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# The optimisation of rapeseed yield and growth duration through adaptive crop management in climate change: evidence from China

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## Highlights

- *The growth duration of winter rapeseed was shortened, and the yield increased in most stations.*
- *Crop management to changes in GD and yield of winter rapeseed was greater than the impact of climate change.*
- *Cumulative sunshine hours may be the most critical climate factor limiting rapeseed yield in the Yangtze River Basin.*

## Abstract

Crop yield is influenced by plant growth and development; both are affected by climatic variables and crop management practices. Therefore, understanding the effects of climate variables and management practices on rapeseed (*Brassica napus* L.) yield and growth duration (GD) is essential for developing strategies for agricultural systems based on changing climatic conditions. Thus, we quantified the respective contributions of climate change and crop management to rapeseed yield and GD between 2008 and 2019 in China using a first-difference multivariate regression model. Our results showed that: i) based on observed rapeseed yield and phenological data, the average planting date was delayed by –1.1 to 9.5 days decade$^{-1}$, the average maturity date was advanced by 4.4 to 9.9 days decade$^{-1}$, the average GD was shortened by 6.0 to 19.6 days decade$^{-1}$ and the average yield increased by 12.82 to 61.5 kg ha$^{-1}$ year$^{-1}$; ii) the relative contributions of climate change and crop management to winter rapeseed yield were changed from –20% to +39% and from +61% to +80%, respectively, and the relative contributions to GD were changed from –10% to +15% and from –85% to +97%, respectively; iii) among the three climatic factors considered in this study, the climatic factor that caused the most remarkable change in winter rapeseed yield and GD was different in different regions. Overall, compared with cumulative temperature, cumulative sunshine hours may be the most critical climate factor limiting rapeseed yield in the Yangtze River Basin, especially in the upper reaches of the Yangtze River. Our results suggest that stakeholders select high-yielding cultivars to optimise crop management and adaptation strategies in different agroecological zones.

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*See online Appendix for additional material.*

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## Introduction

Rapeseed (*Brassica napus* L.) is the oil crop with the largest planting area and total oil production in China. Sustainable production of rapeseed for high yield and high production efficiency is crucial for edible oil food security. The area of rapeseed production in China accounts for 18.8% of the total production area in the world, and rapeseed yield in China accounts for 20% of the worldwide rapeseed production (USDA, 2018). Moreover, rapeseed oil has a balanced fatty acid composition and is therefore considered optimal for nutritional purposes. In addition, rapeseed meal is a relatively high protein feed for livestock (Watts *et al.,* 2021). However, China's self-produced vegetable oil amounted to 11 million tons per year, and the self-sufficiency rate was only 30.8%, resulting in a gradual expansion of the supply and demand gap (Yin and Wang, 2012). The Yangtze River Basin and Huang-Huai-Hai Plain constitute the largest winter rapeseed production areas in China, where farmers commonly use an intensive crop production system to obtain high yields (Li *et al.,* 2018). It is widely accepted that both crop yield and growth duration are influenced by climate change and management practices, including cultivation methods and cultivar changes (Ahmad *et al.,* 2017; Liu *et al.,* 2018b). Winter rapeseed is vulnerable to local climatic conditions because of its long growing season (Zhang *et al.,* 2017b). A better understanding of how climate change and agronomic factors contribute to changes in rapeseed yield and growth duration could provide a scientific basis for adapting to and mitigating climate change impacts.

The global average surface temperature increased by 0.99°C from 2001 to 2022 compared with the period from 1850 to 1900, and the period from 2010 to 2020 may be the hottest 10 years of the past 1400 years, and global warming is expected to continue (IPCC 2021). Increasing temperature generally accelerates crop development, shortens the growing season, and may reduce crop productivity (Asseng *et al.,* 2015, He *et al.,* 2020). For example, previous reports have stated that climate warming delayed planting, emergence, and dormancy dates. In contrast, the green-up dates after winter dormancy, anthesis, and maturity of winter wheat (*Triticum aestivum* L.) were advanced (Xiao *et al.,* 2013; He *et al.,* 2015). Recent studies have established that every 1°C increase in temperature reduces global wheat yield by 4.1-6.4% (Liu *et al.,* 2016) and reduces rice (*Oryza sativa* L.) yield by 10% (Peng *et al.,* 2004). Additionally, some farmers have adopted some effective management measures to mitigate the negative effects of climate change on crop production. Although global warming could lead to a reduction in the length of the rice growing season and decreased rice yields, varietal improvements were able to stabilise growth duration and increase rice grain yield (Liu *et al.,* 2012). Wang *et al.* (2012) showed that the 'Double-Delay' technology led to an overall 4-6% increase in total grain yield of the wheat-maize (*Zea mays* L.) system. High nitrogen input reduced yield loss resulting from low temperatures during the seedling stage in early-season rice (Zhou *et al.,* 2018).

Crop management is also one of the main factors that affect crop yield and growth duration, and numerous studies have provided valuable insights into the relationship between management practice and food security (Liu *et al.,* 2018a; He *et al.,* 2020; Liu *et al.,* 2020). Rapeseed yield loss caused by lodging can be reduced by selecting the optimum planting density and N application rate to construct an ideotype and suitable population structure (Khan *et al.,* 2018). It is well known that planting density influences yield components of winter rapeseed. Increasing planting density usually leads to increased seed yield and oil production of winter rapeseed through increases in the main raceme numbers per unit area and the production capacity of the main raceme (Zhang *et al.,* 2012). However, increased planting density was observed to lower rhizome diameter and snapping resistance, and hence, the common planting density is 30 to 45 plants $m^{-2}$ for hybrid rapeseed under the direct-seeding cropping system in China (Wang *et al.,* 2015; Li *et al.,* 2018).

Furthermore, it is necessary to understand the effects of agronomic management practices and climatic variables on the growth duration and yield of winter rapeseed in China. Under these circumstances, data from the 'Summary Report of National Winter Rapeseed Regional Trial' can represent the average level of local production. Therefore, in this study, we attempted to quantify the relative contributions of critical influencing factors in different planting regions.

The overall objective of this study was to further understand the impacts of climate change and crop management practices on rapeseed yield and growth duration during the past decade in China and to provide suggestions for high-yield cultivation of rapeseed cultivars. In this study, we investigated the observed trends of yield and growth duration of winter rapeseed at 44 experiment stations in China for 2008-2019 and the corresponding meteorological data (average temperature, accumulated precipitation, and accumulated sunshine hours). The specific objectives of the study were to: i) isolate and quantify the impacts of climate change and crop management on changes in winter rapeseed yield and growth duration; ii) evaluate the relative contributions of climate change and crop management to yield and growth duration and identify the spatial differences of the impacts; iii) quantify the relative contributions of temperature, precipitation, and sunshine hours to yield and growth duration of rapeseed.

## Materials and methods

### Data collection

More than 90% of China's winter rapeseed is planted in the Yangtze River Basin and the Huang-Huai-Hai Plain. According to local farming practices and climate conditions, we divided the area into four regions, including the Huang-Huai-Hai region (HH), the upper reaches of the Yangtze River (UYR), the middle reaches of the Yangtze River (MYR), and the lower reaches of the Yangtze River (LYR) (Figure 1). The data for rapeseed yield and growth duration (days between planting and maturity) were obtained from 'Summary Report of National Winter Rapeseed Regional Trial' (compiled by the Research Institute of Oil Crops in the Chinese Academy of Agricultural Sciences and National Technology Extension and Service Centre) for 2008-2019. In addition, daily meteorological data, including mean temperature, precipitation, and sunshine hours, have been downloaded from the China Meteorological Data Website (http://data.cma.cn/site/index.html). In the four major winter rapeseed planting zones, 44 stations (10 stations in HH, 12 stations in UYR, 12 stations in MYR, and 10 stations in LYR) were selected for this study (Table A1). The stations were chosen based on data availability for yield, planting

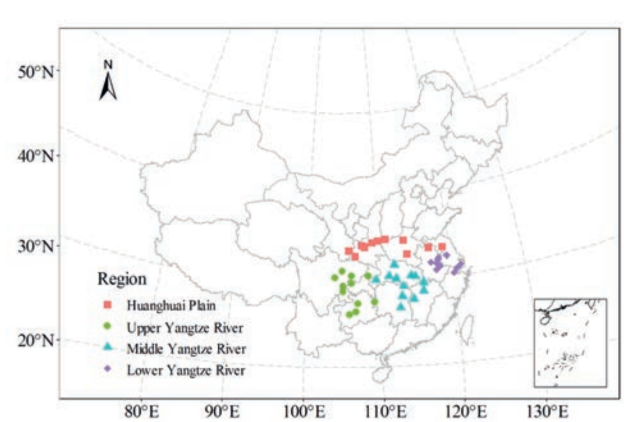


**Figure 1. Locations of winter rapeseed experiment stations in four different regions of China.**

dates (PD), maturity dates (MD), and GD and on meteorological record completeness. Rapeseed management practices have changed in recent years from transplanting to direct seeding and from low-density to higher-density planting. There have also been improvements in water and fertilizer management. Therefore, we selected data for rapeseed varieties that are widely grown and less frequently replaced over time by other varieties (Table A2). The average values of rapeseed PD, MD, GD, and climatic factors during the corresponding periods in each rapeseed cropping region are presented in Table 1.

## Analysis methods

### *Change trends of rapeseed yield, growth duration, and climate*

Trends of observed rapeseed GD, yield, and climatic variables (average temperature, cumulative precipitation, and cumulative sunshine hours) during corresponding GD were calculated by establishing a linear regression model with year as the independent variable. The planting date and maturity date were the average months of planting and maturity, and the GD was the period from the average planting date to the average maturity date in the past at each station. Our analysis indicated that winter rapeseed was generally planted in late September and early October and harvested in May (Table 1). By holding GD constant for every year at the same station, the calculated trends of average temperature, cumulative precipitation, and cumulative sunshine hours are independent of phenology changes (Liu *et al.,* 2018b, He *et al.,* 2020). For each station, the trends of average temperature, cumulative precipitation, and cumulative sunshine hours for the corresponding periods were calculated using the following equation:

$$Cli = T_{cli} \times Year + \beta_{cli} \quad (1)$$

where *Cli* represents observed climatic factors [average temperature (°C), cumulative precipitation (mm), or cumulative sunshine hours (h)]; *Year* represents the year; $\beta_{cli}$ represents the intercept; $T_{cli}$ represents the linear regression slope that is the trend of the climatic factor. For each station, the trends of winter rapeseed GD and yield were calculated using the following equation:

$$V = T_v \times Year + \beta_v \quad (2)$$

where *V* represents the observed phenological stage (DOY), GD (days), or yield (kg ha$^{-1}$); *Year* represents the year; $\beta_v$ represents the intercept; $T_v$ represents the slope of the linear regression that reflects the impacts of both climate change and crop management.

### *Isolating impacts of climate change and crop management practices on rapeseed growth duration and yield*

To investigate correlations between crop growth and climate variables during each growing season at several stations in each planting zone, yields were first linearly detrended to obtain the detrended yield series that were mainly affected by seasonal climate variability. The first-difference method is a common detrending technique used to establish climate-crop relationships because it can reduce the influence of long-term trends due to technological improvements or other effects caused by changes in crop management practices (Zhang and Huang, 2013, Liu *et al.,* 2018b, He *et al.,* 2020). The first-difference value of yield is the absolute difference ($\Delta Y = |Y_{t+1} - Y_t|$) and is the response variable; the first-difference values of the climate variables ($\Delta T$, $\Delta P$, $\Delta S$) are the explanatory variables. Here we used the first-difference method to establish relationships between climate and GD or yield. The established multiple regression model was:

$$\Delta V = S_{tem} \times \Delta T + S_{pre} \times \Delta P + S_{ssh} \times \Delta S + int \quad (3)$$

where $\Delta V$ represents the first-difference value of the phenological stage (PD, MD), GD, or yield; $\Delta T$, $\Delta P$, and $\Delta S$ represent the first-difference values of average temperature, cumulative precipitation, and cumulative sunshine hours, respectively. For each corresponding period, *int* represents the intercept of the regression model; $S_{tem}$, $S_{pre}$, and $S_{ssh}$ represent the sensitivity of rapeseed to temperature, cumulative precipitation, or cumulative sunshine hours, respectively.

Thus, the trend of rapeseed PD and MD as affected by only climate change was calculated as follows:

$$T_{v\_cli} = S_{tem} \times T_{tem} + S_{pre} \times T_{pre} + S_{ssd} \times T_{ssd} \quad (4)$$

where $T_{v\_cli}$ represents the trends of the phenological stage, GD (days year$^{-1}$), or yield (kg ha$^{-1}$ year$^{-1}$) under the isolated impacts of climate change; $T_{tem}$, $T_{pre}$, and $T_{ssd}$ represent the trends of average temperature, cumulative precipitation, and cumulative sunshine hours, respectively, for the corresponding period; and other parameters are defined the same as in Eq. (3). The observed crop growth

**Table 1. Mean and standard deviation for day of year of planting and maturity, growth duration, and climatic factors during corresponding periods in each rapeseed cropping region.**

| Phenology | Region* | Day of year or days | TEM (°C) | PRE (mm) | SSH (h) | AT0 (°C) | Yield (kg/ha) |
|---|---|---|---|---|---|---|---|
| PD | HH(10) | 267±8 | 17.9±1.4 | 155±96 | 263±83 | 1090±90 | - |
| | UYR(12) | 272±10 | 20.0±1.5 | 207±80 | 156±50 | 1220±100 | - |
| | MYR(12) | 275±6 | 21.6±1.1 | 170±92 | 276±70 | 1317±81 | - |
| | LYR(10) | 276±9 | 21.2±0.9 | 185±121 | 283± 80 | 1302± 109 | - |
| MD | HH(10) | 146±6 | 20.5±1.5 | 65±37 | 198±39 | 635±53 | - |
| | UYR(12) | 125±9 | 21.1±1.4 | 133±66 | 113±38 | 654±48 | - |
| | MYR(12) | 126±7 | 22.3±0.8 | 181±89 | 138±36 | 691±37 | - |
| | LYR(10) | 139±5 | 21.9±0.5 | 104±53 | 175±41 | 685±67 | - |
| GD | HH(10) | 245±11 | 9.4±0.9 | 254±63 | 1220±102 | 2374±201 | 3249±409 |
| | UYR(12) | 220±12 | 12.2±1.5 | 310±104 | 487±86 | 2671±318 | 2491±232 |
| | MYR(12) | 218±8 | 11.9±0.8 | 598±177 | 760±123 | 2580±179 | 2571±331 |
| | LYR(10) | 230±10 | 11.4±0.8 | 550±133 | 1016±117 | 2636±155 | 2695±268 |

PD, planting date; MD, maturity date; GD, growth duration; TEM, average temperature; PRE, cumulative precipitation; SSH, cumulative sunshine hours; AT0, accumulated temperature above 0°C; HH, Huang-Huai-Hai region; UYR, upper reaches of Yangtze River; MYR, middle reaches of Yangtze River; LYR, lower reaches of Yangtze River. *Number of stations is given in parentheses. Tabulated values are mean±standard deviation.

trend ($T_v$) is the combined impact of climate factors and management. Thus, the sole impact of crop management was calculated as follows:

$$T_{v\_man} = T_v - T_{v\_cli} \quad (5)$$

where $T_{v\_man}$ represents the trend of phenological stage, GD (days year$^{-1}$), or yield (kg ha$^{-1}$ year$^{-1}$) under the isolated impact of crop management. The statistical test for the difference of the means of $T_v$ and $T_{v\_cli}$ was conducted by a two-sample t-test at all stations grouped by rapeseed cropping system.

***Calculating relative contributions of each impact factor to rapeseed phenology and yield trends***

According to Eq. (4), the trends in rapeseed phenology and yield under the isolated impacts of climate change depended on average temperature, precipitation, and sunshine hours. For example, the relative contribution from changes in average temperature ($RC_{tem}$) on rapeseed phenology and yield was calculated as follows:

$$RC_{tem} = \frac{S_{tem} \times T_{tem}}{|S_{tem} \times T_{tem}| + |S_{pre} \times T_{pre}| + |S_{ssh} \times T_{ssh}|} \times 100\% \quad (6)$$

where parameters are defined the same as in Eq. (4). The relative contributions from changes in cumulative precipitation ($RC_{pre}$) and cumulative sunshine hours ($RC_{ssd}$) on rapeseed phenology and yield can be calculated similarly.

For a specific phenological stage, GD, or yield, the average relative contribution from changes in average temperature ($\overline{RC}_{tem}$) for winter rapeseed was calculated as follows:

$$\overline{RC}_{tem} = \frac{\sum_{i=1}^{n} RC_{tem,i}}{|\sum_{i=1}^{n} RC_{tem,i}| + |\sum_{i=1}^{n} RC_{pre,i}| + |\sum_{i=1}^{n} RC_{ssh,i}|} \times 100\% \quad (7)$$

where $n$ represents the number of stations in each zone; $RC_{tem,i}$, $RC_{pre,i}$, and $RC_{ssh,i}$, represent relative contributions from changes in average temperature, cumulative precipitation, and cumulative sunshine hours, respectively, at station $i$. The average relative contributions from cumulative precipitation and cumulative sunshine hours for each rapeseed-cropping system can be calculated similarly and are defined as ($\overline{RC}_{pre}$) and ($\overline{RC}_{ssh}$) , respectively.

According to Eq. (5), combined effects of climate change and crop management affect trends of rapeseed phenology and yield. Therefore, the relative contribution of climate change ($RC_{cli}$) at each station was calculated as follows:

$$RC_{cli} = \frac{T_{v\_cli}}{|T_{v\_cli}| + |T_{v\_man}|} \times 100\% \quad (8)$$

where the parameters are defined the same as in Eq. (5). The relative contribution of crop management can be calculated similarly and is defined as $RC_{man}$.

The average relative contribution of climate change ($\overline{RC}_{cli}$) for winter rapeseed was calculated as follows:

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

where $n$ represents the number of stations in each zone; $RC_{cli,i}$ and $RC_{man,i}$ represent the relative contributions from climate change and crop management, respectively, at station $i$. The average relative contribution from crop management for each station can be calculated similarly and is defined as ($\overline{RC}_{man}$) .

## Results

### Trends of climate change

The mean planting dates for winter rapeseed in each zone (HH, UYR, MYR, and LYR) were in late September and early October, and the mean maturity dates were in May (Table 1). The average yield of winter rapeseed was the largest in HH (3249 kg ha$^{-1}$), and this result may be related to this region having the longest GD and greatest cumulative sunshine hours. On the other hand, although the average temperature and cumulative temperature were the highest in UYR, the average yield of winter rapeseed was the lowest. Among the climate factors, the average temperature and cumulative precipitation in the whole growth period of winter rapeseed exhibited an increasing tendency from 2008 to 2019, and the rates of increase ranged from 0.1 to 0.6°C decade$^{-1}$ and from 62.1 to 124.4 mm decade$^{-1}$, respectively. The trends in sunshine hours varied between planting zones (Table 2). However, the average temperature and cumulative temperature tended to decrease during corresponding periods of planting date for winter rapeseed except for the HH. In contrast, an increasing trend was observed for precipitation except for the HH.

***Trends of planting date, maturity date, growth duration, and yield***

The spatial trends for planting date (PD) are shown in Figure 2A. Over the 2008-2019 period, except for LYR, PD was delayed by an average of 1.4, 9.5, and 1.3 days decade$^{-1}$ in HH, UYR, and MYR, respectively. Delayed PD (red circles) occurred at 28 stations (delays at 14 stations were statistically significant at $P<0.05$). However, PD at the other 16 stations (blue circles) was advanced, but it was only significant at six stations. In contrast, the trends for maturity date (MD) were different from the trends of PD (Figure 2B). MD was advanced at 42 stations (significantly at 30 stations), and average MD values were 4.4, 9.9, 6.4, and 7.8 days decade$^{-1}$ in HH, UYR, MYR, and LYR, respectively.

The GD (from planting to maturity) decreased by 6.0 to 19.6 days decade$^{-1}$ from 2008 to 2019, with the decreasing trend observed at 38 stations, ranging from 0.0 to 36.0 days decade$^{-1}$. The decreasing trend was significant at 27 stations. The delayed PD (3.0 days decade$^{-1}$, Figure 2A) and the advancement of MD (7.2 days decade$^{-1}$, Figure 2B) led to a reduction in GD (10.4 days decade$^{-1}$, Figure 2C). In contrast, an increasing trend for rapeseed yield was observed at 32 stations, and it was significant at 11 stations. The yield increased by an average of 61.48, 12.82, 24.22, and 18.09 kg ha$^{-1}$ decade$^{-1}$ in HH, UYR, MYR, and LYR, respectively.

***Sensitivity of planting date, maturity date, growth duration, and yield to different climatic factors***

The sensitivities of winter rapeseed PD, MD, GD, and yield to climatic factors in the four planting zones based on the first-difference method are shown in Figure 3. On average, seed yield showed a positive sensitivity to cumulative sunshine hours in each zone (Figure 3C, right-hand cluster of bars). In comparison, yield showed a negative sensitivity to cumulative precipitation except in

**Table 2. Mean trends of precipitation ($T_{pre}$), sunshine hours ($T_{ssh}$), temperature ($T_{tem}$), and accumulated temperature above 0°C ($T_{AT0}$) per year during corresponding periods for winter rapeseed cropping regions.**

| Phenology | Region | $T_{pre}$ (mm yr$^{-1}$) | $T_{ssh}$ (hr yr$^{-1}$) | $T_{tem}$ (°C yr$^{-1}$) | $T_{AT0}$ (°C yr$^{-1}$) |
|---|---|---|---|---|---|
| PD | HH | 1.54 | 1.83 | 0.00 | 0.09 |
| | UYR | 2.81 | –4.39 | –0.07 | –4.30 |
| | MYR | 5.07 | –2.58 | –0.07 | –4.38 |
| | LYR | 14.90 | 1.54 | –0.10 | –1.28 |
| MD | HH | –3.38 | 1.82 | 0.04 | 1.22 |
| | UYR | 2.67 | 1.95 | 0.02 | 0.62 |
| | MYR | 0.49 | –0.84 | 0.03 | 0.99 |
| | LYR | 4.17 | –2.95 | 0.01 | 2.73 |
| GD | HH | 6.21 | –4.72 | 0.06 | 11.86 |
| | UYR | 7.81 | 2.44 | 0.05 | 10.87 |
| | MYR | 12.44 | –16.18 | 0.02 | 2.74 |
| | LYR | 11.99 | –12.21 | 0.05 | 18.87 |

PD, planting date; MD, maturity date; GD, growth duration (planting to maturity); HH, Huang-Huai-Hai region; UYR, upper reaches of Yangtze River; MYR, middle reaches of Yangtze River; LYR, lower reaches of Yangtze River.



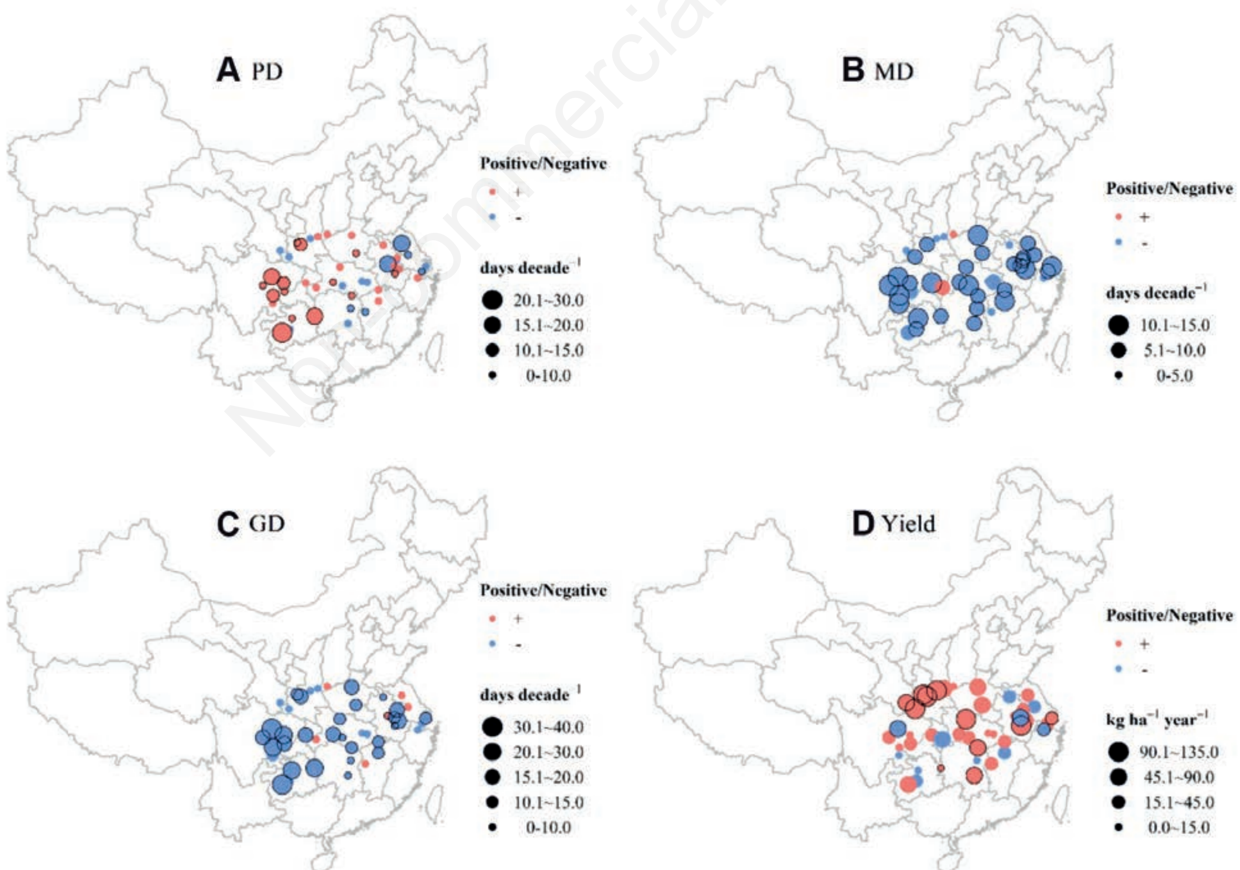


**Figure 2. Observed trends in: A) planting date (PD), B) maturity date (MD), C) growth duration (GD), and D) yield (yield) for rapeseed in China from 2008 to 2019. Black circle outlines indicate statistically significant trends (P=0.05).**

MYR (Figure 3B, right-hand cluster of bars). The yield in LYR was the most sensitive to cumulative sunshine hours, with an increase of 80.9 kg ha$^{-1}$ for every 10 h increase. On the other hand, the yield in UYR was the most sensitive to precipitation, with a decrease of 97.5 kg ha$^{-1}$ for every 100 mm.

PD, MD, and GD of winter rapeseed varied in their sensitivities to average temperature, cumulative precipitation, and cumulative sunshine hours in different regions. Generally, GD and yield responded positively to average temperature and cumulative sunshine hours but negatively to cumulative precipitation. Furthermore, PD showed positive sensitivity to average temperature and cumulative precipitation. In contrast, MD showed a negative sensitivity to average temperature and cumulative precipitation.

## Impacts of climate change and crop management

Figure 4 shows the distribution of trends of rapeseed PD, MD, GD, and yield under the isolated and combined impacts of climate change and crop management practices. Overall, the variability of the trends influenced by climate change was smaller than those influenced by crop management only or by the combined impacts of climate change and management in each planting zone. When considered across both combined and isolated impacts of climate change and crop management, PD at most stations was delayed, MD at most stations was advanced, and GD at most stations was shortened. Notably, seed yield at most stations increased.

The mean values of trends of GD influenced only by climate (Table 3) were positive (except for UYR), and the GD trends that were influenced only by management were negative in all four planting zones, leading to a negative mean trend value for the combined effects of climate change and crop management. The trends of winter rapeseed yield influenced only by climate were positive

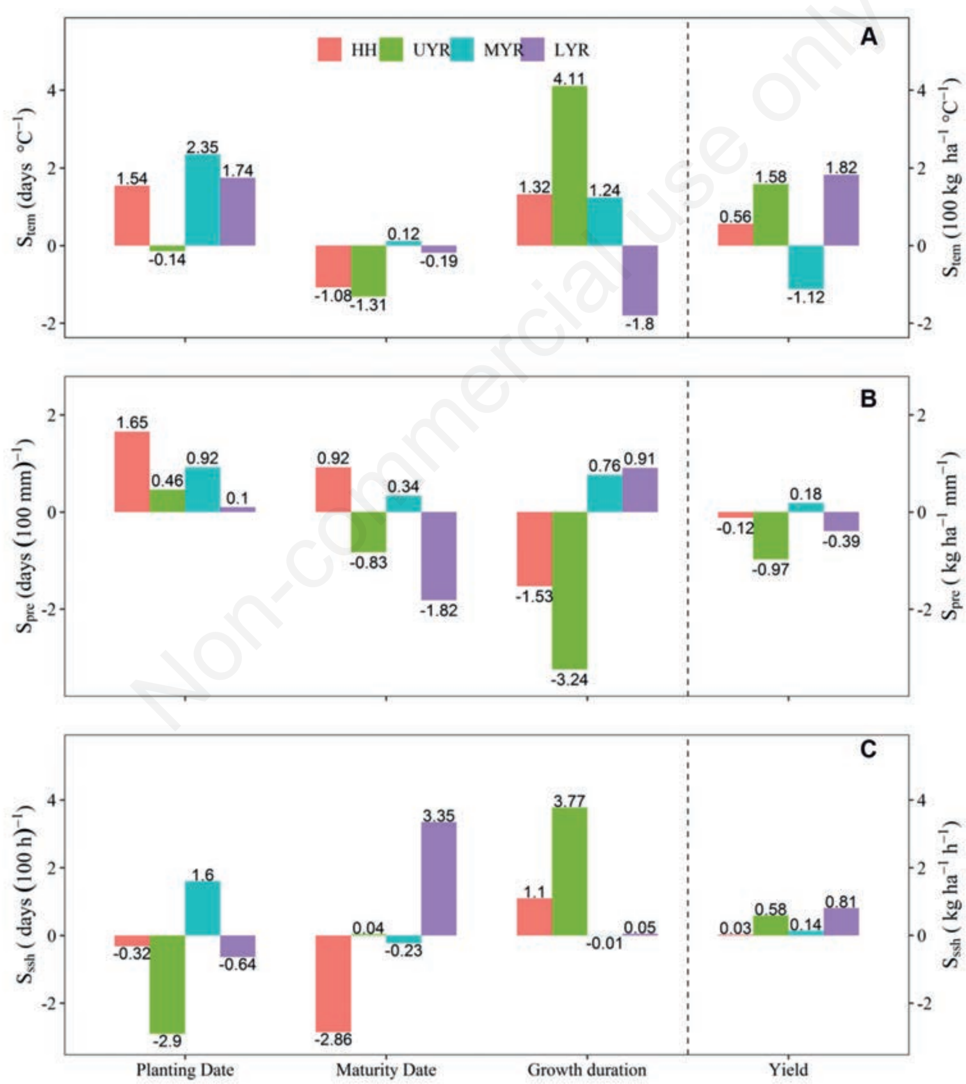


**Figure 3. Sensitivity (S) of rapeseed growth duration (left three bar clusters in each panel) and yield (right bar cluster in each panel) to climatic factors for winter rapeseed cropping systems using observed data. Values denote the mean sensitivity of all stations in each rapeseed cropping system. tem, mean temperature; pre, cumulative precipitation; ssh, cumulative sunshine hours; HH, Huang-Huai-Hai region; UYR, upper reaches of Yangtze River; MYR, middle reaches of Yangtze River; LYR, middle reaches of Yangtze River.**

**Table 3. Comparison of mean values of trends of rapeseed phenology (days year$^{-1}$) and yield (kg ha$^{-1}$ year$^{-1}$) under the effects of climate change, crop management, and combined climate change and crop management for winter rapeseed.**

| Variable | Region* | $Trend_{cli}$ | $Trend_{man}$ | $Trend_{cli\_man}$ | t-test (P-value) |
|---|---|---|---|---|---|
| PD | HH(10) | 0.01 | 0.13 | 0.14 | 0.620 |
| | UYR(12) | 0.50 | 0.45 | 0.95 | 0.196 |
| | MYR(12) | –0.04 | 0.17 | 0.13 | 0.332 |
| | LYR(10) | –0.15 | 0.04 | –0.11 | 0.921 |
| MD | HH(10) | –0.29 | –0.15 | –0.44 | 0.495 |
| | UYR(12) | –0.10 | –0.89 | –0.99 | 0.000 |
| | MYR(12) | –0.02 | –0.62 | –0.64 | 0.000 |
| | LYR(10) | –0.12 | –0.65 | –0.78 | 0.008 |
| GD | HH(10) | 0.16 | –0.77 | –0.60 | 0.013 |
| | UYR(12) | –0.04 | –1.92 | –1.96 | 0.000 |
| | MYR(12) | 0.32 | –1.11 | –0.79 | 0.003 |
| | LYR(10) | 0.13 | –0.82 | –0.69 | 0.055 |
| Yield | HH(10) | 5.28 | 56.21 | 61.49 | 0.071 |
| | UYR(12) | 4.35 | 13.74 | 18.09 | 0.413 |
| | MYR(12) | 3.56 | 20.66 | 24.22 | 0.102 |
| | LYR(10) | –4.90 | 17.72 | 12.82 | 0.384 |

PD, planting date; MD, maturity date; GD, growth duration; $Trend_{cli}$, trend as affected only by climate change; $Trend_{man}$, trend as affected only by management; $Trend_{cli\_man}$, trend as affected by the combination of climate change and management. Note that the P-values are the result of a two-sample t-test performed on trends under the combined effects ($Trend_{cli\_man}$) and trends under only the effects of climate change ($Trend_{cli}$). HH, Huang-Huai-Hai region; UYR, upper reaches of Yangtze River; MYR, middle reaches of Yangtze River; LYR, lower reaches of Yangtze River. *Number of stations is given in parentheses.



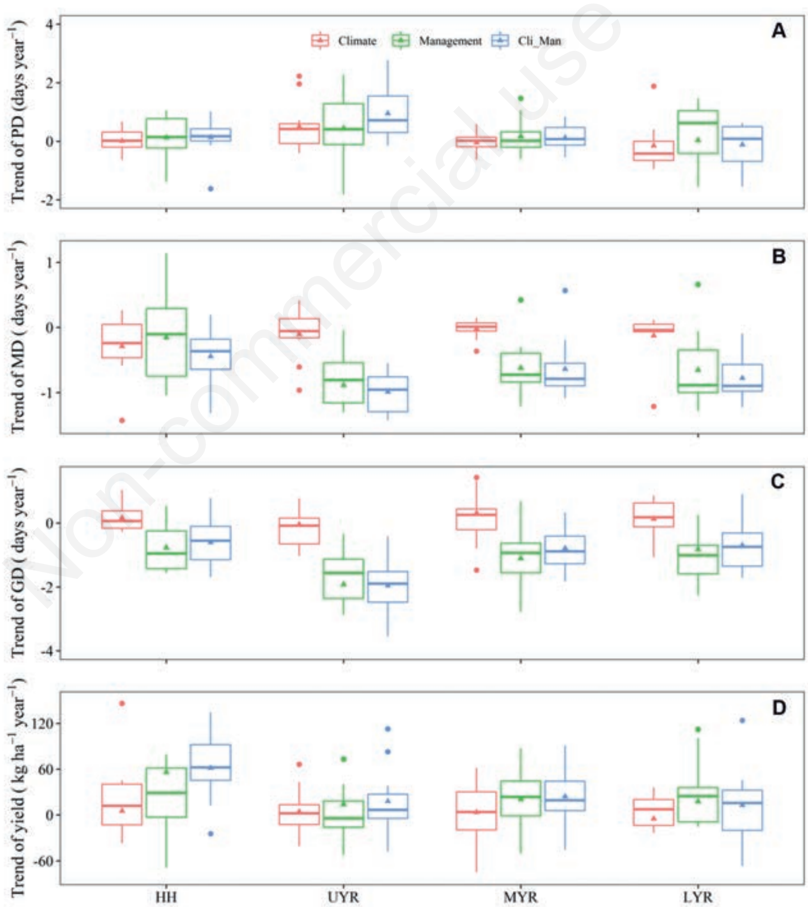


**Figure 4. Box plots of trends of: A) planting date (PD), B) maturity date (MD), C) growth duration (GD), and D) yield for winter rapeseed at each station based on observed data. 'Climate' (red box plots) indicates the impact of only climate change; 'Management' (green box plots) indicates the impact of only crop management practices, and 'Cli_Man' (blue box plots) indicates the combined impacts of climate change and crop management. The lower and upper box boundaries are the 25$^{th}$ and 75$^{th}$ percentiles; the horizontal bar in the box is the median; the triangle in the box in the mean; the lower and upper whiskers are the 10$^{th}$ and 90$^{th}$ percentiles, respectively; the dots outside the box are outliers. HH, Huang-Huai-Hai region; UYR, upper reaches of Yangtze River; MYR, middle reaches of Yangtze River; LYR, middle reaches of Yangtze River.**

at most stations. The smallest yield increases over time were observed at LYR (12.82 kg ha$^{-1}$ year$^{-1}$ for the combined influence of climate change and crop management), and the yield decreased by 4.9 kg ha$^{-1}$ year$^{-1}$ at LYR because of climate change. There were some differences in the combined effects of climate change and management compared with the isolated effect of climate change on the maturity date and the GD (Table 3). However, the trends in yield were not significantly different between those obtained with only climate influences and those obtained with the combined effects of climate and management, indicating that the influence of climate change on yield trend was slight.

## Discussion

### Comparison of the impacts of climate change and crop management

Figure 5 illustrates the average relative contributions of climate change and crop management influences to observed rapeseed phenology trends and yield trends. Negative values in the figure indicated that climate change or crop management advanced phenology, shortened a growth phase, or decreased rapeseed yield, and positive values indicated the opposite response. In general, our results were consistent with earlier reports showing that the relative contributions of management on phenology and yield trends were more significant than climate change (Liu *et al.,* 2018b; Liu

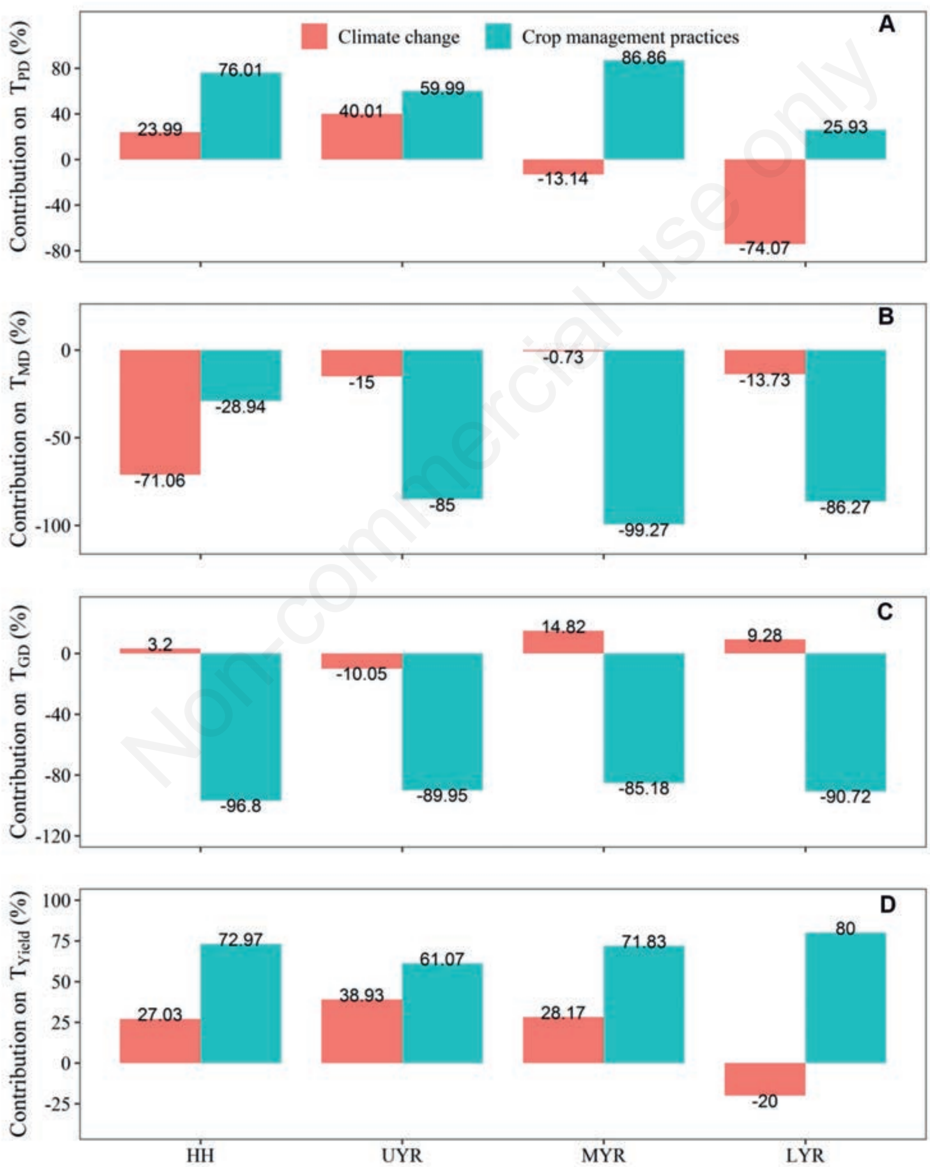


**Figure 5. Average relative contribution of climate change and crop management on observed yield and growth period trends for rapeseed. Values above bars indicate the mean percentage of all stations. PD, planting date; MD, maturity date; GD, growth duration; HH, Huang-Huai-Hai region; UYR, upper reaches of Yangtze River; MYR, middle reaches of Yangtze River; LYR, middle reaches of Yangtze River.**

*et al.,* 2020). On average, under the combined effects of climate change and crop management for winter rapeseed, planting dates were delayed (except for LYR), maturity dates were advanced, the length of GD was shortened, and rapeseed yield increased in each zone (Table 3 and Figure 4). This finding was consistent with the results of previous studies conducted within winter wheat (Liu *et al.,* 2018b, Liu *et al.,* 2020), soybean (*Glycine max* L.) (He *et al.,* 2020), canola (*Brassica napus* L.) (Ahmad *et al.,* 2017), and other crops (Siebert and Ewert, 2012).

Climate change's relative contribution had positive and negative effects on PD, GD, and yield. The PD was delayed (Figure 2A, red circles) at 28 stations and was significant at 14 stations. On the one hand, climate warming produces more adequate heat/thermal conditions to increase crop production. On the other hand, it is noteworthy that climate change may increase the frequency of extreme climate events, leading to greater production uncertainty. Previous studies have established that every 1°C increase in minimum temperature reduces rice yield by 10% (Peng *et al.,* 2004). Rapeseed planting date is mainly affected by farmers' management practices, and farmers can plant rapeseed earlier or later to wait for adequate rain to promote germination. Therefore, it is likely that the delays in planting date in the past decades was a response of farmers to climate change. In addition, planting date changes in the past might also be related to the preceding crop in a crop rotation system (*e.g*., single rice or late rice) when GD was extended in the Yangtze River Basin (Zhao *et al.,* 2016).

Overall, our results showed that the average relative contribution of crop management was more significant than the contribution of climate change to winter rapeseed yield and GD, and similar results have been reported for winter wheat (Liu *et al.,* 2018b, Liu *et al.,* 2020). In particular, we also found that the direction of the relative contribution of crop management was identical for the observed phenology and yield trends in different winter rapeseed planting zones. This finding implies that crop management practices determined by farmers were, to some extent, a response to climate change, *e.g*., cultivation method changes, adjusting planting dates, plant density, fertiliser management, and cultivar shifts. Previous studies have shown that direct seeding showed favourable changes that produced high-yield components compared with the transplanting of rapeseed, including earlier seedling emergence, stronger root activity, and greater biomass production (Yasumoto *et al.,* 2011; Wang *et al.,* 2015). It seems widely accepted that a shorter-season cultivar is likely to result in yield reductions because there is less time for biomass accumulation during the vegetative phase. Therefore, despite the possible yield loss, using a shorter-season cultivar could be a positive strategy for adapting to climate change since the warmer climate would accelerate crop growth. In addition, whether or not crop yield would be lost depends on the duration of the grain-filling period rather than on GD. Increasing grain-filling duration by 20% could increase potential yield by 10% for winter rapeseed (He *et al.,* 2017). Previous studies have demonstrated that the optimum plant density for seed yield varies with the environment and that a longer post-flowering period is critical for increasing rapeseed yield (Gan *et al.,* 2016).

Our results showed that advanced maturity date was the main reason for the shortened GD of winter rapeseed compared with delayed planting date. The reason for the advanced maturity date was the increased cumulative temperature during the maturity month. Moreover, early-maturing rapeseed cultivars also played an important role in GD (Lu *et al.,* 2011; Xu *et al.,* 2019). Additionally, reducing GD is beneficial to increasing the frequency of cropland harvested each year, especially in the rapeseed-rice rotation system or the rapeseed-rice-rice rotation system of the Yangtze River Basin. Previous studies have proposed that increasing global cropland production by increasing the multiple crop index or harvest frequency each year is more conducive to reducing impacts on the ecological environment than increasing crop yield on existing agricultural lands and expanding the area under cultivation (Ray and Foley, 2013; Xu *et al.,* 2021). To improve the rapeseed oil self-sufficiency rate, the Chinese government has planned to revitalise the rapeseed industry in recent years and encourage farmers to plant more winter rapeseed to sufficiently use the thermal and light resources in the Yangtze River Basin.

## Comparison of impacts of temperature, precipitation, and sunshine hours

Our results showed that compared with cumulative temperature, cumulative sunshine hours might be the most critical climatic factor limiting rapeseed yield in the Yangtze River Basin, especially in the upper reaches of the Yangtze River (Table 1). The relative contribution of each climate factor to phenology trends and rapeseed yield trends are illustrated in Figure 6. The relative contributions varied among the three climate factors because of the different sensitivities of phenology and yield to each climate factor (Figure 3) and different trends of climate factors during various corresponding periods (Table 2). Previous studies found that average temperature impacts were the greatest for phenology and yield (Liu *et al.,* 2018b, He *et al.,* 2020, Liu *et al.,* 2020). However, we found that the dominant climate factor affecting winter rapeseed yield across regions varied. For example, the cumulative sunshine hours were the dominant factor in HH, cumulative precipitation in UYR, and the average temperature in MYR and LYR. Hence, our results do not fully support the results of earlier studies indicating that temperature change was the main driver of crop phenological and yield changes (Wang *et al.,* 2013) due to crop characteristics and different regional environmental conditions surrounding rapeseed cultivation in China. We also found that thermal resources have increased over time for rapeseed GD in each planting region (Cong *et al.,* 2019). However, the average temperature, cumulative precipitation, and cumulative sunshine hours during the rapeseed GD were varied in time and space, pointing to the use of different varieties over time and across eco-regions (Siebert and Ewert, 2012). We found that temperature changes positively affected rapeseed yield in the UYR and LYR and a negative effect in the HH and MYR. Our results agree with those of Tao *et al*. (Tao *et al.,* 2013), who reported that rapeseed yield would generally increase with mean temperature at most stations because $T_{tem}$ during the rapeseed GD is generally below the threshold temperature level. Additionally, the mean temperature changes positively affected GD at most stations. However, there is an increased probability of crop failures and lower yields due to the increased frequency of extremely high temperatures with climate warming during the flowering or grain-filling stages, forcing early rapeseed maturity and leading to reductions in 1000-seed weight and oil content (Xu *et al.,* 2019). In some areas, there are major challenges to increasing rapeseed productivity in the future (Tao *et al.,* 2012). Therefore, developing new varieties that are heat tolerant or have higher thermal requirements is likely to be a potentially effective way to ensure adequate rapeseed production in some planting zones. Changes in sunshine hours affect the total solar radiation available for photosynthesis. Our results showed that the cumulative sunshine hours parameter positively affected yield (Figure 3C) but decreased in most planting areas during 2008-2019 (Table 2). The overwintering period is critical for the growth of winter rapeseed, and winter haze and cloudy conditions reduce the intensity and stability of radiation, leading to a decrease in the photosynthetic productivity of winter rapeseed during vegetative growth (Cong *et al.,* 2020). We also found that the UYR had the least cumulative sunshine hours and the lowest rapeseed yield compared with the other three planting zones (Table 1). The highest value of cumulative sunshine hours was observed at HH. In a recently published paper, He *et al*. (He *et al.,* 2017) performed a more in-depth study to model the climate change effects with the APSIM-Canola model. They found that an increase in radiation use efficiency (or sunshine hours) would increase yield in the Yangtze River Basin, but the radiation use efficiency increase would only slightly affect yield in the Northern Region. Our results are consistent with the reports. This finding further confirms that sunshine hour was the most significant limiting factor for increasing rapeseed production. Applying higher amounts of N fertiliser under winter haze and cloudy conditions could compensate for their adverse effects and ensure adequate rapeseed yield (Cong *et al.,* 2020). In addition, more researchers believe that breeding for high photosynthetic efficiency is a critical strategy needed to improve the yield potential of rapeseed varieties further, and this breeding strategy should be an essential focus for the future development of super-high-yield rapeseed varieties (Xu *et al.,* 2015; Zhang *et al.,* 2017a).

We found that changes in accumulated precipitation during the 2008-2019 GD negatively impacted most stations, especially in the UYR planting zone. Precipitation was the most crucial agroclimatic constraint, and the optimum range for rapeseed production was 410-567 mm each year in Hubei province (Zhang *et al.,* 2017b). The lower rainfall in the HH planting zone did not affect rapeseed yield, and this finding may be attributed to irrigation easing the water deficit. However, excessive precipitation during the period from flowering to harvest causes rapeseed to suffer from waterlogging stress, ultimately leading to the yield decline (Zhou *et al.,* 1997; Xu *et al.*. 2015). Furthermore, outbreaks of sclerotinia stem rot were induced by muggy and humid field conditions at flowering, indirectly leading to the loss of production (Koch *et al.,* 2007; Ficke *et al.,* 2018).

Additionally, global climate change is predicted to lead to extreme temperatures and prolonged periods of severe drought in



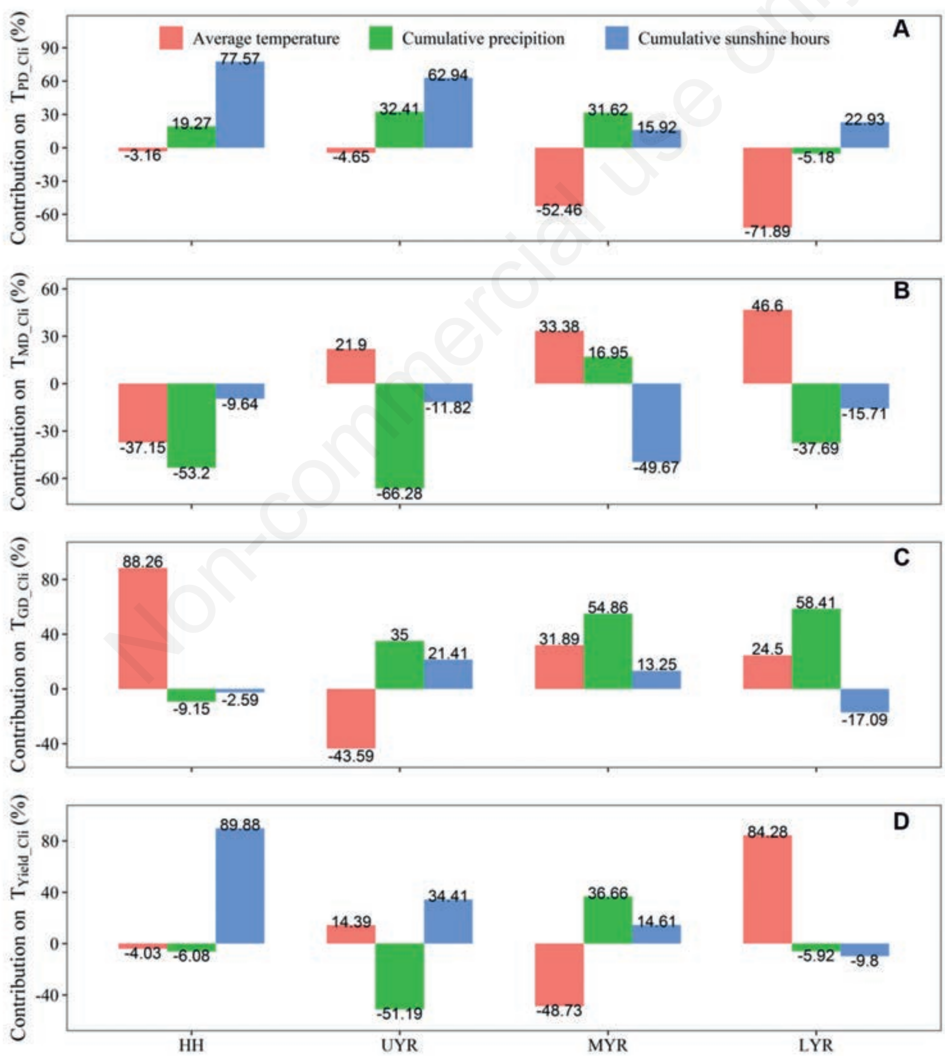


**Figure 6. Average relative contribution of each climate factor on winter rapeseed growth period trends and yield affected only by climate change (*Trend*$_{cli}$). Values indicate the mean percentage of all stations. PD, planting date; MD, maturity date; GD, growth duration; HH, Huang-Huai-Hai region; UYR, upper reaches of Yangtze River; MYR, middle reaches of Yangtze River; LYR, middle reaches of Yangtze River.**

some locations that will dramatically impact crop growth and productivity (Wu *et al.,* 2018). Rapeseed is highly sensitive to water deficits. Therefore, an urgent need is the development of tolerant cultivars to ensure adequate yields under such adverse conditions (Zhang *et al.,* 2014).

## Uncertainties

Two approaches have been used to isolate the impacts of climate change from the impacts of crop management in recent years. One of the most commonly used approaches is crop modelling (He *et al.,* 2015; Abbas *et al.,* 2017; Ahmad *et al.,* 2017; Liu *et al.,* 2018a). Another commonly used approach involves statistical methods (Zhang and Huang, 2013; Liu *et al.,* 2018b; He *et al.,* 2020; Liu *et al.,* 2020). In our study, we used a statistical model based on observed data, and this method had the advantage that the data were empirical. However, there is a potential, albeit challenging to verify, the assumption that consecutive years used consistent crop management practices. A general limitation of regression models (Eq. 3) is that only the apparent relationships between phenology and climatic factors are identified. Collinearity among climate variables can cause difficulty in distinguishing the actual contributions of different climatic factors. In addition, process-based crop modelling can simulate crop phenology under specific circumstances, but the simulated results are uncertain and depend on the simulation accuracy and the calibration precision of the crop model being used. Thus, our methods can be improved in future studies by incorporating the latest developments in statistical analysis.

## Conclusions

In China's four major winter rapeseed-planting zones, between 2008 and 2019, the mean temperature and cumulative precipitation increased during the winter rapeseed GD. However, the cumulative sunshine hours decreased at most stations, thereby decreasing the region's photosynthetic productivity. Our results demonstrated that, under the combined impact of climate change and crop management, the planting date at most stations tended to be delayed, the maturity date at most stations tended to be advanced, the length of GD at most stations was shortened, and the yield of winter rapeseed at most stations increased. The average relative contribution of crop management to changes in dates of planting and maturity, GD, and yield of winter rapeseed was greater than the impact of climate change in each planting zone. The relative contributions of climate change and crop management to winter rapeseed yields were −20.00% to +38.93% and +61.07 to +80.00%, respectively, and the relative contributions to GD were –10.05 to +14.82% and –85.18 to –96.8%, respectively. Among the three climate factors, the most dominant climate factor impacting winter rapeseed yield and GD was spatially different. Average temperature contributed the most in MYR and LYR, cumulative sunshine hours contributed the most in the HH region, and cumulative precipitation contributed the most in the UYR region. The reduced GD will be beneficial for solving seasonal contradictions and increasing the frequency of crops harvested each year, especially in the rapeseed-rice rotation system or the rapeseed-rice-rice rotation system of the Yangtze River Basin. Our results provide essential insights into the impacts of climate change on agriculture production and high-yield breeding of crops.

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