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

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Abstract

An extensive dataset on rice phenology in China, including 202 series broadly covering the past three decades (1980s–2000s), was compiled. From these data, we estimated the responses of growth duration length to temperature using a regression model based on the data with and without detrending. Regression coefficients derived from the detrended data reflect only the temperature effect, whereas those derived from data without detrending represent a combined effect of temperature and confounding cultivar shifts. Results indicate that the regression coefficients calculated from the data with and without detrending show an average shortening of the growth duration of 4.1–4.4 days for each additional increase in temperature over the full growth cycle. Using the detrended data, 95.0% of the data series exhibited a negative correlation between the growth duration length and temperature; this correlation was significant in 61.9% of all of the data series. We then compared the difference between the two regression coefficients calculated from data with and without detrending and found a significantly greater temperature sensitivity using the data without detrending (−2.9 days °C⁻¹) than that derived from the detrended data (−2.0 days °C⁻¹) in the period of emergence to heading for the late rice, producing a negative difference in temperature sensitivity (−0.9 days °C⁻¹). This implies that short-duration cultivars were planted with increase in temperature and exacerbated the undesired phenological change. In contrast, positive differences were detected for the single (0.6 days °C⁻¹) and early rice (0.5 days °C⁻¹) over the full growth cycle, which might indicate that long-duration cultivars were favoured with climate warming, but these differences were insignificant. In summary, our results suggest that a major, temperature induced change in the rice growth duration is underway in China and that using a short-duration cultivar has been accelerating the process for late rice.

Keywords: climate warming, cultivar shifts, growth duration length, rice, short-duration cultivar

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Introduction

The phenology and growth duration of plants have been shown to change as temperature has risen in recent decades, a process that occurs worldwide in both wild plants (Menzel et al., 2006; Askeyev et al., 2010; Doi et al., 2010; Gordo & Sanz, 2010; Ibanez et al., 2010) and agricultural crops (Tao et al., 2006; Estrella et al., 2007; Fujisawa & Kobayashi, 2010; Webb et al., 2011; Lobell et al., 2012). The accelerated developmental rate caused by climate warming is often associated with a harmful effect on production, particularly for agricultural crops for which sunlight, water and nutrient resources would be consequently reduced (Craufurd & Wheeler, 2009). A number of modelling studies have shown that future crop productivity will strongly depend on the magnitude of the change in the duration of crop growth brought on by climate warming (Adams et al., 1990; Matthews et al., 1997; Aggarwal & Mall, 2002; Xiong et al., 2008). Therefore, alterations in the duration of crop growth are an important indicator of agricultural vulnerability to climate warming and have captured great attention.

In spite of the growing evidence from various regions stating that climate warming leads to earlier maturation of crops, several recently published articles have found little or no change in crop phenology in some areas (Liu et al., 2010, 2012; Sacks & Kucharik, 2011). The major argument is that farmers have successfully adapted to climate warming by shifting to long-duration crop cultivars, which are more suitable for warm-climate cultivation. Such a cultivar shift reduced
phenological sensitivity and even altered the direction of the phenological response, counteracting the supposed negative impact of climate warming. However, these new findings are at odds with previous results, and contradictions have arisen regarding the response of crop phenology to climate warming. For example, Tao et al. (2006) have shown a statistically significant shortening of the growth duration of rice in China as the temperatures rose based on two field stations during 1981–2000. However, this result is inconsistent with the results of Liu et al. (2012) who found that the growth duration of Chinese rice was constant or even prolonged due to the use of long-duration cultivars at four stations during 1981–2009. Clearly, the key unknown of the contradiction is the strength of the cultivar shifts on rice phenology relative to the temperature increases in China and contradictions have arisen regarding the response of crop phenology to climate warming. For example, these new findings are at odds with previous results, and the regression coefficients produced by the analysis should be viewed as a reflection of the combined effects of the temperature and cultivar shift. A list of the stations, longitude/latitude and cultivar shifts is presented in Appendix S1.

**Materials and methods**

**Data on rice phenology from Agrometeorological Experimental Stations**

The data for rice phenology in China were collected at 140 Agrometeorological Experimental Stations (AESs) operated by the Chinese Meteorological Administration and provincial-level meteorological administrations (Fig. 1). This dataset includes 202 data series over various observational periods. These stations encompass the majority of the rice-growing areas in China, including single rice-cropping systems in the subhumid northeast and semiarid north regions, single and double rice-cropping systems in the subhumid east, central and southwest regions and double rice-cropping systems in the humid south region.

Most of the data series cover the period of 1981–2006 (with some extending to 2009). At each station, agrotechnicians documented the dates of the major phenological events during the rice growth cycle, including the sowing, emergence, transplanting, panicle initiation, heading and maturity stages. The date of panicle initiation was omitted due to a lack of recorded observation at many stations. With these data, the growth duration length (GDL) for emergence to heading, heading to maturity and emergence to maturity was calculated for each series. According to our interviews with the agrotechnicians, the choice of rice cultivars planted was based on the major cultivar grown by the local farmers. Approximately every 3–5 years, the agrotechnicians switched to a new rice cultivar. Therefore, the above observations can be viewed as a reflection of the combined effects of the temperature and cultivar shift. A list of the stations, longitude/latitude and cultivar shifts is presented in Appendix S1.

**Determination of the average temperature during each growth stage**

The daily climate dataset was downloaded from the China meteorological data sharing service system (http://cdc.cma.gov.cn/), which includes a total of 756 ground-based meteorological stations distributed throughout China. A total of the 63 meteorological stations matched the locations of the AESs; however, the remaining 77 AESs were not located near the meteorological stations. For those 77 stations, we estimated their daily climate data using an algorithm presented by Thornton et al. (1997) that interpolated the aforementioned data of the 756 climate stations to 10 km grid cells. Following these steps, the daily average air temperature (calculated as the average of the daily minimum and maximum air temperatures) was available for each AES during the period of observation.

We then calculated three average growth stage temperatures (AGSTs) for each data series by averaging the air temperature over the time windows of emergence to heading, heading to maturity and emergence to maturity dates.

**Statistical analysis**

We performed the following analyses to demonstrate the GDL responses to changes in the AGST. All of the statistical analyses were executed using R software version 2.12.2 (R Development Core Team, 2011).

1. To show the historical temperature changes over time, temperature trends for the three growth stages (emergence to heading, heading to maturity and emergence to maturity) in each series were estimated using a linear regression model with the year as the explanatory variable. Difference from the AGST calculated above (as AGST was influenced by both temperature change and phenology shift), the time windows for calculating temperature trends in the step were determined by the month of mean onset of those phenological events.

2. To test whether the beginning of cultivation (i.e. sowing and transplanting) are driven by temperature, we correlated dates of sowing with mean monthly temperature (the month of occurrence of sowing); and correlated seedbed duration (the period from sowing to transplanting) with the mean temperature over the period.

3. To obtain a general response of GDL to change in AGST, we directly correlated the GDL with AGST using a linear regression model for each series at the three growth stages (Eqn 1). The regression coefficients produced by the analysis should be viewed as the metric of the GDL response to the two factors combined, i.e. temperature and cultivar shifts.
\[ GDL_{st} = a_s \text{AGST}_{st} + b_s + e_s \]  
\[ \Delta GDL_{st} = c_s \Delta \text{AGST}_{st} + d_s + \Delta e_s \]

where \( GDL_{st} \) is the growth duration length (days) for the \( st \)th series in year \( t \), \( \text{AGST}_{st} \) is the average growth stage temperature (°C) for the \( st \)th series in year \( t \), \( a_s \) is the coefficient of the GDL response to temperature (days °C\(^{-1}\)) for each series, \( b_s \) represents an intercept for each series and \( e_s \) is the error term for each series.

To remove the confounding influences of the cultivar shifts, the original data of the GDL and AGST for each series were transformed to their detrended value. To this end, the trends in the time series were firstly obtained by fitting the data with a smoothing spline in each series, and the detrended values from the time trend were then calculated as the differences in the amount by subtracting the above time trends from the observations in each year. The detrended values of the GDL and AGST were then correlated using a linear regression model for each series (Eqn 2). The regression coefficients calculated by this analysis can be viewed as the metric of the response of GDL to change in temperature exclusively.

\[ \Delta GDL_{st} = c_s \Delta \text{AGST}_{st} + d_s + \Delta e_s \]  

where \( \Delta GDL_{st} \) is the detrended growth duration length (days) for the \( st \)th series in year \( t \), \( \Delta \text{AGST}_{st} \) is the detrended average growth stage temperature (°C) for the \( st \)th series in year \( t \), \( c_s \) is the coefficient of the GDL response to temperature (days °C\(^{-1}\)) for each series, \( d_s \) represents an intercept for each series and \( \Delta e_s \) is the error term for each series.

5 To detect the effect of cultivar shifts on the GSL, we calculated the difference of regression coefficients between Eqns 1 and 2 for each series, i.e. \( a_s - c_s \). Given the regression coefficients \( (c_s) \) calculated from Eqn 2 using the detrended data reflect the GDL responses to temperature, whereas the regression coefficients \( (a_s) \) derived in Eqn 1 could also include the influences of the shifts in cultivar in addition to temperature trend, their difference would represent the GDL change due to the cultivar shift. A negative difference would indicate a short-duration cultivar, whereas a positive difference would indicate that a long-duration cultivar was planted. The statistical test for their difference in regression coefficient was conducted by a paired t-test for each growth stage of all samples and of each cropping system. \( P < 0.05 \) was considered statistically significant and meaningful.

Results

Temperature trends

Table 1 provides the time trends of the temperature for emergence to heading, heading to maturity and emergence to maturity and is grouped by the rice-cropping system; the results for each series can be found in Appendix S1. According to Table 1, on average, there is a general warming trend with the increasing temperature rate of 0.45 °C 10 yr\(^{-1}\) for emergence to heading, 0.43 °C 10 yr\(^{-1}\) for heading to maturity and 0.45°C 10 yr\(^{-1}\) for emergence to maturity. Of 200 (99.0%) data series showing a positive trend in the period of emergence to maturity, 144 (71.3%) series were found to have undergone a significant increase in temperature \( (P < 0.05) \). In contrast, the temperature decreased over time for the
Late rice
Early rice
Single rice
All rice

emergence to heading for the late rice, with a 0.28
ies of significance (in 144 (71.3%) data series and there were 32 (15.8%) ser-
case of sowing date, negative correlations were found

date and seedbed duration with temperature. In the
Table 2 gives the regression coefficients of the sowing

Responses of the sowing and seedbed duration to
temperature
Table 2 Summary of the sowing date and seedbed duration
responses to temperature for all of the rice and grouped by
each rice-cropping system

(53.5%) for the period between emergence and maturity (Table 3). The number of series with a positive correlation was much lower: 16 (7.9%) series showed a positive correlation for the period between emergence and maturity and only 2 (1.0%) series had a significant correlation. On average, the GDL was reduced by 3.3 days °C\(^{-1}\) during emergence to heading, 1.2 days °C\(^{-1}\) during heading to maturity and 4.1 days °C\(^{-1}\) during emergence to maturity.

The regression coefficients were also analysed by grouping the rice-cropping systems (Table 3); in most of the series, the rice grown for each cropping system had a shorter GDL with an increased AGST. On average, the rice grown in a single cropping system had greater responses to the temperature (−4.9 days °C\(^{-1}\)) than the early rice (−3.1 days °C\(^{-1}\)) or late rice (−4.2 days °C\(^{-1}\)) from emergence to maturity.

**Responses of ΔGDL to changes in ΔAGST**

On the basis of detrended data, we calculated the relationships between ΔGDL and ΔAGST at each growth stage (Fig. 3; Table 4). Consistent with the results using the original data, there is also a generally negative relationship between ΔGDL and ΔAGST (Fig. 3). We saw negative coefficients in 187 (92.6%) data series for the period between emergence and heading (Fig. 3a), 191 (94.6%) series for the period between heading and maturity (Fig. 3b) and 192 (95.0%) series for the period between emergence and maturity (Fig. 3c). The number of series with a significantly negative correlation is 95 (47.0%) data series for the period between emergence and heading, 75 (37.1%) series for the period between heading and maturity and 125 (61.9%) series for the period between emergence and maturity (Table 4). However, relatively few series show positive correlations; 10 (5.0%) data series showed a positive correlation over the period between emergence and maturity, and there were no significant positive relationships (Table 4). On average, the mean regression coefficient of ΔGDL against ΔAGST was −3.0 days °C\(^{-1}\) for emer-
Table 4 Summary of the ΔGDL responses to changes in ΔAGST using the detrended data for all of the rice and grouped by each rice-cropping system

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Neg_All (%)</th>
<th>Neg_Sig (%)</th>
<th>Pos_All (%)</th>
<th>Pos_Sig (%)</th>
<th>Regmean (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All rice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emg.–Head</td>
<td>202</td>
<td>92.6</td>
<td>47.0</td>
<td>7.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Head–Matu</td>
<td>202</td>
<td>94.6</td>
<td>37.1</td>
<td>5.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Emg.–Matu</td>
<td>202</td>
<td>95.0</td>
<td>61.9</td>
<td>5.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Single rice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emg.–Head</td>
<td>74</td>
<td>91.9</td>
<td>48.6</td>
<td>8.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Head–Matu</td>
<td>74</td>
<td>93.2</td>
<td>37.8</td>
<td>6.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Emg.–Matu</td>
<td>74</td>
<td>93.2</td>
<td>63.5</td>
<td>6.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Early rice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emg.–Head</td>
<td>62</td>
<td>96.8</td>
<td>58.1</td>
<td>3.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Head–Matu</td>
<td>62</td>
<td>93.5</td>
<td>37.1</td>
<td>6.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Emg.–Matu</td>
<td>62</td>
<td>96.8</td>
<td>61.3</td>
<td>3.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Late rice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emg.–Head</td>
<td>66</td>
<td>89.4</td>
<td>34.8</td>
<td>10.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Head–Matu</td>
<td>66</td>
<td>97.0</td>
<td>36.4</td>
<td>3.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Emg.–Matu</td>
<td>66</td>
<td>95.5</td>
<td>60.6</td>
<td>4.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>

n, sample size; Neg_All/Pos_All, proportions of series showing negative and positive regression coefficients (including significant and insignificant); Neg_Sig/Pos_Sig, proportions of series showing significantly negative and positive regression coefficients (P < 0.05); Regmean, mean of regression coefficients.

gence to heading, −1.1 days °C−1 for heading to maturity and −4.4 days °C−1 for emergence to maturity.

Negative correlations were also chiefly present in each cropping system (Table 4). The period of emergence to maturity for single rice is the most sensitive to the temperature increase (−5.5 days °C−1), whereas the early rice had the lowest (−3.6 days °C−1) sensitivity for this period.

Differences in the GDL responses

Table 5 compares the differences in the above GDL responses to the AGST calculated using the original and detrended data. Temperature sensitivity derived from detrended data was greater than that calculated from original data for the single and early rice during emergence to maturity, yielding difference of 0.6 days °C−1 and 0.5 days °C−1, respectively. However, their differences were insignificant (P > 0.05). The significant difference was found in the period of emergence to heading for the late rice. The regression coefficients based on the original data (−2.9 days °C−1) was greater than that calculated from detrended data (−2.0 days °C−1) during the period of emergence to heading, producing a sensitivity difference of −0.9 days °C−1 (P < 0.05).

Discussion

Due to the 202 series included and the wide representative of the Chinese rice-growing areas in our dataset, our results demonstrate a general picture of the responses of the rice phenology to past climate warming, which has occurred in most areas during the rice season in China (Table 1).

The dates of sowing and transplanting are dependent on not only temperature but also farmer’s decision (Estrella et al., 2007). However, based on our results, they are still strongly influenced by temperature; on average, an increase in the temperature of one degree resulted in an average 0.6 days’ advance of sowing date and 1.4 days’ reduction for seedbed duration (Table 2).

More importantly, our results also indicate that the GDL between emergence and maturity shortened for 92.1% of the data series with 53.5% series of significance (Fig. 2). An increase in the temperature of one degree resulted in an average reduction of 4.1 days in the period (Table 3). Reanalyzing using the detrended data, the series with a negative relationship reaches 95.0% with 61.9% series of significance in the period of emergence to maturity, and the average of the regression coefficients is −4.4 days °C−1 (Fig. 3 and Table 4).

The above regression results based on extensive rice phenological data solve the disparity between the previous studies in China that relied on a limited amount of observations (Tao et al., 2006; Liu et al., 2012). Our results suggest that climate warming induced a generally shorter GDL in Chinese rice. These are also in accordance with the earlier studies of a variety of agricultural crops that used phenological data from laboratory experiments (Summerfield et al., 1992; Yin et al., 1996), field trials (Hu et al., 2005; De Vries et al., 2011), simulation models (Yao et al., 2007; Xiong et al., 2008) and satellite observations (Li et al., 2012; Lobell et al., 2012), all reporting that temperature increase is the most important driver to crop phenology.

In comparison with the earlier meta-analyses on crop phenology, the average 4.1–4.4 days shortening for each additional temperature increase revealed in our study is evidently above the average phenology advance in Europe (no greater than −2.52 days °C−1, Menzel et al., 2006). However, our regression coefficient is very close to that for Indian wheat (Lobell et al., 2012) for which, based on satellite observations, the GDL was shortened by roughly 9 days as a result of 2 degrees of warming, i.e. approximately −4.5 days °C−1.

Despite the major effect of temperature on the GDL, we also detected the confounding effect of the cultivar shifts. By comparing the regression results derived from
the original data and the detrended data in a paired t-test (Table 5), using the original data had a significantly greater temperature sensitivity (−2.9 days °C⁻¹) than using the detrended data (−2.0 days °C⁻¹) for the period of emergence to heading of the late rice, with a difference of −0.9 days °C⁻¹. The negative sign of the above differences implies that the short-duration cultivars were planted with warming, accelerating the growth development by 0.9 days for each additional increase in temperature. In contrast, the positive differences were detected for the single (0.6 days °C⁻¹) and early rice (0.5 days °C⁻¹), which may indicate that long-duration cultivars were favoured and offset some warming effect on GSL, but their differences were statistically insignificant.

Table 5  Comparison of the responses of the GDL with AGST using the original and detrended data based on a paired t-test

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>n</th>
<th>Regression coefficient using original data (days °C⁻¹)</th>
<th>Regression coefficient using detrended data (days °C⁻¹)</th>
<th>Difference between original and detrended data (days °C⁻¹)</th>
<th>t-test (P-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All rice</td>
<td></td>
<td>Regmean</td>
<td>Regmean</td>
<td>Regmean</td>
<td></td>
</tr>
<tr>
<td>Emg.-Head</td>
<td>202</td>
<td>−3.3</td>
<td>−3.0</td>
<td>−0.3</td>
<td>0.124</td>
</tr>
<tr>
<td>Head-Matu</td>
<td>202</td>
<td>−1.2</td>
<td>−1.1</td>
<td>−0.1</td>
<td>0.096</td>
</tr>
<tr>
<td>Emg.-Matu</td>
<td>202</td>
<td>−4.1</td>
<td>−4.4</td>
<td>0.3</td>
<td>0.179</td>
</tr>
<tr>
<td>Single rice</td>
<td></td>
<td>Regmean</td>
<td>Regmean</td>
<td>Regmean</td>
<td></td>
</tr>
<tr>
<td>Emg.-Head</td>
<td>74</td>
<td>−3.6</td>
<td>−3.6</td>
<td>0.0</td>
<td>0.427</td>
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<tr>
<td>Head-Matu</td>
<td>74</td>
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<td>0.446</td>
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<td>Emg.-Matu</td>
<td>74</td>
<td>−4.9</td>
<td>−5.5</td>
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<td>0.163</td>
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<tr>
<td>Early rice</td>
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<td>Regmean</td>
<td>Regmean</td>
<td>Regmean</td>
<td></td>
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<tr>
<td>Emg.-Head</td>
<td>62</td>
<td>−3.2</td>
<td>−3.4</td>
<td>0.2</td>
<td>0.225</td>
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<td>Head-Matu</td>
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<td>−0.1</td>
<td>0.102</td>
</tr>
<tr>
<td>Emg.-Matu</td>
<td>62</td>
<td>−3.1</td>
<td>−3.6</td>
<td>0.5</td>
<td>0.056</td>
</tr>
<tr>
<td>Late rice</td>
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<td>Regmean</td>
<td>Regmean</td>
<td>Regmean</td>
<td></td>
</tr>
<tr>
<td>Emg.-Head</td>
<td>66</td>
<td>−2.9</td>
<td>−2.0</td>
<td>−0.9</td>
<td>0.005**</td>
</tr>
<tr>
<td>Head-Matu</td>
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<td>−1.3</td>
<td>−1.1</td>
<td>−0.2</td>
<td>0.085</td>
</tr>
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<td>Emg.-Matu</td>
<td>66</td>
<td>−4.2</td>
<td>−3.8</td>
<td>−0.4</td>
<td>0.128</td>
</tr>
</tbody>
</table>

n, sample size; Regmean, mean of regression coefficients; **P < 0.01.

that, in spite of certain associated yield penalties, using a short-duration cultivar could be a viable choice for adapting climate change. Cultivation of short-duration cultivar may benefit the rice yields by avoiding extreme heat stress at the heading (i.e. anthesis) stage (Nagarajan et al., 2010) and by reducing the exposure to drought (Jagadish et al., 2012). Because Chinese rice breeding is determined by both the climate and also the demands of consumers (Peng et al., 2008), we would recommend further study to ascertain the reason for the observed cultivar shift by combining the data or obtaining information that could reflect the rice breeding objectives in China.

It has been widely accepted that rice yields would be lost due to shorter GDLs, resulting in less time for biomass accumulation during the vegetative phase (Yao et al., 2007), increased leaf senescence rates during the reproductive phase (Kim et al., 2011) and restricted agricultural resource availability (Craufurd & Wheeler, 2009). Therefore, the reduction in the GDL induced by climate warming reported in this study would potentially be detrimental to the rice harvest. However, in this study, we only focused on GDL and did not attempt to quantify the yield decrease due to GDL reduction because we realized that a variety of genetic properties, such as the harvest index (Liu et al., 2012) and spikelet fertility (De Vries et al., 2011), are equally important for determining the actual yields and are progressively evolving. It is possible that, in the long-term, the yield benefits due to the positive shifts in cultivar traits could

offset the losses caused by the above undesirable phenological changes to a certain degree. Further study is underway to address alterations in the rice yield as a consequence of climate change and the shifts in multiple cultivar traits in China.

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References


Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Summary of Agrometeorological Experimental Station used in this study.