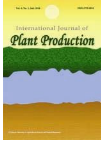

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Effects of climate change and cultivar on summer maize phenology

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Abstract

To identify countermeasures to the effects of climate warming on crop production, we must understand the changes in crop phenology and the relationships between phenology and climate change and cultivar. We used summer maize phenological and climate data in the North China Plain, collected from 1981 to 2010. This study analyzed the spatiotemporal trends in phenological data and lengths of different growing phases, mean temperatures and rainfall. The analyses showed that sowing, jointing and anthesis occurred relatively early at 13 (48.1%), 11 (40.7%) and 13 (48.1%) stations, respectively. Maturity dates were delayed significantly at 10 (37.0%) stations. The lengths of the vegetative growing phases, vegetative and reproductive growing phase at most stations showed a negative trend. The lengths of the reproductive growing phase increased at 25 (92.6%) stations, respectively. Furthermore, at most stations, the correlations between T_{means} and lengths of the various growing phases were negative, whereas the correlations between rainfall and lengths of various growing phases were positive. Furthermore, a field experiment, including four summer maize cultivars which were introduced during the 1950s, 1970s, 1990s and 2000s, was carried out during 2012 to 2014. The analyses showed that the durations of the various growing phases increased significantly. These results indicated that climate warming accelerates summer maize growth and shortens the growing periods of maize growth, whereas cultivars shift might prolong the maize growing season. Therefore, the maize cultivars with more longer whole growing period should be adopt in the North China Plain under the trend of global warming and the adaptation strategy of maize production under climate change should include crop phenology in response to climate change. The findings presented here could guide the development of options to adapt maize production to climate change in the North China Plain and other areas with similar ecologies.

Keywords: Climate change; Cultivar; Summer maize; Phenology.

Introduction

Climate change is a major force with which China and the rest of the world must cope in the 21st century (Piao et al., 2010). According to the 2014 report by the Intergovernmental Panel on Climate Change (IPCC), the global mean surface temperature increased by approximately 0.89 °C (0.69–1.08) during the period of 1901–2012. Each of the past three decades has been warmer than all the previous decades (IPCC 2014). Therefore, the potential impacts of climate changing on the development and productivity of field crops are of great concern and have been evaluated extensively in simulation models, statistical analyses and field experiments (Tao et al., 2006; Tao et al., 2008; Lobell et al., 2011; Liu et al., 2013; Lobell et al., 2013; Lv et al., 2013; Wilcox and Makowski, 2014).

Phenology is the study of the timing of recurring biological events, as affected by biotic and abiotic factors (Ma et al., 2012). Phenological stages, such as jointing and anthesis, represent critical physiological processes in crops and are strongly influenced by climate (Lu et al., 2014). Phenological studies made major contributions to the conclusion in the IPCC's Fourth Assessment Report (Parry et al., 2007) that "there is very high confidence, based on more evidence from a wider range of species" (Arnold et al., 2014).

Recently, interest in spatiotemporal changes of crop phenology has increased. Several studies have reported phenological changes in response to climate factors (Tao et al., 2006; Shimono et al., 2011; Croitoru et al., 2012; Tao et al., 2012; Deng et al., 2013; Arnold et al., 2014; Li et al., 2014; Lu et al., 2014; John et al., 2014; Tao et al., 2014). Studies have used climate data-driven crop models to investigate crop phenological developments (Ma et al., 2011; Sacks et al., 2011; Kovalskyy et al., 2012; Zhou et al., 2013; Amiri Larijani et al., 2014). These studies provide strong evidence that the dates of crop phenology phases shift markedly in response to ongoing climate change, recognizing the complex effects of agronomic factors such as agronomic management practices and cultivar (Li et al., 2014; Tao et al., 2014). Thus, it is important to study the impact of the future climate on maize phenology to define adaptation strategies for maintaining yield.

Crop phenology has been affected by modifications made to agronomic practices in response to climate change. Adjusting crop sowing and harvesting dates and introducing new crop cultivars with longer growing seasons have been recommended as adaptations to climate change (Jørgen and Marco, 2002; Waha et al., 2013; Moradi et al., 2013). For example, the application of so-called "double-delay" technology in the north part of the North China Plain (NCP) could at least partially counteract the perceived negative effects of climate change (Wang et al., 2012). Therefore, investigating the spatiotemporal changes of crop phenology and understanding the mechanisms of crop phenological responses to sources of agro-meteorological stress, might facilitate appropriate agronomic adjustments needed to mitigate various agricultural production risks caused by climate change (Li et al., 2014; Tao et al., 2014).

The NCP is one of the most important agricultural regions of China, covering 300,000 km^2 and accounting for 23% of China's cropland. This area produces as much as 25.70% of China's maize (DRSESSBS, 2014). The average surface temperatures of this region have increased at a rate of 0.25 °C per decade over the past 50 years. Moreover, a study by Wang et al. (2014) showed that, over the past 30 years, the numbers of growing degree days during the summer maize (*Zea mays* L.) season have increased in this region. These large increases in temperature are thought to have had considerable impacts on summer maize growth and harvest (Tao et al., 2006). These would threaten China's food security. Therefore, investigating the effects of climate change and cultivar on summer maize phenology in the NCP is urgently required. Tao et al. (2014) reported that the duration of the maize growing season was prolonged during the past three decades in response to the combined effects of temperature, agronomic management practices and cultivars. However, there exists relatively less work on different growing phase of summer maize phenological trend assessments. The relationship between rainfall and crop phenology and the changes in the vegetative (V), vegetative and reproductive (VR) and reproductive (R) growing phases might have an impact on the adaptation of agronomic practices, which merits further investigation. Furthermore, relatively less attention has been given to the impact of cultivars shift on phenological trends base on field experiment. To understand the processes and mechanisms controlling maize responses to ongoing climate change and cultivars, the changes summer maize phenology that occurred in over the past few decades in response to climate and cultivar changes must be investigated.

The objectives of this study were (1) to investigate the spatiotemporal changes in summer maize phenology; (2) to examine the relationships between mean temperature, rainfall and summer maize growing periods; (3) to determine the effects of cultivar shift on summer maize phenology and (4) to understand the consequences of phenological changes and the implications for summer maize production and adaptation to climate change in the NCP.

Materials and Methods

Study region

The NCP extends from 112° to 122° E longitude and 32° to 42° N latitude, covering three provinces (Shandong, Hebei and Henan) and two municipalities (Beijing and Tianjin; Figure 1). The double cropping system of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) is the dominant cropping pattern in this region. This pattern is responsible for producing 55.68 million tons of maize, which accounted for 27.08% of the China's total maize production in 2012. Therefore, within the context of climate change, investigating summer maize phenology in the NCP is very important to secure food production in China.

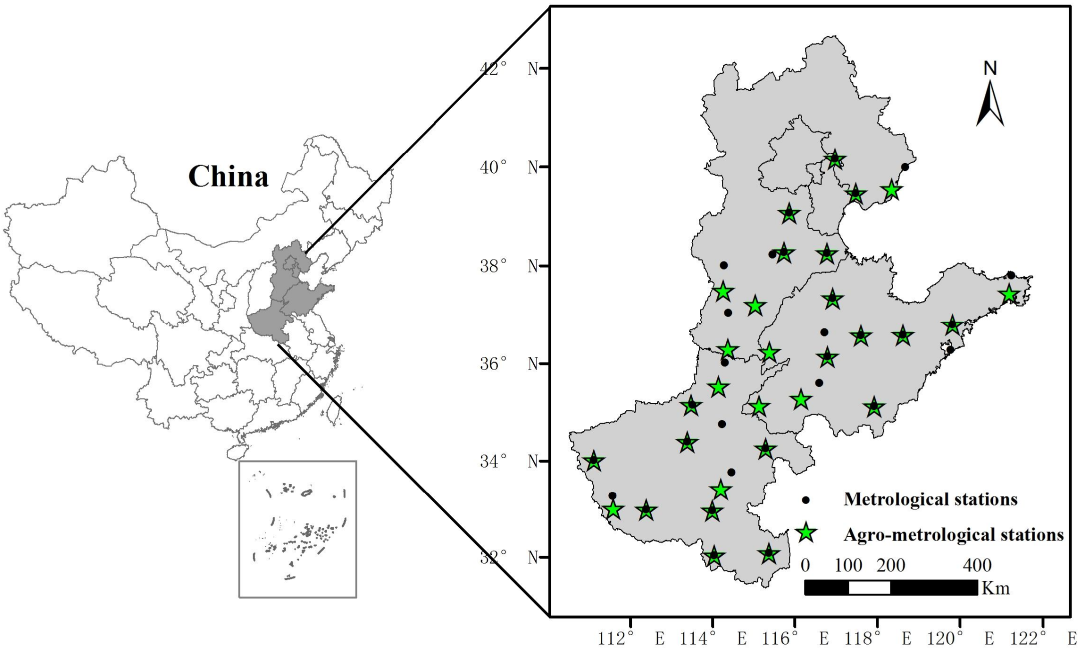


Figure 1. Locations in the North China Plain and the spatial distributions of metrological and agro-meteorological stations. A map of China shows the locations of three provinces and municipalities within China (shaded area). Black dots and green pentagrams represent the meteorological and agro-meteorological stations, respectively. Lines indicate province boundaries.

Historical summer maize phenology and climate data

Summer maize phenological data from 1981 to 2010 were obtained from agro-meteorological experiment stations maintained by the China Meteorological Administration (CMA). The Julian dates (day of year, or DOY) of four phenological stages (sowing, jointing, anthesis and maturity) were recorded at each station. A standardized observation method was used to collect phenological data (China Meteorological Administration, 1993). On alternate days, observations were recorded by well-trained agricultural technicians. Each phenological event was clearly defined. For example, the jointing date was recorded when 50% of the first internodes were 1.5–2.5 cm aboveground. The anthesis date was recorded when 50% of the tassels shed pollen (China Meteorological Administration, 1993). Daily mean temperature data were recorded at the stations from 1981 to 2010. In addition, in this study, the whole growing (WG) period from sowing to maturity was divided into three phases including the vegetative (V) phase from sowing to jointing, the vegetative and reproductive (VR) phase from jointing to anthesis and the reproductive (R) phase from anthesis to maturity. The meteorological observation data, which included daily mean temperature and rainfall, were also collected by the CMD.

Historical summer maize climate data

The meteorological observation data, including daily maximum, minimum temperature and precipitation for the same period were also collected from the CMD. 20 agro-meteorological stations were located at the same sites as the meteorological stations and the remaining 7 agro-meteorological stations were located in the vicinity of meteorological stations (Figure 1). Using the interpolated daily temperature data, the daily mean temperature was estimated as the average of the daily minimum and maximum air temperatures for each agrometeorological station.

Phenology of summer maize varieties released from 1950 to 2010

Summer maize phenological data for maize varieties released during the three decades from 1950 to 2010 were obtained from field experiments. The phenological data corresponded to the sowing, anthesis and maturity phases. The experiments were conducted at the Wuqiao Experimental Station of the China Agricultural University (37° 41′ N, 116° 37′ E and elevation 17 m) located in the Heilonggang region of Hebei Province which is representative of agricultural production and climate conditions of the NCP. The double cropping system of winter wheat and summer maize is the dominant pattern in this region.

The experimental site has a warm temperate, semi-humid monsoon climate. The average annual temperature is 12.9 °C, with 201 frost-free days. During the summer maize season (June–September) over the last 30 years, the average precipitation was 518.28 mm. Precipitation during the summer maize seasons in 2012, 2013 and 2014 was 587.4, 503.7 and 514.6 mm, respectively. The experimental site had loam soil with sandy loam in the topsoil (0–30 cm) and light/medium loam subsoil. The topsoil had a pH of 8.7 and contained 0.79 g/kg total nitrogen (N), 36.95 mg/kg hydrolyzed N, 44.60 mg/kg available phosphorus (P), 94.20 mg/kg available potassium (K) and 12.4 g/kg soil organic carbon (C). The soil chemical data were recorded before the field experiments commenced.

The experiments were conducted from 2012 to 2014. The four summer maize cultivars Baimaya, Zhongdan 2#, Zhongdan 13# and Zhengdan 958#, which were introduced during the 1950s, 1970s, 1990s and 2000s, respectively, were seeded with a no-till precision planter. The four cultivars were representative of the cultivars grown from 1950 to 2010 (Chen et al., 2012).

Treatments were arranged in a randomized complete block design, with four replicates. The plot size was 6 m × 11 m. Urea (46% N) was applied as N fertilizer. All plots received 130 kg ha^{-1} P_2O_5 (17% calcium superphosphate) and 120 kg ha^{-1} K_2O (50% potassium sulphate). Half of the N fertilizer and all of P and K fertilizers were applied at the time of sowing and the remaining half of the N fertilizer was applied as topdressing at the jointing stage. Summer maize was planted on 12 June 2012, 11 June 2013 and 10 June 2014 and harvested on 5 October 2012, 4 October 2013 and 3 October 2014. Irrigation water (75 mm) was applied immediately after planting, using the level-basin irrigation method. Irrigation water was pumped from a deep well near the experimental field and transported by plastic pipes to the plots. The planting density of summer maize was 6×10^4 plants ha^{-1}, with row spacing of 0.6 m and 0.28 m between plants within a row. Recommended agronomic practices were used for seeding depth and for pest and weed control.

Data analysis

Means and trends of summer maize phenology, temperature and rainfall were calculated using Microsoft Office 2013 software. Correlations between the WG, V, VR and R growing phases and the mean temperatures (T_{means}) or rainfall were investigated using Pearson's correlation analysis. Statistical significance of trends was tested using the two-tailed t test, with the SPSS 11.0 analytical software package (SPSS Inc., Chicago, IL, USA).

Results

Spatial distribution of mean sowing, jointing, anthesis and maturity dates

The mean phenological values of summer maize exhibited an obvious regional trend from 1981 to 2010 (Figure 2). Mean sowing, jointing, anthesis and maturity dates were earliest in the south, occurring mainly in late May to early June (day of year [DOY] 150.0–160.0), mid-July (DOY 190.0–200.0), early August (DOY 210.8–220.0) and early to mid-September (DOY 250.8–260.0), respectively, whereas in the north they generally began in late June (DOY 170.0-177.0), late July (DOY 200.0-211.3), mid-August (DOY 225.0–230.5) and late September or early October (DOY 270.0–278.2), respectively.

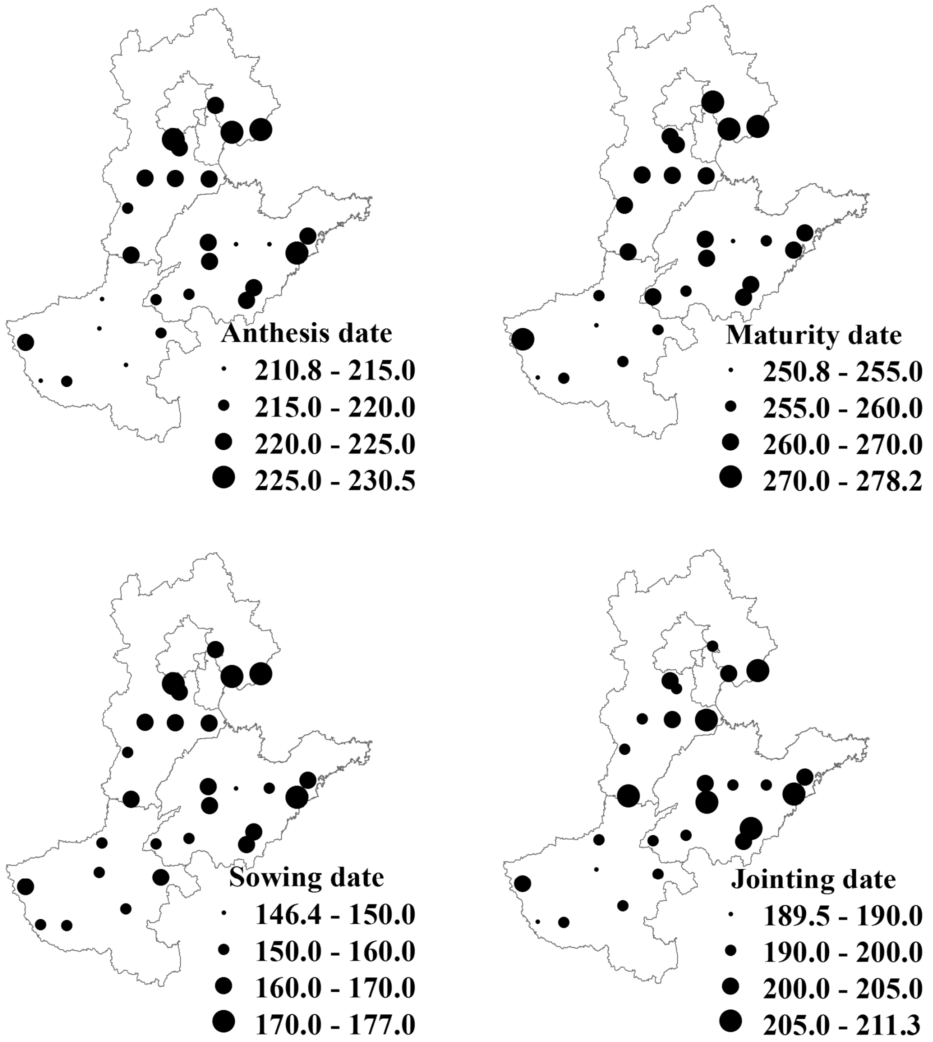


Figure 2. Mean dates of summer maize sowing, jointing, anthesis and maturity across the North China Plain during 1981–2010.

Dynamic change in sowing, jointing, anthesis and maturity dates of summer maize

Figure 3 shows the dynamic changes in phenology that occurred during the period studied. Among the 27 stations, 13 (48.1%), 11 (40.7%) and 13 (48.1%) stations recorded early sowing, jointing and anthesis dates, respectively and 13 (51.9%), 11 (59.3%) and 13 (51.9%) stations recorded delayed sowing, jointing and anthesis dates, respectively. The maturity dates were significantly delayed at 10 (37.0%) stations ($P<0.05$).

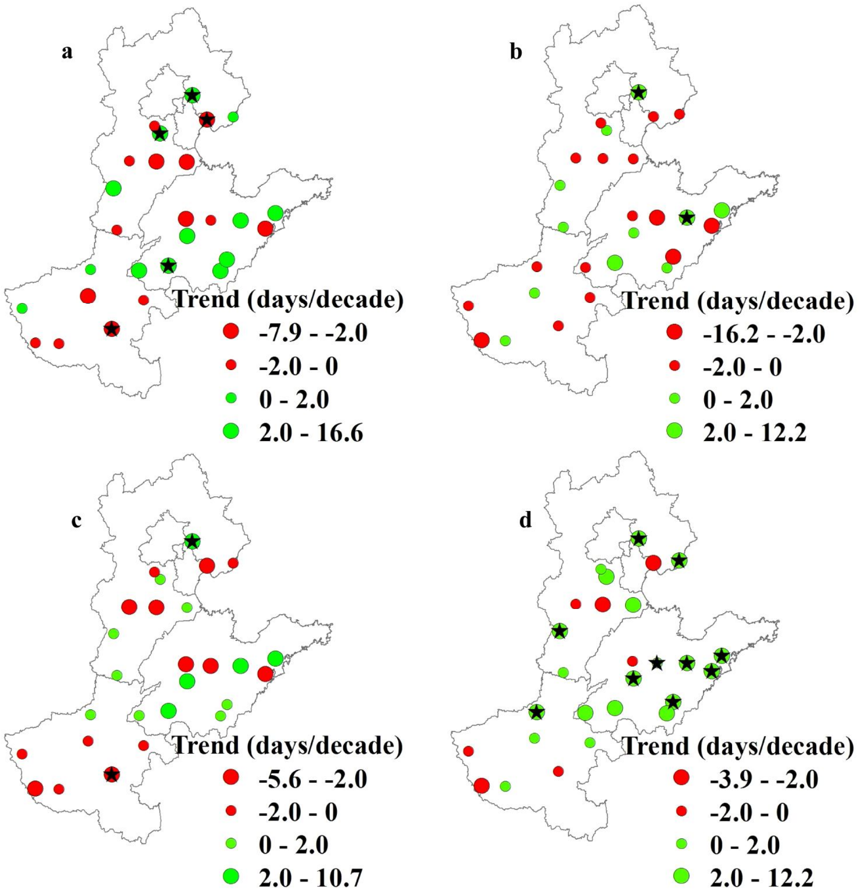


Figure 3. Trends in summer maize sowing (a), jointing (b), anthesis (c) and maturity (d) dates across the North China Plain during 1981–2010. Black pentagrams represent the trends at the stations, with a 0.05 probability level of significance.

Spatial distribution of vegetative (V), vegetative and reproductive (VR), reproductive (R) and whole growth (WG) phase lengths.

The mean lengths of the V, VR, R and WG phases during the study period and across the 27 stations are shown in Figure 4. In general, the mean lengths of the V, VR, R and WG phases in the northern region were relatively short, with ranges in length of 39.0–46.6, 22.0–25.3, 44.0–50.3 and 105.0–108.7 days, respectively. In contrast, the mean lengths of the V, VR, R and WG phases in the southern region were greater, with ranges in length of 33.0–39.0, 15.0–20.0, 38.0–44.0 and 91.1–100.0 days, respectively. These differences might be attributed to variation in climate, cultivar maturity and farmers' management practices.

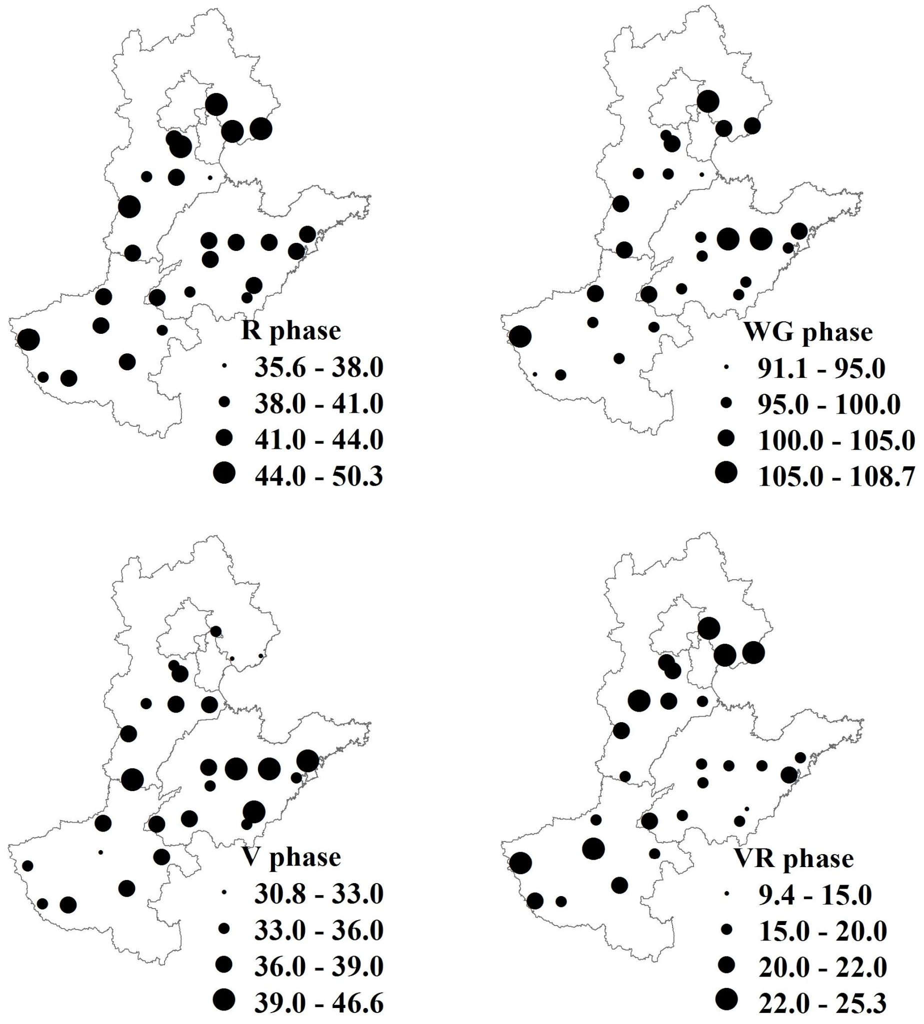


Figure 4. Mean lengths of the summer maize vegetative (V) growth, vegetative and reproductive (VR) growth, reproductive (R) and whole growth (WG) phases across the North China Plain during 1981–2010.

Dynamic change in the lengths of vegetative (V), vegetative and reproductive (VR), reproductive (R) and whole growth (WG) phases.

Figure 5 shows the trends in the lengths of the growth phases. The lengths of the V and VR phases showed a negative trend at 18 (63.0%) and 17 (66.7%) stations, respectively. In contrast, the lengths of the R and WG phases increased at 25 (92.6%) and 18 (63.0%) stations, respectively and at 7 (25.9%) and 5 (18.5%) stations showed a significant increasing across 27 stations in NCP.

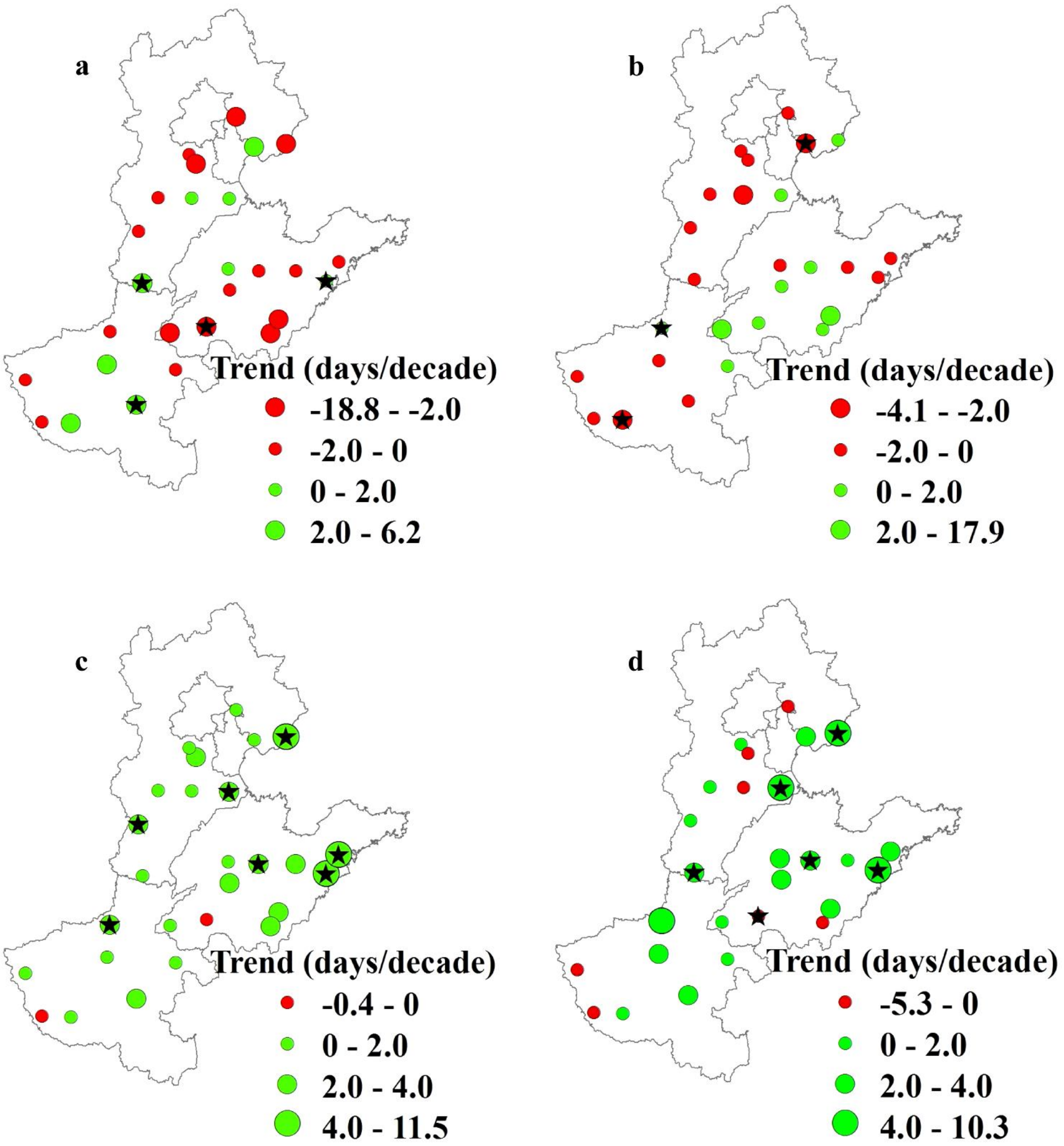
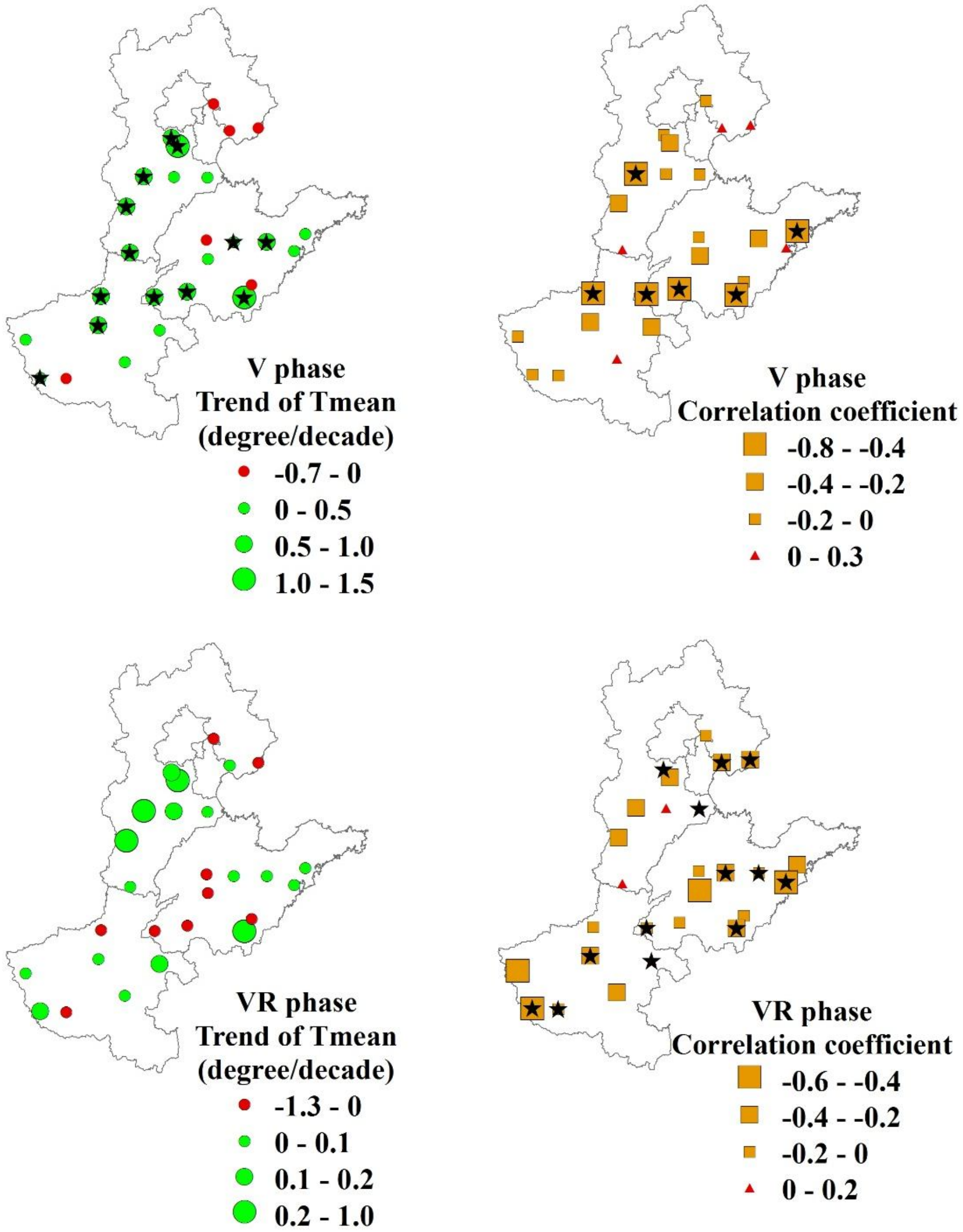


Figure 5. Trends in the lengths of the summer maize V (a), VR (b), R (c) and WG (d) phases across the North China Plain during 1981–2010. Black pentagrams represent trends at the 0.05 probability level.

Spatial distribution of changes in T_{mean} and the relationship to the lengths of summer maize growing phases

The trends in the T_{mean} during the V, VR, R and WG growing phases are shown in Figure 6. On average, there was a general warming trend, with temperature increases of 0.46, 0.07 and 0.12 °C per 10 years for the V, VR and WG phases, respectively; however, a decreasing trend in the T_{mean} was found during the R phase at 18 (66.7%) stations, with temperature decreases of as much as –0.10 °C per 10 years.

The correlation coefficients between T_{mean} and length of the V, VR, R and WG phases were negative (Figures 6b, d, f, h). A negative correlation was found at 22 (81.4%), 24 (88.9%), 26 (96.3%) and 26 (96.3%) stations for the V, VR, R and WG phases, respectively. Furthermore, the lengths of the V, VR, R and WG phases exhibited statistically significant negative correlations with the T_{mean} at 6 (22.2%), 6 (22.2%), 8 (29.6%) and 12 (44.4%) stations, respectively ($P<0.05$).



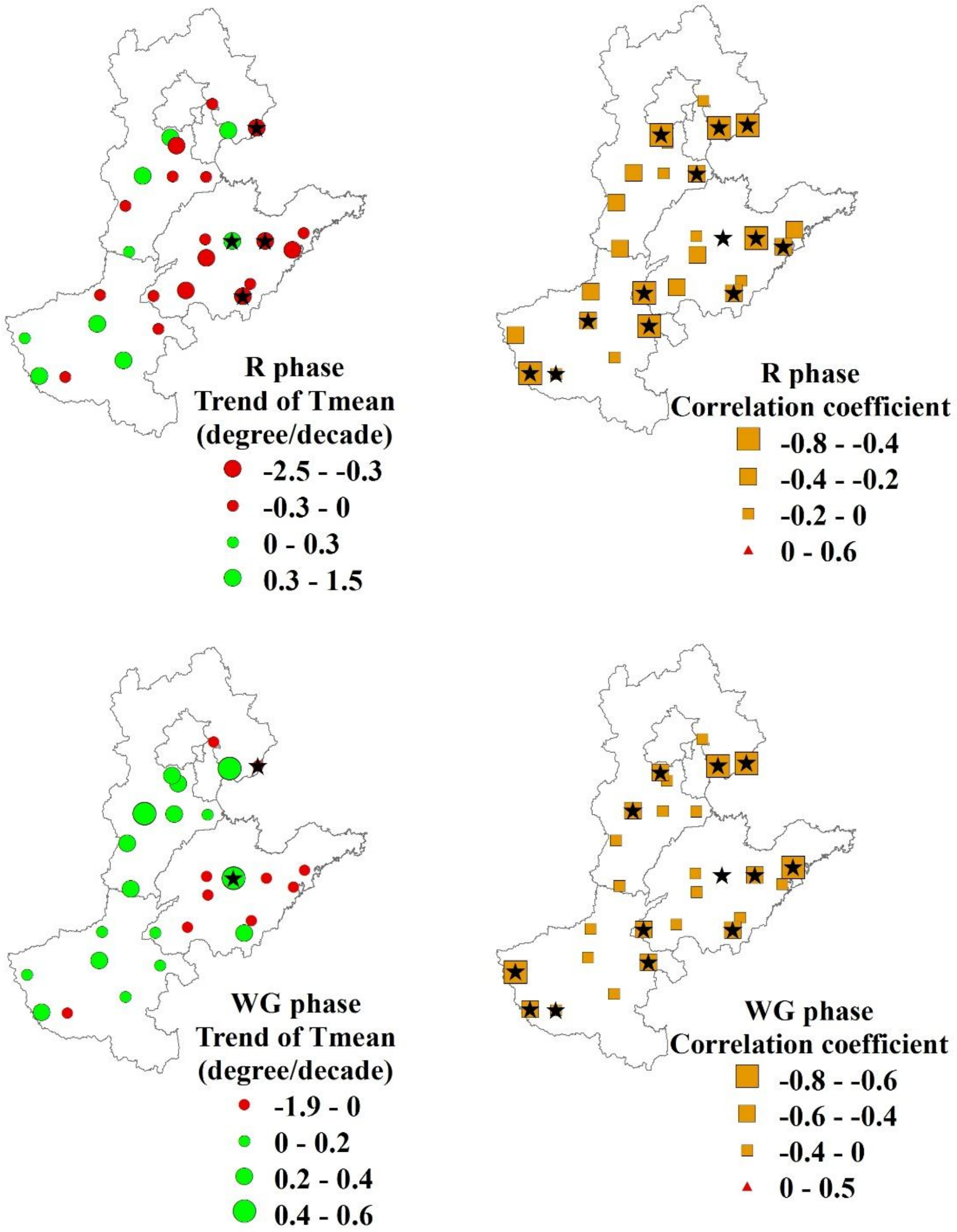
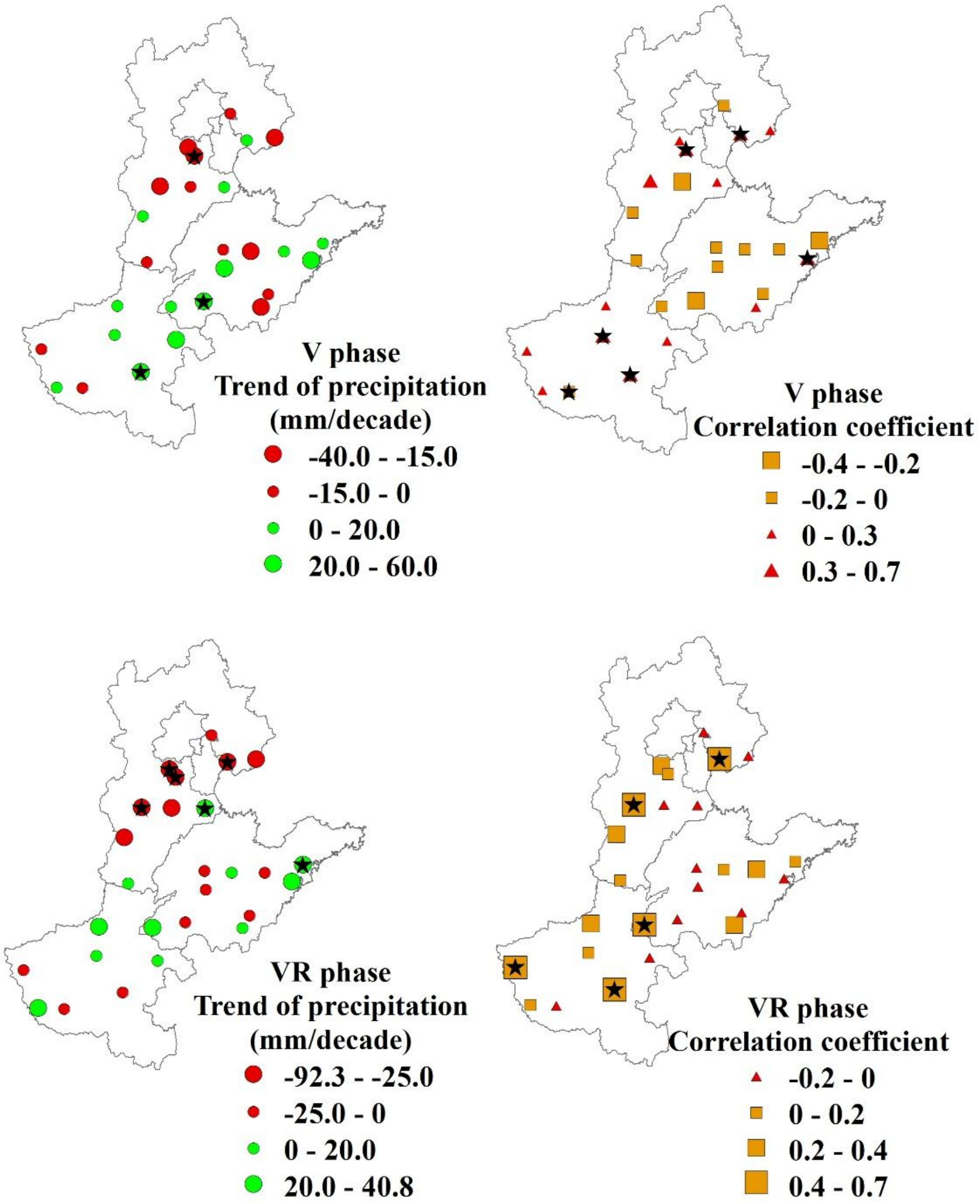


Figure 6. Trends in the T_{mean} during the V, VR, R and WG phases and the correlation between T_{mean} and lengths of the V, VR, R and WG phases across the North China Plain during 1981–2010. Black pentagrams represent significance at the 0.05 probability level.

Spatial distribution of changes in rainfall and the relationship to the lengths of summer maize growing phases

The rainfall trends during the V, VR, R and WG phases are shown in Figure 7. On average, there was a general decreasing trend in rainfall in the northern region. A decreasing trend in rainfall was found at 7 (66.7%), 8 (88.9.7%) and 7 (77.8%) stations at Hebei during the V, VR and WG phases, respectively. However, rainfall in the R phase increased at 18 (66.7%) stations. Nevertheless, the correlation coefficients between rainfall and lengths of the V, VR, R and WG phases were positive. A positive relationship was found between rainfall and phase length at 16 (59.3%), 22 (74.1%), and 18 (66.7%) stations for the VR, R and WG phases, respectively. Furthermore, the lengths of the VR, R and WG phases were significantly and positively correlated with rainfall at 5 (18.5%), 5 (18.5%) and 4 (14.8%) stations, respectively (P<0.05).



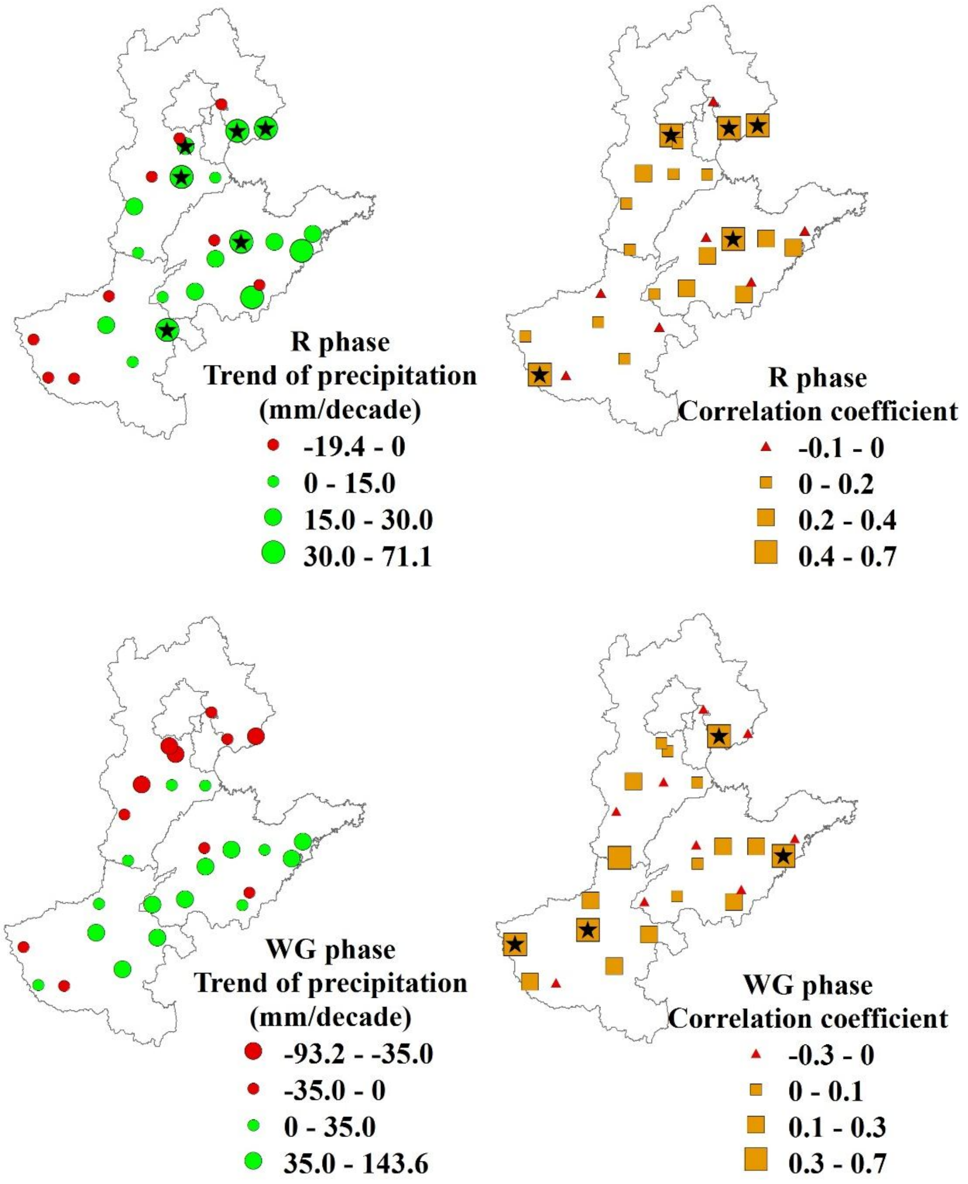


Figure 7. Rainfall trends during the V, VR, R and WG phases and the correlation between rainfall and lengths of the V, VR, R and WG phases across the North China Plain during 1981–2010. Black pentagrams represent significance at the 0.05 probability level.

Impact of cultivar changes on the summer maize growth period duration

Figure 8 shows the changes in the duration of the growth phases of summer maize cultivars representative of cultivars grown during the decades from 1980 to 2010. The durations of the sowing-to-anthesis (~1.3 days/decade), anthesis-to-maturity (~0.8 days/decade) and sowing-to-maturity (~2.2 days/decade) periods increased significantly. These results indicated that changes in cultivars prolonged the WG phase of summer maize.

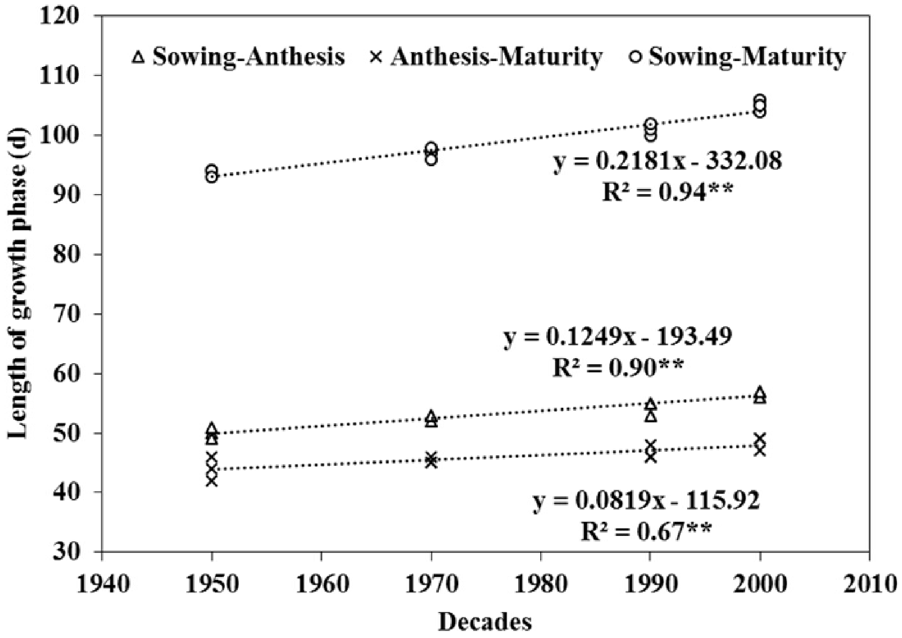


Figure 8. Impact of cultivar eras on the duration of the summer maize growth period. Black pentagrams represent significance at the 0.05 probability level. * and ** indicate that the slope is significant at P = 0.05 and 0.01, respectively.

Discussion

Observed climate-induced changes in summer maize phenology

While crop growth might be accelerated by climate warming, the length of the crop growing period has shortened during the last several decades (Olesen and Bindi, 2002; Deng et al., 2012; Lv et al., 2013). In this study, mean temperatures during the V and VR phases of maize growth increased at most stations, with only 22.2 and 33.3% of the stations, respectively, showing decreasing trends. Furthermore, the lengths of the V and VR phases at most stations showed a negative trend, with increasing lengths at 18 (66.7%) and 17 (63.0%) stations, respectively. In addition, the lengths of the V and VR phases were negatively correlated with mean temperature at most stations. These results indicated that climate warming has accelerated summer maize growth and shortened the length of the growing period in the early stages of maize growth, although changes in farming practices and cultivar maturity over time may have also prolonged the duration of the maize growth period (Tao et al., 2014).

Moreover, the length of the R phase at most stations showed a positive trend. Our study showed that only two stations experienced a reduced length of the R phase. Furthermore, most stations showed a positive trend for the WG phase length. A significant increase in the summer maize WG phase length over the past three decades was found at 5 (18.5%) stations ($P<0.05$), which might be attributed to delayed maturity of the cultivars. A significant delay in summer maize maturity over the past three decades was found at 10 (37.0%) stations ($P<0.05$). In addition, field experiment results showed that cultivars prolonged the growth duration of summer maize. Therefore, these results indicated that farming practices and cultivars have had a relatively strong effect on summer maize phenology by prolonging the maize growing season, which was consistent with Tao et al. (2014).

The T_{mean} during the R phase of maize growth was reduced at most stations and the length of the R phase increased over the past three decades. These not means that the extension of the R phase was due to lower temperatures, because the delay of maturity lead to the changing date of R phase and lowing the T_{mean} during the R phase. These results indicated that changes in farming practices and cultivars resulted in delayed maturity and increased R phase. Furthermore, the lengths of the VR, R and WG phases exhibited significant positive correlations with rainfall. These results suggest that rainfall might influence crop phenology, which might affect the agricultural strategies and policies needed for adaptation to global climate warming.

In general, the results of this study were not consistent with previous research on the effects of temperature, agronomic practices and cultivars on summer maize phenology (Olesen and Bindi, 2002; Shimono, 2011; Deng et al., 2012; Lv et al., 2013). Previous research showed that climate warming might accelerate crop growth and shorten the length of the growing period, whereas the maize growing period duration was actually extended during the past three decades across China in response to the combined effects of changing temperature, agronomic management practices and cultivars. The lengths of the V, VR, R and WG phases were negatively correlated with T_{mean} and the lengths of the R and WG phases were extended. However, the lengths of the V and VR phases became shorter under the combined effects of changing temperature, agronomic management practices and cultivars. This was not consistent with the results of previous studies (Olesen and Bindi, 2002; Deng et al., 2012; Lv et al., 2013).

Impacts of climate change on maize phenology and countermeasures

Increasing temperature could accelerate crop growth and shorten the length of a growing period. These changes might affect grain yield and facilitate planting maize further north, leading to a negative impact on crop yield if the cultivars are replaced (Olesen and Bindi, 2002; Liu et al., 2012; Liu et al., 2013). Therefore, adjusting farming practices and cultivars, such as by adjusting sowing dates and using newer cultivars, would be needed to adapt to these changes.

Furthermore, this study indicated that anthesis occurred earlier as a result of climate warming. The risk of heat damage might be increased by the combination of seasonal temperature changes and crops that are particularly sensitive to extreme heat during the reproductive period. The result could be substantially reduced grain number and yield (Ferris et al., 1998; Wheeler et al., 2002; Gourdji et al., 2013). Therefore, heat resistant varieties and appropriate cultivation practices are needed to reduce the impact of excessive heat. In addition, the shorter V and VR phases and the increased length of the R phase might affect the economic coefficient. At the same time, the farming practices and cultivars also affected the economic coefficient.

Potential limitations of this study

This study investigated the spatiotemporal changes of summer maize phenology and the relationships between summer maize phenology and climate change or cultivars. However, the study did not quantify the impact of climate change or cultivars on summer maize phenology. Changes in phenology occurred in response to the combined effects of temperature, rainfall, agronomic management practices and cultivars. Therefore, the conclusions from this study were limited. Addressing these shortfalls requires further structured experimental approaches, such as factorial experiments or model simulation. Furthermore, this study did not consider the effect of climate change on summer maize yield, we will study it in the future research.

Conclusions

This study investigated the observed climate-induced and cultivar-induced changes in summer maize phenology in the NCP over the past 30 years. The results showed that climate warming could accelerate crop growth and shorten the length of the growing period. Farmers have adopted appropriate farming practices and cultivars in response to climate warming. Therefore, the lengths of the V and VR phases have shortened, while the R and WG phases have become longer in response to the combined effects of temperature, agronomic management practices and cultivars. The results indicated that summer maize production in NCP is adapting to ongoing climate change by adoption of cultivars with longer growing and more longer growing cultivar should be adapt in the future. Furthermore, the changes in summer maize phenology and the increasing risk of heat damage during the R phase support exploration of appropriate agricultural strategies and policies for adaptation to global climate warming in the North China Plain and other areas with similar ecologies.

Acknowledgements

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