualities, applications of nitrogenous fertilizers and irrigation may be effective measures for semi-humid regions to maintain maize production [7].

5. Conclusions

This study aimed to determine whether the adoption of longer-season cultivars is an effective measure for the whole northeast China (NEC) to sustainably increase the grain yield. For humid areas, the adoption of longer-season cultivars during the 2000s and 2011–2018 caused increases in yield ranging from 6.3% to 13.3% compared with the 1980s, which showed that the negative effects of climate warming on maize yield were reversed by cultivar selection. A longer maturity hybrid showed to generally result in higher yields when soil water availability is not limited during the season. For semi-humid areas, grain yield decreased or slightly increased (from -12.7% to 8.0%) when longerseason cultivars were adopted during the 2000s and 2011–2018. Maize yield was limited by water when cultivars with higher thermal time requirements under climate change conditions were introduced. Thus, having a secure food supply will depend on increases in water-use efficiency and other adaptive strategies, such as varietal diversification, droughtresistant varieties, conservation tillage and irrigation. Therefore, we should take differential measures for humid and semi-humid areas of NEC to achieve the increase of maize yield sustainably.

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