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Shifts in cultivar and planting date have regulated rice growth duration under climate warming in China since the early 1980s

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ABSTRACT

Climate warming accelerates crop development and shortens growth duration. The adoption of new cultivars and changes in planting date may either retard or amplify this acceleration. However, the extent to which the cultivar and planting date shifts have impacted rice growth duration under climate warming remains largely unknown. Using an up-to-date data series from 82 agro-meteorological stations in China where rice phenology was observed from 1981 to 2012, we quantified the impacts of climate warming, cultivar and planting date shifts on rice growth duration based on a degree-days calculation. The results indicate that climate warming shortened the growth duration length (GDL) between emergence and maturity at rates of 4.2 ± 0.7 (mean ± SE), 1.8 ± 0.3 and 3.9 ± 0.5days 10-yr^{-1} for single, early and late rice. GDL shortening was more pronounced in the vegetative phase than in the reproductive phase for single and early rice, but it was opposite for late rice system. Cultivar shifts prolonged the GDL at rates of 6.1 ± 1.0 and 1.7 ± 0.6days 10-yr^{-1} for single and early rice but induced GDL shortening of 4.1 ± 1.6days 10-yr^{-1} for late rice. The effect of planting date shifts (advanced or delayed) on GDL change was variable and depended on the rice cropping system. On average, climate warming accelerated crop development, with a relative contribution to GDL changes of −40% in single rice, −45% in early rice, and −35% in late rice. Cultivar shifts compensated for the GDL shortening induced by climate warming in single and early rice with the relative contribution of 58% and 44%, respectively, but accelerated crop development in late rice with a contribution of −37%. Nevertheless, the planting date at two-thirds of the late rice stations was significantly delayed, which retarded the acceleration by 29% in terms of GDL changes.

1. Introduction

Each of the last three decades has been successively warmer on the Earth's surface than any preceding decade since 1850 (IPCC, 2013). China has also experienced a rapid increase in temperature (Li et al., 2010; Wang et al., 2010; Ren et al., 2012) since the early 1980s. During the rice growing season, the temperature trends from the early 1980s to the mid-2000s were detected to be within a range of 0.33–0.45 °C 10-yr^{-1} for single rice, 0.28–0.96 °C 10-yr^{-1} for early rice, and 0.33–0.75 °C 10-yr^{-1} for late rice (Zhang et al., 2013). Warming was identified in late rice cropping system in the middle and lower reaches of the Yangtze River and occurred at a rate of 1.10 °C 10-yr^{-1} from 1981 to 2009 (Tao et al., 2013).

Climate warming accelerates crop development and shortens growth duration. In a free air temperature increase experiment conducted in East China, an increase of 1.1–2.0 °C in air temperature during the rice growing season led to a reduction in the pre-heading phase by 1.7–3.3days but did not change the post-heading phase duration (Dong et al., 2011). Cai et al. (2016) reported that the pre-heading phase of rice was shortened by 3–5days but did not observe a significant change in the post-heading phase when the canopy temperature was increased by 1.5–2.0 °C in a FACE system located in East China. Another FACE experiment conducted in Tsukuba, Japan, found an increase of 1.6–2.0 °C in soil temperature that shortened the rice growth duration by 1.3days from transplanting to panicle initiation under ambient CO_2 concentrations (Usui et al., 2016).

The adoption of new cultivars and changes in planting date may either retard or amplify the acceleration of rice development. Tao et al. (2013) reported that climate warming had a negative impact on the growth period but that cultivar shifts prolonged the growth period for single rice between 1981 and 2009. Zhang et al. (2013) found that cultivar shifts shortened the growth duration for late rice over the past three decades. By contrast, the growing season length was found to be extended for single, early, and late rice from 1991 to 2012 in China,

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which was attributed to the shift in transplanting dates (Zhao et al., 2016).

Model simulations have suggested that cultivar changes lead to a longer growing duration for single rice (Liu et al., 2013a), but an adoption of new cultivars in double-rice systems may only partly mitigate the negative impact of warming on rice growth duration (Liu et al., 2013b). Using five rice phenological models and/or modules, Zhang and Tao (2013) simulated that rice growing season in China would be shortened by 0.45–5.78days under future (2021–2040) climate change scenarios without considering cultivar shift. In the context of climate change, warmer temperatures that shorten the development stages of determinate crops will probably reduce the yield of a given cultivar (Craufurd and Wheeler, 2009).

A considerable number of new rice cultivars in China have been released to achieve high and stable yields over the last several decades. Between the early 1980s and the late 2000s, 702 new rice cultivars were released by the Ministry of Agriculture in China (National Rice Data Centre, http://www.ricedata.cn/variety/index.htm, Accessed: 20 July 2016). Meanwhile, local governments also released a great number of new cultivars. For instance, 312 new rice cultivars were released in Jiangsu Province, where single rice was dominant, and 518 new rice cultivars were released in Hunan Province, where double rice was planted (National Rice Data Centre, http://www.ricedata.cn/variety/index.htm, Accessed: 20 July 2016). The release of new rice cultivars allowed farmers to select/manipulate the life cycle duration and phenology to maximize the range of environments in which rice crops grow as well as their yields.

Previous studies (e.g., Tao et al., 2013; Zhang et al., 2013; Zhang et al., 2014; Cai et al., 2016) have shown that climate warming shortened rice growth duration for a given cultivar and that cultivar shifts could either prolong or shorten rice growth duration. However, the extent to which the cultivar and planting date shifts regulate the rice growth duration subjected to climate warming remains largely unknown. The objective of this research was to quantify the effects of climate warming, cultivar and planting date shifts on rice growth duration using an up-to-date data series from 82 agro-meteorological stations in China.

2. Materials and methods

2.1. Data on rice phenology and temperature

Rice phenological data were collected from 82 Agro-meteorological Experimental Stations (AESs), including rice phenology observations of emergence, heading and maturity from 1981 to 2012. These AESs, operated by the Chinese Meteorological Administration, are widely distributed across a vast area that spans wide ranges of temperate, subtropical and tropical climates (Fig. A.1). We obtained a total of 123 data series. Of these, 41 data series were for single rice cropping system, and 82 data series were for double rice cropping systems, including 41 for early rice and 41 for late rice (Table A.1).

More than 10 cultivars were planted in 90%, 88% and 88% of the single, early and late rice AESs over the period 1981–2012, respectively (Table A.1). For the single rice cropping system, 51% of the cultivars were traditional *japonica* planted in Northeast China, Mid-lower Yangtze River Valley and Yunnan Province, and 38% of the cultivars were hybrid *indica* planted in Sichuan Basin and some regions in the Mid-lower Yangtze River Valley. The remaining 11% were traditional *indica* and hybrid *japonica* cultivars. *Indica* rice cultivars were planted in the double rice cropping systems. Traditional and hybrid *indica* cultivars accounted for 52% and 47% for early rice, and 26% and 74% for late rice.

The emergence dates of single rice had a wide time span from mid-March in Sichuan Province to late-May in Jiangsu Province. Accordingly, the earliest and the latest maturity dates occurred in mid-August (Sichuan Province) and mid-October (Jiangsu Province). For early rice, the earliest emergence dates (February) occurred in Fujian Province and the latest emergence dates (mid-April) appeared in Hunan Province; the maturity generally occurred in July. The emergence and maturity dates of late rice occurred in the period of mid-June to mid-July and in the period of mid-October to mid-November, respectively.

The daily air temperature was downloaded from the China meteorological data sharing service system (http://data.cma.cn/), which includes a total of 756 ground-based meteorological stations distributed across China. Of the 82 AESs, 43 AESs matched the locations of ground-based meteorological stations, and the remaining 39 AESs were not located near the meteorological stations. Following Zhang et al. (2013), we estimated the daily temperatures by using an algorithm presented by Thornton et al. (1997) that interpolated the above-mentioned data of the 756 climate stations for the remaining 39 AESs.

2.2. Determination of the changes in temperature, phenology and growth duration length (GDL)

On the assumption that an earlier planting date leads to earlier emergence, and vice versa, we used the emergence date to indicate the planting date. The growth duration length (GDL) of the vegetative phase (from emergence to heading, E-H), the reproductive phase (from heading to maturity, H-M) and the entire growing season (from emergence to maturity, E-M) were calculated for each data series. The mean temperatures during the vegetative phase, reproductive phase and entire growth period for a given data series were calculated based on the average occurrence of phenological stages from 1981 to 1985 over a 10-day window. For instance, the average occurrences of emergence, heading and maturity were May 23, August 27 and October 25, respectively. The daily air temperature was averaged from May 21 to August 31 for the vegetative phase, from August 21 to October 31 for the reproductive phase, and from May 21 to October 31 for the entire growth period.

Linear regression was used to detect the trends in temperature change, in the occurrence of phenological stages, and in the GDL.

$$y = kt + c + \varepsilon \quad (1)$$

where y is the mean air temperature, the GDL, or the date of a phenological stage in year t. k is the slope of the linear regression and represents the time trend in y. c is an intercept, and ε is the residual error for each data series.

2.3. Determination of the contribution of climate warming, cultivar and planting date shifts to GDL change

Cultivar(s) planted in the period 1981–1985 were used as reference cultivar(s) for each data series. The developmental stages of emergence (E), heading (H) and maturity (M) were viewed as phenological characters of the cultivar(s) in the early 1980s. Growing degree-days (GDD) are commonly used to express the amount of heat required to reach a specific phenological stage of development (Grigorieva et al., 2010; Hu et al., 2015). We accumulated the daily temperatures above 10 °C (Gao et al., 1992) during the vegetative phase (E-H), reproductive phase (H-M) and entire growth period (E-M) as the reference GDD denoted by GDD_{ref}.

For cases when the planting date did not change, we first accumulated the daily mean temperature from a given developmental stage (e.g., emergence) to the next stage (e.g., heading) using the GDD_{ref} as a criterion. The date ($Heading_{sim}$) was recorded when the accumulated temperature reached the GDD_{ref}. The GDL between emergence and $Heading_{sim}$ was denoted as L_{sim}. Changes in GDL attributed to temperature change ($\triangle GDL_{tem}$) and cultivar shift ($\triangle GDL_{cul}$) were then determined by Eq. (2).

$$\Delta GDL_{tem}\ (days) = L_{sim} - L_1 \quad (2a)$$