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Differences in the impacts of nighttime warming on crop growth of rice-based cropping systems under field conditions

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A B S T R A C T

Great attentions have been taken to the effects of climatic warming on crop production, however, fewer were known about the actual impacts of nighttime warming under different cropping systems. Therefore, a three-year field experiment with a passive nighttime warming (PNW) facility and a one-year field experiment with free air temperature increase (FATI) facility were conducted in major Chinese rice cropping systems. Four-year field observations from different rice cropping systems all showed that nighttime warming less than 1.0 °C could shorten the length of crop pre-flowering phase period while prolonged the length of post-flowering phase period, resulting in insignificant reduction in the length of crop entire growth period. The temperature increase caused significant increments in grain yields by 16.2, 12.7 and 12.0% for late rice in the rice–rice cropping system, wheat in the rice-wheat cropping system and rice in the single rice cropping system, respectively. However, this warming declined grain yields significantly by 4.5 and 6.5% for early rice in the rice–rice cropping system and rice in the rice-wheat cropping system, respectively. Since warming-induced yield reduction was less than warming-induced increment in each cropping system, the annual yields was higher in the warmed plots than the non-warmed under all systems. Our findings can provide important references to cropping system adjustment for coping with global warming in China and other regions.

1. Introduction

Global mean surface air temperature has increased about 0.74 °C since 100 years ago (IPCC, 2007), and is predicted to further increase 1.3–7 °C by 2050 (IPCC, 2014). Moreover, great asymmetry exists in warming levels between the daily maximum and the daily minimum temperatures, the daily minimum temperature increasing at a faster rate than the daily maximum (Karl et al., 1993; Easterling et al., 1997). Rice-based cropping systems are the major systems of global grain production and support more than half of global population. Meanwhile, total grain production needs to increase by 50% to ensure food security in the world by 2050 (Carriger and Vallee, 2007). Theoretically, the asymmetry warming might affect crop growth more seriously due to the decreased diurnal temperature range (DTR) (Porter and Gawith, 1999). Therefore, it is necessary to enhance the understanding of the impacts of nighttime warming on crop growth in rice-based cropping systems.

Great efforts have been made on the impacts of climatic warming on crop production in rice-based cropping systems. For example, some studies reported that the increase in daily minimum temperature might reduce both rice and wheat yields globally

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due to the reduction in crop growth period and the stress of high temperature (Peng et al., 2004; Welch et al., 2010; Lobell et al., 2011; Shah et al., 2014). However, Porter and Gawith (1999) argued that warming might relieve low temperature stress to crop growth and even shift the crop to a more suitable temperature condition through advancing crop flowering date if current air temperature is lower than the optimal level of crop growth. Therefore, the impacts of climatic warming depend on the specific location and crop growing season (Lobell, 2007; Liu et al., 2010). For one particular crop, its temperature conditions during the growing season, especially post-flowering period, may vary considerably among cropping systems. In rice-based cropping systems, for example, there are large differences in crop growing temperature conditions. Recently, we found that air temperature increase less than 1.5 °C was beneficial to rice production in Chinese single cropping systems (Chen et al., 2012), but harmful to rice production in Chinese rice-wheat cropping system (Dong et al., 2011). To date, most studies were conducted during crop key growth stages under artificial conditions, or during an entire growth period for one crop rather than a cropping system. Thus, further observations need to be conducted at cropping system scale so as to reduce the assessment uncertainties of warming impacts on crop production.

China is the largest country in grain production and consumption in the world. And its grain production comes from cropping systems with a great diversity. For rice-based cropping systems, nearly all systems can be found in the country, including annually single rice cropping system in the Northeast, rice-upland crop rotation system along the Yangtze River, and rice–rice cropping system in the South (Frolking et al., 2002). During the past decades, there were significant warming trends in the major Chinese rice cropping regions, especially the daily minimum temperature (Liu et al., 2004; Huang et al., 2005). In order to further learn the actual responses of crop growth to daily minimum temperature increase in rice-based cropping systems, a three-year field experiment with passive nighttime warming (PNW) facility and a one-year field experiment with free air temperature increase (FATI) facility were conducted in major Chinese rice cropping regions. Crop phenology, biomass production and grain yield were recorded during the experimental durations. Simultaneously, crop leaf area and photosynthesis and grain yield component were measured to understand the mechanisms underlying the impacts of nighttime warming.

2. Materials and methods

2.1. Site descriptions

The present study was carried out at four sites located in major rice cropping regions in China (Table 1, Fig. 1). The first experimental station was located in Nanchang (28°21′N, 116°11′E), Jiangxi province, with the typical rice–rice cropping system in South China. The second and third were located in Nanjing (32°2′N, 118°38′E, 2007–2008) and Zhenjiang (31°55′N, 119°30′E, 2007–2010), respectively, Jiangsu province, with the typical rice-wheat cropping system along Yangtze River. The last was located in Gongzhuling (43°38′N, 124°57′E), Jiling province, with the typical annually single rice cropping system in Northeast China (Fig. 1). The average annual temperatures and of four sites are correspondingly 17.5, 16.7, 14.6 and 5.6 °C, respectively, and the precipitations are 1587, 1050, 1058, and 595 mm, respectively. The daily temperatures of pre-flowering, post-flowering and entire growth period of the different crops are shown at the four sites during the four-year experimental durations (Fig. 2). Relevant crop cultivars and soil properties were presented in Tables 1 and 2.

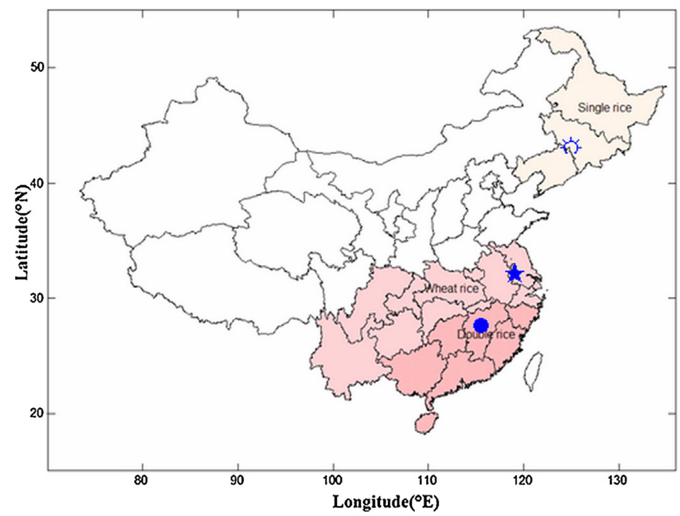

Fig. 1. Layout of major Chinese rice cropping systems and the field warming experimental sites. ☼, ★, and ● represent the field warming locations in single cropping region, rice-wheat cropping region and rice–rice cropping region, respectively.

2.2. Experimental design

Two warming facilities were applied under field conditions, including a passive nighttime warming (PNW) facility and a free air temperature increase (FATI) facility in different cropping systems.

The PNW experiments were conducted in Nanchang, Zhenjiang and Gongzhuling for three years, based on the design of previous studies (Zeiher et al., 1994; Beier et al., 2004). Reflective curtains covered the warming plots during the night for an entire growth period of each cropping system, so to increase nighttime temperature through reducing the loss of infrared radiation. The reflective curtains, which were fixed galvanized steel tubes at both ends, were spread out at sunset (around 19:00) and rolled up at sunrise (around 6:00) by hand. The curtain material consisted of aluminum foil knitted into a fiberglass cloth (Jiangyin Zhongchang Fiberglass Composite Material Co., Ltd., China). The curtain height was always kept 0.3 m above crop canopy throughout the whole growth period. During rainy and snowy days, the curtains were rolled up to maintain similar precipitation conditions between the warmed and the un-warmed plots. In order to protect the curtains from damaging by wind, the curtains were also rolled up when wind speed exceeded 10 m s^{-1}. For each experiment site, six plots (4 m × 5 m per plot) were established, including three un-warmed plots and three warmed plots. The PNW experiment was implemented in 2007, 2008 and 2010 at Nanchang and Gongzhuling sites, and over 2007–2010 at Zhenjiang site. The un-warmed plots were kept open.

The FATI experiments were also conducted in three cropping systems to further test the nighttime warming impacts on crop growth. The FATI facility was designed by reference to Zhang et al. (2005). One 1.8 m × 0.2 m infrared heater with 1500 W (Jiangsu Tiande Special Light Source Co., Ltd., China) was suspended 1.5 m above the field surface for the warmed treatment. In the un-warmed control, a ‘dummy’ heater of the same shape and size was suspended at the same height to copy the shading impacts of the heater. In order to avoid heating contamination between the treatments, the distance between adjacent plots was approximately 6 m. The uniform and reliable warming area was about 2 m × 2 m in size for sampling. Nighttime warming with the FATI facility was conducted in 2011 at Nanchang and Gongzhuling sites and over 2007–2008 at Nanjing site. Six plots (6 m × 7 m per plot) were established in each site, including three un-warmed plots and three warmed plots. The infrared heaters were positioned in the plot centre. The FATI facility was turn on at 19:00 and turn off at

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