Agricultural Systems 224 (2025) 104260

Contents lists available at ScienceDirect

Agricultural Systems

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

Cultivar shifts have offset climate warming impacts on soybean phenology in China since 1981

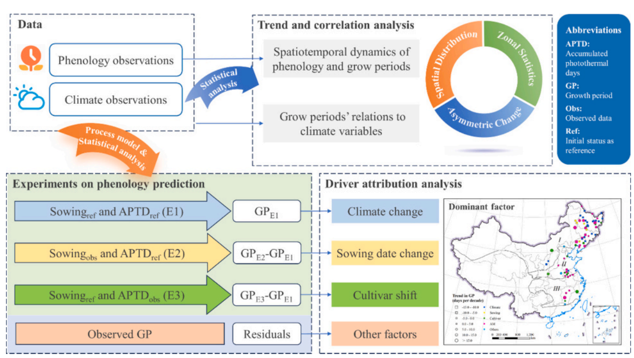
Qinghang Mei [a,b,c], Zhao Zhang [a,b,*], Jichong Han [a,b,d], Jie Song [a,b,d], Fei Cheng [a,b,c], Huimin Zhuang [a,b], Huaqing Wu [e], Jialu Xu [a,b]

[a] *Joint International Research Laboratory of Catastrophe Simulation and Systemic Risk Governance, Beijing Normal University, Zhuhai 519087, China*
[b] *School of National Safety and Emergency Management, Beijing Normal University, Beijing 100875, China*
[c] *Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China*
[d] *School of Systems Science, Beijing Normal University, Beijing 100875, China*
[e] *State Key Laboratory of Marine Environmental Science, College of Ocean and Earth Sciences, Xiamen University, Xiamen 361104, China*

HIGHLIGHTS

- Process and statistical models are integrated to investigate soybean phenological changes.
- Asymmetric changes in phenology are indicated between 1981 and 2000 and 2001–2020.
- Phenology is more sensitive to sunshine than to temperature and precipitation.
- Cultivar shifts offset the impacts of climate warming on the duration of soybean growth.
- The impacts of climate on soybean phenology have weakened in the last two decades.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Leonard Rusinamhodzi

Keywords:
Crop phenology
Climate change
Cultivar shift
Agricultural management
Asymmetric change

ABSTRACT

CONTEXT: Crop phenology is a critical ecological indicator reflecting the impact of climate change on agricultural systems. As soybean is one of the most important economic crops in China, investigating the dynamics and drivers of soybean phenology is essential for developing adaptation options.

OBJECTIVE: The objectives of this study are to investigate the trends in key soybean phenological stages and growth periods across China from 1981 to 2020, understand their responses to various climatic factors, and disentangle the contributions of different climatic and anthropogenic factors between the cooler (1981–2000) and the warmer (2001−2020) periods.

METHODS: The latest and comprehensive observations, including phenological and climatic information, at 71 agro-meteorological stations across China from 1981 to 2020 were used. By using the Decision Support System for Agrotechnology Transfer–CROPGRO (DSSAT-CROPGRO) crop phenology mechanism model and statistical methods, we first analyzed the spatiotemporal dynamics of soybean phenology, and then disentangled the

* Corresponding author at: Joint International Research Laboratory of Catastrophe Simulation and Systemic Risk Governance, Beijing Normal University, Zhuhai 519087, China.

E-mail address: zhangzhao@bnu.edu.cn (Z. Zhang).

https://doi.org/10.1016/j.agsy.2024.104260
Received 15 May 2024; Received in revised form 24 December 2024; Accepted 30 December 2024
Available online 4 January 2025

contributions of different climatic and anthropogenic factors to changes in the growth period through factorial simulation experiments.

RESULTS AND CONCLUSIONS: The overall trends in all the soybean phenological dates were delayed, with the growth period (GP) slightly shortened. On average, climate change shortened the GP by 1.7 days/decade from 1981 to 2020, whereas cultivar shifts extended the GP by 3.1 days/decade, offsetting the negative impact of climate change. The impacts of climate on soybean phenology significantly weakened from 2001 to 2020 relative to 1981–2000. The shortening of the GP by climatic drivers decreased from 5.9 to 1.3 days/decade, whereas the GP elongation by cultivar shifts decreased from 6.7 to 3.3 days/decade.

SIGNIFICANCE: Our findings reveal the trends in soybean phenology and its drivers in China over the past 40 years, and deepen the understanding of the impacts of climate change and the adaptation of soybean production, providing a solid foundation for the development of climate change adaptation options.

1. Introduction

As a sensitive indicator of climate change impacts, phenology has been widely used to quantify climate change in recent decades (Tang et al., 2016; Walther et al., 2002). For example, global warming has significantly modified the phenology of vegetation, primarily by accelerating phenological events, which is a normal response of the self-adaptability of organisms to the environment (Cohen et al., 2018; Ge et al., 2015; Menzel et al., 2006). Compared with those of natural vegetation, such as forests and grasslands, the phenological dynamics of agricultural crops are influenced not only by climatic variations but also by anthropogenic factors, which makes crop dynamics in phenology a major challenge (Estrella et al., 2007; Mo et al., 2016; Wu et al., 2019). Understanding the responses of crop phenology to climate change, along with exploring the effects of human interventions, is crucial for ensuring the sustainability of agricultural production and developing scientific adaptation strategies to address climate change, but these responses and effects are still unclear (Fatima et al., 2020; Li et al., 2021; Liu et al., 2021).

Previous studies have revealed trends in crop phenology and their responses to both climatic factors and human management activities. The temperature and photoperiod are key factors in regulating these phenological processes (Flynn and Wolkovich, 2018; Xiao et al., 2021). Specifically, climate warming has generally led to a reduction in crop growth periods, although their responses varied by crops (Estrella et al., 2007; Mo et al., 2016). Human management and technology enhance crop adaptability by adjusting the photothermal requirements through cultivar renewal; moreover, field management activities (e.g., changing sowing dates) can also change the growth environment of crops. However, the impacts of climatic and anthropogenic factors on phenology vary by crop type, geographical area, and studying period, and consistent findings have yet to be obtained (Ahmed et al., 2020; Azmat et al., 2021; Eyshi Rezaei et al., 2017; Fatima et al., 2022). Quantifying the compensatory effects of these anthropogenic activities against climate change is essential for understanding the capability of crop adaptation.

As one of the most significant cash crops, the responses of soybean phenology have been studied by various methods. However, these studies are often constrained by the limited years and sites. For example, some studies have conducted indoor-chamber experiments to investigate the effects of temperature, photoperiod, and their interactions on soybean development across different varieties (Mathur et al., 2024; Wu et al., 2015). However, such shorter periods and smaller locations hugely limit the studies on quantifying the effects of climate change (usually $\geq$30 years) on soybean phenology. Moreover, many previous studies have not assessed the impacts of human interventions (e.g. variety renewing) on crop phenology. To comprehensively explore the impacts of both natural and human factors on soybean phenology, the approach integrating field experiments and statistical models together has been widely applied to quantify the effects of sowing dates and varieties on soybean phenology worldwide (Bateman et al., 2020; Chen and Wiatrak, 2010; Junior et al., 2015; Kessler et al., 2020; Rowntree et al., 2014). The combined approach help overcome the limitations of indoor-chamber experiments to some extent, however, it remains highly labor-intensive, leaving the impact assessments over a larger region a big challenge. More recently, larger-scale observations and satellite products have used to explore the phenological responses to various environmental factors (He et al., 2020; Liu and Dai, 2020; Tan et al., 2021; Xiao et al., 2021; Zhang et al., 2021). However, these impact assessments still focused on local observations during a limited period (usually <30 years). Soybean cultivation in China covers vast areas with significant climate and environmental variability, leading to different phenological responses across regions (Li et al., 2008). A limited time span can lead to unrepresentative conclusions, and using observational data over a broader space and longer periods can yield more generalizable results. Recent research has indicated that the impacts of climate warming on plant phenology have decelerated or even reversed since around 1999 (Fu et al., 2015; Piao et al., 2019). It is unknown whether the weakened effects of climate change on natural vegetation will have similar effects on soybean phenology. Existing research has not yet addressed the impact of the recent slowdown in climate change on soybean phenology. Therefore, it is necessary to segment the study period to explore potential asymmetric changes in phenology and their responses.

Additionally, a consensus on the sensitivity of soybean phenology to climatic factors and the related dominant drivers has not been reached. A recent study (1981–2010) revealed that the mean temperature dominated soybean phenological changes and that the impact of climatic on the growth period was greater than that of management measures (He et al., 2020). Conversely, another study suggested that crop management practices (1992–2011) contributed more to changing phenology than did climate change (Liu and Dai, 2020). This inconsistency may arise from their statistical methods, which often overlook the underlying mechanisms of phenological changes (de Los Campos et al., 2020; Zhang et al., 2013). Given the intrinsic interactions between human and climatic factors, together with very limited observation samples, it is challenging to isolate the different impacts of various drivers by using only statistical methods (Abbas et al., 2017; Tao et al., 2022). This suggests that using only statistical methods to assess the contributions of different drivers to changes in soybean phenology may be unreliable, as the results are heavily dependent on data quality and quantity. To overcome this limitation, integrating long-term comprehensive observations with carefully calibrated process models has proven to be an effective approach for distinguishing the impacts of different drivers, including diverse agricultural management practices (Lobell and Asseng, 2017; Luo et al., 2022; Tao et al., 2022). In previous studies, different crop models have been used to simulate soybean phenology and its response to climate factors, with the Decision Support System for Agrotechnology Transfer–CROPGRO (DSSAT-CROPGRO) performing superior compared with other similar models, such as SoySim and HERMES (Sima et al., 2020; Sun et al., 2022). The integration of process models can not only be used to address the limitations of field experiments but also provide more objective and reliable results regarding the response of soybean phenology and its key driving factors, addressing the inconsistencies among sensitivity analyses and contribution separations both derived only from the statistical models (Wang et al., 2018).

We firstly complied the latest and most comprehensive dataset, including 2033 soybean phenological records at 116 agro-meteorological stations and the corresponding daily climate data across China from 1981 to 2020, and then combined DSSAT–CROPGRO process model simulation and statistical methods to (1) analyze the spatiotemporal dynamics of soybean phenology and growth periods separately from 1981 to 2000 and 2001–2020 to investigate whether the slowdown in climate change has decelerated or even reversed the phenological patterns; (2) compare the responses of growth periods to different climatic variables; and (3) disentangle the impacts of climate change, cultivar shifts, and sowing date adjustments to find the dominant factors controlling soybean phenology.

2. Materials and methods

2.1. In-situ phenology and climate observations

Phenological observation data were obtained from 116 soybean agro-meteorological stations (AMSs) across China, spanning the years 1981 to 2020, which included key phenological phases: sowing, emergence, anthesis, seed filling, and maturity. Each phenological date was observed and recorded by well-trained agricultural technicians on alternate days or once a day, and then checked and managed by the Chinese Agricultural Meteorological Monitoring System. With a total of 2033 records, this dataset represents the most up-to-date spatially and temporally extensive soybean phenological dataset available in China. We selected stations with more than 10 years of observations for analysis, including 71 stations (Fig. 1). The factors, including geographical and climatic conditions, sowing season type, maturity group, and photoperiod-temperature response characteristics, all show important impacts on soybean agroecological division (Song et al., 2023; Wang and Gai, 2002), together with their actual distribution, we categorized them into three agroecological zones: the Northeast Spring Soybean Zone (Zone I), the Huang-Huai Summer Soybean Zone (Zone II), and the Southern Spring–Summer Soybean Zone (Zone III). The soybeans in Zones I and II are typically sown in May and June, respectively. Zone III encompasses a more diverse planting schedule, allowing for sowing in both spring (March and April) and summer (June and July), catering to different cropping systems within this zone (Fig. 1). The daily mean temperature, precipitation, and sunshine hours were obtained from the corresponding meteorological stations across China and sourced from the National Meteorological Data Center (https://data.cma.cn/). We calculated the annual mean temperature (T_{mean}), cumulative precipitation (P_{sum}), and cumulative sunshine hours (S_{sum}) during the growth periods of the soybeans at each station.

2.2. Calculating the temperature and APTDs during the soybean growth period

The growing period (GP) of soybeans is defined as the phase from sowing to maturity. This includes the vegetative growth period (VGP, from emergence to anthesis), and the reproductive growth period (RGP, from anthesis to maturity). The mean dates of emergence, anthesis and maturity at each station from 1981 to 2020 are shown in supplementary Fig. S1. Accumulated photothermal days (APTDs) refer to the cumulative photothermal requirements a specific soybean cultivar needs to achieve a certain developmental stage, reflecting its sensitivity to the photoperiod and temperature (Messina et al., 2006; Salmerón and Purcell, 2016). Hence, variations in APTDs indicate changes in cultivar characteristics. We use the mechanism of DSSAT–CROPGRO phenology model to calculate the APTDs of soybeans (Jones et al., 2003). The APTDs are the aggregate of the daily photothermal days (PTDs), which is calculated as follows:

$$APTD = \sum_{i=1}^{d} PTD_i \tag{1}$$

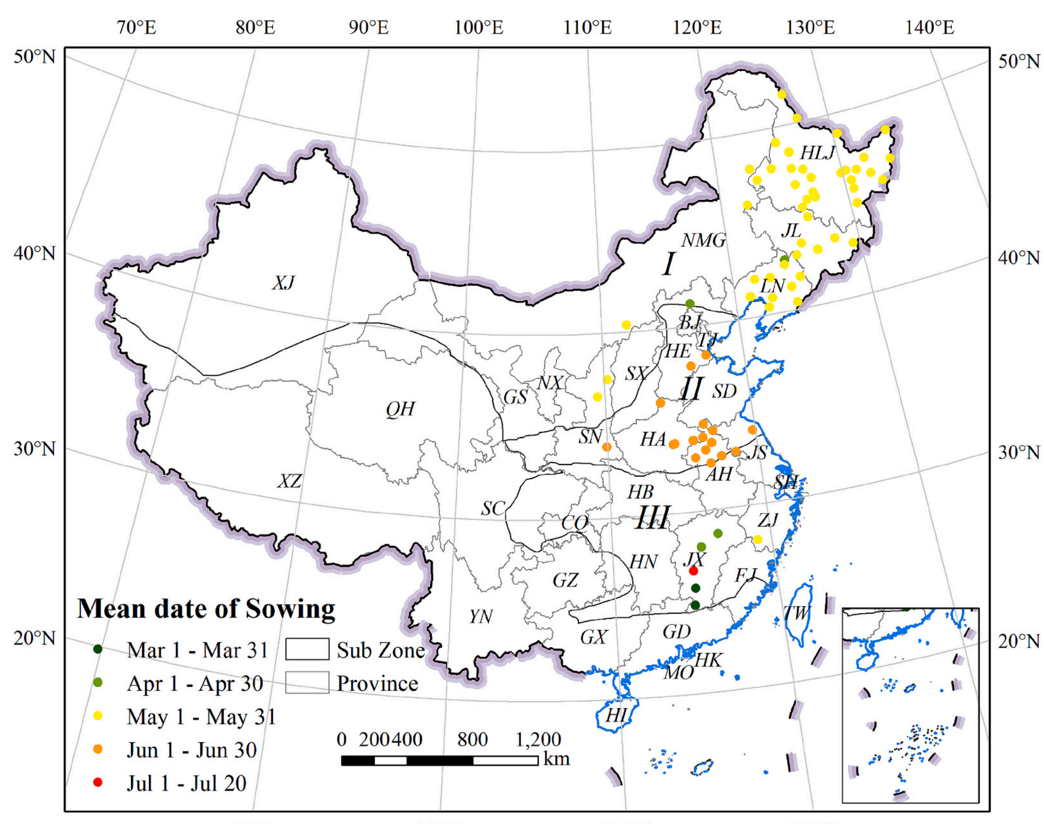


Fig. 1. Locations of agro-meteorological stations in each agro-ecological zone for soybean phenology observations and the mean date of sowing.

$$PTD = f(T) \times f(P) \tag{2}$$

$$f(T) = \begin{cases} 0, T_{mean} \leq T_{base} \text{ or } T_{mean} \geq T_{max} \\ \dfrac{T_{mean} - T_{base}}{T_{opt1} - T_{base}}, T_{base} < T_{mean} < T_{opt1} \\ 1, T_{opt1} \leq T_{mean} \leq T_{opt2} \\ \dfrac{T_{max} - T_{mean}}{T_{max} - T_{opt2}}, T_{opt2} < T_{mean} < T_{max} \end{cases} \tag{3}$$

$$f(P) = \begin{cases} 1, DL \leq CSDL \\ \dfrac{CLDL - DL}{CLDL - CSDL}, CSDL < DL < CLDL \\ 0, DL \geq CLDL \end{cases} \tag{4}$$

$$CLDL = CDSL + \frac{1}{PPSEN} \tag{5}$$

where T_{mean} is the daily mean temperature, T_{base} is the base temperature, T_{max} is the maximum temperature above which development ceases, and T_{opt1} and T_{opt2} are the lower and upper optimum temperatures, respectively. *CSDL* is the critical short-day length below which the crop develops at a maximum rate. *CLDL* is the critical long day length above which development ceases. *PPSEN* is the photoperiod sensitivity coefficient. *DL* is the daily day length estimated as a function of the day of year (DOY) and the latitude at a certain station (Allen and Food and Agriculture Organization of the United Nations, 1998; Thompson, 1998):

$$DL = \begin{cases} 24, r \leq -1 \\ \dfrac{24}{\pi} \times cos^{-1} r, -1 < r < 1 \\ 0, r \geq 1 \end{cases} \tag{6}$$

$$r = -tan\varnothing \times tan\delta \tag{7}$$

$$\delta = 0.39637 - 22.9133 \times cos\frac{2 \times \pi \times n}{365} + 4.02543 \times sin\frac{2 \times \pi \times n}{365}$$
$$-0.3872 \times cos\frac{4 \times \pi \times n}{365} + 0.52 \times sin\frac{4 \times \pi \times n}{365} \tag{8}$$

where r is the solar hour angle for a specific day, $\varnothing$ is the observer's geographic latitude (in radians), δ is the solar declination (in radians), and n is the day of the year (DOY).

Soybeans exhibit no photoperiod sensitivity from sowing until emergence, with only temperature being a relevant factor during this initial phase. After the emergence stage, the calculated PTD is segmented into three growth stages: vegetative (emergence to anthesis), early reproductive (anthesis to seed filling), and late reproductive (seed filling to maturity). The temperature sensitivity across all the cultivars is notably uniform; however, their sensitivity to the photoperiod varies among the different cultivars. We selected the DSSAT genetic coefficients (critical short-day length (CSDL) and photoperiod sensitivity coefficient (PPSEN)) for maturity groups (MGs) MG 0, MG I, and MG II, which are predominantly cultivated in Zones I, II, and III, respectively (Li et al., 2017; Wang et al., 2016). Given the relatively small changes in genetic parameters within the same maturity group, together with

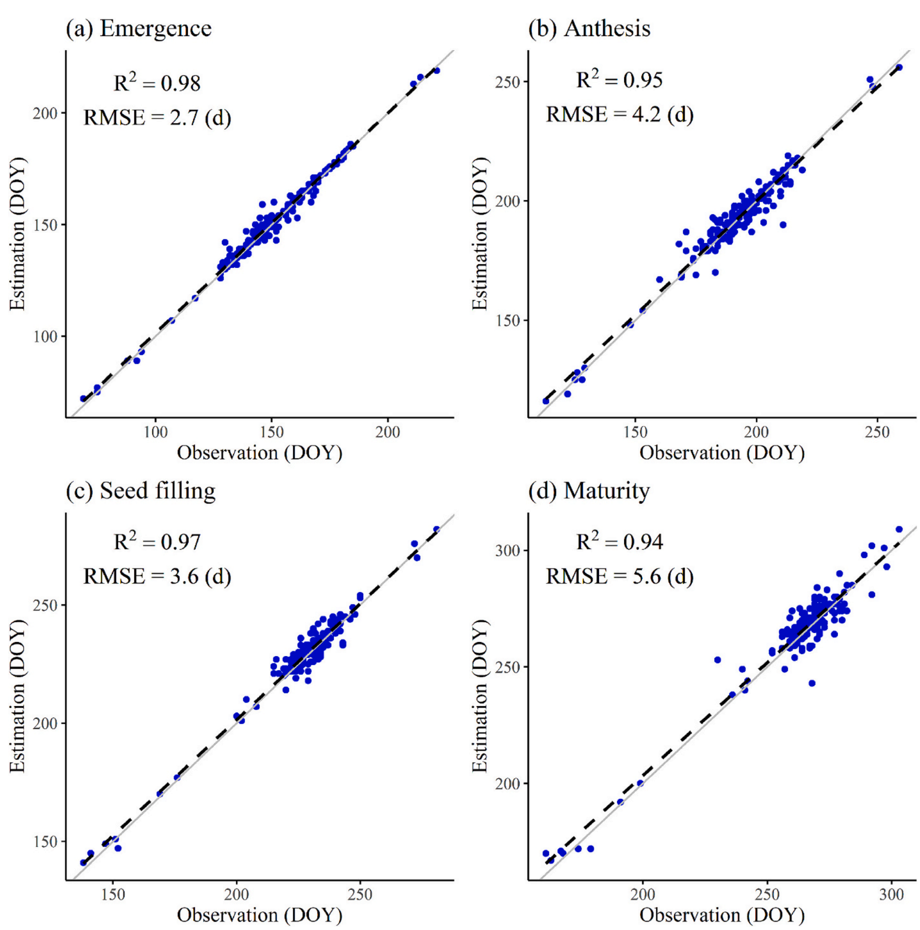


Fig. 2. Validation of the methods and parameters used to calculate the APTDs and estimating dates of emergence (a), anthesis (b), seed filling (c), and maturity (d) in reference years across the study stations.

APTDs also charactering the group's variability (with the validations further supporting their acceptability and robustness because of the minimal errors (Fig. 2)), we assume that the genetic parameters remain stable throughout the study period to ensure the comparability of the findings. We obtained temperature-related parameters and photoperiod parameters for each maturity group from the DSSAT Cropping System Model Documentation (Jones et al., 2003). The values for the temperature function and the photoperiod function at each growth stage are detailed in Table 1. Considering the diversity of cultivar varieties at the different stations, we used the average APTDs derived from the initial three years of observations (reference years) at each station as the reference APTDs for every growth period. We verified the phenology predicted by this method using observations from reference years at all 71 stations (Fig. 2). The results show that this method is robust in predicting phenology dates.

2.3. *Disentangling the effects of climate change and agricultural management on phenology*

To isolate the effects of climate change and agricultural management factors on soybean phenology, we designed three sets of experiments to predict soybean phenological stages. We assumed that the sowing dates and cultivars at each station would not change significantly during the first three years of observation and taking this period as the reference years. Thus, we defined the average sowing date and average APTDs during the reference years as $Sowing_{ref}$ and $APTDs_{ref}$, respectively, characterizing the initial state for the study period. Based on this, in experimental group E1, we used $Sowing_{ref}$ and $APTDs_{ref}$ to predict the emergence, anthesis, seed filling, and maturity dates; in E2, we utilized observed sowing dates and $APTDs_{ref}$ to predict each phenological date; and in E3, $Sowing_{ref}$ and observed APTDs derived from actual phenological dates and climate conditions were used for predictions. The phenological trends obtained from E1 reflect the impact of climate change, considering sowing dates and cultivars as constants (Tao et al., 2014). The trend in differences in phenology between E1 and E2 illustrates the effect of sowing date variations, as E2 integrates actual sowing dates compared with E1. Similarly, the differences between E1 and E3 indicate the influence of cultivar changes, as E3 employs actual APTD values. The residuals between the observed phenological trends and the trends driven by climate, sowing, and cultivar factors can be attributed to the impacts of other variables, such as water and fertilizer management, on phenology (Luo et al., 2022; Tao et al., 2022; Zhang et al., 2022). The difference in the trend between the observed phenology and E1 predictions represents the impact of all agricultural management factors on phenology (Tao et al., 2014).

Table 1
Parameters for calculating the APTDs in each subzone. The parameters include the critical short-day length (CSDL), the photoperiod sensitivity coefficient (PPSEN), the base temperature (T_{base}), the lower (T_{opt1}) and upper (T_{opt2}) optimum temperatures, and the maximum temperature (T_{max}).

		CSDL (h)	PPSEN (h^{-1})	T_{base} (°C)	T_{opt1} (°C)	T_{opt2} (°C)	T_{max} (°C)
PL-EM [a]	Zone I	/	/	7	28	35	45
	Zone II	/	/				
	Zone III	/	/				
EM-FL [a]	Zone I	13.84	0.203	7	28	35	45
	Zone II	13.59	0.249				
	Zone III	13.40	0.285				
FL-SD [a]	Zone I	13.61	0.203	6	26	30	45
	Zone II	13.31	0.249				
	Zone III	13.08	0.285				
SD-PM [a]	Zone I	13.61	0.203	−15	26	34	45
	Zone II	13.31	0.249				
	Zone III	13.08	0.285				

[a] PL-EM: Period from sowing to emergence; EM-FL: Period from emergence to anthesis (vegetative); FL-SD: Period from anthesis to seed filling (early reproductive); SD-PM: Period from seed filling to maturity (late reproductive).

2.4. *Statistical analysis*

Piecewise linear regression was utilized to detect turning points in phenological events, growth periods, and climate variables. Notably, turning points were identified in approximately the year 2000 (supplementary Fig. S2); thus, we divided the entire study period into two intervals: 1981–2000 and 2001–2020. We performed linear regression to determine the trends and significance levels of the soybean phenological dates (sowing, emergence, anthesis, and maturity) and growth periods (VGP, RGP, and GP) at each station over each interval. We employed partial correlation coefficients to assess the sensitivity of the soybean growth periods to the climate variables. We used several climate variables to calculate the partial correlations: T_{mean}, maximum temperature (T_{max}), minimum temperature (T_{min}), P_{sum}, and S_{sum}. In each case, the other variables were treated as control factors. Controlling for other climate variables over the same period helps reduce potential bias caused by the interdependence between the GP and a specific variable. The significance of differences in the trends between these two intervals was evaluated using two-tailed *t*-tests.

3. Results

3.1. *Spatiotemporal dynamics of soybean phenological dates*

From 1981 to 2020, various phenological dates of soybean were delayed overall, which occurred in 60–70 % of the stations. Sowing dates were significantly delayed at approximately 30 % of the stations, with a few stations showing a significantly earlier trend. This delayed trend was evident in Zone I, specifically in Liaoning Province, whereas the changes in Zone II were relatively stable (Fig. 3 a1). Compared with 1981–2000, the delayed trend in Zone I weakened from 2001 to 2020, averaging 3.1 days/decade of advancement, whereas Zone II shifted to further delays, with an average delay of 2.2 days/decade (Fig. 3 a2). Similarly, emergence dates were significantly delayed at 24 % of the stations from 1981 to 2020. The trend in Zone I was relatively stable, whereas the delay in Zone II was more pronounced (Fig. 3 b1). Both Zone I and Zone II showed further delays in the latter twenty years, with average delays of 1.9 and 1.3 days/decade, respectively (Fig. 3 b2). The anthesis dates were significantly delayed at 23 % of the stations, with most stations in Zones I and II showing delays, whereas there was an overall earlier trend in Zone III (Fig. 3 c1). Notably, compared with those in 1981–2000, anthesis dates in Zone I from 2001 to 2020 were significantly delayed by 6.3 days/decade, indicating a markedly asymmetrical change (Fig. 3 c2). The maturity dates were significantly delayed at approximately 25 % of the stations from 1981 to 2020, particularly in Zone II (Fig. 3 d1). Compared with 1981–2000, the maturity dates in Zone I advanced on average by 1.3 days/decade, whereas they were delayed by 1.0 days/decade in Zone II. Zone III presented significant station-specific advancements or delays, with substantial spatial variability across all phenological dates, which was possibly related to limited samples and different management practices (Fig. 3 a3-d3). The difference in the trend decreased from 1981 to 2000 to 2001–2020, suggesting a relative stabilization of soybean phenology in the latter period (Fig. 3 a2-d2).

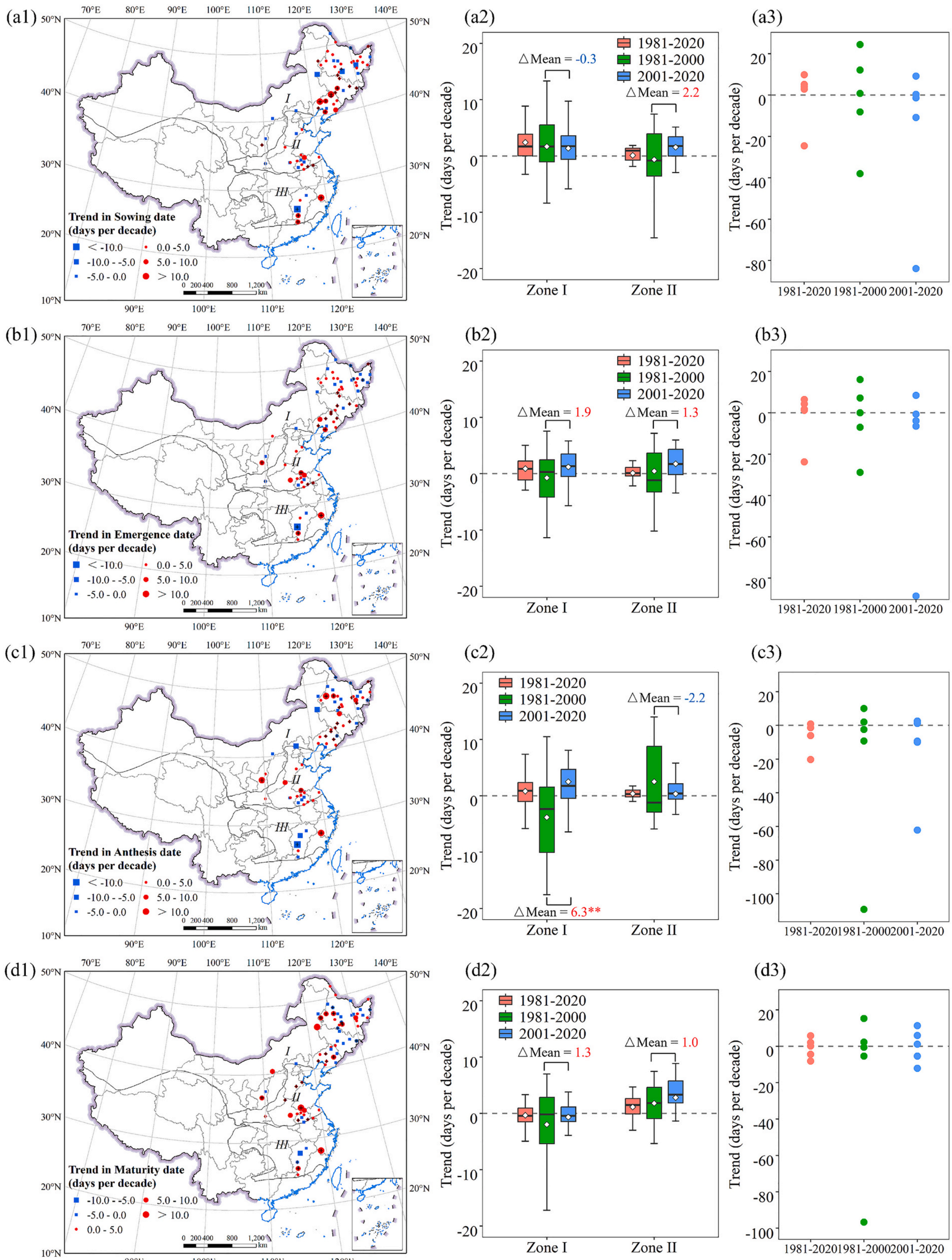


Fig. 3. Spatial patterns of trends in the soybean sowing date (a1-a3), emergence date (b1-b3), anthesis date (c1-c3), and maturity date (d1-d3) from 1981 to 2020. The stations with a trend that was significant at $p < 0.05$ are marked by +. Box plots and scatter plots show zone-specific trends during three periods and differences (in Zone III, the data are expressed by scatter points, rather than boxes, because of better expressing their large variability) between 1981 and 2000 and 2001–2020 (significant differences at $p < 0.05$ marked by **). In the box plots, the horizontal lines represent the maximum and minimum values; the middle line represents the median; the upper and lower edges of the boxes represent the 75th and 25th percentiles, respectively; and the white circles represent the means of the trends.

3.2. Changes in the lengths of the GP, VGP, and RGP, and their relationships with climate variables

From 1981 to 2020, the total growth period (GP) shortened at 62 % of the stations. For both the vegetative growth period (VGP) and the reproductive growth period (RGP), the stations displaying lengthening or shortening trends were approximately evenly divided. The GP shortened significantly at 23 % of the stations. In Zone I, most stations showed a reduction trend, whereas in Zone II, the GP was extended at most stations (Fig. 4 a1). From 1981 to 2020, Zone I consistently showed a significant shortening trend, although it lessened in the latter period (2001–2020). Conversely, the GP consistently extended during both periods in Zone II (Fig. 4 a2). 15 % (11 %) of the stations displayed a significant extension (reduction) of VGP, which was distributed evenly across subzones (Fig. 4 b1). Compared with 1981–2000, the VGP lengthened by an average of 4.2 days/decade from 2001 to 2020 in Zone I, whereas it shortened by 4.3 days/decade in Zone II (Fig. 4 b2). The RGP was prolonged and shortened significantly at 14 % and 15 % of the stations, respectively. Stations with a significant shortening trend were located primarily in Zone I (Fig. 4 c1). In contrast to the VGP, from 1981

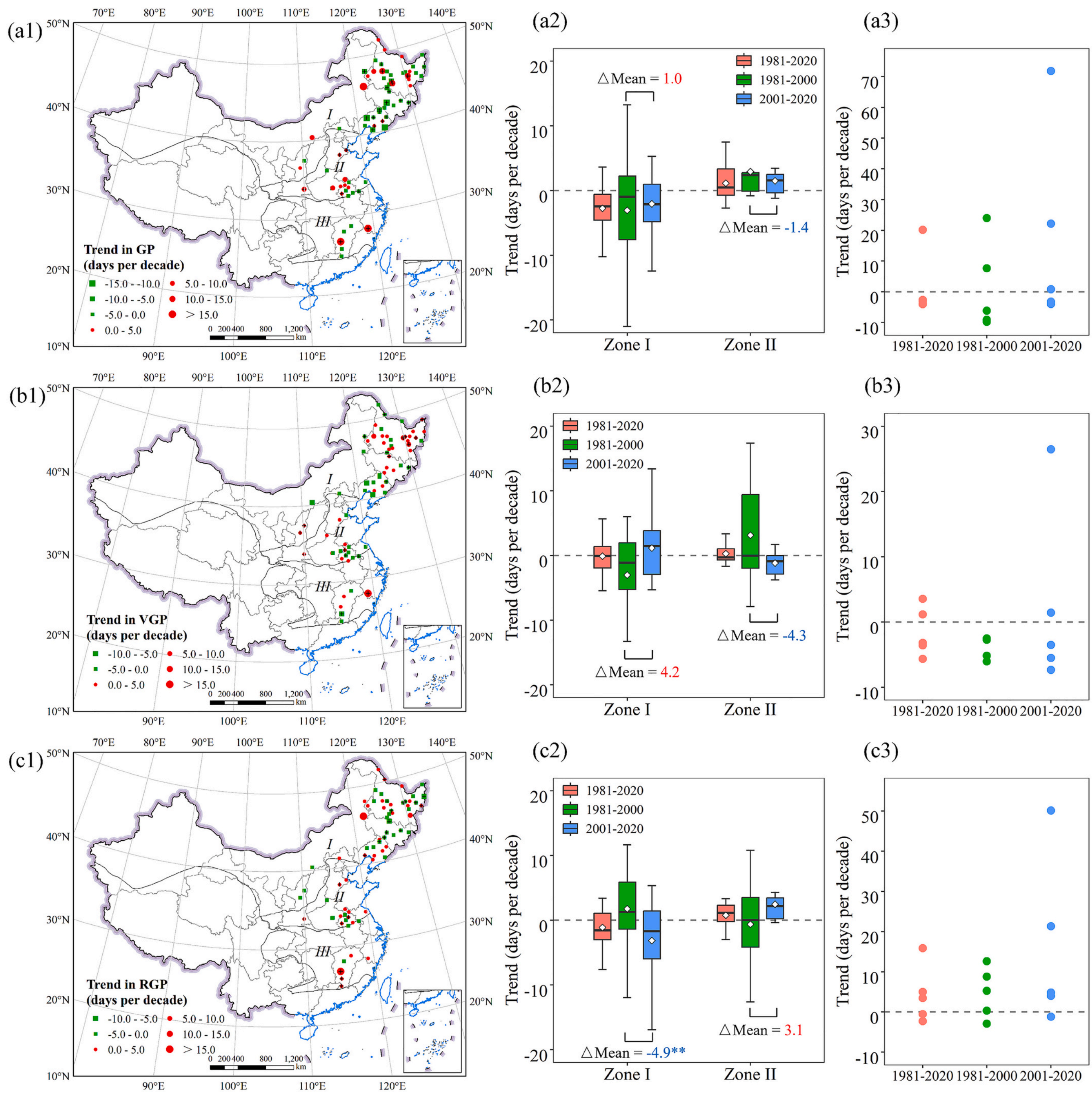


Fig. 4. Spatial patterns of trends in the GP (a1-a3), VGP (b1-b3), and RGP (c1-c3) from 1981 to 2020. The stations with a significant trend at $p < 0.05$ are marked by +. Box plots and scatter plots show zone-specific trends during three periods and differences (in Zone III, the data are expressed by scatter points, rather than boxes, because of better expressing their large variability) between 1981 and 2000 and 2001–2020 (significant differences at p < 0.05 marked by **). In the box plots, the horizontal lines represent the maximum and minimum values; the middle line represents the median; the upper and lower edges of the boxes represent the 75th and 25th percentiles, respectively; and the white circles represent the means of the trends.

to 2000 to 2001–2020, the RGP in Zone I significantly shortened by 4.9 days/decade, whereas it lengthened by 3.1 days/decade in Zone II (Fig. 4 c2). Significant asymmetrical changes occurred in the VGP and RGP across different regions, whereas the GP showed no evident asymmetrical changes over each period. Like the phenological dates, there was high heterogeneity in growth period changes in Zone III (Fig. 4 a3-c3). Compared with that in 1981–2000, the variability in the growth period trends noticeably diminished during the later period (2001–2020) in Zone II (Fig. 4 a2-c2).

From 1981 to 2020, the GP showed a significant negative correlation with T_{mean} at 10 % of the stations, with no stations showing significant positive correlation (Fig. 5 a1). A general negative correlation with T_{mean} was observed in almost all zones throughout each period, except for a slight positive correlation in Zone II from 2001 to 2020 (Fig. 5 a2).

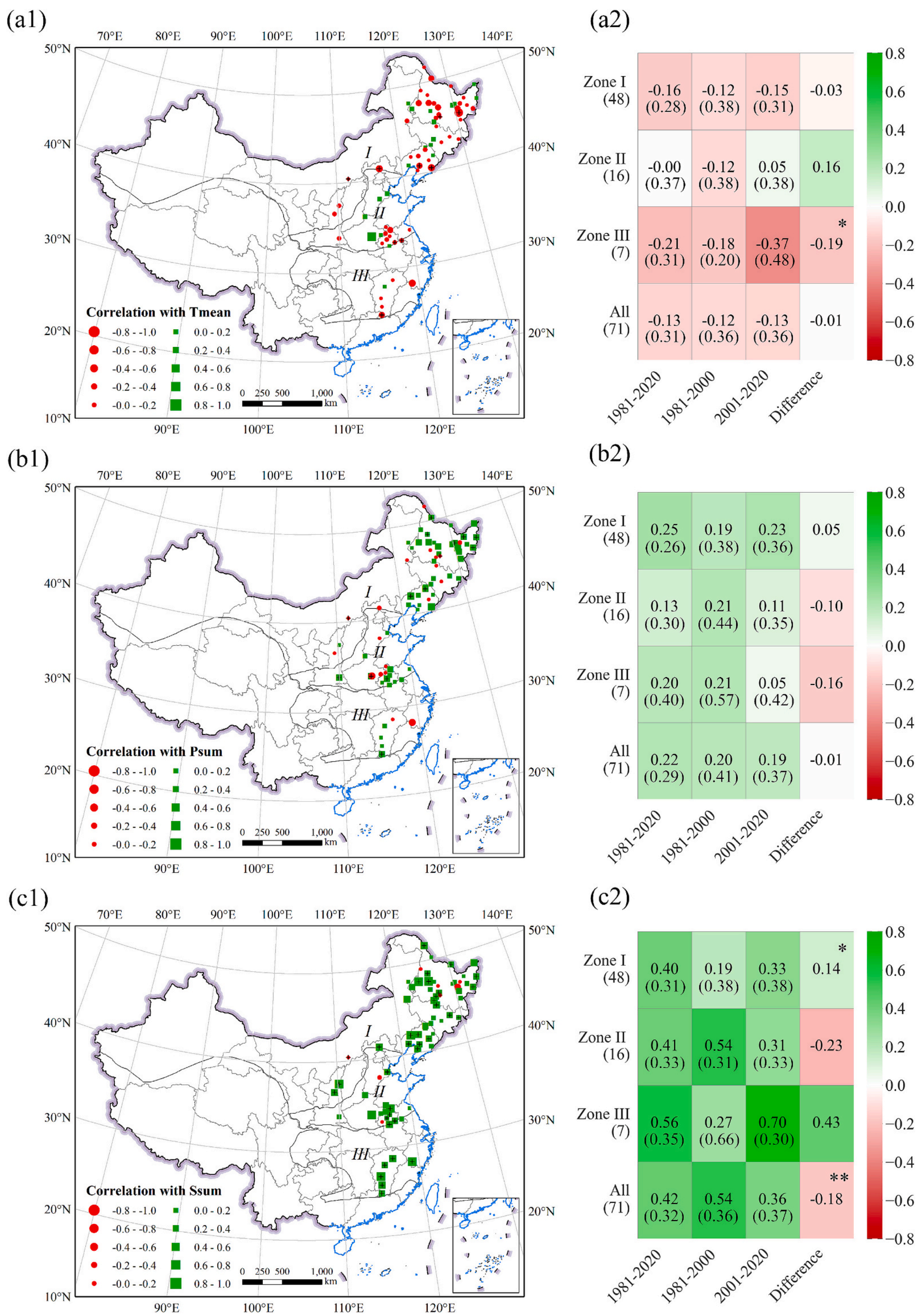


Fig. 5. Partial correlation coefficients between Tmean (a1), Psum (b1), and Ssum (c1) with the length of the soybean GP from 1981 to 2020 (a1-c1). The stations with correlations significant at $P < 0.05$ are marked by $+$. Heatmaps of (a2-c2) show the zone-specific correlation coefficient and standard deviation (in brackets) across all stations during the three periods and the difference between 1981 and 2000 and 2001–2020 (correlation coefficients and differences with statistical significance at the levels of 0.1 and 0.05 are marked by * and **).

A similar pattern was also observed for the VGP (supplementary Fig. S3a1-a2). The RGP showed a minimal correlation with T_{mean} in Zones I and II, but it was negatively correlated in Zone III (supplementary Fig. S4a1-a2). The weak correlation with no significant findings across most stations suggests that a nonlinear relationship exists, aligning with the response mechanisms to temperature demonstrated in Section 2.2. Temperatures below or above optimal ranges may slow growth. Overall, the generally weak negative correlation implies that climate warming during the study period tended to shorten the soybean growth period.

Conversely, the GP showed a significant positive correlation with cumulative precipitation (P_{sum}) at 17 % of the stations, with no stations showing significant negative correlation (Fig. 5 b1). Stations in all subzones generally showed a positive correlation with P_{sum} over each period (Fig. 5 b2). Both the VGP and RGP also displayed a generally positive correlation, with a few negatively correlated stations concentrated in Zone I (supplementary Figs. S3-S4). This suggests that increasing precipitation may have extended the soybean growth period over the past several decades.

Unlike both T_{mean} and P_{sum}, the GP was significantly positively correlated with the number of cumulative sunshine hours (S_{sum}) at 48 % of the stations, with no significantly negatively correlated stations (Fig. 5 c1). Approximately one-third of the stations had a strong partial correlation coefficient exceeding 0.6 (Fig. 5 c1). 80 % of the stations showed a significant positive correlation with S_{sum} for the VGP, and 70 % did so for the RGP (supplementary Figs. S3-S4). This finding demonstrates that the linear correlation between soybean growth periods and sunshine is more pronounced, which is consistent with the response of soybeans to the photoperiod as a short-day crop, where longer daylight extends the growth periods.

Generally, the response of the soybean GP to T_{mean} and P_{sum} showed little change nationwide from 1981 to 2000 to 2001–2020, whereas the correlation with S_{sum} significantly decreased by 0.18 (Fig. 5 a2-c2). The VGP's response to T_{mean} slightly strengthened negatively, whereas its response to P_{sum} and S_{sum} weakened (supplementary Fig. S3). The response of the RGP to P_{sum} significantly decreased by 0.49, whereas its response to S_{sum} significantly increased by 0.21 in Zone III (supplementary Fig. S4).

3.3. Roles of climate and agricultural management in the soybean GP

By isolating the impacts of different drivers on soybean growth periods, we found that climate change consistently shortened nearly all growth periods, whereas cultivar shifts and agricultural management notably extended them, particularly from 1981 to 2000. Additionally, changes in the sowing date and other factors had only slight effects (Fig. 6). From 1981 to 2020, climate change shortened the VGP and RGP by 0.2 and 1.1 days/decade, respectively. Conversely, cultivar shifts extended the VGP and RGP by averages of 1.8 and 0.9 days/decade, respectively. Sowing changes slightly reduced the VGP (RGP) by 0.4 (0.1) days/decade, whereas other factors, such as irrigation and fertilization, shortened the VGP by 0.4 days/decade and extended the RGP by 0.2 days/decade. All agricultural management practices extended the VGP (RGP) by 1.0 (1.1) days/decade (Fig. 6).

During the entire study period, climate and sowing changes reduced the GP by 1.7 and 0.8 days/decade, respectively. In contrast, cultivar shifts and agricultural management practices contributed significantly more to extending soybean growth periods (GP, VGP, and RGP) than did climate change shortened them, with former lengthening the GP by 3.1 and 2.4 days/decade, respectively. These anthropogenic factors effectively offset the negative impacts of climate change, resulting in a net increase of only 0.7 days/decade in the GP from 1981 to 2020 (Fig. 6).

Across all the study periods and soybean growth stages, climate change did shorten soybean growing periods (GP, VGP, and RGP) at most stations, whereas cultivar shifts consistently extend them. The extended growing periods by cultivar shifts were greater than the decreasing ones from climate change, particularly for RGP and GP. From 1981 to 2000, climate change shortened the RGP and GP by 3.1 and 5.9

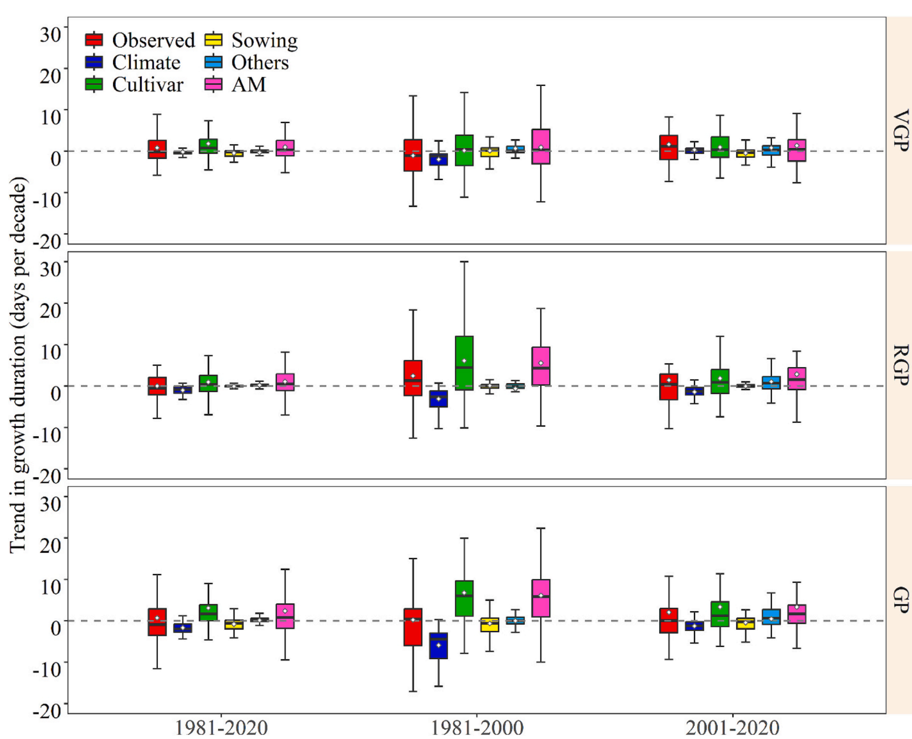


Fig. 6. Effects of climate change, cultivar shifts, sowing date change, other factors such as fertilization and irrigation, and all agricultural managements together on the soybean VGP, RGP and GP from 1981 to 2020, 1981–2000 and 2001–2020. The horizontal lines represent the maximum and minimum values; the middle line represents the median; the upper and lower edges of the boxes represent the 75th and 25th percentiles, respectively; and the white circle represents the mean of the trend in the growth duration. AM represents agricultural management together.

days/decade, respectively, whereas cultivar changes extended them by 6.1 and 6.7 days/decade, respectively. From 2001 to 2020, climate change reduced the RGP and GP by 1.5 and 1.3 days/decade, respectively, whereas cultivar changes extended them by 1.8 and 3.3 days/decade, respectively (Fig. 6). These findings indicate that cultivar changes extended the GP mainly by lengthening the RGP and effectively offset the negative impacts of climate change, ensuring the stability of the soybean growth period. Specifically, from 1981 to 2020, climate change shortened the GP at 93 % of the stations. Among these stations, cultivar shifts extended the GP by 74 %, and at 36 %, the extension from cultivar changes was greater than the reduction caused by climate change (Supplementary Fig. S5).

The asymmetric impact of these factors was pronounced. The impacts of climate change and human activities were stronger in earlier decades (1981–2000). Climate change reduced the GP by 5.9 days/decade from 1981 to 2000, but this trend slowed to 1.3 days/decade in later years (2001–2020). Similarly, the positive impacts of cultivar changes and agricultural management decreased from 6.7 and 6.1 days/decade in the earlier period to 3.3 days/decade in the later period (Fig. 6).

The spatial distribution of the dominant drivers across the stations revealed that cultivar changes and agricultural management were the predominant factors extending the GP at most stations. In contrast, at some northeastern stations, climate change and sowing changes were the main contributors, which typically exhibited a weaker negative impact (Fig. 7). Overall, while climate change had adverse effects, agricultural management, such as cultivar changes, has significantly extended the soybean growth period, offsetting climate-related adversities and playing a major role in phenological changes (Figs. 6–7). These drivers had stronger effects and greater variability in the first two decades, but displayed increased stability in the last two decades, potentially indicating enhanced resilience in soybean cultivation (Fig. 6).

4. Discussion

4.1. Response mechanism of soybean phenology to climatic factors

We found that the length of the soybean GP was weakly negatively correlated with the mean temperature (T_{mean}), weakly positively correlated with the cumulative precipitation (P_{sum}), and significantly positively correlated with the cumulative sunshine hours (S_{sum}) during each soybean growth period (Fig. 5 and supplementary Figs. S3-S4). Previous studies have also shown similar negative associations with T_{mean}, whereas those of P_{sum} and S_{sum} varied by area and study period (He et al., 2020; Liu and Dai, 2020; Tan et al., 2021).

In general, these related studies consistently reported a significant negative correlation between length of the GP and temperature, which is reasonable and explainable. The optimum temperature range for soybean during different growth stages was approximately 26–35 °C (Jones et al., 2003). The mean temperature in our study increased significantly and nearly reached the lower optimum temperature (supplementary Fig. S2), which accelerated the growth rate, and consequently was accompanied by a shortened growth period (Oteros et al., 2015; Setiyono et al., 2007).

The weak positive correlation between the soybean development period and precipitation found in this study aligns with a related research (Tan et al., 2021). In contrast, He et al. (2020) reported a significant positive correlation between the reproductive period of soybeans and precipitation, whereas Liu and Dai (2020) reported a weak correlation between precipitation and various soybean development stages. These discrepancies are relatively minor and may be attributed to different study periods. Precipitation affects the sowing time of soybean, as sowing under optimal soil moisture conditions is beneficial for growth (Liu and Dai, 2020; Xin et al., 2023). We found significantly delayed sowing dates in the northeast region, potentially due to delayed preseason precipitation (He et al., 2020; Shiqi and Li, 2016). Water stress

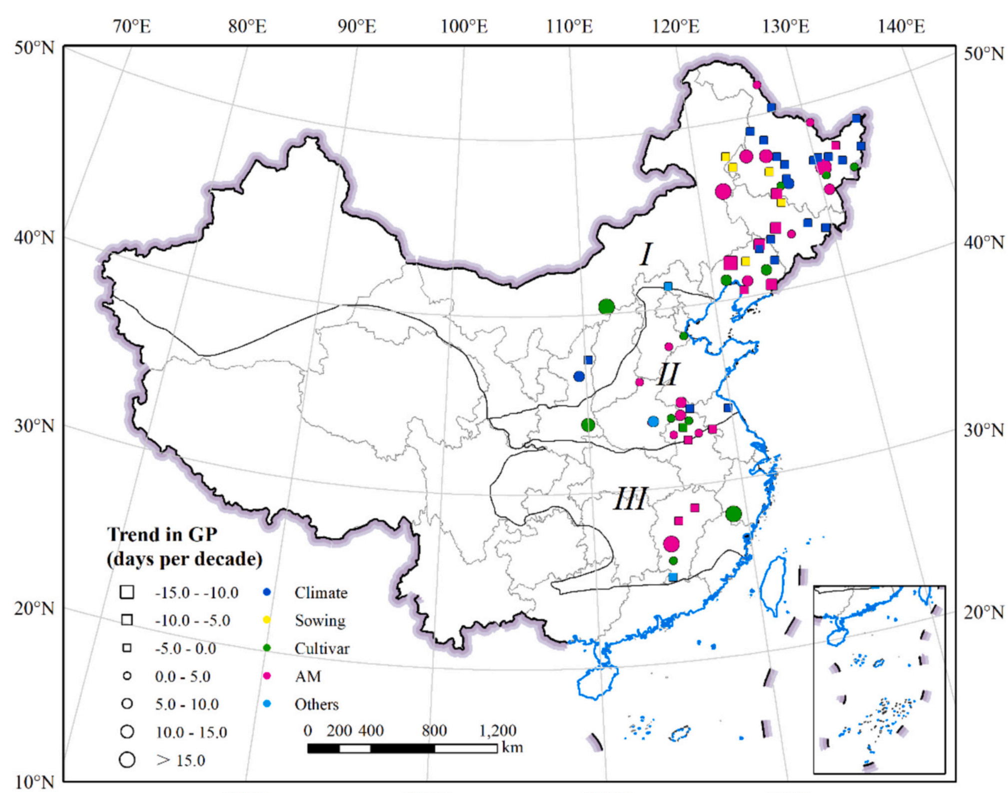


Fig. 7. Spatial patterns of the dominant factors controlling the changes in the soybean growth period from 1981 to 2020. The colours represent categories of dominant drivers, with circles representing positive impacts, squares representing negative impacts, and sizes representing the impact intensity.

occurring during the induction and flowering stages shortens the flowering period (Sionit and Kramer, 1977). However, the mechanism driving the GP length from precipitation has been less explored, although similar findings have been reported (Gong et al., 2021; Xin et al., 2023; Yang et al., 2021).

The findings of our study revealed a positive association between the soybean growth period and sunshine hours. Soybean is a short-day crop, and the photoperiod plays a critical role in both vegetative and reproductive growth, which implies a demand for shorter daylight hours to initiate flowering and regulate reproductive development and leaf senescence processes following flowering (Han et al., 2006). Previous studies have consistently proved that longer sunshine durations lead to

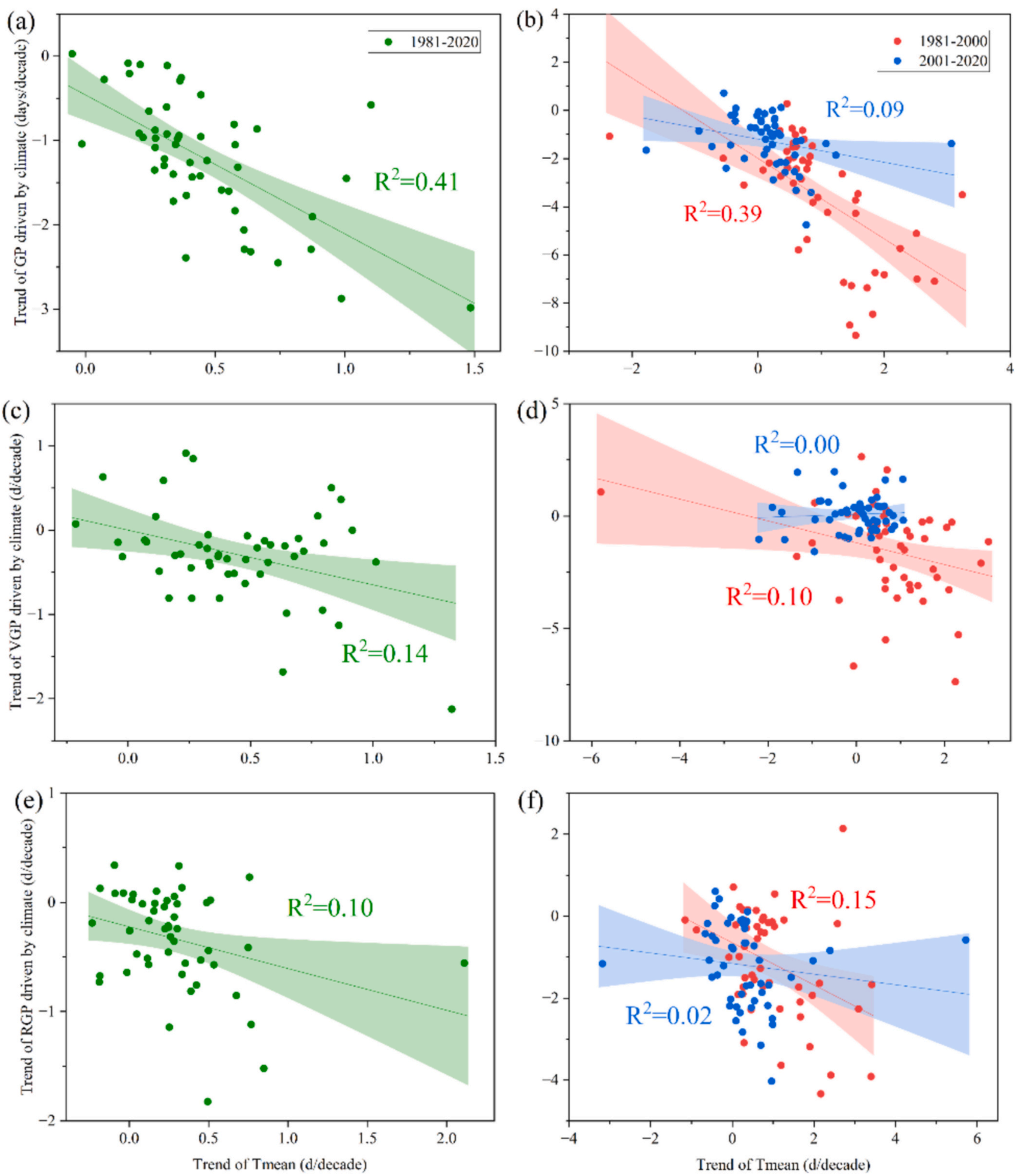


Fig. 8. Relationships of the trends between T_{mean} and GP (a-b), VGP (c-d), and RGP (e-f) driven by climate change. The shaded areas represent 95 % confidence intervals.

decreased growth rates and delayed growth periods (He et al., 2020; Setiyono et al., 2007), which reasonably explains the significant positive associations observed (Fig. 5 c1).

4.2. Weakening impacts of factors driving phenology from 2001 to 2020

We found that the impacts of drivers on the GP were weakened from 2000 to 2020 compared with those from 1981 to 2000. Previous studies have shown that the effects of climate warming on vegetation phenology have diminished in recent decades (Fu et al., 2015; Luo et al., 2022; Vitasse et al., 2018). Both the mean temperature and cumulative precipitation showed weaker trends in the last two decades (supplementary Fig. S6). The mean temperature (T_{mean}) exhibited a noticeable upwards trend from 1981 to 2000, but showed a stable trend from 2001 to 2020 (supplementary Fig. S2 and Fig. S6). Simultaneously, we found that the climate-shortened growth periods also decreased (Fig. 8). In both 1981–2020 and 1981–2000, negative correlations were distinctly evident between the climate-driven shortening trend of the growth periods and the increasing trend of the mean temperature, particularly for the GP (Fig. 8a-b). However, this correlation weakened from 2001 to 2020, even when insignificant relationships were observed (Fig. 8b, d, f). The cumulative precipitation (P_{sum}) distinctly declined from 1981 to 2000, followed by a slight increase from 2001 to 2020 (supplementary Fig. S2 and Fig. S6). All trends of the climatic variables were consistently observed for both the VGP and the RGP, contributing to a consistent effect on the whole growth GP (supplementary Fig. S6). From 1981 to 2000, the increased T_{mean} and decreased P_{sum} might have jointly shortened the growth periods. Despite a relatively significant reduction in S_{sum} from 2001 to 2020, the overall climatic impact was offset by weak changes in temperature and precipitation compared with those from 1981 to 2000.

During 1981–2020, the demand for accumulated photothermal days (APTDs) showed an increasing trend (supplementary Fig. S7), suggesting that cultivars with relatively high APTDs values were favoured because they responded better to the shortened growth periods caused by climate change (Pereira-Flores et al., 2019; Timilsina et al., 2023). Fluctuations in APTDs during the RGP dominated those during the whole GP, implying that cultivar shifts enhanced soybean production mainly by extending the RGP. Similarly, the magnitude and variability of the increasing trend of APTDs from 1981 to 2000 were greater than those from 2001 to 2020, potentially suggesting a slower pace of cultivar renewal in the latter two decades (supplementary Fig. S7).

4.3. Comparison of the dominant drivers with those in previous studies

We detected trends in soybean phenology and the growth period similar to those reported in previous studies, whereas prior studies have shown conflicting results concerning the dominant factors affecting the growth periods of soybean. He et al. (2020) contend that the negative impact of climate on the growth period outweighs the effect of compensation of human interventions in China. Conversely, Liu and Dai (2020) asserted that that crop management contributes more to trends in phenology and growth periods. These inconsistencies might be due to the first-difference method for quantifying the impact of climate variability, which is strongly dependent on the study period and geographic location. Furthermore, prior studies used residual methods to isolate the impact of management factors, generalizing all human activities as a single factor. In contrast, we distinguished and evaluated the impacts of the sowing date, cultivar shifts, and other factors separately. Compared with previous investigations, minimal unexplainable changes were observed in our study (Fig. 6), indicating the need for a comprehensive and systematic study of more factors related to crop phenology (Xin et al., 2023).

The dominant factors affecting the growth period also vary by crop type. By combining process models and statistical methods in China, previous studies on the phenology of the other crops have revealed various findings. The negative impact of climate warming on wheat in China outweighs anthropogenic efforts (Tao et al., 2022). Conversely, for maize and rice, cultivar shifts offset the impacts of climate warming (Luo et al., 2022; Zhang et al., 2022). These findings further substantiated that even within the same study period, the contributions of climate change and field management to phenology vary significantly across different crops. As a significant cash crop in China, soybeans benefit from human management activities (e.g., cultivar shifts), countering the negative impacts of climate change. However, this effect weakened from 2001 to 2020, suggesting a potential slowdown in cultivar upgrades (Fig. 6). Furthermore, substantial regional differences exist in cultivar renewal (Fig. 9). In Northeast China, a key soybean production area, many stations exhibit a minimal APTDs trend, primarily because of the reduced APTDs demand for the RGP. Consequently, the negative influence of climate change predominates during the growth periods at these stations (Fig. 6 and Fig. 9). Therefore, timely updates for new soybean cultivars in these major production areas are highly necessary.

4.4. Uncertainties

In this study, a robust method combining statistical and phenological process models was applied, revealing the asymmetric changes in soybean phenology and disentangling the impacts of climate change and agricultural management. However, some uncertainties remain. Using the same genetic parameters throughout the whole study period may introduce errors in calculating APTDs, as the varieties are constantly being updated. While we focused on changes in photothermal requirements to represent cultivar shifts, the phenological response of a fixed variety to long-term climate change shows that its photothermal requirements may shift over time (Wu et al., 2019). Additionally, other comprehensive characteristics, such as stress resistance, adaptability, and quality traits, may influence soybean phenological responses (Hatfield and Prueger, 2015; Staniak et al., 2023). Future studies incorporating detailed cultivar parameter data from surveys and field experiments could generate more accurate conclusions.

5. Conclusion

By utilizing the latest soybean phenological and meteorological observation data from 1981 to 2020 in China, we explored the spatiotemporal dynamics of their key phenological dates and growth periods over the past 40 years, as well as the impacts of different driving factors. The results indicate that the key phenological dates have generally been delayed, together with slightly shortened lengths of the growth period across different regions. Climate warming has shortened the growth period, which generally has a positive correlation with both precipitation and sunlight duration. Agricultural management measures, particularly cultivar renewals, have extended the soybean growth period, offsetting the negative impacts of climate change and maintaining overall stable growth periods across China. Compared with the period from 1981 to 2000, the warming trend weakened from 2001 to 2020 and reduced the impacts of climatic factors. Simultaneously, the effect of extension from cultivar changes generally weakened, especially in the key production bases of Northeast China, suggesting a potential slowdown from agricultural management measures. Therefore, timely and effective cultivar renewals are crucial for enhancing soybean adaptability to climate change.

CRediT authorship contribution statement

Qinghang Mei: Writing – original draft, Visualization, Methodology. **Zhao Zhang:** Writing – review & editing, Conceptualization. **Jichong Han:** Visualization, Software. **Jie Song:** Writing – review & editing, Methodology. **Fei Cheng:** Data curation. **Huimin Zhuang:** Writing – review & editing. **Huaqing Wu:** Writing – review & editing. **Jialu Xu:** Supervision.

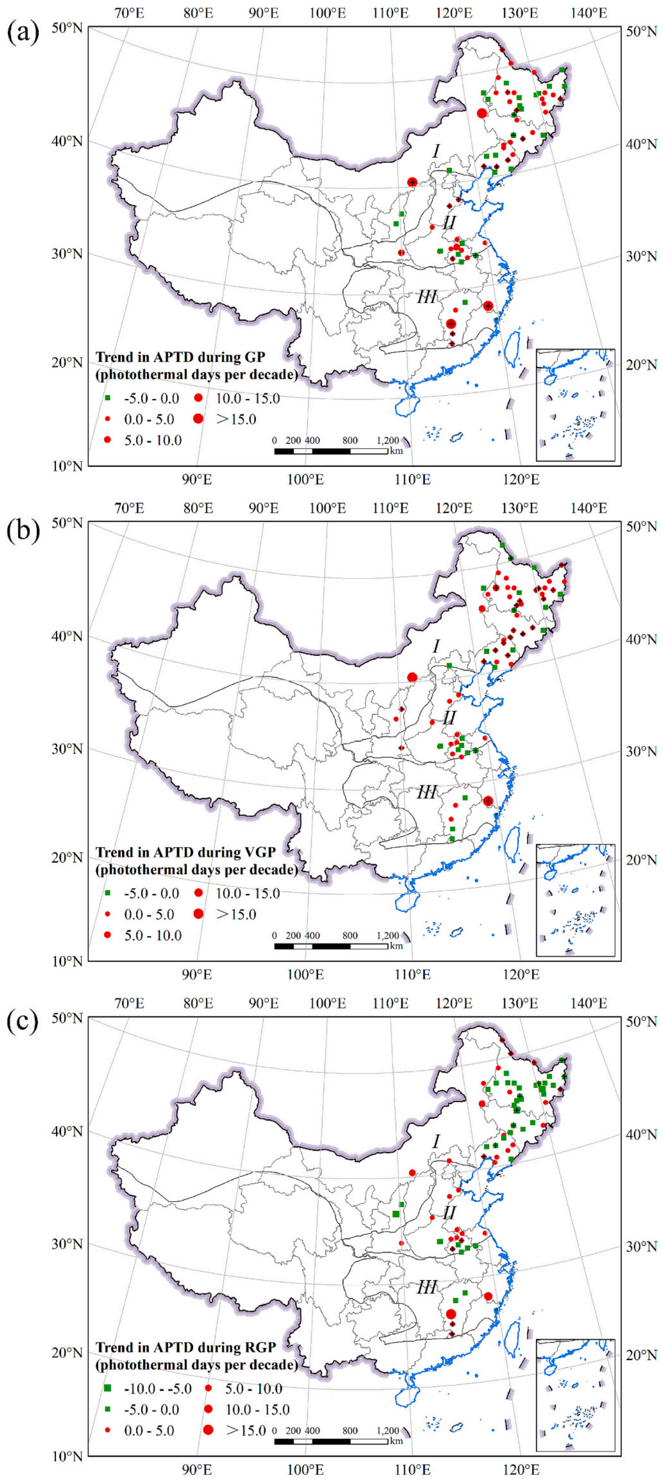


Fig. 9. Spatial patterns of trends in APTDs during the soybean GP (a), VGP (b) and RGP (c) from 1981 to 2020. The stations with a trend significant at $P < 0.05$ are marked by +.

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

This research was funded by the National Key Research and Development Program of China (No. 2020YFA0608201) and the National Natural Science Foundation of China (No. 42061144003).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.104260.

Data availability

Data will be made available on request.

References

Abbas, G., Ahmad, S., Ahmad, A., Nasim, W., Fatima, Z., Hussain, S., Rehman, M.H., Khan, M.A., Hasanuzzaman, M., Fahad, S., Boote, K.J., Hoogenboom, G., 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. https://doi.org/10.1016/j.agrformet.2017.07.012.

Ahmed, M., Seraj, R., Islam, S.M.S., 2020. The k-means algorithm: a comprehensive survey and performance evaluation. Electronics 9, 1295. https://doi.org/10.3390/electronics9081295.

Allen, R.G., Food and Agriculture Organization of the United Nations (Eds.), 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements, FAO Irrigation and Drainage Paper. Food and Agriculture Organization of the United Nations, Rome.

Azmat, M., Ilyas, F., Sarwar, A., Huggel, C., Vaghefi, S.A., Hui, T., Qamar, M.U., Bilal, M., Ahmed, Z., 2021. Impacts of climate change on wheat phenology and yield in Indus Basin, Pakistan. Science of The Total Environment 790, 148221. https://doi.org/10.1016/j.scitotenv.2021.148221.

Bateman, N.R., Catchot, A.L., Gore, J., Cook, D.R., Musser, F.R., Irby, J.T., 2020. Effects of planting date for soybean growth, development, and yield in the southern USA. Agronomy 10, 596. https://doi.org/10.3390/agronomy10040596.

Chen, G., Wiatrak, P., 2010. Soybean development and yield are influenced by planting date and environmental conditions in the southeastern coastal plain, United States. Agron. J. 102, 1731–1737. https://doi.org/10.2134/agronj2010.0219.

Cohen, J.M., Lajeunesse, M.J., Rohr, J.R., 2018. A global synthesis of animal phenological responses to climate change. Nature Clim Change 8, 224–228. https://doi.org/10.1038/s41558-018-0067-3.

de Los Campos, G., Pérez-Rodríguez, P., Bogard, M., Gouache, D., Crossa, J., 2020. A data-driven simulation platform to predict cultivars' performances under uncertain weather conditions. Nat. Commun. 11, 4876.

Estrella, N., Sparks, T.H., Menzel, A., 2007. Trends and temperature response in the phenology of crops in Germany. Glob. Chang. Biol. 13, 1737–1747. https://doi.org/10.1111/j.1365-2486.2007.01374.x.

Eyshi Rezaei, E., Siebert, S., Ewert, F., 2017. Climate and management interaction cause diverse crop phenology trends. Agric. For. Meteorol. 233, 55–70. https://doi.org/10.1016/j.agrformet.2016.11.003.

Fatima, Z., Ahmed, M., Hussain, M., Abbas, G., Ul-Allah, S., Ahmad, S., Ahmed, N., Ali, M.A., Sarwar, G., Haque, E., 2020. The fingerprints of climate warming on cereal crops phenology and adaptation options. Sci. Rep. 10, 18013. https://doi.org/10.1038/s41598-020-74740-3.

Fatima, Z., Naz, S., Iqbal, P., Khan, A., Ullah, H., Abbas, G., Ahmed, M., Mubeen, M., Ahmad, S., 2022. Field crops and climate change. In: Jatoi, W.N., Mubeen, M., Ahmad, A., Cheema, M.A., Lin, Z., Hashmi, M.Z. (Eds.), Building Climate Resilience in Agriculture: Theory, Practice and Future Perspective. Springer International Publishing, Cham, pp. 83–94. https://doi.org/10.1007/978-3-030-79408-8_6.

Flynn, D.F.B., Wolkovich, E.M., 2018. Temperature and photoperiod drive spring phenology across all species in a temperate forest community. New Phytol. 219, 1353–1362. https://doi.org/10.1111/nph.15232.

Fu, Y.H., Zhao, H., Piao, S., Peaucelle, M., Peng, S., Zhou, G., Ciais, P., Huang, M., Menzel, A., Peñuelas, J., Song, Y., Vitasse, Y., Zeng, Z., Janssens, I.A., 2015. Declining global warming effects on the phenology of spring leaf unfolding. Nature 526, 104–107. https://doi.org/10.1038/nature15402.

Ge, Q., Wang, H., Rutishauser, T., Dai, J., 2015. Phenological response to climate change in China: a meta-analysis. Glob. Chang. Biol. 21, 265–274. https://doi.org/10.1111/gcb.12648.

Gong, L., Tian, B., Li, Y., Wu, S., 2021. Phenological changes of soybean in response to climate conditions in frigid region in China over the past decades. Int. J. Plant Prod. 15, 363–375. https://doi.org/10.1007/s42106-021-00145-5.

Han, T., Wu, C., Tong, Z., Mentreddy, R.S., Tan, K., Gai, J., 2006. Postflowering photoperiod regulates vegetative growth and reproductive development of soybean. Environ. Exp. Bot. 55, 120–129. https://doi.org/10.1016/j.envexpbot.2004.10.006.

Hatfield, J.L., Prueger, J.H., 2015. Temperature extremes: effect on plant growth and development. Weather and Climate Extremes 10, 4–10. https://doi.org/10.1016/j.wace.2015.08.001.

He, L., Jin, N., Yu, Q., 2020. Impacts of climate change and crop management practices on soybean phenology changes in China. Sci. Total Environ. 707, 135638. https://doi.org/10.1016/j.scitotenv.2019.135638.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. European Journal of Agronomy, Modelling Cropping Systems: Science, Software and Applications 18, 235–265. https://doi.org/10.1016/S1161-0301(02)00107-7.

Junior, C.P., Kawakami, J., Bridi, M., Müller, M.M.L., Conte, M.V.D., Michalovicz, L., 2015. Phenological and quantitative plant development changes in soybean cultivars caused by sowing date and their relation to yield. AJAR 10, 515–523. https://doi.org/10.5897/AJAR2014.9325.

Kessler, A., Archontoulis, S., Licht, M.A., 2020. Soybean yield and crop stage response to planting date and cultivar maturity in Iowa, USA. Agron. J. 112, 382–394. https://doi.org/10.1002/agj2.20053.

Li, Y., Guan, R., Liu, Z., Ma, Y., Wang, L., Li, L., Lin, F., Luan, W., Chen, P., Yan, Z., Guan, Y., Zhu, L., Ning, X., Smulders Marinus, J.M., Li, W., Piao, R., Cui, Y., Yu, Z., Guan, M., Chang, R., Hou, A., Shi, A., Zhang, B., Zhu, S., Qiu, L., 2008. Genetic structure and diversity of cultivated soybean (Glycine max (L.) Merr.) landraces in China. Theor. Appl. Genet. 117, 857–871. https://doi.org/10.1007/s00122-008-0825-0.

Li, J., Wang, X., Song, W., Huang, X., Zhou, J., Zeng, H., Sun, S., Jia, H., Li, W., Zhou, X., Li, S., Chen, P., Wu, C., Guo, Y., Han, T., Qiu, L., 2017. Genetic variation of maturity groups and four E genes in the Chinese soybean mini core collection. PloS One 12, e0172106. https://doi.org/10.1371/journal.pone.0172106.

Li, N., Li, Y., Biswas, A., Wang, J., Dong, H., Chen, J., Liu, C., Fan, X., 2021. Impact of climate change and crop management on cotton phenology based on statistical analysis in the main-cotton-planting areas of China. J. Clean. Prod. 298, 126750. https://doi.org/10.1016/j.jclepro.2021.126750.

Liu, Y., Dai, L., 2020. Modelling the impacts of climate change and crop management measures on soybean phenology in China. J. Clean. Prod. 262, 121271. https://doi.org/10.1016/j.jclepro.2020.121271.

Liu, Y., Zhang, J., Pan, T., Ge, Q., 2021. Assessing the adaptability of maize phenology to climate change: the role of anthropogenic-management practices. J. Environ. Manage. 293, 112874. https://doi.org/10.1016/j.jenvman.2021.112874.

Lobell, D.B., Asseng, S., 2017. Comparing estimates of climate change impacts from process-based and statistical crop models. Environ. Res. Lett. 12, 015001. https://doi.org/10.1088/1748-9326/aa518a.

Luo, Y.-C., Zhang, Z., Zhang, L.-L., Zhang, J., Tao, F.-L., 2022. Weakened maize phenological response to climate warming in China over 1981–2018 due to cultivar shifts. Adv. Clim. Chang. Res. 13, 710–720. https://doi.org/10.1016/j.accre.2022.08.007.

Mathur, S., Seo, B., Reddy, K.R., Reddy, V.R., 2024. Morpho-phenological responses of early and late soybean maturity groups to diverse day lengths and temperature regimes. Ind. Crop. Prod. 221, 119362. https://doi.org/10.1016/j.indcrop.2024.119362.

Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kübler, K., Bissolli, P., Braslavská, O., Briede, A., Chmielewski, F.M., Crepinsek, Z., Curnel, Y., Dahl, Å., Defila, C., Donnelly, A., Filella, Y., Jatczak, K., Måge, F., Mestre, A., Nordli, Ø., Peñuelas, J., Pirinen, P., Remišová, V., Scheifinger, H., Striz, M., Susnik, A., Van Vliet, A.J.H., Wielgolaski, F.-E., Zach, S., Zust, A., 2006. European phenological response to climate change matches the warming pattern. Glob. Chang. Biol. 12, 1969–1976. https://doi.org/10.1111/j.1365-2486.2006.01193.x.

Messina, C.D., Jones, J.W., Boote, K.J., Vallejos, C.E., 2006. A gene-based model to simulate soybean development and yield responses to environment. Crop. Sci. 46, 456–466. https://doi.org/10.2135/cropsci2005.04-0372.

Mo, F., Sun, M., Liu, X.-Y., Wang, J.-Y., Zhang, X.-C., Ma, B.L., Xiong, Y.-C., 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. https://doi.org/10.1016/j.fcr.2016.06.024.

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. Change 130, 545–558. https://doi.org/10.1007/s10584-015-1363-9.

Pereira-Flores, M.E., Justino, F.B., Pereira-Flores, M.E., Justino, F.B., 2019. Yield components and biomass partition in soybean: climate change vision, in: soybean - biomass, yield and productivity. IntechOpen. https://doi.org/10.5772/intechopen.81627.

Piao, S., Liu, Q., Chen, A., Janssens, I.A., Fu, Y., Dai, J., Liu, L., Lian, X., Shen, M., Zhu, X., 2019. Plant phenology and global climate change: current progresses and challenges. Glob. Chang. Biol. 25, 1922–1940. https://doi.org/10.1111/gcb.14619.

Rowntree, S.C., Suhre, J.J., Weidenbenner, N.H., Wilson, E.W., Davis, V.M., Naeve, S.L., Casteel, S.N., Diers, B.W., Esker, P.D., Conley, S.P., 2014. Physiological and Phenological responses of historical soybean cultivar releases to earlier planting. Crop. Sci. 54, 804–816. https://doi.org/10.2135/cropsci2013.06.0428.

Salmerón, M., Purcell, L.C., 2016. Simplifying the prediction of phenology with the DSSAT-CROPGRO-soybean model based on relative maturity group and determinacy. Agr. Syst. 148, 178–187. https://doi.org/10.1016/j.agsy.2016.07.016.

Setiyono, T.D., Weiss, A., Specht, J., Bastidas, A.M., Cassman, K.G., Dobermann, A., 2007. Understanding and modeling the effect of temperature and daylength on soybean phenology under high-yield conditions. Field Crop Res 100, 257–271. https://doi.org/10.1016/j.fcr.2006.07.011.

Shiqi, Xu, Li, Dongliang, 2016. Characteristics of the first soaking rain in Northeast China and its response to surface heat source over the Tibetan plateau. Meteorological Monthly 42, 271–279.

Sima, M.W., Fang, Q.X., Burkey, K.O., Ray, S.J., Pursley, W.A., Kersebaum, K.C., Boote, K.J., Malone, R.W., 2020. Field and model assessments of irrigated soybean responses to increased air temperature. Agron. J. 112, 4849–4860. https://doi.org/10.1002/agj2.20394.

Sionit, N., Kramer, P.J., 1977. Effect of water stress during different stages of growth of Soybean1. Agron. J. 69, 274–278. https://doi.org/10.2134/agronj1977.00021962006900020018x.

Song, W., Sun, S., Wu, T., Yang, R., Tian, S., Xu, C., Jiang, B., Yuan, S., Hou, W., Wu, C., Han, T., 2023. Geographic distributions and the regionalization of soybean seed compositions across China. Food Res. Int. 164, 112364. https://doi.org/10.1016/j.foodres.2022.112364.

Staniak, M., Szpunar-Krok, E., Kocira, A., 2023. Responses of soybean to selected abiotic stresses—photoperiod, temperature and water. Agriculture 13, 146. https://doi.org/10.3390/agriculture13010146.

Sun, W., Fleisher, D., Timlin, D., Li, S., Wang, Z., Beegum, S., Reddy, V., 2022. Evaluation of models for simulating soybean growth and climate sensitivity in the U.S. Mississippi Delta. Eur. J. Agron. 140, 126610. https://doi.org/10.1016/j.eja.2022.126610.

Tan, Q., Liu, Y., Dai, L., Pan, T., 2021. Shortened key growth periods of soybean observed in China under climate change. Sci. Rep. 11, 8197. https://doi.org/10.1038/s41598-021-87618-9.

Tang, J., Körner, C., Muraoka, H., Piao, S., Shen, M., Thackeray, S.J., Yang, X., 2016. Emerging opportunities and challenges in phenology: a review. Ecosphere 7, e01436. https://doi.org/10.1002/ecs2.1436.

Tao, F., Zhang, S., Zhang, Z., Rötter, R.P., 2014. Maize growing duration was prolonged across China in the past three decades under the combined effects of temperature, agronomic management, and cultivar shift. Glob. Chang. Biol. 20, 3686–3699. https://doi.org/10.1111/gcb.12684.

Tao, F., Zhang, L., Zhang, Z., Chen, Y., 2022. Climate warming outweighed agricultural managements in affecting wheat phenology across China during 1981–2018. Agric. For. Meteorol. 316, 108865. https://doi.org/10.1016/j.agrformet.2022.108865.

Thompson, P.A., 1998. Spatial and temporal patterns of factors influencing phytoplankton in a salt wedge estuary, the Swan River, Western Australia. Estuaries 21, 801–817. https://doi.org/10.2307/1353282.

Timilsina, A.P., Baigorria, G.A., Wilhite, D., Shulski, M., Heeren, D., Romero, C., Fensterseifer, C.A., 2023. Soybean response under climatic scenarios with changed mean and variability under rainfed and irrigated conditions in major soybean-growing states of the USA. J. Agric. Sci. 161, 157–174. https://doi.org/10.1017/S0021859623000011.

Vitasse, Y., Signarbieux, C., Fu, Y.H., 2018. Global warming leads to more uniform spring phenology across elevations. Proc. Natl. Acad. Sci. 115, 1004–1008. https://doi.org/10.1073/pnas.1717342115.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J., Fromentin, J.-M., Hoegh-Guldberg, O., Bairlein, F., 2002. Ecological responses to recent climate change. Nature 416, 389–395. https://doi.org/10.1038/416389a.

Wang, Y., Gai, J., 2002. Study on the ecological regions of soybean in China II • ecological environment and representative varieties. Chin. J. Appl. Ecol. 71–75.

Wang, X., Liu, Z., Yang, Chun-yan, Xu, Ran, Lu, W., Zhang, L., Wang, Q., Wei, S., Yang, Chun-ming, Wang, H., Wang, R., Zhou, R., Chen, H., Chang, R., Qiu, L., 2016. Stability of growth periods traits for soybean cultivars across multiple locations. J. Integr. Agric. 15, 963–972. https://doi.org/10.1016/S2095-3119(15)61152-2.

Wang, Z., Chen, J., Tong, W., Xu, C., Chen, F., 2018. Impacts of climate change and varietal replacement on winter wheat phenology in the North China plain. Int. J. Plant Prod. 12, 251–263. https://doi.org/10.1007/s42106-018-0024-0.

Wu, T., Li, J., Wu, C., Sun, S., Mao, T., Jiang, B., Hou, W., Han, T., 2015. Analysis of the independent- and interactive-photo-thermal effects on soybean flowering. J. Integr. Agric. 14, 622–632. https://doi.org/10.1016/S2095-3119(14)60856-X.

Wu, D., Wang, P., Jiang, C., Yang, J., Huo, Z., Yu, Q., 2019. Measured phenology response of unchanged crop varieties to long-term historical climate change. Int. J. Plant Prod. 13, 47–58. https://doi.org/10.1007/s42106-018-0033-z.

Xiao, D., Zhang, Y., Bai, H., Tang, J., 2021. Trends and climate response in the phenology of crops in Northeast China. Front. Earth Sci. 9. https://doi.org/10.3389/feart.2021.811621.

Xin, M., Zhang, Z., Han, Y., Feng, L., Lei, Y., Li, X., Wu, F., Wang, J., Wang, Z., Li, Y., 2023. Soybean phenological changes in response to climate warming in three northeastern provinces of China. Field Crop Res 302, 109082. https://doi.org/10.1016/j.fcr.2023.109082.

Yang, Y., Tao, B., Liang, L., Huang, Y., Matocha, C., Lee, C.D., Sama, M., Masri, B.E., Ren, W., 2021. Detecting recent crop phenology dynamics in corn and soybean cropping Systems of Kentucky. Remote Sens. (Basel) 13, 1615. https://doi.org/10.3390/rs13091615.

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, 563–570. https://doi.org/10.1111/gcb.12057.

Zhang, M., Abrahao, G., Thompson, S., 2021. Sensitivity of soybean planting date to wet season onset in Mato Grosso, Brazil, and implications under climate change. Clim. Change 168, 15. https://doi.org/10.1007/s10584-021-03223-9.

Zhang, L., Zhang, Z., Zhang, J., Luo, Y., Tao, F., 2022. Response of rice phenology to climate warming weakened across China during 1981–2018: did climatic or anthropogenic factors play a role? Environ. Res. Lett. 17, 064029. https://doi.org/10.1088/1748-9326/ac6dfb.