Response and Adaptation of Single-Cropping Rice Growth Periods to Sowing Date, Cultivar Shift and Extreme Temperatures in China from 1981 to 2010

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Abstract
Crop growth period responses to climate change directly affect yield and quality; these changes have been investigated, but few studies have researched the quantitative effects of the sowing date (SD), cultivar shift and extreme temperatures on the vegetative growth period (VGP) and reproductive growth period (RGP) of crops. Based on the observed growth periods and weather data from 30 agro-meteorological stations in Northeast China (NEC), the middle and lower reaches of the Yangtze River (MLYR), the Sichuan Basin (SB) and on the Yunnan-Guizhou Plateau (YGP) during 1981–2010, we found that (1) advancing the SD resulted in the extension of the VGP but had no significant effect on the RGP. (2) Cultivar shift mainly prolonged the RGP, and its mean contribution to the trend in the RGP (68.4%) was greater than that of climate change (31.6%). (3) Increases in growing degree days (GDD) tended to lengthen the VGP and RGP, and their mean relative contribution to the VGP (65.9%) was higher than that of the RGP (58.4%). (4) Increases in killing degree days (KDD) and decreases in cold degree days (CDD) tended to shorten the VGP and RGP, and the mean relative contribution of KDD to the VGP (~18.8%) was lower than that of the RGP (~29.8%), while the mean relative contribution of CDD to the VGP (~15.2%) was higher than that of the RGP (~10.9%). The findings highlight the adverse effects of KDD and CDD on the growth periods of single-cropping rice and show how a reasonable SD scientifically matched with suitable cultivar types can make full use of climate resources and mitigate the adverse effects of extreme temperatures.

Keywords Crops · Vegetative period · Reproductive period · Climate change · First-difference

Introduction
The increasing trend in global warming has become prominent in the last 100 years, with the average surface temperature increasing by 0.74 °C and the rate of temperature increase reaching 0.13 °C 10a−1 in the past 50 years (IPCC, 2013). There is growing evidence that climate change and more frequent weather extremes have had and will continue to have significant impacts on crop growth (Abbas et al., 2020a; Ahmad et al., 2020; Fahad et al., 2016a; Fatima et al., 2020; Xiao et al., 2019). Climate change is exerting an increasingly profound influence on the crop growth period (Fatima et al., 2020; Tariq et al., 2018). In general, climate warming accelerates crop growth, thereby shortening the crop growth period (Wang et al., 2016, 2017; Xiao et al., 2017; Zhang et al., 2021a) and the time for photosynthesis and grain filling, which ultimately have detrimental effects on yield and even food security (Fahad et al., 2016b; Wang et al., 2018a).

The duration of the critical growth period of crops has a strong association with yield and quality (Chen et al., 2021). A longer filling duration of maize in the US Midwest during 2000–2015 promoted grain dry matter accumulation, and accounted for 25% of the trend in yield increase (Zhu et al., 2013). A longer maize growth period increased maize yield
by 13–38% in Northeast China (NEC) during 1981–2007 (Liu et al., 2013), which corresponds to a 75.2 kg ha⁻¹ yield increase per day-1 extension of the maize growth period (Zhao et al., 2015). In addition, single-cropping rice yield was positively correlated with the length of both the vegetative and reproductive growth periods in NEC and the middle and lower reaches of the Yangtze River (MLYR) during 1981–2009 (Tao et al., 2013). Extreme heat leads to shortened crop growth periods, which are a key mechanism of yield loss (Kim et al., 2011; Lobell et al., 2012; Rani & Maragatham, 2013). Therefore, to maintain stable and high crop yields, in the context of climate warming, there is a dire need to understand the variability in crop growth periods and their influencing mechanisms (Zhang et al., 2016a).

The crop growth period is the response and adaptation to climate change and crop management (Bai et al., 2019; Liu et al., 2018a, 2019). The sowing date (SD) and cultivar shift are the most common crop management practices (Bai et al., 2019; He et al., 2015; Hu et al., 2017; Li et al., 2016; Liu et al., 2012, 2013; Mehdi, 2012; Parker et al., 2017; Rezaei et al., 2018; Ye et al., 2019; Zhang et al., 2013). According to earlier work, temperature is widely recognized as a dominant factor controlling crop growth periods (Chen et al., 2021; Fatima et al., 2020; Wang et al., 2018b; Zhang et al., 2021a). The increase in temperature has accelerated crop growth and shortened the vegetative and reproductive periods (Bai et al., 2020; Hu et al., 2017; Tao et al., 2013; Wang et al., 2017; Zhang et al., 2013a). Prior research methods have mainly focused on statistical correlations and statistical models between growth periods and mean temperature (Li et al., 2013; Ye et al., 2019; Zhang et al., 2013a). Other studies have constructed statistical models of growth periods in relation to mean temperature, precipitation and sunshine hours (Bai et al., 2020; Liu et al., 2018b, 2019). However, few studies have combined the effects of SD, cultivar shift and extreme temperatures on crop growth periods.

Rice (Oryza sativa L.) is a staple food crop in China, accounting for 36.6% of the total cereal crop production and 32.0% of the total cereal crop area in 2016 (Bai et al., 2019; Hu et al., 2015). The major systems of rice production in China are single-cropping rice and double-cropping rice systems (Chen et al., 2021). The single-cropping rice cropping system is the largest and most widespread type of cultivation in China (Duan & Zhou, 2011). At present, the majority of studies regarding climatic factors that affect crop growth periods have included mean temperature, cumulative precipitation and cumulative sunshine hours (Bai et al., 2019; Chen et al., 2021; Tao et al., 2013) and have rarely considered the combined effects of these factors, such as growing degree days (GDD), killing degree days (KDD) and cold degree days (CDD), on the crop growth period.

In this study, to understand the patterns and mechanisms of crop growth period variations, we attempt to quantitatively evaluate the effects of the SD, cultivar shift and extreme temperature on the variation trends of the vegetative and reproductive periods of single-cropping rice by examining the following: (1) the spatiotemporal patterns in the major growth stages [sowing, emergence, heading, maturity, vegetative growth period (VGP), reproductive growth period (RGP) and whole growth period (WGP)] and corresponding climatic characteristics of single-cropping rice in different regions; (2) the response mechanisms of vegetative and reproductive growth period trends of single-cropping rice in different regions to SD, cultivar shift and climate change; and (3) the quantitative contributions of the SD, cultivar shift and climate change to vegetative and reproductive growth period trends of single-cropping rice in different regions.

**Materials and Methods**

**Study Region and Data**

Our study region consists of the four main production regions of single-cropping rice across China, which include NEC, MLYR, the Sichuan Basin (SB), and the Yunnan-Guizhou Plateau (YGP). Single-cropping rice growth periods and weather data were obtained from the agro-meteorological stations of the China Meteorological Administration (CMA). The SD, emergence (ED), heading (HD) and maturity (MD) were converted to day of the year. The growth periods mainly included the VGP (from emergence to heading), the RGP (from heading to maturity) and the WGP (from emergence to maturity) (Hu et al., 2017), which were expressed in days. The climate data included daily mean, maximum and minimum temperature, precipitation, and sunshine hours. In this study, 30 agro-meteorological stations were selected across China during 1981–2010 (Fig. 1). Stations in the study were chosen because they (1) were located in the main single-cropping rice production regions and (2) had complete observation records for both single-cropping rice growth periods and weather data during 1981–2010. The climatic characteristics of the WGP were as follows (Table 1): the highest mean cumulative sunshine hours (1024.4 h) and the lowest mean growing degree days (1421.9 °C-d) were found in NEC; the highest mean cumulative precipitation (428.1 mm) and mean growing degree days (2001.3 °C-d) were found in the MLYR; and the lowest mean cumulative sunshine hours (673.8 h) were found in the SB.

**Climate Indicator Statistics**

Daily weather data were used to measure the climatic characteristics of the growth periods and predominantly included temperature cumulative indicators (GDD, KDD and CDD).
Plant growth is typically described by GDD (Abbas et al., 2017; Abendroth et al., 2019), where GDD is the sum of effective temperatures (Bernáth et al., 2021; Lobell et al., 2011). Extreme temperature is typically described by KDD and CDD, where KDD is the sum of temperatures when the temperature is above the optimum temperature threshold, and CDD is the sum of temperatures when the temperature is below the base temperature. We calculated GDD, KDD and CDD according to the methods in the references (Butler and Huybers 2015; Zhang et al., 2021b). The trends in the growth periods and climatic factors were evaluated by linear regression and statistical significance was analysed by a two-tailed t test.

Daily GDD, KDD and CDD are defined as follows:

\[
\text{GDD}_d = \max \left( 0, \left( \frac{T^{*}_{\max,d} + T^{*}_{\min,d}}{2} - T_b \right) \right)
\]  

\[
\text{KDD}_d = \begin{cases} 
T_{\max,d} - T_b & \text{if } T_{\max,d} > T_b \\
0 & \text{if } T_{\max,d} \leq T_b 
\end{cases}
\]  

\[
\text{CDD}_d = \begin{cases} 
T_b - T_{\min,d} & \text{if } T_{\min,d} \leq T_b \\
0 & \text{if } T_{\min,d} > T_b 
\end{cases}
\]

In Eqs. (1)–(4), Variable GDD\(_d\), KDD\(_d\) and CDD\(_d\) represent GDD, KDD and CDD on the \(d\)th day, respectively. The variable \(T^{*}_{\min,d}\) is defined in an analogous manner as \(T^{*}_{\max,d}\). Variable \(T_{\max,d}\) and \(T_{\min,d}\) denote the maximum and minimum temperatures in the \(d\)th, respectively. Variable \(T_b\) and \(T_h\) denote the base temperature and the optimum temperature for single-cropping rice growth, respectively. This study used a \(T_b\) value of 10\(\degree\)C (Ahmad et al., 2019; Liu et al., 2019) and a \(T_h\) value of 30\(\degree\)C (Wallach et al., 2017; Zhang et al., 2016b).

Table 1  Climatic characteristics of the single-cropping rice growth period during 1981–2010 at the stations. NEC: Northeast China; MLYR: the middle and lower reaches of the Yangtze River; SB: Sichuan Basin; and YGP: Yunnan-Guizhou Plateau

| Zone   | Stations | Mean temperature (\(\degree\)C) | Precipitation (mm) | Sunshine hours (h) | Growing degree days (\(\degree\)C-d) |
|--------|----------|-------------------------------|-------------------|-------------------|------------------------------------|
| NEC    | 7        | 18.7                          | 370.9             | 1024.4            | 1421.9                             |
| MLYR   | 8        | 24.4                          | 428.1             | 878.5             | 2001.3                             |
| SB     | 9        | 22.8                          | 414.9             | 673.8             | 1950.3                             |
| YGP    | 6        | 20.8                          | 374.6             | 848.7             | 1828.1                             |
Panel Regression Model

We proposed a novel modelling approach to assess the impact of SD and climatic factors on the single-cropping rice growth period. First, GDD, KDD, and CDD were calculated for each site according to Eqs. (1)–(4). Second, according to the observed VGP and RGP, GDD, KDD, and CDD were obtained by accumulating GDD, KDD, and CDD, respectively. Third, based on the first-difference method (Liu et al., 2018; Lobell et al. 2011), time series of VGP, RGP, SD, and climatic factors (GDD, KDD, and CDD) were obtained to establish panel regression models of the VGP and RGP (Eqs. (5)–(6)).

The panel regression models for the VGP and RGP are expressed as follows:

\[
\Delta VGP_{t,s} = \beta_0 + \beta_1 \times \Delta SD_{t,s} + \beta_2 \times \Delta GDD_{vgp,t,s} + \beta_3 \times \Delta KDD_{vgp,t,s} + \beta_4 \times \Delta CDD_{vgp,t,s} + \varepsilon_{i,s}
\]

\[
\Delta RGP_{t,s} = \beta_0 + \beta_1 \times \Delta SD_{t,s} + \beta_2 \times \Delta GDD_{rgp,t,s} + \beta_3 \times \Delta KDD_{rgp,t,s} + \beta_4 \times \Delta CDD_{rgp,t,s} + \varepsilon_{i,s}
\]

In Eqs. (5)–(6), variable \(\Delta VGP_{t,s}\) (days) and \(\Delta RGP_{t,s}\) (days) represent the first-difference value of the observed VGP and RGP at the \(t\)th station in the \(s\)th year, respectively; variable \(\Delta SD_{t,s}\) (days) represents the first-difference value of the SD; variable \(\Delta GDD_{vgp,t,s}\) (°C-days), \(\Delta KDD_{vgp,t,s}\) (°C-days), and \(\Delta CDD_{vgp,t,s}\) (°C-days) represent the first-difference value of GDD, KDD, and CDD of the VGP at the \(t\)th station in the \(s\)th year, respectively; \(\beta_1\) is the sensitivity of the growth periods to SD; \(\beta_2\), \(\beta_3\), and \(\beta_4\) are the sensitivity of the growth periods to GDD, KDD, and CDD of the RGP at the \(s\)th station in the \(t\)th year, respectively; and \(\varepsilon\) is the residual which indicates the effect of factors other than the SD and climate change on crop growth periods. The first-difference of the VGP and RGP were dependent variables, so the intercept coefficient \(\beta_0\) was zero (Tigchelaar et al., 2018).

**Separating the Effects of Climate Change and Crop Management on Growth Periods**

It was assumed that the trends in the VGP and RGP were the result of the combined effect of the SD, cultivar shift and climate change. Therefore, based on the sensitivities given by the panel regression model, the effects of the SD, cultivar shift and climate change on the trend of VGP and RGP were calculated as follows:

\[
T_{vgp, SD} = \beta_1 \times T_{SD}
\]

\[
T_{vgp, CLI} = \beta_2 \times T_{GDD_{vgp}} + \beta_3 \times T_{KDD_{vgp}} + \beta_4 \times T_{CDD_{vgp}}
\]

\[
T_{vgp} = T_{vgp, SD} + T_{vgp, CLI} + T_{vgp, CUL}
\]

In Eqs. (7)–(9), variables \(T_{vgp, SD}\), \(T_{vgp, CLI}\), and \(T_{vgp, CUL}\) indicate the effects of the SD, climate change and cultivar shift on the VGP trends (days a^{-1}), respectively, and variable \(T_{vgp}\) indicates the actual observed VGP trends. Variable \(T_{SD}\) indicates the trend in SD (days a^{-1}), and \(T_{GDD_{vgp}}, T_{KDD_{vgp}},\) and \(T_{CDD_{vgp}}\) indicate the trends in GDD (°C·d a^{-1}), KDD (°C·d a^{-1}) and CDD (°C·d a^{-1}) of the VGP obtained during the average growth period of 1981–2010, respectively. The effects of SD and climate change on the RGP trends were similarly obtained according to Eqs. (7)–(8). The effects of cultivar shift on the trends in the VGP (\(T_{vgp, CUL}\)) and RGP (\(T_{rgp, CUL}\)) were converted according to Eq. (9).

From this, the contributions of the SD, cultivar shift and climate change to the trends in the VGP were calculated as in Eqs. (10)–(12). Taking GDD as an example, the relative contribution of GDD to the trend in the VGP was calculated as Eq. (13), and the contributions of the SD, cultivar shift and climate change to the trends in the RGP were calculated similarly to Eqs. (10)–(12).

\[
C_{vgp, SD} = \frac{T_{vgp, SD}}{T_{vgp}} \times 100
\]

\[
C_{vgp, CLI} = \frac{T_{vgp, CLI}}{T_{vgp}} \times 100
\]

\[
C_{vgp, CUL} = \frac{T_{vgp, CUL}}{T_{vgp}} \times 100
\]

\[
RC_{vgp, GDD} = \frac{\beta_2 \times T_{GDD_{vgp}}}{|\beta_2 \times T_{GDD_{vgp}}| + |\beta_3 \times T_{KDD_{vgp}}| + |\beta_4 \times T_{CDD_{vgp}}|} \times 100
\]
Results

Trends in Single-Cropping Rice Growth Periods

The results indicated that the trends in SD, ED, HD, MD, VGP, RGP, and GP of single-cropping rice during 1981–2010 in the four main production regions were not completely consistent (Fig. 2(a)–(d)). For NEC, there was a delay trend for the SD, ED, HD and MD. Meanwhile, a shortening trend was detected in the VGP, RGP and WGP (−0.08 days a⁻¹, −0.01 days a⁻¹ and −0.09 days a⁻¹, respectively) (Fig. 2(a)). For the MLYR, the SD and ED showed advancing trends (−0.06 days a⁻¹ and −0.06 days a⁻¹, respectively), while the HD (0.13 days a⁻¹) and MD (0.36 days a⁻¹) were generally delayed. The VGP, RGP, and WGP were generally prolonged, with a higher trend of prolongation for the RGP (0.23 days a⁻¹) than for the VGP (0.19 days a⁻¹) (Fig. 2(b)). For the SB, the SD and ED showed advancing trends (−0.27 days a⁻¹ and −0.16 days a⁻¹, respectively), while the HD (0.06 days a⁻¹) and MD (0.21 days a⁻¹) showed delayed trends. The VGP, RGP and WGP showed an extended trend (0.22 days a⁻¹, 0.15 days a⁻¹ and 0.36 days a⁻¹, respectively) (Fig. 2(c)). For the YGP, advancing trends were observed for the SD, ED and HD (−0.14 days a⁻¹, −0.17 days a⁻¹ and −0.21 days a⁻¹, respectively), while the MD showed a delayed trend (0.02 days a⁻¹). The RGP showed a prolonged trend (0.22 days a⁻¹) (Fig. 2(d)). In summary, the VGP, RGP and WGP showed shortened trends in NEC and lengthening trends in the MLYR, SB and on the YGP. The lengthening trend in the WGP was the largest (0.42 days a⁻¹) in the MLYR, followed by that in the SB (0.36 days a⁻¹), and the weakest (0.19 days a⁻¹) occurred on the YGP.

Climate Variation Trends

There was a warming trend in the critical growth periods in the four main production regions. Significant increases in GDD were detected during both the VGP and RGP from 1981 to 2010 (Fig. 3(a)). The increasing rate of GDD was higher during the VGP in NEC, the MLYR and SB (3.17 °C-days a⁻¹, 5.24 °C-days a⁻¹ and 5.65 °C-days a⁻¹, respectively) than during the RGP (0.55 °C-days a⁻¹, 2.72 °C-days a⁻¹ and 2.42 °C-days a⁻¹, respectively). On the YGP, the increasing rate of GDD during the RGP (3.68 °C-days a⁻¹) was higher than that during the VGP (1.87 °C-days a⁻¹). There was a similar variation in GDD and KDD during the VGP and RGP. The increasing rate of KDD was higher during the VGP (0.46 °C·days a⁻¹, 1.82 °C·days a⁻¹, 1.84 °C·days a⁻¹, and 0.24 °C·days a⁻¹, respectively) than during the RGP (−0.11 °C·days a⁻¹, 0.19 °C·days a⁻¹, 0.84 °C·days a⁻¹ and 0.23 °C·days a⁻¹, respectively) in NEC, the MLYR, the SB and on the YGP (Fig. 3(b)). Regarding CDD, the trends differed significantly among the four main production regions. In NEC, CDD showed a decreasing trend.
during both the VGP and RGP (−2.1 °C-days a⁻¹ and −0.3 °C-days a⁻¹, respectively). On the YGP, CDD was close to 0 during the RGP. In the MLYR and SB, CDD was close to 0 during both the VGP and RGP (Fig. 3(c)). In conclusion, climate warming was obvious, and the change rate of the VGP was generally higher than that of the RGP.

Sensitivity of Growth Periods to Sowing Date and Climatic Factors

The sensitivities of the growth periods to SD and climatic factors are shown in Table 2. The VGP was positively correlated with GDD and CDD and negatively correlated with SD and KDD in the four main production regions, indicating that the increase in thermal resources (increased GDD) and an advance in the SD contributed to longer VGP. However, extreme temperatures (increased KDD and decreased CDD) led to a shortening of the VGP. The RGP was positively correlated with GDD and CDD and negatively correlated with KDD, indicating that an increase in thermal resources (increased GDD) resulted in an increase in the RGP, while extreme temperatures (increased KDD and decreased CDD) resulted in a shortened trend in the RGP.

The effect of SD on RGP was not significant. In contrast, we found a high degree of association between the VGP and SD in the four main production regions. The VGP was prolonged by 0.57 d and 0.42 d per day⁻¹ for the advanced SD in NEC and the SB, respectively. However, in

Table 2 The panel regression model parameters for the effect of the sowing date (SD), growing degree days (GDD), killing degree days (KDD) and cold degree days (CDD) on the growth periods

| Zone | Growth periods | β₁, ** | β₂, ** | β₃, * | β₄, ** | R² |
|------|----------------|--------|--------|--------|--------|----|
| NEC  | VGP            | – 0.57** | 0.051** | – 0.089** | 0.061** | 0.59 |
|      | RGP            | –       | 0.054** | – 0.058*  | 0.091** | 0.54 |
| MLYR | VGP            | – 0.29** | 0.062** | – 0.048** | 0.15**  | 0.78 |
|      | RGP            | –       | 0.056** | – 0.064** | 0.44**  | 0.63 |
| SB   | VGP            | – 0.42** | 0.044** | – 0.037** | 0.19**  | 0.54 |
|      | RGP            | –       | 0.062** | – 0.034*  | –       | 0.83 |
| YGP  | VGP            | – 0.24** | 0.056** | – 0.060** | 0.13**  | 0.71 |
|      | RGP            | –       | 0.072** | – 0.076*  | 0.31**  | 0.76 |

β₁, β₂, β₃ and β₄ indicate the sensitivities of SD, GDD, KDD and CDD to growth periods

*Significant at P value of 0.05

**Significant at P value of 0.01
the MLYR and on the YGP, the VGP was less sensitive to the SD, extending the VGP by 0.29 d and 0.24 d per day-1 for the advanced SD, respectively (Table 2). The sensitivities of the VGP and RGP to GDD and KDD were almost identical in the four main production regions. On average, the VGP and RGP were prolonged by 0.05 d and 0.06 d, respectively, when the GDD increased by 1 °C·d. Similarly, the VGP and RGP were shortened by 0.06 d and 0.06 d, respectively, when KDD increased by 1 °C·d. In NEC and on the YGP, the absolute values of the sensitivity of the VGP and RGP to KDD were higher than that of GDD, indicating that further warming caused higher adverse effects of KDD on the VGP and RGP when the daily maximum temperature exceeded 30 °C. The sensitivities of the VGP and RGP to CDD were lower in NEC and higher in the MLYR and SB and on the YGP. On average, the VGP and RGP were prolonged by 0.13 d and 0.28 d per 1 °C·d increase in CDD, respectively, indicating that the increase in CDD meant that a longer RGP was required to reach the thermal time requirement. In conclusion, the panel regression model in this study has an excellent simulation effect on the VGP and RGP of single-cropping rice in the four main production regions, with a correlation coefficient (R²) ranging from 0.54 to 0.83 (Table 2). In particular, for the SB, CDD had no effect on the RGP, while 83% of the variation in RGP was explained by the combined effect of GDD and KDD.

Effects and Contributions of Climate Change and Crop Management on Growth Periods

For NEC, the shortening of the VGP was mainly caused by the SD delay, with a trend of 0.10 days a⁻¹; climate change had a smaller effect on the VGP (0.028 days a⁻¹) (Fig. 4a). The lengthening of the VGP in both the MLYR and SB was caused by the positive effects of the SD, cultivar shift and climate change. Cultivar shift and climate change lengthened the VGP by 0.07 days a⁻¹ and 0.10 days a⁻¹ in the MLYR, respectively. The extension trends of the SD and climate change in the VGP were 0.11 days a⁻¹ and 0.08 days a⁻¹ in the SB, respectively, and 0.03 days a⁻¹ and 0.08 days a⁻¹ on the YGP, respectively. The prolonged RGP in the MLYR, SB and on the YGP was mainly caused by the positive effect of cultivar shift and climate change, but the effect of climate change was less than that of cultivar shift, and the effect of cultivar shift on the trend in the RGP was 0.21 days a⁻¹, 0.15 days a⁻¹ and 0.16 days a⁻¹ in the MLYR, SB and on the YGP, respectively. The results showed that the contributions of the SD, cultivar shift and climate change to the trends in the VGP differed significantly in the four main production regions. On average, the contribution of the SD to the trend in the VGP was greater than that of the cultivar shift (Fig. 5(a)). The mean contribution of the SD to the trend in the VGP was negative (−68.1%) in NEC and positive (59.3%) in the SB. The mean contribution of climate change to the trend in the VGP was positive (22.1%, 68.8%, 28.5% and 45.9% in NEC, the MLYR, SB and on the YGP, respectively). Cultivar shift and climate change jointly dominated the trend in the RGP in the four main production regions (Fig. 5(b)). In addition to technological progress, sowing date, cultivar shifts and climatic factors on the VGP and RGP trends. a Effects of the sowing date, cultivar shift and climatic factors on the VGP in the MLYR, b effects of cultivar shift and climatic factors on the trend in the RGP, Tvgp, Trgp, Tvgp_SD, Tvgp_CUL and Tvgp_CL indicate the effect trends of climatic factors and crop management, cultivar shifts and climatic factors on the RGP, respectively.
NEC, the mean contribution of the cultivar shift to the trend in the RGP was more than 60% in the MLYR, SB and YGP. Particularly in the MLYR and SB, the mean contribution of the cultivar shift to the trend in RGP was more than 80%.

The mean relative contribution of GDD to the VGP and RGP trends was positive, while that of KDD and CDD to the VGP and RGP trends was negative (Fig. 5(c)–(d)). Furthermore, we found that GDD played a leading role in the mean relative contribution of the trend in the VGP. While CDD had the least influence on the VGP trend of the MLYR and SB. In contrast, KDD had a significant influence on the VGP trend in the MLYR and SB, and the mean relative contributions were −26.4% and −25.8%, respectively. For NEC and the YGP, the mean relative contributions of CDD to VGP were −27.9% and −23.6%, respectively. However, KDD had little influence on the VGP trend of NEC and the YGP. It was found that GDD had the greatest impact on the RGP trend in the YGP, with a mean relative contribution of 78.3%, followed by NEC, with a mean relative contribution of 59.5%. In addition, this study found that unlike CDD, the effect of KDD on the trend in the RGP was significantly greater in the MLYR and SB. Meanwhile, unlike KDD, CDD had a greater impact on the VGP trend in NEC.

In summary, the VGP trend was mainly affected by the SD, cultivar shift and climate change; the RGP trend was mainly affected by cultivar shift and climate change; and the mean contribution of cultivar shift to the trend in the RGP (68.4%) was greater than that of climate change (31.6%). The mean relative contributions of KDD and CDD to the trends in the VGP and RGP varied greatly due to the different climates in the four main production regions.

**Discussion**

**Response and Adaptation of Growth Periods to Climate Change and Crop Management**

The variation trends of rice growth periods in different regions of China are different (Liu et al., 2019). This study found that the VGP and RGP showed an extension trend in most of the main rice production regions in China (Fig. 1), which was consistent with previous studies (Bai et al., 2020). Previous studies have shown that the extension of the growth period is beneficial to biomass accumulation and yield increase (Zhu et al., 2018). The results indicated that the extension of the growth period, especially the reproductive period, was a response to and adaptation of the single-cropping rice growth periods to climate change and crop management (Liu et al., 2009, 2019). Our study pointed out that the SD in single-cropping rice was significantly and negatively correlated with the VGP in the four main production regions, and that advancing the SD prolonged the VGP, which was consistent with previous studies (Bai et al., 2019; Liu et al., 2013) and similar results for other crops (Wang et al., 2012). These results indicated that adjusting the SD can make full use of climate resources to extend the VGP and improve yields in the context of a warming climate (Tao et al., 2014). However, the effect of the SD on the RGP was not obvious,

![Fig. 5](image_url)
suggested that cultivar shift may be an important factor to consider (Hu et al., 2017). The effects and contributions of the SD, cultivar shift and extreme temperatures on the trends in the VGP and RGP of single-cropping rice were quantitatively separated (Fig. 5). The trends in the VGP were the combined effect of the SD, cultivar shift and climate change. In particular, the SD played a dominant role in shortening the VGP in NEC. In contrast, the lengthening trends in the VGP were the combined effect of the SD and climate change in other main production regions. In addition, the combined effects of cultivar shift and climate change determined the trends in the RGP. Apart from NEC, the main contributor to the RGP trend in single-cropping rice in the MLYR, SB and on the YGP was the cultivar shift, indicating the use of a longer-growing cultivar to compensate for the shortening effect of climate warming (Ahmad et al., 2019).

A province study indicated that extreme temperatures modified photosynthesis-related and grain yield-related traits (Mirosavljević et al., 2021). Our research also found that both KDD and CDD were detrimental to lengthening the VGP and RGP in the context of climate warming. The positive effects of increased GDD were offset by increased KDD as future warming intensified, leading to an overall negative impact of climate change on the growth periods (Zhang et al., 2016b). Furthermore, the same crop for the same growth period of GDD varied in different regions and years, result inconsistent with existing crop models that determine growth period based on a constant GDD (Liu et al., 2013). Therefore, an accurate assessment of the growth periods is required to consider the combined effects of climate resources and climate stresses (Lobell et al., 2012). The occurrence of extreme climatic events may severely affect the VGP and RGP of single-cropping rice, and future research is recommended to enhance the impact of extreme climate events on crop growth periods (Sánchez et al., 2014; Zhang et al. 2013).

**Growth Period Strategies for Extreme Temperatures**

The implementation of crop management is conducive to coordinating crop growth, making full use of effective light and temperature resources during the growing season, obtaining maximum photosynthetic production, increasing the ripening rate and thousand seed weight, and achieving high-yield, high-quality and high-efficiency cultivation (Hu et al., 2017). To cope with the increased heat or cold stress caused by climate variation, it is necessary to select and breed high-yielding, high-quality and resistant single-cropping rice cultivar shifts according to climate change in different main production regions, to mitigate the adverse effects of climate change. For example, the duration and intensity of extreme temperatures in the main rice production regions of China increased significantly during 1981–2010 (Sun et al., 2018). In particular, the provinces of central and eastern Hubei, central Anhui, western Jiangsu, northern Zhejiang and northeast Hunan were vulnerable to heat stress. During 2021–2050 and 2071–2100, the heat stress in the whole region is expected to increase significantly (Zhang et al., 2018). Heat stress mainly occurred between July and August in the MLYR, which coincided with the RGP of single-cropping rice, especially its flowering and filling periods, which overlapped with the highest temperature period (Meng et al., 2016; Wang et al., 2019). Therefore, avoiding high temperatures is the main strategy to prevent heat stress (Wang et al., 2019), and breeding heat-resistant cultivars is one of the most effective measures to ensure food security (Wu et al., 2021).

Optimizing the SD is another effective measure to mitigate the adverse effects of climate warming, and studies such as (Abbas et al., 2020b; Bai et al., 2019) have shown that adjusting the SD mainly changes the flowering and maturity dates of single-cropping rice without affecting the length of the RGP; these results were also confirmed in this study. Spatially, the adaptation mechanisms of single-cropping rice to climate warming were different throughout China. For instance, the SD was mainly delayed in eastern NCE, Jiangsu, Anhui, Hubei and Yunnan Provinces, as an adaptation strategy to avoid extreme temperatures in the RGP (Ding et al., 2020). Therefore, adjusting the SD in response to climate change to obtain different light and temperature configurations is an effective way to improve resource utilization and rice adaptation (Deng, 2018; Wang 2021). Furthermore, a reasonable SD scientifically matched with suitable single-cropping rice cultivar types is of great importance to fully utilize local light and temperature resources, to exploit the potential of cultivar shifts and to ensure high and stable yields. Therefore, three adaptation measures, such as early sowing of single-cropping rice to avoid high temperatures at flowering, shifting to existing heat-tolerant cultivars, and breeding superior cultivars with long RGP, can effectively offset the negative effects of climate change to varying degrees (Xu et al., 2015).

In addition to cultivating new cultivars and optimizing sowing dates to adapt to extreme temperatures, reasonable irrigation, fertilization and spraying exogenous chemicals alleviated the adverse effects of the external environment on crop growth periods (Abbas et al., 2020a; Muleke et al., 2022). For example, irrigation is an effective real-time cultivation measure to reduce canopy temperature during rice flowering (Wang et al., 2019), thereby avoiding the influence of heat stress. In addition, reasonable irrigation alleviated the early flowering caused by climate warming (Muleke et al., 2022); nitrogen application enhanced crop tolerance to heat stress during the reproductive growth period, thereby increasing the leaf life span and growth period length (Smith et al., 2018); spraying exogenous spermidine before the filling period significantly increased the
activities of superoxide dismutase and peroxidase, reduced the accumulation of malondialdehyde, increased the soluble sugar content of rice leaves under heat stress, maintained the osmotic pressure balance of leaves, and improved the photosynthetic and transpiration rates (Tang et al., 2018). The weakness of this study is that the effects of crop management such as irrigation, fertilization or spraying of exogenous chemicals on crop growth period were not considered. Identifying and separating the quantitative impacts of these management measures on crop growth periods are of great practical significance to accurately and timely respond to climate change.

Conclusion

The study analysed the effects of SD, cultivar shift and extreme temperatures on the vegetative and reproductive periods. The increase in GDD prolonged the VGP and RGP, while the VGP and RGP were shortened by increasing KDD and decreasing CDD. The dominant climatic factor in the extension of the VGP and RGP was the GDD. Furthermore, advancing the SD compensated for the shortening of the VGP caused by climate stress. The contribution of the cultivar shift to the trend in the RGP was greater than that of climate change. Therefore, reasonable scientific matching of the SD with suitable cultivars can make full use of climatic resources and alleviate the adverse effects of extreme temperatures.

Acknowledgements This study is supported by the National Key Research and Development Program of China (No. 2018YFA0606103), National Natural Science Foundation of China (No. 42130514), and the Basic Research Fund of Chinese Academy of Meteorological Sciences (2020Z004).

Declarations

Conflict of 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.

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