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Warming and Dimming: Interactive Impacts on Potential Summer Maize Yield in North China Plain

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Abstract: Global warming and dimming/brightening have significant implications for crop systems and exhibit regional variations. It is important to clarify the changes in regional thermal and solar radiation resources and estimate the impacts on potential crop production spatially and temporally. Based on daily observation data during 1961–2015 in the North China Plain (NCP), the impacts of climate change associated with climate warming and global dimming/brightening on potential light–temperature productivity (*PTP*) of summer maize were assessed in this study. Results show that the NCP experienced a continuous warming and dimming trend in maize growing season during the past 55 years, and both *ATT10* and solar radiation had an abrupt change in the mid-1990s. The period of 2000–2015 was warmer and dimmer than any other previous decade. Assuming the maize growing season remains unchanged, climate warming would increase *PTP* of summer maize by 4.6% over the period of 1961–2015, which mainly occurred in the start grain filling–maturity stage. On the other hand, as negative contribution value of solar radiation to the *PTP* was found in each stage, dimming would offset the increase of *PTP* due to warming climate, and lead to a 15.6% reduction in *PTP* in the past 55 years. This study reveals that the changes in thermal and solar radiation have reduced the *PTP* of summer maize in the NCP. However, the actual maize yield could benefit more from climate warming because solar radiation is not a limiting factor for the current low production level.

Keywords: climate warming; dimming; summer maize; potential production; North China Plain

1. Introduction

Global warming and dimming/brightening are caused by the changes in thermal and solar radiation in the context of global climate change. The Earth's surface air temperature has increased by approximately 0.6 ± 0.2 °C during the 20th century (Intergovernmental Panel on Climate Change [1], indicating that global warming has definitely occurred [2]. This warming trend is expected to continue in the coming decades [3]. Observations show that China has experienced a more pronounced climate warming [4], and north China especially showed a greater warming trend than south China [5]. The amount of solar radiation has exhibited more complicated changes, which undergoes significant decadal and regional variations [6,7]. Global dimming was observed from the late 1950s to the early 1990s at different locations throughout the world [8–10], and after the 1990s a worldwide brightening was observed in United States [11], South America [12] and Japan [13]. This phenomenon is partly resulted from the reduced levels of air pollution and decreased aerosol content in the atmosphere [14]. By contrast, a continuous solar dimming was found in most regions of China, and the brightening trend was weak and insignificant [15].

Previous studies have shown that global warming and dimming/brightening could have significant impacts on crops [16], and maize yield is vulnerable to climate variability and climate change [17]. However, climate change varies significantly in different regions, thus it is important to evaluate the changes in thermal and solar radiation resources and their interactive impacts on for specific regions. This study took the North China Plain (NCP) of China as a case study and the findings can be of global use. The NCP is one of the key grain-producing regions of China, and plays a vital role in guaranteeing the national food security [18]. The dominate agronomic cropping system in the NCP is a winter wheat (*Triticum aestivum* L.)–summer corn (*Zea mays* L.) rotation system, which produces over 30% of national total corn yield [19,20]. Previous studies on estimation of climate change and its impacts have shown that the NCP has been experiencing a warming and dimming trend [5,21], which has significantly affected crop phenology, grain yield, and cropping system [22,23]. However, most of these assessments focus on the variations of annual temperature or radiation, and few studies evaluate the combined effects of those climate changes in maize growing season, i.e., there is a lack of integrated assessment of warming and dimming/brightening impacts on potential maize yield in the NCP. Therefore, a systemic analysis of the spatial and temporal changes in thermal and solar radiation resources in the NCP and evaluation of the impacts of those climate changes on potential crop production are necessary, and the results drawn from this study could provide a scientific basis for making policy for adaptation to and mitigation of climate change.

This study focused on the impacts of temperature and solar radiation on potential light–temperature productivity (*PTP*) [24]. The *PTP* of summer maize represents the maximum yield under well-watered and stress-free conditions in a given region, which has been widely used to evaluate the spatiotemporal changes of crops under climate change [25,26]. As *PTP* was only determined by radiation and temperature, the contribution of the changes in *ATT10* and solar radiation on *PTP* could be separated and calculated by using sensitivity analysis method.

The objectives of this study were to evaluate the spatiotemporal variations of climatic variables (thermal and solar radiation) and maize potential yield during maize growing season, and estimate the combining effect of climate warming and dimming/brightening on maize potential production in NCP during 1961–2015.

2. Materials and Methods

2.1. Study Area

The North China Plain (NCP) is also known as the Yellow-Huai-Hai Plain since three major rivers, i.e., Yellow River, Huaihe River, and Haihe River, drain the NCP, and covers three provinces, i.e., Hebei, Shandong, and Henan, and two municipalities, i.e., Beijing and Tianjin (see Figure 1). As the largest national alluvial plain, the NCP has low and flat terrain with a mean elevation of less than 50 m above the mean sea level. The climate in the NCP generally shows a temperate and monsoonal climate pattern characterized by hot and rainy summer. Nearly 70% of annual precipitation occurs from July to September, which is suitable for planting summer maize. The typical cropping system in the NCP is a rotation between winter wheat and summer maize (sowed around 10 June and harvested around 10 October).

Historical daily observations of meteorological parameters at 55 meteorological stations from 1961 to 2015 were obtained from China Meteorological Data Sharing Service Network (http://cdc.cma.gov.cn/home.do). The original dataset's quality was strictly checked to ensure the missing values less than 0.1%. All missing data were filled using the linear interpolation method. The datasets include daily mean temperature, maximum temperature, minimum temperature, sunshine hours, wind speed, relative humidity, and precipitation, whose average and standard deviation values in summer maize growing season in the NCP are listed in Table 1.

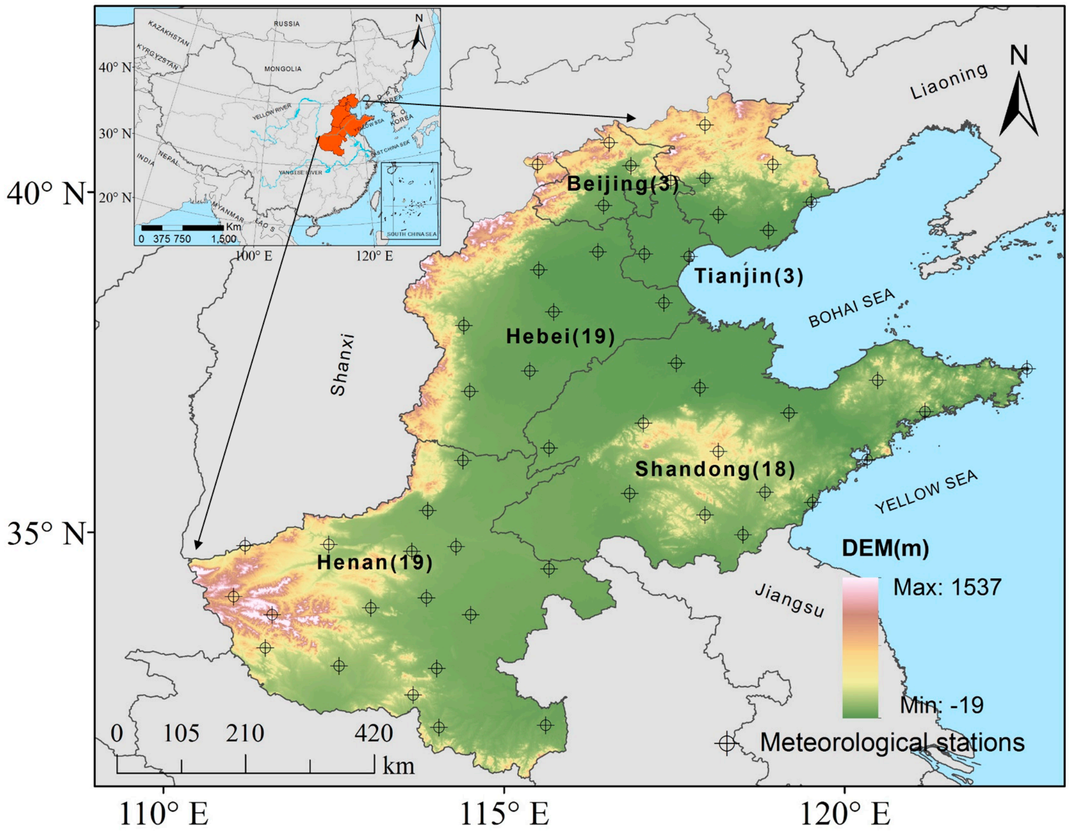

Figure 1. Boundary and meteorological stations in NCP. Digital Elevation Model (DEM) data were from Chinese Academy of Sciences and downloaded at http://www.resdc.cn/.

Table 1. The average and standard deviation values of the meteorological variables in summer maize growing season in the NCP.

	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)	Relative Humidity (%)	Precipitation (mm)	Wind Speed (m/s)	Sunshine Hours (h)
Average value	23.6	28.7	19.2	75.0	469.9	2.3	831.3
Standard deviation	1.1	1.3	1.4	3.7	78.3	0.7	79.8

2.2. Technique Description

2.2.1. Active Accumulated Temperature (ATT)

Active accumulated temperature (*ATT*, unit °C) is an effective parameter for describing the thermal condition for crop growth, which has been widely applied in studying crop physiological ecology, as well as analyzing cropping systems [27]. Bunting [28] found a strong relationship between *ATT* with a given threshold temperature of 10 °C (*ATT10*) and corn growth, and Bai et al. [29] confirmed similar results in China. In this study, *ATT10* was calculated by summing up daily temperature during the growing season—when the daily temperature was above 10 °C—as the follows:

$$AAT10 = \sum_{i=planting\ date}^{harvest\ date} T_i\ ,\ for\ T_i \geq 10 \quad (1)$$

where T_i (°C) is the daily mean air temperature on the ith day.

2.2.2. Solar Radiation

Since it is difficult to obtain the long-term solar radiation observational data at all 55 meteorological stations, we first estimated the extraterrestrial radiation (R_a, unit MJ m^{-2} day^{-1}) according to the radiation formula given in FAO56-PM [30,31]:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r (\omega \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega) \tag{2}$$

where G_{sc} = 0.0820 MJ m^{-2} min^{-1} is the solar constant, *dr* is the inverse relative distance Earth–Sun (unit m), ω is the sunset hour angle (unit rad), φ is latitude (unit rad), and δ is solar declination (unit rad). d_r, ω and φ are given by Equation (3):

$$d_r = 1 + 0.033\cos(\frac{2\pi}{365}J);\ \delta = 0.409\sin(\frac{2\pi}{365}J - 1.39);\ \omega = \arccos[-\tan(\varphi)\tan(\delta)] \tag{3}$$

where *J* is the number of the day in the year, between 1 (1 January) and 365 or 366 (31 December). Solar radiation (R_S, unit MJ m^{-2}) was then calculated by Angstrom model [32]:

$$R_s = R_a(a + b\frac{n}{N}) \tag{4}$$

where *n* is the actual sunshine hour duration (unit h), *N* is the maximum possible sunshine hour duration (unit h), *n/N* is the relative sunshine hour, and a and b are empirical coefficients. He et al. [33] calibrated R_s model with the actual solar radiation data, and recommended the coefficients of a = 0.143 and b = 0.585 in NCP.

2.2.3. Maize Potential Light–Temperature Productivity (*PTP*)

The potential light–temperature productivity of summer corn (*PTP*, unit kg ha^{-1}), determined by radiation and temperature, represents the maximum potential crop yield under stress-free condition [23]. In this study, we first estimated the photosynthetic productivity (*PP*, unit kg ha^{-1}) by using an empirical model, which has been widely used in calculating potential crop productivity in China [34,35]:

$$PP = R_s k(1 - A)(1 - B)\eta C q^{-1}(1 - g)(1 - h) \tag{5}$$

where K = 0.49 is the conversion coefficient of photosynthetically active radiation (*PAR*), A = 0.065 is the field crop reflectance, B = 0.06 is the radiation leakage rate, η = 0.1568 is the solar energy use efficiency, C = 0.35 is the crop harvest index, q is the heat content of plant organic matter with a value of 17.81KJ/g, g = 0.08 is the ash content of plant, and h is the yield water content. The water content of actual crop yield in the statistical data is around 15%, thus the *PP* is also expressed as the potential yield with 15% water content in this study.

The *PTP* was then determined by considering the impact of suboptimal temperatures in each growth stage of maize [34]:

$$PTP = \sum_{j=1}^{4}(\sum_{i=1}^{d_j} PP f(t)) \tag{6}$$

where *j* represents each maize growth period (sowing–jointing, jointing–heading, heading–start grain filling, and start grain filling–maturity), d_j is the length of each stage, and *f(t)* is the temperature stress coefficient and calculated by Equation (7) [35]:

$$f(t) = \begin{cases} 0 & t < t_{\min}\ or\ t > t_{\max} \\ (t - t_{\min})/(t_0 - t) & t_{\min} < t < t_0 \\ (t_{\max} - t)/(t - t_0) & t_0 < t < t_{\max} \end{cases} \tag{7}$$

where t is the daily average temperature (unit °C), and t_{min}, t_o, and t_{max} are the minimum, optimum, and maximum temperatures for each summer maize developmental stages (unit °C), respectively, which are listed in Table 2.

Table 2. Minimum (t_{min}), optimum (t_0), and maximum (t_{max}) temperatures for each summer maize developmental stages (°C).

Stage	t_{min}	t_o	t_{max}
Initial (sowing–jointing)	6	25	32
Development (jointing–heading)	10	27	35
Middle (heading–start grain filling)	15	27	34
Late (start grain filling–maturity)	15	23	32

2.2.4. Climate Trend

Climate trend, widely used in analyzing climate change, is a common and effective method. Linear regression method was used in this study for analyzing the trend of *ATT10*, solar radiation and *PTP*, as given by Equation (10) [36]:

$$X = k_1 t + k_0, t = 1, 2, 3, \ldots, n \tag{8}$$

where X is climatic variable, k_1 is the linear slope, k_0 is the y-axis intercept value, t is the number of years, and n = 55 is the length of data record (1961–2015). The climate trend value (β, unit of value per decade) equals 10 times k_1. A positive (or negative) β value indicates an increasing (or decreasing) trend. The F-test method was used to assess the significance of the trends at 0.05 level.

2.2.5. Mann–Kendall (MK) Test

The breakpoint of time series of temperature or solar radiation in this study was identified by using the rank-based nonparametric Mann–Kendall (*MK*) test [37,38]. The *MK* test is a non-parametric method and has been widely used in detecting monotonic trends for the non-normally distributed and censored data [39,40]. For the sequential time series x1, x2, ... xn, which belong to a sample of n independent and identically distributed random variables, the *MK* rank statistic value (*Sk*) is calculated as [41]:

$$S_k = \sum_{i=1}^{k} r_i, 2 \le k \le n$$
$$r_i = \begin{cases} 1, when x_i > x_j \\ 0, when x_i \le x_j \end{cases}, 1 \le j \le i \tag{9}$$

The statistic of the Mann–Kendall test, *UFk*, was then computed by Equation (10) [42]:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{Variance(S_k)}}, 1 \le k \le n \tag{10}$$

where E(*Sk*) and Vaiance(*Sk*) are the expectation and variance of *Sk* and estimated by the following formulas:

$$\begin{cases} E(S_k) = \frac{k(k-1)}{4} \\ Variance(S_k) = \frac{E(S_k)(2k+5)}{18} \end{cases} 2 \le k \le n \tag{11}$$

Inversed time series $x_n, x_{n-1}, \ldots x_1$, and *UBk* were determined using the same method. The intersection point of *UF* and *UB* curves was considered as the breakpoint of the series. More details for the *MK* test can be found in Hamed [43] and Adamowski et al. [44].

2.2.6. The Contribution Rate

The contribution rate method was employed in this study to estimate the impacts of the changes in *ATT10* and solar radiation on *PTP* in the past 55 years, given as follows [45,46]:

$$Con_v = CR_v Sen_v \quad (12)$$

where Con_v is the contribution rate of a meteorological variable V, and CR_V is the relative change rate of V, as given by the following formula:

$$CR_v = \frac{n\beta}{10\overline{V}} \quad (13)$$

where n is the length of time series, β is the decadal climate trend, and is the average value of the meteorological variable V during the study period. Sen_v is the sensitivity coefficient, which is computed as the ratio of the relative change of a dependent variable to the relative changes of independent variable as follows [47,48]:

$$Sen_v = \frac{\Delta PTP/PTP}{\Delta V/V} \quad (14)$$

where V and ΔV are the daily meteorological variable value and its variation. ΔPTP is the daily variation in *PTP* and depends on ΔV.

A positive/negative Con_v indicates that the changes of the variable V over the study period have caused the increase/decrease in *PTP*. Since the temperature stress coefficient given in Equation (9) is not a continuous function, it is difficult to calculate the sensitivity coefficient value of temperature. Therefore, we first calculated the Con_{solar}, and the contribution rate of temperature was then estimated as the changes of *PTP* minus Con_{solar}.

For the decadal scale, three periods were first defined in this study, i.e., Period 1 (P1, 1961–1979), Period 2 (P2, 1980–1999), and Period 3 (P3, 2000–2015), and then the variation characteristics of *ATT10*, solar radiation and *PTP* were analyzed Matlab2014 software was used for the data processing and calculation. As it is hard to identify regional patterns purely based on the individual stations, spatial analysis was also used to explore the spatial changes. All spatial distribution maps (Figure 1, Figure 2, Figure 4, Figure 5 and Figure 6) were constructed using the Inverse Distance Weighting (*IDW*) interpolation method embedded in the ArcGIS 10.1 software package with a grid cell size of 0.02° (about 2 km).

3. Results

3.1. ATT10 and Solar Radiation at the Decadal Scale

The spatial distribution of *ATT10* and solar radiation in summer maize growing season in three time periods is shown in Figure 2. The NCP showed a warming trend at the decadal scale, and P3 showed the greatest increasing trend and the average *ATT10* value in the three time periods was 2737.7, 2746.5, and 2787.0 °C·day, respectively. The *ATT10* value was higher in P2 and P3 than that in P1 at the same place, leading to a northward shift of the contour lines for *ATT10* (see Figure 2(a1–a3)). Compared with P1, 2800 °C·day and 2900 °C·day contour lines of *ATT10* moved northward by approximately 1.2° and 3° latitudes in P3, and the area of *ATT10* over 2800 °C·day and 2900 °C·day increased by 21.0% and 53.9%, respectively.

Unlike *ATT10*, a significant dimming trend was found in the NCP as the total solar radiation in summer maize growing season decreased in all the three time periods. Compared to P1, the total solar radiation in P2 and P3 decreased by 6.7% and 16.2%, respectively, and the corresponding contour lines all moved northward noticeably. The 2000MJ·m^{-2} contour line moved northward from the southwest NCP in P1 (around Lushi city, Figure 2(b1)) to the central NCP in P2 (Figure 2(b2)), and the 1900 MJ·m^{-2} contour line shifted northward from 36°N (around Zhengzhou city, Figure 2(b2)) to the northeast NCP

(Figure 2(b3)). A decreasing trend of the area with solar radiation above 1900 MJ·m^{-2} was found, and the area in P2 and P3 were 32.6% and 91.3% lower than that in P1, respectively.

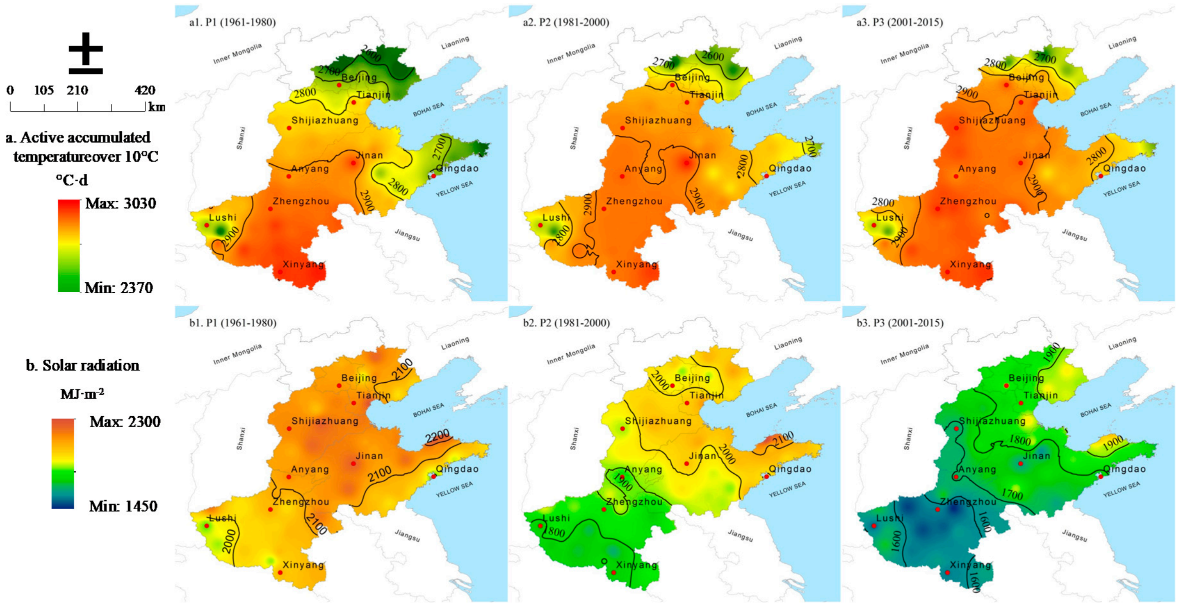

Figure 2. Changing characteristics of *ATT10* (°C·day) (**a**) and solar radiation (MJ·m^{-2}) (**b**) in maize growing season at decadal scale. Three time periods are divided, i.e., Period 1 (P1, 1961–1979), Period 2 (P2, 1980–1999), and Period 3 (P3, 2000–2015).

In summary, P3 exhibited the largest increasing trend for *ATT10* and decreasing trend for solar radiation. We further explored the abrupt change point by using the *MK* method, as shown in Figure 3. Both *ATT10* and solar radiation had an abrupt change in the mid-1990s (P < 0.05) with the intersection of *UB* and *UF* line within −2 to 2.

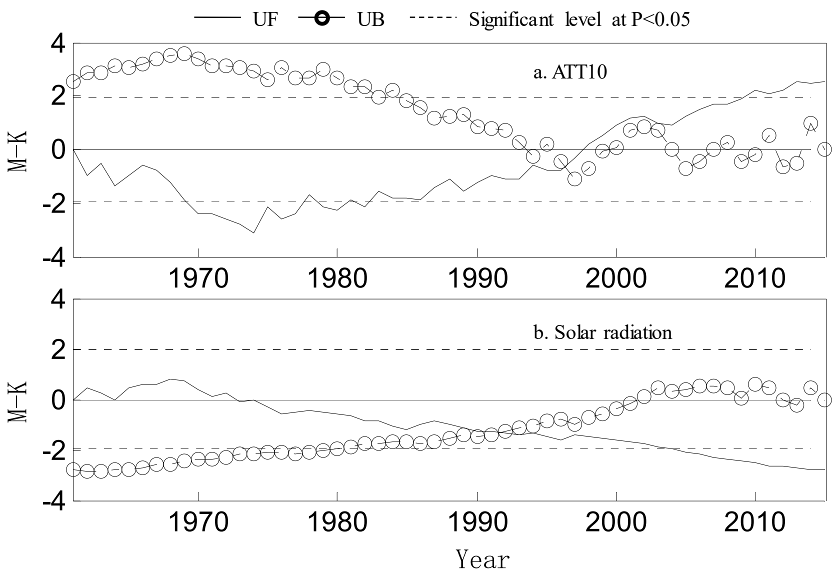

Figure 3. M-K test for *ATT10* (**a**) and solar radiation (**b**) in maize growing season over the period of 1961–2015. The values for each year were calculated for the average of 55 meteorological stations in NCP.

3.2. *ATT10* and Solar Radiation at the Annual Scale

Climate trends for *ATT10* and solar radiation in maize growing season and the number of stations with significant trend values in the NCP are listed in Table 3. According to Table 3, the *ATT10* in maize growing season in the NCP increased by about 75.4 °C·day in the recent 55 years with the average trend value of 13.7 °C·day·decade^{-1}, and 63.6% of stations (n = 35) showed a significant increasing trend at 0.05 level. All stations showed significant negative trend for solar radiation ($P < 0.05$) with the average trend value of −62.4MJ·m^{-2}·decade^{-1}, indicating that the solar radiation in the NCP significantly decreased over the period of 1961–2015.

Table 3. Climate trend for *ATT10* and solar radiation in maize growing season and the number of stations with significant trend value in NCP.

	ATT10 **°C·Day·Decade^{-1}**	**Solar Radiation MJ·m^{-2}·Decade^{-1}**
Climate trend	13.7	−28.3
Number of stations with significant increasing trend ($P < 0.05$)	35	0
Number of stations with significant decreasing trend ($P < 0.05$)	0	55

Spatial distribution of the climatic trend rates of *ATT10* and solar radiation are shown in Figure 4. *ATT10* trend rates increased from south to north, and the largest temperature increasing rate occurred in the central and northern NCP with trend value larger than 10 °C·day·decade^{-1} ($P < 0.05$) (Figure 4a). In contrast, most areas in the southern NCP showed non-significant *ATT10* trend. Solar radiation decreased more in the eastern Henan than that in other areas, with trend value more than 100 MJ·m^{-2}·decade^{-1} ($P < 0.05$). The Northeast NCP (around Qingdao, Beijing and Tianjin) and the southwest NCP (around Lushi) showed the smallest solar radiation decreasing rate with trend value less than 80MJ·m^{-2}·decade^{-1} ($P < 0.05$), as shown in Figure 4b.

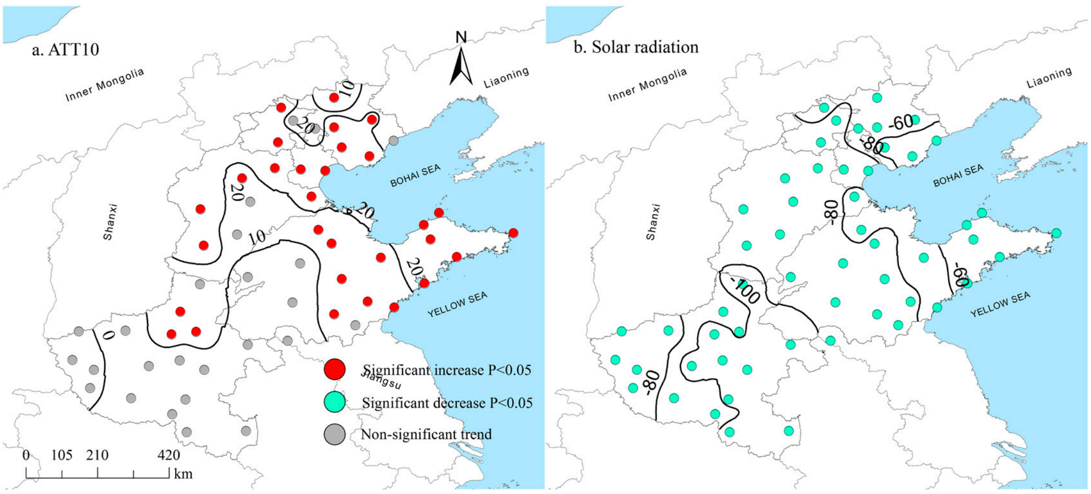

Figure 4. Spatial distribution of climate trend rates for *ATT10* (°C·day·decade^{-1}) (**a**) and solar radiation (MJ·m^{-2}·decade^{-1}) (**b**) in maize growing season in NCP over the period of 1961–2015.

3.3. Variation and Cause Analysis of *PTP*

Influenced by the changes of radiation resources and thermal resources, the *PTP* of summer maize in the NCP showed a significant decreasing trend at the decadal scale, as shown in Figure 5. Compared with P1, the average *PTP* in P2 and P3 decreased by 0.1% and 8.2%, respectively, and all contour lines had a noticeable shift. The area with high *PTP* (greater than 21 ton·ha^{-1}) decreased continuously in the three time periods with the proportion of the total area reduced from 83.8% (P1, Figure 5a) to 20.3% (P3, Figure 5c).

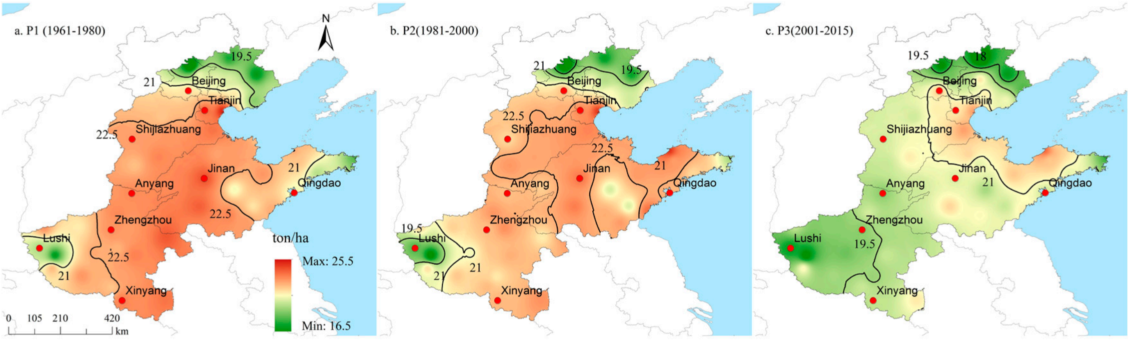

Figure 5. Changing characteristics of the *PTP* of summer maize (ton·ha^{-1}) in NCP at decadal scale.

The *PTP* of summer maize in the NCP was significantly reduced in the recent 55 years with the average trend value of −424.5kg·ha^{-1}·decade^{-1}, and 65.5% of stations (n = 36) showed a significant decreasing trend at 0.05 level (see Figure 6). The greatest decreasing rate for *PTP* was found in the central NCP with trend value more than 600 kg·ha^{-1}·decade^{-1} ($P < 0.05$). East Shandong and northeast Hebei showed slightly increasing trend, but the change was insignificant.

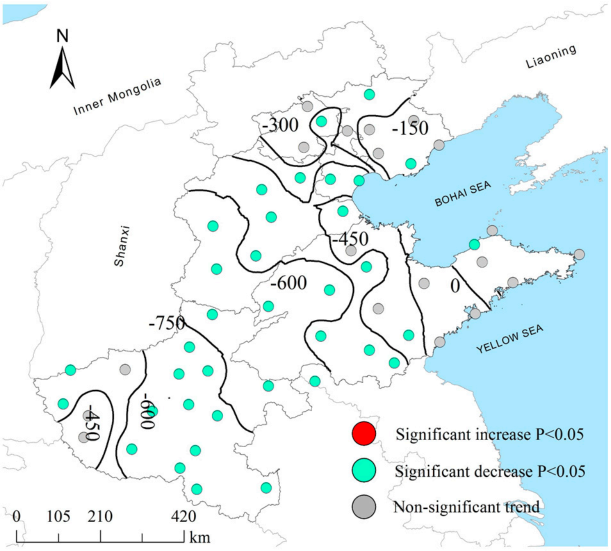

Figure 6. Spatial distribution of climate trend rate for the *PTP* of summer maize (kg·ha^{-1}·decade^{-1}) in NCP over the period of 1961–2015.

The *PTP* of summer maize in the NCP has reduced by 11.0% in the recent 55 years, which was caused by the changes in temperature and solar radiation. Climate warming had positive impacts on maize production with an average contribution value of 4.6% (see Figure 7). On the other hand, dimming offset the increase of *PTP* due to warming climate, which led to a 15.6% reduction in *PTP* in the recent 55 years.

We further explored the change rate of the *PTP* of summer maize and the contribution rate of temperature and solar radiation to the *PTP* in each stage. Negative contribution value of solar radiation to the *PTP* was found in each stage. The greatest contribution rate was found in the heading–start grain filling stage, leading to a 5.7% decrease in the *PTP*. The late stage (start grain filling–maturity) showed largest contribution of temperature, which caused the *PTP* of summer maize to increase by 1.9%.

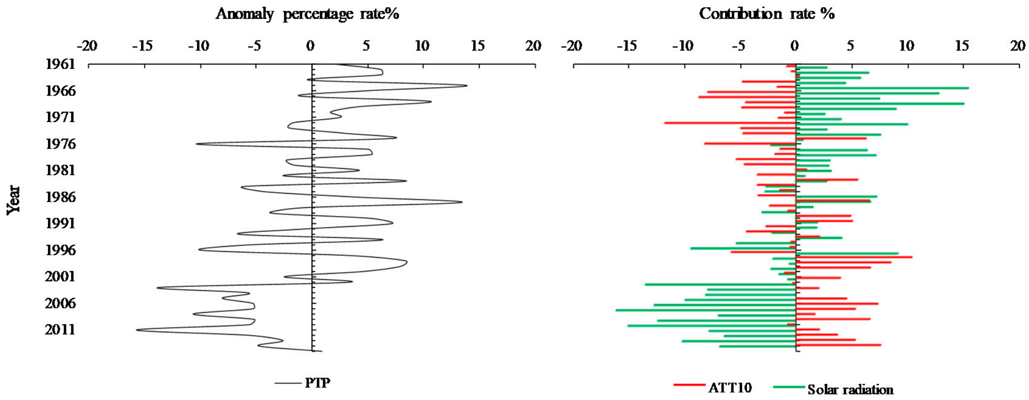

Figure 7. Annual anomaly percentage rate of the *PTP* of summer maize and the contribution rate of *ATT10* and solar radiation to the *PTP* in NCP over the period of 1961–2015.

4. Discussion

4.1. Climate Warming and Dimming in the NCP

The NCP has experienced noticeable climate warming trend in summer maize growing season, and the greatest *ATT10* increasing trends occurred in the last 15 years. Ma et al. [49] also reported that climate change has enriched the thermal resources in the NCP, resulting in a northward shift for *ATT10*. As thermal resources are the important limiting factors for the winter wheat-summer corn annual cropping system in the NCP, climate warming would have positive effects on improving the grain yield by extending the geographical distribution and providing longer growing season [26,50,51]. Similar results were also reported in northeast China by Liu et al. [52]. It should be noted that this conclusion is based on the assumption of an invariant maize growing season. However, rising temperatures are expected to accelerate crop growth [53] and shorten the length of reproductive growth stage [54], and thus reduce the total dry biomass; similar results are also reported in the future climate projections [55–58]. Therefore, some effective management options, as well as shifting cultivars in longer growing season, must be used to offset the negative impact caused by climate warming. For example, Wang [19] reported that "Double-Delay" technology, i.e., delaying both the sowing time of wheat and the harvesting time of maize, was an effective option for wheat and maize cropping system in the NCP. Liu et al. [31] also found that a delayed harvest could increase the summer corn yield by 83.8–158.1 kg ha^{-1} day^{-1} in the NCP. Climate warming provides favorable thermal conditions for this technology, especially in the northern NCP, where the double cropping system is strictly limited by available thermal time.

Climate dimming/brightening has been wildly discussed in previous studies [7,59,60], but the published results show large discrepancies and inconsistencies in different regions. A decline in land surfaces' solar radiation was found in many observational records up to the 1990s; a widespread brightening has been observed since the late 1980s in the Northern Hemisphere [11] and South America [12]. In Asia, India is one of the few regions that exhibited a continuous solar dimming from the 1970s to the 2000s [61]. Most regions in China showed a similar dimming trend, and the brightening trend mainly occurred in southeast China since 1990, which was weak and insignificant [18]. In this study, we found that all stations in the NCP showed a steady dimming trend during summer maize growing season at both decadal and annual scales. Yadav et al. [62] reported that dimming of global radiation could significantly affect grain yield and harvest index, and they found that dimming has led to a 15.6% decline in the *PTP* in the recent 55 years.

4.2. The Combining Impacts of Climate Warming and Dimming on the PTP

Influenced by climate warming and dimming, the *PTP* of summer maize in the NCP showed a significant decreasing trend, which indicates that the negative effect of dimming on the *PTP* is greater than the positive effect of climate warming. Tao et al. [25] analyzed the temporal and spatial changes of maize yield potentials in the southwestern China and obtained a similar result. It is worth mentioning that the actual summer maize yield per unit area showed an opposite changing trend compared with the *PTP* trend in the NCP. Here, we further analyzed the changes for the *PTP* of summer maize, statistical yield, and yield gap between the *PTP* and statistical yield in the NCP at the decadal scale, as shown in Figure 8. The actual summer maize yield has continuously increased since the 1960s, thus narrowing the yield gap. The growth rate for the statistical yield of summer maize reached 864 kg·ha^{-1}·decade^{-1} ($P < 0.05$), which resulted from the improvement of agronomic measures and techniques, such as crop varieties, irrigation, and fertilization. However, the average productivity level was still relatively low in the study area, and the statistical yield in the past 15 years (P3, 2001–2015) only accounted for 26.1% of the *PTP*.

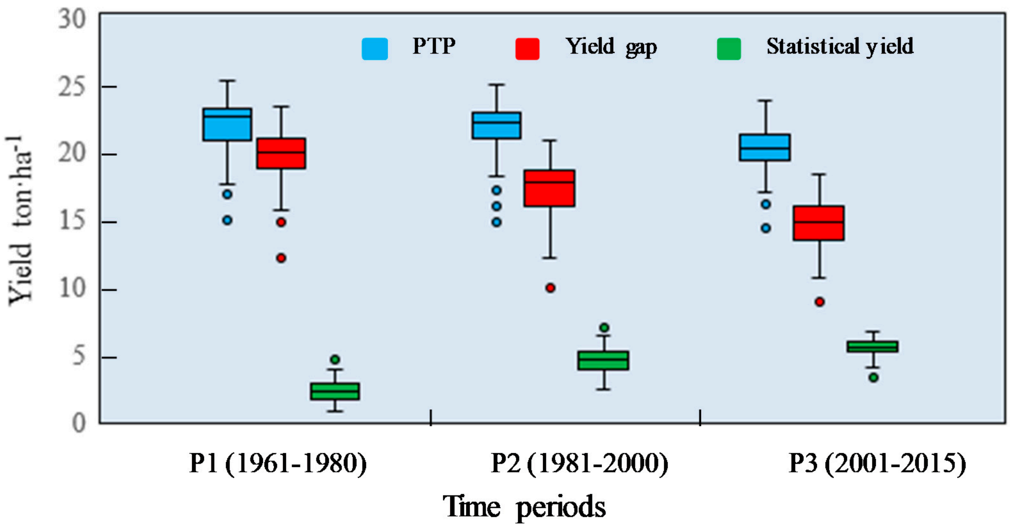

Figure 8. Changes for the *PTP* of summer maize, statistical yield, and yield gap in NCP at decadal scale. The statistical yield data were obtained from National Bureau of Statistics of China (http://www.stats.gov.cn/).

Moreover, we calculated the maize radiation use efficiency in the NCP and found that the efficiency value was only 1.06 ± 0.11% during 2001–2015, indicating that solar radiation was sufficient and not a limiting factor over maize growing period in the NCP. Under these circumstances, maize production could benefit more from climate warming. Li et al. [63] found that maize yield per unit area in the 2000s was almost double the yield in the 1970s, and 11.2% of the increase was resulted from climate change. This study confirmed that climate warming has positive impact on the *PTP* with an average contribution rate of 4.6% in the past 55 years. Meng et al. [64] also found a similar result in northeast China.

Theoretically, the *PTP* determines the maximum value that the actual summer maize yield can be reached when the water and soil conditions are fully satisfied. In recent years, many scholars have been studying how to narrow the yield gap [65–67], and the latest high yield record of summer maize in the NCP has reached 20.04 kg·ha^{-1} (2014, Laizhou City, Shandong Province). This study highlights that the decrease in the *PTP* of summer maize in the NCP may be a limit factor to obtain high yield when the agricultural technology achieves significant progress in the future.

Obviously, the impact of climate change on the actual summer maize production in the NCP is complicated. For example, the increase in the risk of freezing damage in the late stage of maize growth, as well as diseases and insect damage, need to be considered when early maturity varieties are replaced by middle and late maturing varieties. Meanwhile, limited precipitation during the summer-rainy season is one of the major production constraints in most areas of the NCP [68], where high level of production depends largely on irrigation [69]. Therefore, a comprehensive analysis of climatic factors (solar radiation, temperature and precipitation), as well as agronomic measures and pest control, is needed in further research, which could provide scientific basis for the distribution and adjustment of summer maize production to adapt to the climate change in the NCP.

5. Conclusions

The NCP showed a warming trend in maize growing season with the average *ATT10* trend value of 13.7 °C·day·decade^{-1} during the period of 1961–2015. Climate dimming was found in the recent 55 years, and all stations showed significant decline in solar radiation with the average trend value of −62.4 MJ·m^{-2}·decade^{-1}. Continuous warming and diming trends were found at the decadal scale, leading to a shift of the contour lines of *ATT10* and solar radiation. P3 (2001–2015) showed the greatest mean values for *ATT10* and least mean values for solar radiation in the three periods, and both *ATT10* and solar radiation had an abrupt change in the mid-1990s. Influenced by climate warming and dimming, the *PTP* of summer maize in the NCP was significantly reduced at the changing rate of −424.5 kg·ha^{-1}·decade^{-1} in the recent 55 years. Compared with P1, the average *PTP* in P2 and P3 decreased by 0.1% and 8.2%, respectively. Assuming the maize growing season remains unchanged, climate warming could have positive impact on maize potential production and increase *PTP* by 4.6% over the period of 1961–2015. By contrast, dimming offset the increase of the *PTP* due to climate warming, leading to a 15.6% reduction in the *PTP* in the recent 55 years. Overall, climate warming and dimming in maize growing season has occurred in the NCP, which reduced the *PTP* of summer maize. However, actual maize yield could benefit more from climate warming because solar radiation is not a limiting factor for the current low production level. The government may promote some agronomic technical measures or new varieties to improve radiation use efficiency, which could greatly increase the farmers' maize yield. A comprehensive analysis of impacts of climatic factors (solar radiation, temperature and precipitation), as well as agronomic measures and pest control on maize yield in the NCP is necessary in future.

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