Science of the Total Environment 707 (2020) 135638

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Impacts of climate change and crop management practices on soybean phenology changes in China

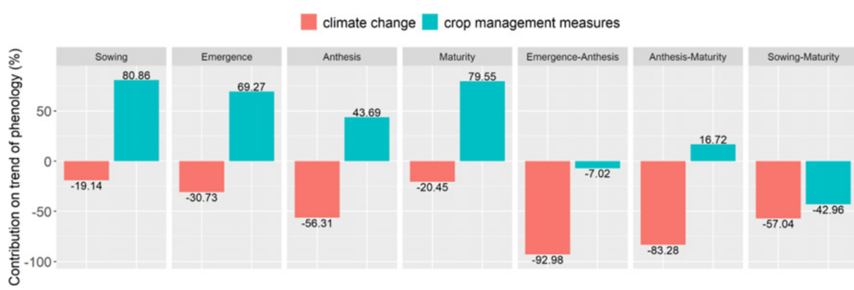
Liang He [a,b,*], Ning Jin [a], Qiang Yu [a,c]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling 712100, China
[b] National Meteorological Center, Beijing 100081, China
[c] School of Life Sciences, University of Technology Sydney, Sydney, NSW 2007, Australia

HIGHLIGHTS

- Trends in soybean phenology in China from 1981 to 2010 were examined.
- Impacts of climate change and crop management on changes in soybean phenology were isolated.
- Crop management accounted for 80.9%, 69.3%, 79.6% of sowing, emergence, maturity trends.
- Mean temperature accounted for >40% of soybean phenology variation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 July 2019
Received in revised form 9 November 2019
Accepted 18 November 2019
Available online 20 November 2019

Editor: Charlotte Poschenrieder

Keywords:
Climate change
Soybean phenology
Crop management
Statistical model

ABSTRACT

Crop phenology is determined by both climatic factors and agronomic management practices such as sowing date and cultivar characteristics. Exploring the interactive effects of climate change and crop management practices on crop phenology can be used to devise adaptation strategies to mitigate climate change. The objectives of this study were to: 1) examined trends in soybean (*Glycine* max L.) phenological development in China from 1981 to 2010; 2) isolate and quantify impacts of climate change and crop management on changes in soybean phenology; 3) determine the relative contribution of climate change and crop management to observed changes in soybean phenology; and 4) determine the relative contribution of temperature, precipitation, and sunshine hours to changes in soybean phenology. Changes in soybean phenology were observed across the major soybean producing area of eastern China during 1981–2010. Observed dates of sowing, emergence, anthesis, and maturity were delayed by an average of 1.78, 0.83, 0.19, and 0.62 days decade^{-1}, respectively. Additionally, the lengths of the vegetative growth period and the soybean growing season were shortened by an average of 0.62 and 1.16 days decade^{-1}, respectively. Conversely, the reproductive period was lengthened by an average of 0.43 days decade^{-1}. Crop management practices had greater influence on sowing, emergence, and maturity dates than climate change. The direction of the changes to phenology trends created by management and climate change were opposite to each other. The relative influence of climate change on dates of anthesis, lengths of the vegetative and reproductive growth periods and growing season was larger than the influence of crop management practices. Mean temperature was the dominant climatic factor influencing most soybean phenological stages and phases. Delayed sowing dates and use of longer-duration cultivars are management adaptations that farmers have used to adapt to climate change occurring in past decades and that can continue to be used.

* Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling 712100, China.
E-mail address: heliang@cma.gov.cn (L. He).

https://doi.org/10.1016/j.scitotenv.2019.135638

These results indicate that farmers have a wider sowing window in spring and can select cultivars with long growing season duration and frost-tolerance to mitigate detrimental effects of a future warmer climate.

1. Introduction

Climate factors such as temperature, precipitation, and solar radiation are important determinants of crop development and yield. Climate change is characterized by increasing temperature, modified precipitation, and increasing frequency of extreme weather events (IPCC, 2007). Increasing temperature generally accelerates crop phenological development and shortens the growing period, which may be reduce crop productivity (Asseng et al., 2015; Asseng et al., 2013; Lobell et al., 2011). Additionally, drought due to decreased precipitation results in a large threat to crop development (Parent and Tardieu, 2014). A better understanding of how crops respond to climate change can provide a scientific basis for adapting to and mitigation of climate change impacts.

Recent studies conducted at local, regional, and continental scales have shown that phenology of both annual and perennial crops was significantly impacted by climate warming. For two examples of perennial crops, Fujisawa and Kobayashi (2010) reported that flowering and budding of apple (*Malus* × *domestica* Borkh.) in Japan occurred earlier due to increasing air temperatures, and Chmielewski et al. (2004) found a similar response for phenological phases of natural vegetation in Germany. A national survey in Germany regarding 78 agricultural and horticultural events indicated that perennial crops responded more significantly to increasing temperature than annual crops (Estrella et al., 2007). Observed heading and flowering dates of wheat (*Triticum aestivum* L.) in the U.S. Great Plains occurred earlier by 0.8–1.8 days decade^{-1} (Hu et al., 2005), and most winter cereal phenophases on the Iberian Peninsula (Oteros et al., 2015) were advanced due to increasing temperature. In China, dates of green-up after winter dormancy, anthesis, and maturity of winter wheat occurred earlier due to a shortened growing period (He et al., 2015; Tao et al., 2012; Wang et al., 2008; Xiao et al., 2013). Length of both the flowering-boll opening and boll opening-harvest periods for cotton (*Gossypium hirsutum* L.) grown on the North China Plain increased due to increasing mean temperature (Wang et al., 2017b). Crop phenology is a widely used indicator for assessing effects of climate and environmental conditions (Xiao et al., 2015).

Crop phenology is affected by both environmental conditions (mainly thermal time requirement) and agronomic management practices, including sowing date and cultivar characteristics (Estrella et al., 2007; He et al., 2015; Liu et al., 2018). Previous studies have shown that changes in sowing date and cultivars used would counteract climate-induced changes in phenology (Abbas et al., 2017; Ahmad et al., 2019; He et al., 2015; Hu et al., 2017; Mo et al., 2016; Tao et al., 2013; Wang et al., 2017a; Xiao et al., 2016b). Moreover, day length was found to slightly counterbalance the effect of temperature on the duration of the vegetative period of rice (*Oryza sativa* L.) (Zhang et al., 2014) and of winter wheat (Tao et al., 2012). The introduction of new cultivars with longer thermal time requirements have compensated for some of the increased temperature-induced changes in wheat phenology in the North China Plain (Wang et al., 2013; Xiao et al., 2013) and the Loess Plateau (He et al., 2015). Zhang et al. (2013) suggested that use of short-duration cultivars has been accelerating the shortened growth duration for late rice, while cultivars with longer duration of the vegetative period have been adopted for single rice (Zhang et al., 2014). Hu et al. (2017) investigated how cultivar shifts compensated for the shortening of the rice growing season induced by climate warming and reported that cultivar shifts contributed 58% and 44% to the shortening of the growth period for single rice and early rice, respectively, but accelerated crop development in late rice with a contribution of −37%. Recent research regarding rice phenology in China indicated that management practices such as transplanting were the predominant drivers of growth period change for early and single rice (Wang et al., 2017a; Zhao et al., 2016). A significant portion of the negative impact of global warming on rice, wheat (Ahmad et al., 2019), sunflower (*Helanthus annuus* L.) (Tariq et al., 2018), cotton (Ahmad et al., 2017b), canola (*Brassica napus* L.) (Ahmad et al., 2017a), maize (*Zea mays* L.) (Abbas et al., 2017), and sugarcane (*Saccharum* spp.) (Ahmad et al., 2016) was offset by growing new cultivars that had higher thermal time requirements or by implementing sowing date changes. The literature sources cited above implied that increasing temperatures would advance crop phenology and shorten growth periods while changing cultivars or sowing dates could either shorten or lengthen growth periods, depending on the specific crop or region. Those studies focused on detecting whether crop phenology changes were caused by rising temperature or by management practices (Tao et al., 2013; Wang et al., 2013; Wang et al., 2017a; Zhang et al., 2013), while crop phenology responses to other climate factors such as precipitation and sunshine hours were not investigated (Liu et al., 2018).

China is the world's largest consumer of soybean. About 100 million tons per year of soybean were consumed in China during the past five years. But only 10% of that amount was produced in mainland China (Zhang et al., 2016). To improve the soybean self-sufficiency rate, the Chinese government planned to revitalize the soybean industry in 2019 and to encourage farmers to plant more soybean. Because soybean yields are much lower in China than in the U.S., Brazil, and Argentina, there is an urgent need to improve soybean production in China. Crop management, cultivar breeding, and climate are the primary factors that affect soybean yield. However, from the literature review presented above, it can be seen that less attention has been given to how climate change affects soybean in China. Those studies have raised the following questions: 1) How has observed soybean phenology changed in China? 2) How do crop management practices (i.e., sowing date and cultivar shifts) and climate change affect soybean phenology in China? 3) What are the relative contributions of temperature, precipitation, and sunshine hours to influencing soybean phenology?

In this study, we examined trends in soybean phenological development in China from 1981 to 2010, and isolated and quantified impacts of climate change and crop management on changes in soybean phenology to answer the above questions. The results of this study should offer insights into how the negative impacts of climate warming on soybean production in China can be mitigated by shifting cultivars and using improved management practices.

2. Materials and methods

2.1. Soybean agro-meteorological stations and data

Soybean cultivation is concentrated in northeast China and the Huang-Huai-Hai Plain, which includes Heilongjiang, Jilin, Liaoning, Hebei, Henan, Anhui provinces et al. More than 80% of China's soybean production is located in these provinces. In this study, 38 soybean agro-meteorological stations were selected (Fig. 1 and Table A1). Phenology records from 1981 to 2010 were available for all 38 stations, operated by the Chinese Meteorological Administration (CMA). Phenology records included dates of sowing, emergence, anthesis (50% anthesis in observed field), and physiological maturity. Using these phenological data, we calculated three phenological phases, i.e. growing season (from sowing to maturity), vegetative growth period (from emergence to anthesis), and reproductive growth period (from anthesis to maturity). Local farmers would change to a new soybean cultivar about

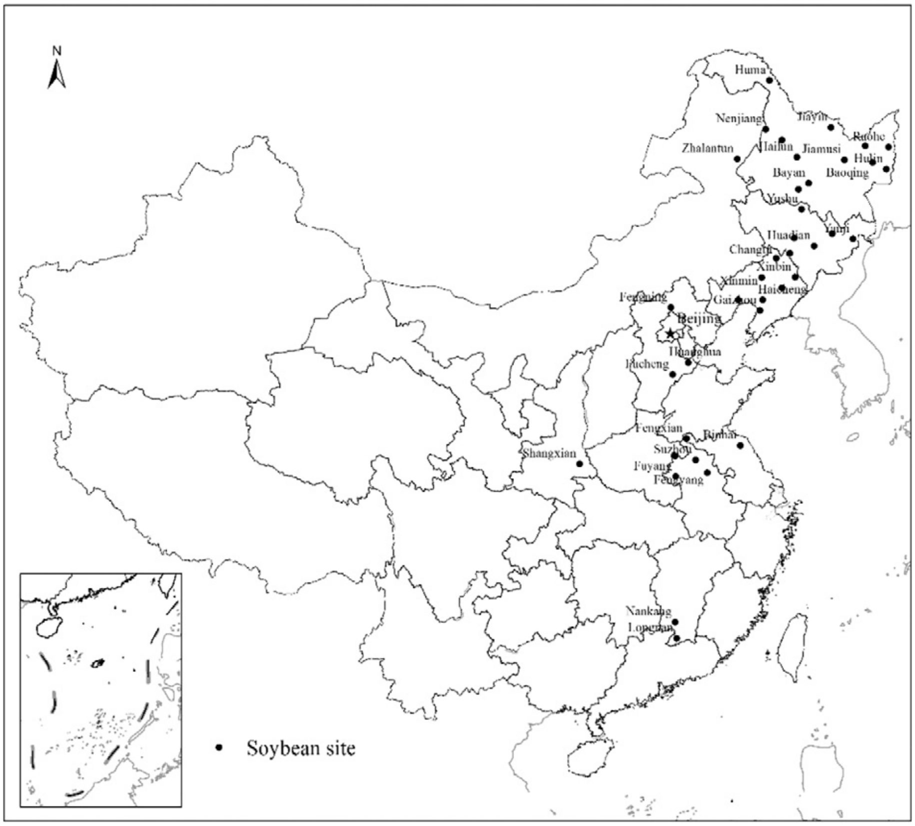


Fig. 1. Locations of soybean agro-meteorological experimental stations used in the current study of eastern China.

every 3–5 years due to cultivar improvement through crop breeding. Crop management practices at the observed soybean stations were generally the same as local traditional practices. Irrigation and fertilizer applications were made several times every year. Pesticides were used to control pests and diseases.

Meteorological data from 1981 to 2010 at the 38 stations were also available from the CMA, and included daily mean temperature, precipitation, and sunshine hours.

2.2. Data analysis method

2.2.1. Trends in observed climate factors and soybean phenology

Trends in observed climate factors were calculated using a linear regression:

$$O_{cli} = Trend_{cli} \times t + \beta_{cli} \quad (1)$$

where O_{cli} is the observed climate factor, such as temperature (O_t), accumulated precipitation (O_p), sunshine hours (O_s); $Trend_{cli}$ is the trend of the observed climate factor, and $Trend_t$(°C decade^{-1}), $Trend_p$(mm decade^{-1}), and $Trend_s$(hr decade^{-1}) represent the trends of temperature, precipitation, and sunshine hours, respectively; t is the year; β_{cli} is the regression intercept. Time windows for calculating climate factor trends were determined by the mean phenological stages at each station. For example, the time window for the growing season was from the mean sowing date to the mean maturity date during the last three decades at each station. By holding a time window of a growing season constant, the calculated climate factor trend was independent of the corresponding phenology changes (He et al., 2015; Liu et al., 2018).

Trends in observed soybean phenology were similarly calculated using a linear regression:

$$O_{phe} = Trend_{phe} \times t + \beta_{phe} \quad (2)$$

Table 1
Mean and standard deviation of observed dates of soybean phenological stages and phases, and climate factors at 38 stations in eastern China from 1981 to 2010.

Phenological stages or phases	Date (DOY[a]) or phase length (days)	T_{mean}[b] (°C)	Pre[c] (mm)	SSH[d] (hr)
Sowing	135 (24)[e]	15.9 (5.3)	72 (68)	224.5 (56.0)
Emergence	149 (22)	18.6 (4.1)	90 (79)	231.8 (61.7)
Anthesis	194 (20)	23.5 (2.6)	149 (83)	211.5 (54.0)
Maturity	262 (24)	15.1 (4.8)	60 (58)	211.0 (39.3)
Emergence-Anthesis	45 (10)	21.6 (3.2)	182 (107)	332.9 (102.1)
Anthesis-Maturity	69 (13)	21.1 (2.7)	267 (114)	477.0 (133.2)
Sowing-Maturity	128 (20)	20.8 (2.9)	473 (163)	910.9 (253.7)

[a] Day of year.
[b] Mean temperature.
[c] Cumulative precipitation.
[d] Cumulative sunshine hours.
[e] Values in parentheses are standard deviations.

Table 2
Observed trends in mean temperature ($Trend_{tem}$), precipitation ($Trend_{pre}$), and sunshine hours ($Trend_{ssh}$) during soybean phenological stages and phases at 38 stations in eastern China from 1981 to 2010.

Phenological stages or phases	$Trend_{tem}$ (°C decade^{-1})	$Trend_{pre}$ (mm decade^{-1})	$Trend_{ssh}$ (hr decade^{-1})
Sowing	0.53	5.01	−3.44
Emergence	0.58	4.14	−2.68
Anthesis	0.23	−1.34	−6.41
Maturity	0.66	−3.41	−3.75
Emergence-Anthesis	0.52	7.87	−6.29
Anthesis-Maturity	0.20	−14.27	2.73
Sowing-Maturity	0.35	−4.93	−4.74

where O_{phe} is the observed soybean phenological phase or stage; $Trend_{phe}$ is the trends of observed soybean phenological phase or stage (days decade^{-1}); t is the year; β_{phe} is the regression intercept.

2.2.2. Isolating impacts of climate change and crop management practices on soybean phenology trends

We assumed that the time series of crop growth consisted of two components. One was the tendency of phenology to vary as a result of technological improvements, such as the use of new varieties, increased use of chemical fertilizers.

and biocides, etc. The other component was the variation in phenology caused by a temporal variation in climate. $Trend_{phe}$ in Eq. (2) is the observed phenology trend, which is the mixed trend response to climate change and management. The phenology trend influenced only by management ($Trend_{phe\_man}$) can be determined as:

$$Trend_{phe\_man} = Trend_{phe} - Trend_{phe\_cli} \quad (3)$$

where $Trend_{phe\_cli}$ is the phenology trend influenced only by climate change.

We used the first-difference method to detrend the influence of long-term trends due to technological improvements or other effects caused by farm management. This created a series of phenological date differences by progressively differentiating the phenological dates of two successive years. This detrending method is a common technique used by many scholars (Liu et al., 2018; Lobell et al., 2005; Yu et al., 2001; Zhang et al., 2013). After detrending the trends of phenology and climate factors, a multiple regression model between phenology and climate factors was determined as:

$$\Delta Phe = S_{temperature}\,\Delta T + S_{precipitation}\,\Delta P + S_{sunshine}\,\Delta S + intercept \quad (4)$$

where ΔPhe is the first-difference value of the phenological phase or stage; ΔT, ΔP and ΔS represent the first-difference values for average temperature, cumulative precipitation, and cumulative sunshine hours for the corresponding period, respectively; $S_{temperature}$(days °C^{-1}), $S_{precipitation}$(days mm^{-1}), and $S_{sunshine}$(days hr^{-1}) indicate the sensitivity of soybean phenology to temperature, precipitation, and sunshine hours, respectively; *intercept* is the regression model intercept.

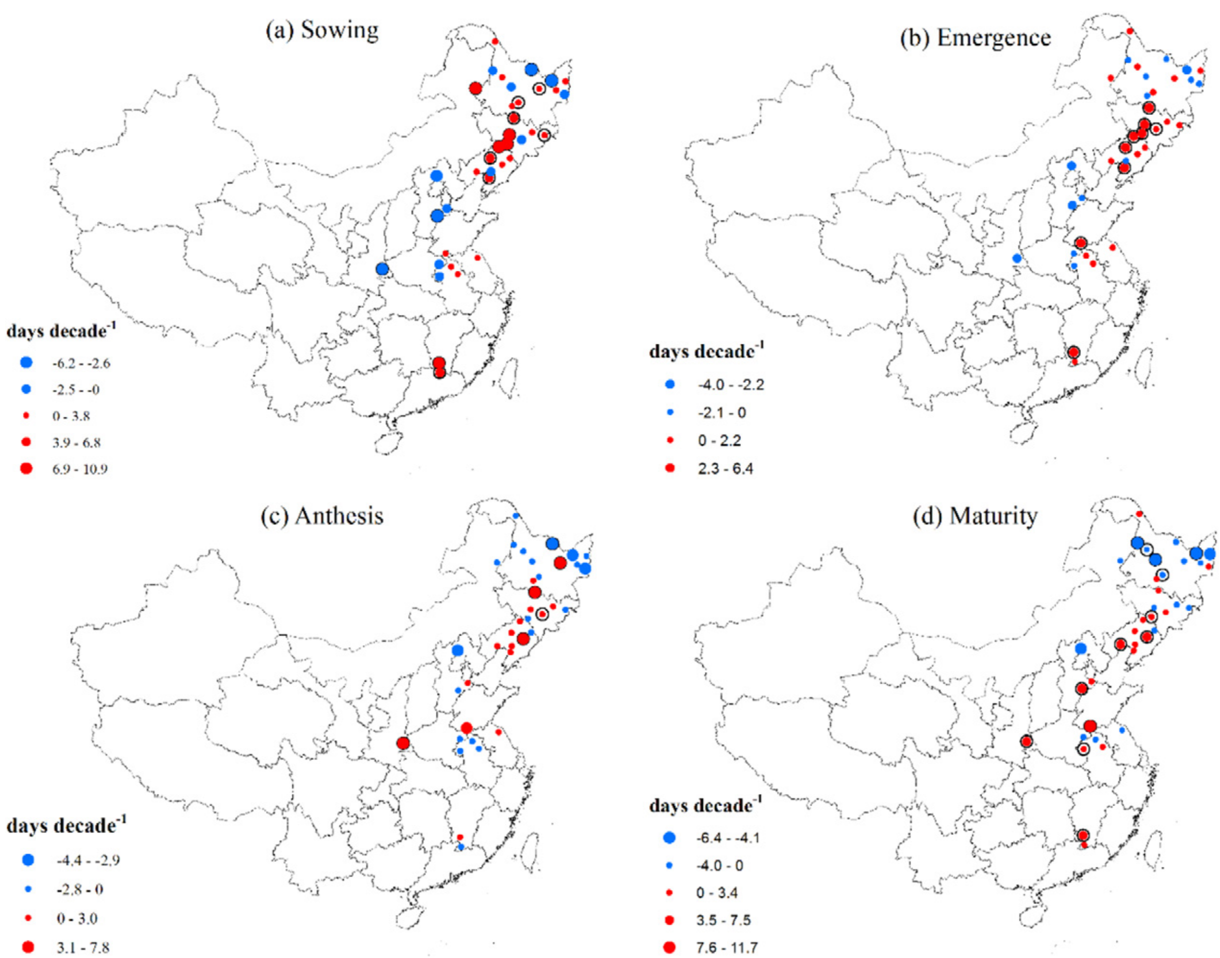


Fig. 2. Observed trends in soybean phenology in eastern China from 1981 to 2010. (a) sowing; (b) emergence; (c) anthesis), and (d) maturity). Black circles indicate statistically significant trends at $p = .05$.

Thus, the phenology trend influenced only by climate change ($Trend_{phe\_cli}$) is calculated as:

$$Trend_{phe\_cli} = S_{temperature}\ Trend_t + S_{precipitation}\ Trend_p + S_{sunshine}\ Trend_s \quad (5)$$

We used a two-sample *t*-test to test the statistical significance of the difference between the mean values of $Trend_{phe}$ and $Trend_{phe\_cli}$ at all 38 stations. When $P < .05$, the difference between $Trend_{phe\_man}$ and $Trend_{phe\_cli}$ was statistically significant.

2.2.3. Relative contribution of each factor to soybean phenology trends

From Eq. (5), phenology trends influenced only by climate change ($Trend_{phe\_cli}$) were obtained for every station. Thus, the relative contribution of temperature ($C_{temperature}$), precipitation ($C_{precipitation}$), and sunshine hours ($C_{sunshine}$) influence on soybean phenology was calculated as follow:

$$C_{temperature} = \frac{S_{temperature}\ Trend_t}{|S_{temperature}\ Trend_t| + |S_{precipitation}\ Trend_p| + |S_{sunshine}\ Trend_s|} \times 100\% \quad (6)$$

where $C_{temperature}$ is the contribution of temperature influence on soybean phenology. In a similar way, the contribution of precipitation ($C_{precipitation}$) and sunshine hours ($C_{sunshine}$) influence on soybean phenology was also calculated by Eq. (6).

For a specific phenological phase or stage, the average relative contribution of average temperature changes ($\overline{C_{temperature}}$) on the soybean system was calculated as:

$$\overline{C_{temperature}} = \frac{\sum_{i=1}^{n} C_{temperature,i}}{\left|\sum_{i=1}^{n} C_{temperature,i}\right| + \left|\sum_{i=1}^{n} C_{precipitation,i}\right| + \left|\sum_{i=1}^{n} C_{sunshine,i}\right|} \times 100\% \quad (7)$$

where n is the number of stations, $C_{temperature,\ i}$, $C_{precipitation,\ i}$, $C_{sunshine,\ i}$ represent the relative contribution of changes in temperature, precipitation, and sunshine hours, respectively, at station *i* from Eq. (6). Similarly, the average relative contribution of changes in precipitation ($\overline{C_{precipitation}}$) or sunshine hours ($\overline{C_{sunshine}}$) on the soybean cropping system can be calculated in the same way.

The relative contribution of climate change (C_{cli}) influence on soybean phenology at every station was calculated as:

$$C_{cli} = \frac{Trend_{phe\_cli}}{|Trend_{phe\_cli}| + |Trend_{phe\_man}|} \times 100\% \quad (8)$$

The variables in Eq. (8) are the same as in Eq. (3). The relative contribution of management (C_{man}) influence on soybean phenology at every station was also similarly calculated using Eq. (8). Thus, the average relative contribution of climate change influence on the soybean system was calculated as:

$$\overline{C_{cli}} = \frac{\sum_{i=1}^{n} C_{cli,i}}{\left|\sum_{i=1}^{n} C_{cli,i}\right| + \left|\sum_{i=1}^{n} C_{man,i}\right|} \times 100\% \quad (9)$$

where n is the number of stations, $C_{cli,\ i}$ and $C_{man,\ i}$ represent the relative contributions of climate change and crop management influence at station *i*. The average relative contribution of management ($\overline{C_{man}}$) influence on the soybean system was calculated using Eq. (9) in a similar way.

2.3. Thermal time calculation

The total thermal time (GDD, °C d) for the growing season (from sowing to maturity) was calculated as:

$$GDD = \sum_{d_s}^{d_m} (T_{mean} - T_{base}) \quad (10)$$

where T_{mean} is the daily mean temperature (°C), T_{base} is the biological lower limit temperature for soybean (10 °C), and d_s and d_m are the sowing and maturity dates, respectively.

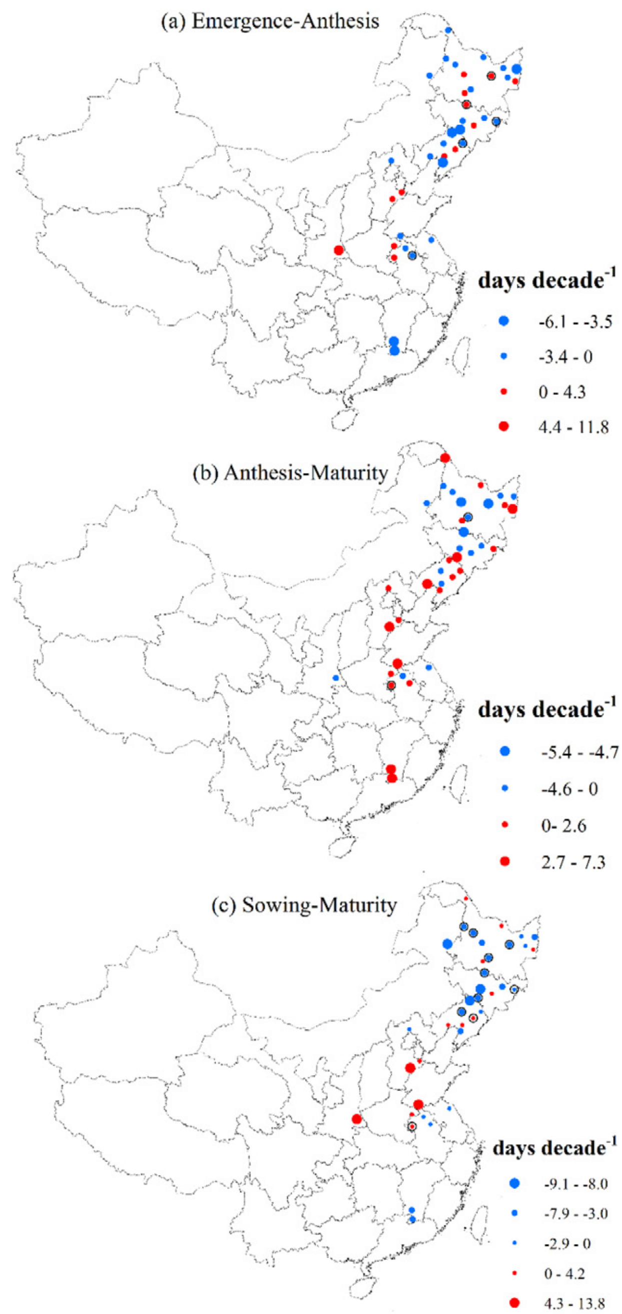


Fig. 3. Observed trends in soybean phenology in eastern China from 1981 to 2010. (a) emergence to anthesis; (b) anthesis to maturity; and (c) sowing to maturity. Black circles indicate statistically significant trends at p = .05.

3. Results

3.1. Climate trends

The mean sowing and maturity dates for soybean in eastern China were at the beginning of May and late of September, respectively (Table 1). The mean temperature, precipitation, and sunshine hours over the growing season were about 20.8 °C, 473 mm, 910.9 h, respectively.

There was a general warming trend of between 0.20 and 0.66 °C decade^{-1} over the observed soybean phenological stages or phases (Table 2). The rates of increase in mean temperature at sowing, emergence, and maturity stages (>0.5 °C decade^{-1}) were larger than at other phenological stages or phases.

The cumulative precipitation at sowing, emergence, and during the vegetative period (emergence-anthesis) tended to increase over time, and the rate of increase ranged between 4.14 and 7.87 mm decade^{-1} (Table 2). In contrast, cumulative precipitation tended to decrease over time at anthesis and maturity and during the reproductive period (anthesis-maturity), and the rate of decrease ranged between 1.34 and 14.27 mm decade^{-1}.

Cumulative sunshine hours decreased over time during the soybean growing season with the rate of decrease ranging from 2.68 to 6.41 h decade^{-1} overall soybean growth stages and phenological phases except during the reproductive development period (anthesis-maturity) when sunshine duration increased at a rate of 2.73 h decade^{-1} (Table 2). This increasing trend in cumulative sunshine hours during the anthesis-maturity phase appears to be directly related to the decreasing trend in precipitation (14.27 mm decade^{-1}) during this reproductive period.

3.2. Trends of soybean phenology stages, phases, and cultivar thermal characteristics

The spatial trends for sowing dates are shown in Fig. 2a. Over the 1981–2010 period, sowing dates were delayed an average of 1.78 days decade^{-1}. A delay (red circles) occurred at 25 stations (delays at 11 stations were statistically significant at $p < .05$). However, sowing dates at the 13 other stations (blue circles) were advanced, but the advance was only significant at three stations. The trends for emergence dates were similar to sowing dates and were likely directly related to trends detected for sowing dates (Fig. 2b). Emergence was delayed at 24 stations (significantly at nine stations), ranging from 0.0 to 6.4 days decade^{-1}. The average delay in emergence date was 0.83 days decade^{-1}. Anthesis dates at 17 stations were delayed (significantly at five stations) while anthesis dates at 21 stations were advanced (significantly only at one station) (Fig. 2c). Similarly, maturity dates were delayed at 20 stations (significantly at eight stations) and advanced at 18 stations (significantly at four stations) (Fig. 2d). Anthesis and maturity dates were delayed by an average of 0.19 and 0.62 days decade^{-1}, respectively.

The length of the soybean vegetative period (emergence-anthesis) (Fig. 3a) decreased by an average of 0.62 days decade^{-1} from 1981 to 2010, with a decreasing trend observed at 25 stations, ranging from 0 to 6.1 days decade^{-1}. The decreasing trend was significant at three stations. Similarly, the length of the reproductive growth period (anthesis to maturity) increased at 21 stations by an average of 0.43 days decade^{-1}. The length of the reproductive growth period decreased at 17 stations, but only significantly at one station. The delay of sowing date (1.78 day decade^{-1}, Fig. 2a) and a lesser delay in maturity date (0.62 day decade^{-1}, Fig. 2d) led to a reduction in the length of the growing season (sowing to maturity) by −1.16 days decade^{-1} (Fig. 3c). The length of the growing season was decreased at 24 stations and the decreasing trend ranged from 0 to −9.1 days decade^{-1}.

The thermal time requirements of soybean (Fig. 4) from sowing to maturity increased at 36 of the 38 observed stations by an average of 57.7 °C d decade^{-1}, ranging from 0.1 to 135.5 °C d decade^{-1} (the increasing trend was significant at 25 stations).

3.3. Sensitivity of soybean phenology to different climatic factors

Sensitivity of soybean phenological stages and phases to climatic factors using the first-difference method as presented in Eq. (4) are shown

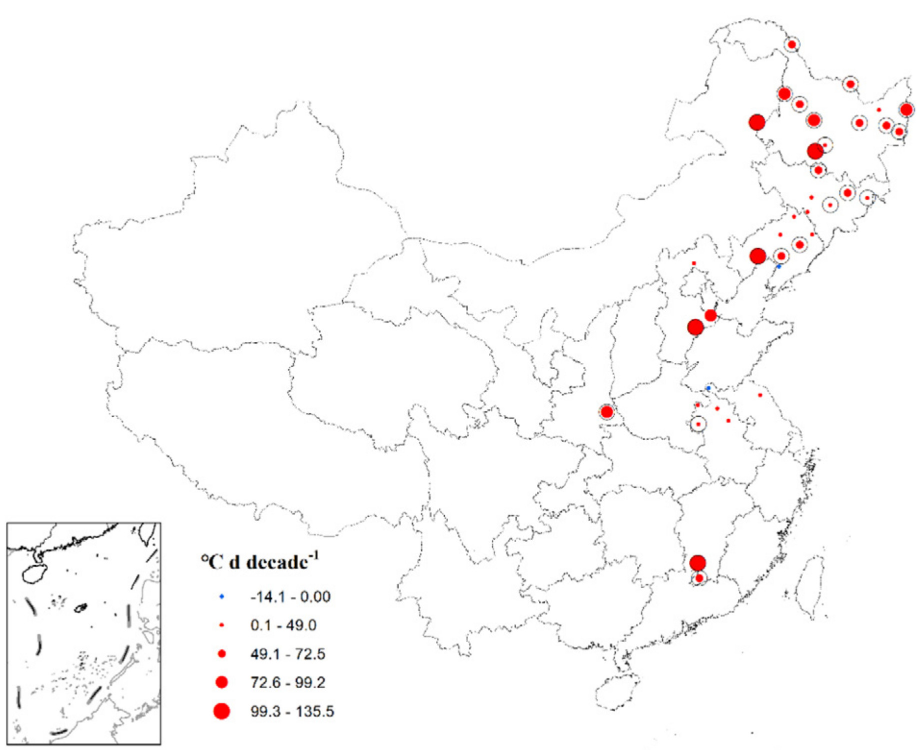


Fig. 4. Observed trends in thermal time required for soybean to grow from sowing to maturity in eastern China (1981–2010). Black circles indicate statistically significant trends at p = .05.

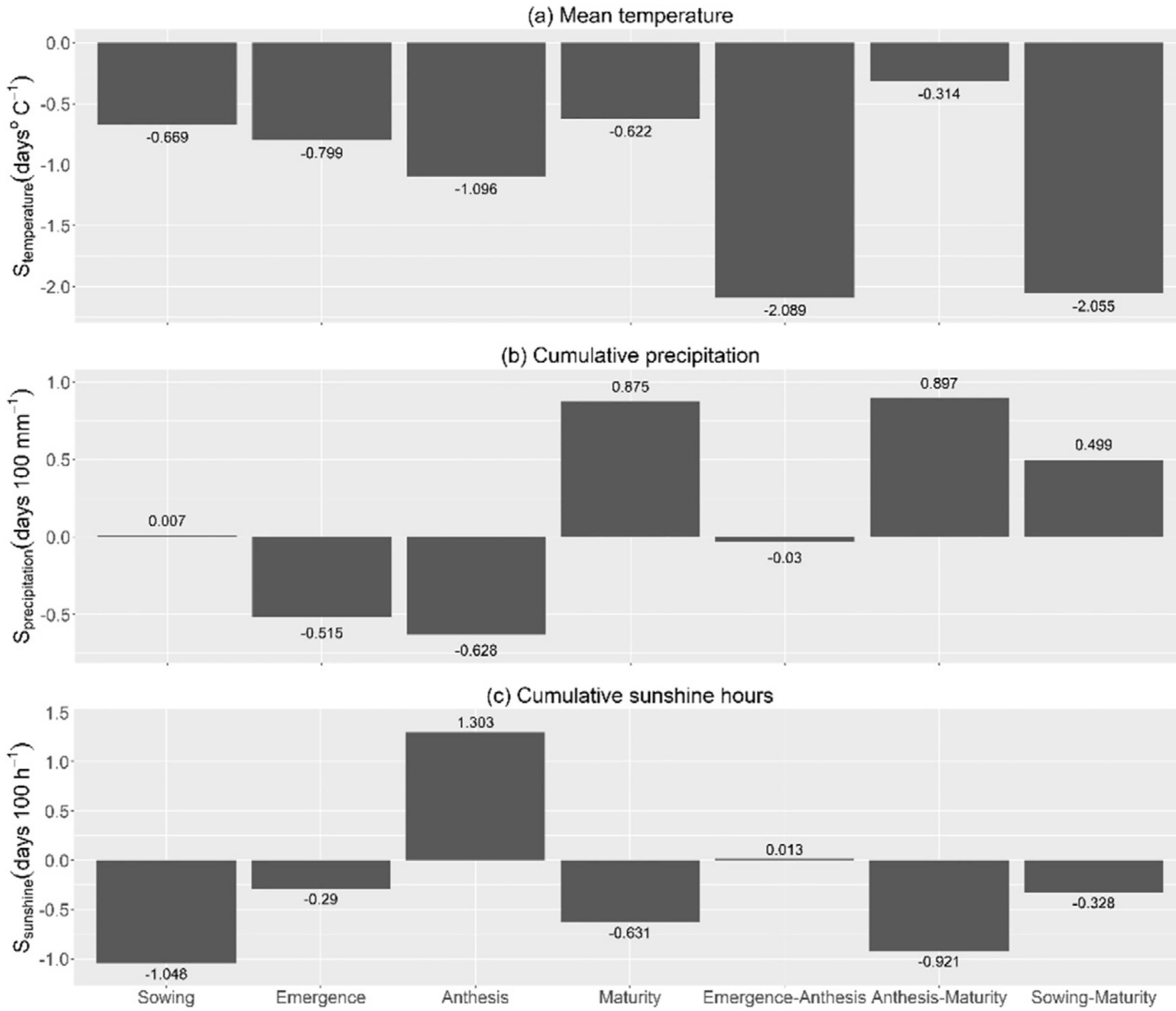


Fig. 5. Sensitivity of soybean phenology to climatic factors in eastern China (1981–2010) using detrended data. Values indicate the mean sensitivity of all stations.

in Fig. 5. On average, all phenological stages or phases showed negative sensitivity to mean temperature. The sensitivity values ranged from −0.314 to −2.089 days °C^{-1}.

Emergence and anthesis dates and the vegetative period (emergence-anthesis) were negatively sensitive to cumulative precipitation, while the sensitivity value during the vegetative period was very small (−0.03 days 100 mm^{-1}). In contrast, sowing and maturity dates and the reproductive period (anthesis-maturity) exhibited positive sensitivity to precipitation.

All soybean phenological stages and phases were negatively sensitive to cumulative sunshine hours expect for anthesis and the vegetative period (emergence-anthesis). Among all phenology stages, the

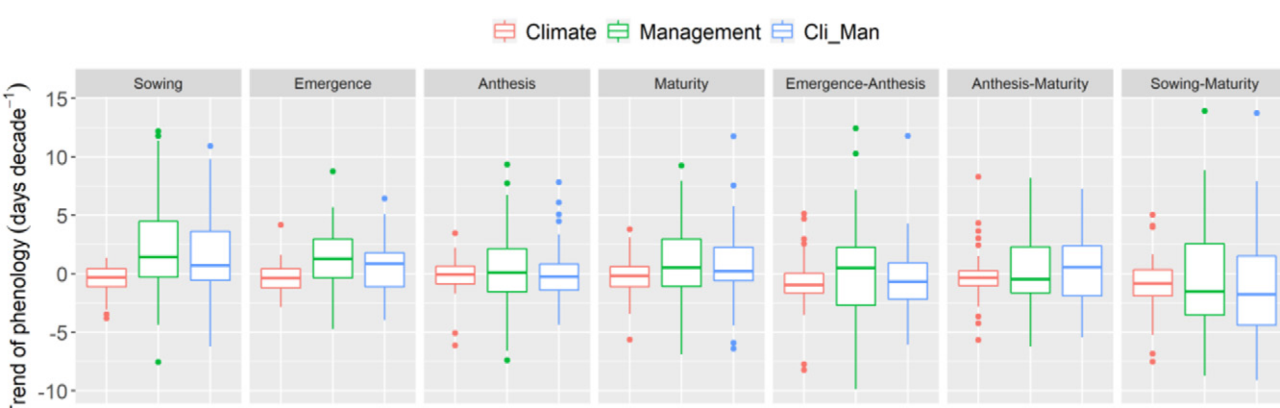


Fig. 6. Whisker plots of trends of soybean phenology for 38 stations in eastern China based on observed and detrended data. Climate denotes impact of climate change parameters on soybean phenology; Management indicates the impact of crop management practices on soybean phenology; and Cli_man indicates the combined impacts of climate change and crop management on soybean phenology. The top and bottom sides of the whisker plot box represent the 75th and 25th percentiles, the line within the box is the median, and the filled circles represent outliers.

Table 3
Comparison of soybean phenology trends under the combined and single factors of climate change and management in eastern China.

Phenological stages or phases	$Trend_{phe}$[a] (days dacade^{-1})	$Trend_{phe\_cli}$[b] (days dacade^{-1})	$Trend_{phe-man}$[c] (days dacade^{-1})	t-Test (*p*-value)
Sowing	1.78	−0.5	2.28	0.00**
Emergence	0.83	−0.4	1.23	0.01**
Anthesis	0.19	−0.26	0.45	0.38
Maturity	0.62	−0.26	0.88	0.18
Emergence-Anthesis	−0.62	−0.77	0.15	0.82
Anthesis-Maturity	0.43	−0.12	0.55	0.37
Sowing-Maturity	−1.16	−0.88	−0.28	0.75

[a] Soybean phenology trends as affected by climate change and management.
[b] Soybean phenology trends as affected only by climate change.
[c] Soybean phenology trends as affected only by management.
** Significant at 0.01 probability level.

sensitivity of anthesis date to cumulative sunshine hours was largest (1.303 days 100 h^{-1}).

3.4. Impacts of climate change and crop management on soybean phenology

Fig. 6 illustrates the individual and combined impacts of climate change and management practices on the trends of soybean phenology at four growth stages (sowing, emergence, anthesis, and maturity) and during three growing season phases. The variations of trends of soybean phenology only influenced by climate change were smaller than those influenced by management or combined impacts at all growth stages and growing season phases. According to Table 3 and Fig. 6, the mean or median values of trends of soybean phenology influenced only by climate change were negative, which indicated that soybean phenology was advanced or length of growing season was shortened under the influence of climate change. Sowing, emergence, anthesis, and maturity were delayed, and the vegetative period and growing season were shortened under the combined impacts of climate change and management, while the reproductive period was lengthened (Table 3). Trends of all growth stages or lengths of growth phases under crop management alone were advanced or prolonged except for length of the growing season (sowing to maturity) (Table 3). The combined effects and isolated climatic effect were significantly different for sowing and emergence.

Fig. 7 shows the average relative contribution of climate change and crop management influences to the observed soybean phenology trend ($Trend_{phe}$). Negative values in the figure indicate that climate change or crop management changes advanced phenology or shortened a growth phase, and positive values indicate that climate change or crop management delayed phenology or lengthened a growth phase. The relative contributions of climate change to trends in sowing, emergence, anthesis, and maturity dates, and length of the anthesis-maturity period were negative while the contribution of management was positive. The impacts of climate change and management on length of the emergence-anthesis period, and length of the growing season were negative. The relative contributions of management on sowing, emergence, and maturity date trends were larger than the contributions of climate change. However, the contributions of climate change to trends in anthesis date and lengths of the emergence-anthesis, anthesis-maturity, and growing season periods were larger than the contributions of management. In particular, during the emergence-anthesis and anthesis-maturity periods, climate change accounted for 92.98% and 83.28%, respectively, of the phenology trend.

3.5. Comparison of impacts of temperature, precipitation, and sunshine hours on soybean phenology

The relative contribution of each climate factor to trends of changes to growth stages and phenological phases are illustrated in Fig. 8. The relative contributions varied among the three climate factors because of different sensitivity of phenology to each climate factor (Fig. 5). The contribution of mean temperature was largest and negative for all three factors at all four growth stages and the emergence-anthesis and sowing-maturity phenological phases. The negative values indicated that increasing temperatures advanced stages or shortened phenological phases. The contribution of precipitation was largest (46.62%) for the anthesis-maturity phase while it was the smallest in the other phenological stages and phases. Number of sunshine hours was a positive contributor to the trends of sowing and emergence dates and the length of the anthesis-maturity period and growing season. Sunshine hours were a negative contributor to the trends of anthesis and maturity dates and the length of the emergence-anthesis period.

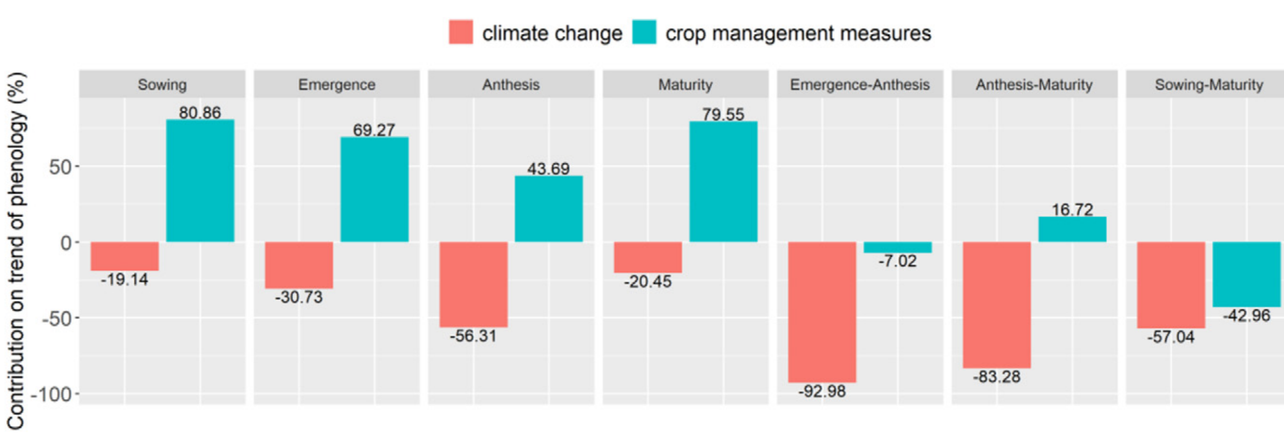


Fig. 7. Average relative contribution of climate change and crop management on observed phenology trend (Trendphe) for soybean grown in eastern China (1981–2010). Values indicate the mean percentage of all stations.

4. Discussion

4.1. Comparison of the impacts of climate change and crop management practices, and the implications for adaptation

The results of this study indicated that soybean phenology was influenced by climate change and management practices at 38 locations in eastern China. Anthesis and maturity dates were more often observed to be delayed, which was different from previous studies conducted with winter wheat (He et al., 2015; Liu et al., 2018; Xiao et al., 2013), maize (Xiao et al., 2016a), spring wheat (Xiao et al., 2016b), and other agricultural crops (Hu et al., 2005; Siebert and Ewert, 2012). However, the length of the growing season and the vegetative period were shortened while length of the reproductive period was lengthened, which was consistent with earlier studies with winter wheat (He et al., 2015; Tao et al., 2012; Xiao et al., 2013) and spring wheat (Xiao et al., 2016b). The observed soybean phenological stages were not advanced even though the temperature increased significantly at all stages and during all phenological phases in the past three decades. The negative sensitivity coefficients between temperature and phenology (Fig. 5) indicated that increased temperature would accelerate soybean anthesis and maturity. However, crop management outweighed or counteracted climate change effects at sowing, emergence, anthesis, and maturity (Fig. 7). Crop management factors mainly included two practices, i.e., changing sowing dates and soybean cultivar characteristics, which are important adaption strategies in response to climate change. Observed sowing dates at most stations occurred significantly later by an average of 1.78 days decade $^{-1}$, which has also been reported for winter wheat (He et al., 2015; Xiao et al., 2013) in China, and for canola (Ahmad et al., 2017a) and autumn maize (Abbas et al., 2017) in Pakistan. Increasing spring temperatures did not result in farmers sowing soybean earlier in eastern China because soil moisture also influenced sowing date decisions. From Fig. 2a in can be seen that sowing dates were delayed at 19 stations in eastern China (significantly at 10 stations). The reason for delayed sowing date was precipitation changes during the sowing month. Farmers in the Northeast China often begin sowing after a soaking spring rain. However, the first soaking rain during the spring sowing month in Northeast China had exhibited a delayed trend during the past decades (Xu and Li, 2016). On the other hand, the crop growing season has increased and the frost risk during autumn has decreased due to increasing temperature (Chu et al., 2017). Thus, farmers can sow soybean later in order to wait for a soaking rain because they only plant a single crop each year. Cultivar shifts also played an important role in crop phenology. In our study, the increasing thermal time requirements during the soybean growing season indicated that the introduction of soybean cultivars with high thermal-time requirements during 1981–2010 partially influenced the changing climate effect on soybean phenology. Similar results of using cultivars adapted to climate change were reported for winter wheat in the China (He et al., 2015; Xiao et al., 2013), rice in China (Tao et al., 2013), corn in the U.S. corn belt (Sacks and Kucharik, 2011), and maize and sunflower in Pakistan (Ahmad et al., 2017a; Tariq et al., 2018). In contrast, a short-duration, early-flowering late rice cultivar was bred for accelerated phenology in order to avoid terminal drought risk (Hu et al., 2017; Zhang et al., 2013). In response to increasing temperatures, farmers could plant longer-duration soybean cultivars to counteract the negative impacts of climate change. On the other hand, lower frost risk during autumn associated with increasing temperatures in the eastern China has caused farmers to select varieties with greater total degree days in order to better utilize the temperature resource.

4.2. Mean temperature influences soybean phenology more than other climate factors

Among the three climatic factors investigated in this study, the major contributor influencing soybean phenology (>40%) was mean temperature. Additionally, the values of the temperature contributions (Fig. 8) and sensitivity of temperature on phenology trends (Fig. 5a) were negative, which meant that increasing temperature would cause soybean stages to be advanced or growth phases to be shortened. Our findings supported results published in previous studies (Ahmad et al., 2019; Estrella et al., 2007; He et al., 2015; Hu et al., 2005; Xiao et al., 2013; Xiao et al., 2016b). For the entire growing season period (sowing-maturity), temperature's contribution accounted for 85.29% of the phenology trend (Fig. 8). Zhang et al. (2016) reported field experiment results that showed that a 0.4 °C increase in air temperature within the soybean canopy and a 0.7 °C increase in soil temperature within the canopy shortened the length of entire growing season by 4.5 days. The negative value of sensitivity of sunshine hours on soybean maturity (Fig. 5c) indicated that anthesis was delayed because of an increase in sunshine hours, a result of soybean being a short-day plant. However, the contribution of cumulative precipitation during the reproductive period was largest influence on phenology trend (Fig. 8) among the three climatic factors, and these results should be further explored.

It is expected that the climate will be warmer in the future than in past decades (IPCC, 2013). The annual average temperature in eastern China (the main soybean producing area) is projected to increase by approximately 2 °C under RCP4.5 and 3 °C under RCP8.5 by 2010. Additionally, the cumulative temperature will increase by 400–700 °C d by 2100 (Chu et al., 2017). The increasing temperature will accelerate soybean phenology development and provide a greater heat resource for crop development. Accordingly, for the single-soybean system, farmers can select cultivars with long growing season requirements and frost

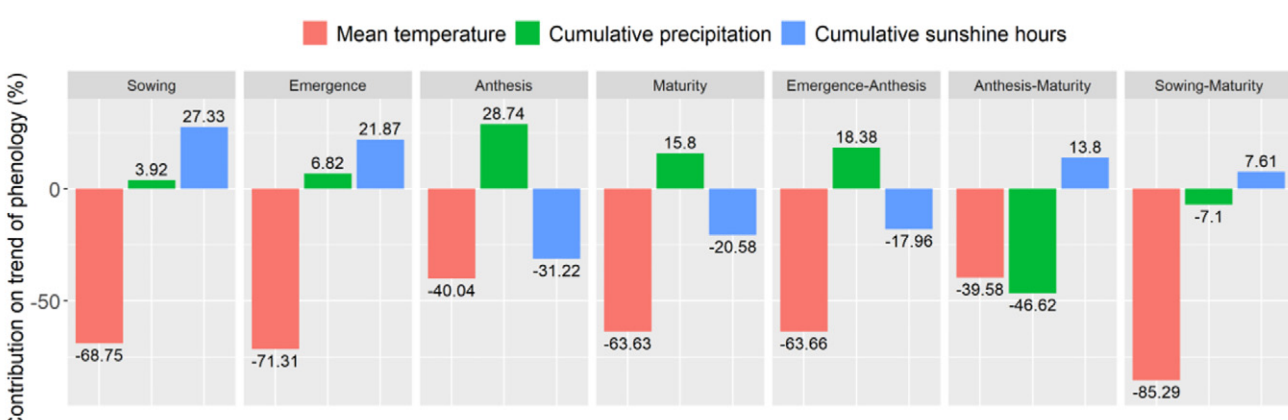


Fig. 8. Average relative contribution of each climate factor on trends of soybean phenology affected only by climate change (Trendphe_cli) in eastern China (1981–2010). Values indicate the mean percentage of all stations.

tolerance and have a feasible spring sowing window to mitigate future climate change.

4.3. Uncertainties

It is difficult to isolate the impacts of climate change from crop management. Two approaches that have been used are statistical methods (Hu et al., 2005; Liu et al., 2018; Zhang et al., 2013; Zhao et al., 2016) and crop models (Abbas et al., 2017; He et al., 2015; Hu et al., 2017; Mo et al., 2016; Wang et al., 2017a). Whether one method is better than the other one is uncertain. Process-based crop models can dynamically simulate the interactions between crops, environmental conditions, and management practices, but they need more information for model calibration and validation than statistical methods, and have uncertainties regarding model parameters and structures. We acknowledge that there were uncertainties in the statistical method used in our study, including our assumption that crop management (technical improvement) changes occurred gradually, such that the crop management-driven phenology change was taken as a constant. A general limitation of regression models (Eq. (4)) is that only the apparent relationships between phenology and climatic factors are identified. Such relationships are not always causal. Additionally, climatic variables in a regression model must have mechanistic meaning as climatic factors are correlated with each other. Collinearity among climate variables is the most difficult and common issue to consider when choosing climate variables, as this collinearity can cause difficultly in distinguishing the true contributions of different climatic factors.

5. Conclusions

Observed soybean phenology in China has changed between 1981 and 2010 due to climate change and crop management. Sowing, emergence, anthesis, and maturity dates at most sites tended to be delayed. The length of the emergence-anthesis and sowing-maturity periods at most sites was shortened and the length of anthesis-maturity period at most stations was lengthened. The relative contributions of climate change and crop management to the trends in soybean phenology were different. The relative contributions of management to trends in sowing, emergence, and maturity dates were 80.9%, 69.3%, and 79.6%, respectively, and were greater than the relative contributions of climate change, and the directions of the effects on trends were opposite. Mean temperature, which accounted for >40% of the phenology changes, was the dominant climatic factor affecting changes of most soybean phenological stages and phases. Delaying sowing dates and using cultivars with higher total degree day requirements would be two important management practices to mitigate detrimental effects of climate change. With future climate warming, farmers have a larger feasible spring sowing window and can select cultivars with long growing seasons and frost tolerance in order to mitigate some of the detrimental effects of future climate change and to maintain or increase soybean production in China.

Declaration of competing interest

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

Acknowledgements

We gratefully acknowledge the support of Natural Science Foundation of China (No. 41730645, No. 41705095), the International Partnership Program of the Chinese Academy of Sciences (161461KYSB20170013), Chinese Academy of Sciences "Light of West China" Program, Special-Fund of talents (Thousand Talents Program) in Northwest A&F University (Z111021701).

Appendix A

Table A1
Information regarding soybean sites in eastern China.

No.	Station name	Province	Latitude (°N)	Longitude (°E)	Elevation (m)
1	Zhalantun	Neimenggu	48.0	122.7	306.5
2	Huma	Heilongjiang	51.7	126.6	173.9
3	Nenjiang	Heilongjiang	49.2	125.2	242.2
4	Wudalianchi	Heilongjiang	48.5	126.2	266.8
5	Jiayin	Heilongjiang	48.9	130.4	90.4
6	Hailun	Heilongjiang	47.5	127.0	239.2
7	Fujin	Heilongjiang	47.2	132.0	66.4
8	Bayan	Heilongjiang	46.1	127.4	134.1
9	Jiamusi	Heilongjiang	46.8	130.3	82.0
10	Baoqing	Heilongjiang	46.3	132.2	83.0
11	Raohe	Heilongjiang	46.8	134.0	54.4
12	Hadongbin	Heilongjiang	45.9	126.6	118.3
13	Hulin	Heilongjiang	45.8	133.0	100.2
14	Yushu	Jilin	44.9	126.5	196.5
15	Shuangyang	Jilin	43.6	125.6	219.5
16	Donghua	Jilin	43.4	128.2	524.9
17	Liaoyuan	Jilin	42.9	125.1	252.9
18	Huadian	Jilin	43.0	126.8	263.3
19	Yanji	Jilin	42.9	129.5	257.3
20	Changtu	Liaoning	42.8	124.1	165.1
21	Xinmin	Liaoning	42.0	122.9	30.9
22	Jinzhou	Liaoning	41.1	121.1	65.9
23	Benxixian	Liaoning	41.3	124.1	258.9
24	Xinbin	Liaoning	41.7	125.1	328.4
25	Haicheng	Liaoning	40.9	122.7	25.3
26	Gaizhou	Liaoning	40.4	122.4	24.8
27	Fengning	Hebei	41.2	116.6	735.1
28	Huanghua	Hebei	38.4	117.3	4.5
29	Fucheng	Hebei	37.9	116.2	18.6
30	Shangxian	Shannxi	33.9	110.0	742.2
31	Fengxian	Jiangsu	34.7	116.6	40.1
32	Binhai	Jiangsu	34.0	119.8	4.1

Table A1 (*continued*)

No.	Station name	Province	Latitude (°N)	Longitude (°E)	Elevation (m)
33	Bozhou	Anhui	33.9	115.8	37.7
34	Suzhou	Anhui	33.6	117.0	25.9
35	Fuyang	Anhui	32.9	115.7	32.7
36	Fengyang	Anhui	32.9	117.6	24.6
37	Nankang	Jiangxi	25.7	114.8	127.0
38	Longnan	Jiangxi	24.9	114.8	206.3

References

Abbas, G., et al., 2017. Quantification the impacts of climate change and crop management on phenology of maize-based cropping system in Punjab, Pakistan. Agric. For. Meteorol. 247, 42–55.

Ahmad, S., et al., 2016. Quantification of the effects of climate warming and crop management on sugarcane phenology. Clim. Res. 71 (1).

Ahmad, S., et al., 2017a. Quantification of the impacts of climate warming and crop management on canola phenology in Punjab, Pakistan. Journal of Agronomy & Crop Science 203.

Ahmad, S., et al., 2017b. Quantification of climate warming and crop management impacts on cotton phenology. Plants 6 (1).

Ahmad, S., et al., 2019. Climate warming and management impact on the change of phenology of the rice-wheat cropping system in Punjab, Pakistan. Field Crop Res. 230, 46–61.

Asseng, S., Ewert, F., Rosenzweig, C., et al., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Chang. 3, 827–832. https://doi.org/10.1038/nclimate1916.

Asseng, S., Ewert, F., Martre, P., et al., 2015. Rising temperatures reduce global wheat production. Nat. Clim. Chang. 5, 143–147. https://doi.org/10.1038/nclimate2470.

Chmielewski, F.-M., Müller, A., Bruns, E., 2004. Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. Agric. For. Meteorol. 121 (1), 69–78.

Chu, Z., Guo, J., Zhao, J., 2017. Impacts of future climate change on agroclimatic resources in Northeast China. J. Geogr. Sci. 27 (9), 1044–1058.

Estrella, N., Sparks, T.H., Menzel, A., 2007. Trends and temperature response in the phenology of crops in Germany. Glob. Chang. Biol. 13 (8), 1737–1747.

Fujisawa, M., Kobayashi, K., 2010. Apple (Malus pumila var. domestica) phenology is advancing due to rising air temperature in northern Japan. Glob. Chang. Biol. 16 (10), 2651–2660.

He, L., et al., 2015. Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. Agric. For. Meteorol. 200, 135–143.

Hu, Q., Weiss, A., Feng, S., Baenziger, P.S., 2005. Earlier winter wheat heading dates and warmer spring in the U.S. Great Plains. Agric. For. Meteorol. 135 (1), 284–290.

Hu, X., Huang, Y., Sun, W., Yu, L., 2017. Shifts in cultivar and planting date have regulated rice growth duration under climate warming in China since the early 1980s. Agric. For. Meteorol. 247, 34–41.

IPCC, 2007. Climate change 2007: Synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, p. 446.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)], Cambridge, United Kingdom and New York, NY, USA, in pressin press.

Liu, Y., et al., 2018. Modelling the impacts of climate change and crop management on phenological trends of spring and winter wheat in China. Agric. For. Meteorol. 248, 518–526.

Lobell, D.B., et al., 2005. Analysis of wheat yield and climatic trends in Mexico. Field Crop Res. 94 (2), 250–256.

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Science 333 (6042), 616–620.

Mo, F., et al., 2016. Phenological responses of spring wheat and maize to changes in crop management and rising temperatures from 1992 to 2013 across the Loess Plateau. Field Crop Res. 196, 337–347.

Oteros, J., García-Mozo, H., Botey, R., Mestre, A., Galán, C., 2015. Variations in cereal crop phenology in Spain over the last twenty-six years (1986–2012). Clim. Chang. 130 (4), 545–558.

Parent, B., Tardieu, F., 2014. Can current crop models be used in the phenotyping era for predicting the genetic variability of yield of plants subjected to drought or high temperature? J. Exp. Bot. 65 (21), 6179–6189.

Sacks, W.J., Kucharik, C.J., 2011. Crop management and phenology trends in the U.S. Corn Belt: impacts on yields, evapotranspiration and energy balance. Agric. For. Meteorol. 151 (7), 882–894.

Siebert, S., Ewert, F., 2012. Spatio-temporal patterns of phenological development in Germany in relation to temperature and day length. Agric. For. Meteorol. 152, 44–57.

Tao, F., Zhang, S., Zhang, Z., 2012. Spatiotemporal changes of wheat phenology in China under the effects of temperature, day length and cultivar thermal characteristics. Eur. J. Agron. 43, 201–212.

Tao, F., et al., 2013. Single rice growth period was prolonged by cultivars shifts, but yield was damaged by climate change during 1981–2009 in China, and late rice was just opposite. Glob. Chang. Biol. 19 (10), 3200–3209.

Tariq, M., et al., 2018. The impact of climate warming and crop management on phenology of sunflower-based cropping systems in Punjab, Pakistan. Agric. For. Meteorol. 256–257, 270–282.

Wang, H.L., et al., 2008. Phenological trends in winter wheat and spring cotton in response to climate changes in northwest China. Agric. For. Meteorol. 148 (8), 1242–1251.

Wang, J., Wang, E., Feng, L., Yin, H., Yu, W., 2013. Phenological trends of winter wheat in response to varietal and temperature changes in the North China Plain. Field Crop Res. 144, 135–144.

Wang, X., et al., 2017a. Management outweighs climate change on affecting length of rice growing period for early rice and single rice in China during 1991–2012. Agric. For. Meteorol. 233, 1–11.

Wang, Z., et al., 2017b. Response of cotton phenology to climate change on the North China Plain from 1981 to 2012. Sci. Rep. 7 (1), 6628.

Xiao, D., et al., 2013. Observed changes in winter wheat phenology in the North China Plain for 1981–2009. Int. J. Biometeorol. 57 (2), 275–285.

Xiao, D., et al., 2015. Spatiotemporal variability of winter wheat phenology in response to weather and climate variability in China. Mitig. Adapt. Strateg. Glob. Chang. 20 (7), 1191–1202.

Xiao, D., et al., 2016a. Impact of warming climate and cultivar change on maize phenology in the last three decades in North China Plain. Theor. Appl. Climatol. 124 (3), 653–661.

Xiao, D., Tao, F., Shen, Y., Qi, Y., 2016b. Combined impact of climate change, cultivar shift, and sowing date on spring wheat phenology in Northern China. Journal of Meteorological Research 30 (5), 820–831.

Xu, S., Li, D., 2016. Characteristics of the first soaking rain in Northeast China and its response to surface heat source over the Tibetan Plateau. Meteorological Monthly 42 (3), 271–279.

Yu, Q., Hengsdijk, H., Liu, J.D., 2001. Application of a progressive-difference method to identify climatic factors causing variation in the rice yield in the Yangtze Delta, China. Int. J. Biometeorol. 45 (2), 53–58.

Zhang, T., Huang, Y., Yang, X., 2013. Climate warming over the past three decades has shortened rice growth duration in China and cultivar shifts have further accelerated the process for late rice. Glob. Chang. Biol. 19 (2), 563–570.

Zhang, S., Tao, F., Zhang, Z., 2014. Rice reproductive growth duration increased despite of negative impacts of climate warming across China during 1981–2009. Eur. J. Agron. 54, 70–83.

Zhang, L., Zhu, L., Yu, M., Zhong, M., 2016. Warming decreases photosynthates and yield of soybean [Glycine max (L.) Merrill] in the North China Plain. The Crop Journal 4 (2), 139–146.

Zhao, H., et al., 2016. Timing of rice maturity in China is affected more by transplanting date than by climate change. Agric. For. Meteorol. 216, 215–220.