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Nighttime warming increases winter-sown wheat yield across major Chinese cropping regions

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ABSTRACT

Understanding the actual impacts of climatic warming on winter-sown wheat production will benefit cultivar breeding efforts and agronomic innovations and may help to improve food security. Therefore, we conducted a comprehensive study across the main Chinese winter wheat cropping regions, comprising field warming experiments at four locations and an analysis of 36 years of winter wheat yield data. In the field warming experiments, an increase of 1.0 °C in nighttime temperature enhanced wheat yield by 10.1% on average ($P < 0.05$). Warming-induced enhancement of 1000-grain weight explained most of these yield increases. Warming shortened the length of pre-flowering phase by 5.4 days, while it prolonged the length of post-flowering phase by 3.8 days. Grain yield increases with warming were similar across experimental sites, even though warming-induced changes in the length of growth periods decreased with increasing ambient temperature. Our analysis of the historical data set was consistent with our field warming experiments; between 1980 and 2015, the major Chinese cropping regions experienced significant warming, especially in daily minimum temperature. Across the historical data set, daily minimum temperature was positively correlated with wheat yield (142.0 kg ha^{-1} °C^{-1}). Our findings are inconsistent with previous reports of yield decreases with warming and may help to inform policy decisions and agronomic innovations of Chinese wheat production to better cope with future climate warming.

1. Introduction

To ensure global food security, grain production needs to increase by more than 60% relative to its 2005–2007 level by 2050. However, global mean air temperature is predicted to increase by about 1.0–1.7 °C by 2050 (IPCC, 2014). Since temperature is a key factor regulating crop development and growth, future climatic warming will affect global grain production substantially (Peng et al., 2004; Lobell et al., 2011a). Wheat is the most important staple crop in the world, and China is the largest country in terms of wheat production and consumption (FAO, 2013). Almost all kinds of wheat-based cropping systems can be found in China. More than 80% of the Chinese wheat is grown between 20°N to 53°N during winter and spring seasons, when most of climatic warming is anticipated (IPCC, 2007). Thus, understanding the impacts of climatic warming on winter-sown wheat (winter wheat) production in China will greatly facilitate the development of strategies and technological innovations needed to ensure future food security.

Numerous efforts have been made to understand warming impacts on Chinese wheat production. Employing modeling methods, several studies linking crop yield to historical weather data suggest that Chinese wheat production will decline due to climatic warming (Lobell et al., 2011b; Roberts and Schlenker, 2011; Zhang et al., 2013a; Liu et al., 2014). For example, You et al. (2009) found that a 1.0 °C increase in average temperature during the wheat growing season might reduce wheat grain yield by about 3–10%. However, other studies suggest that

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wheat production could benefit from future climatic warming if the background temperature during crop growing season is lower than the optimal temperature for wheat growth (Porter and Gawith, 1999; Chavas et al., 2009). For example, a recent modeling study suggests that warming will increase wheat yield by 3.1% at low altitude and by 4.0% at high altitude in Northwest China by 2030 (Xiao et al., 2008). Since air temperature and precipitation patterns differ strongly between cropping regions, climatic warming impacts on the phenological phases and yield of winter wheat could vary both spatially and temporally (Porter and Gawith, 1999; Sadras and Monzon, 2006; Ortiz et al., 2008; Lv et al., 2013; Xiao et al., 2013). Therefore, the most suitable adaptation regime to climatic warming might differ among cropping regions, and further evidence is needed to assess climatic warming impacts on winter wheat production in China (Aronson and McNulty, 2009).

Here, we show results of a comprehensive study that combines field warming experiments with an analysis of a 36-year historical data set of winter wheat yield in three major Chinese cropping regions. The field warming experiments were performed at four locations to study the impacts of increases in daily minimum temperature on winter wheat production. Our objective was to determine the responses of winter wheat phenology and yield to nighttime warming across China, and whether this response varies with climate.

2. Materials and methods

2.1. Field warming experiments

2.1.1. Experimental sites

The field warming experiments were carried out at four sites (Fig. 1B): Shijiazhuang (38°4′N, 114°21′E; 104 m) in Hebei province, Xuchang (34°50′N, 116°40′E; 56 m) in Henan province, and Xuzhou (33°56′N, 114°17′E; 33 m) and Danyang (31°55′N, 119°30′E; 6 m) in Jiangsu province. The mean annual precipitation and average temperature of the four experimental sites are 540.5 mm and 13.3 °C (Shijiazhuang), 630.4 mm and 14.6 °C (Xuchang), 640.9 mm and 14.3 °C (Xuzhou), and 1058.4 mm and 16.2 °C (Danyang). The background daily temperatures of pre-flowering, post-flowering and entire growth period at the four sites are shown in Table S1. According to the USDA soil taxonomy, the soil types at the four sites are Alfisols, Inceptisols, Inceptisols and Alfisols, respectively. Relevant soil properties i.e. pH, organic matter content, total N, available P and available K were respectively 7.6, 18.1 g kg^{-1}, 2.0 g kg^{-1}, 30.2 mg kg^{-1} and 64.1 mg kg^{-1} in Shijiazhuang; 7.7, 18.1 g kg^{-1}, 2.2 g kg^{-1}, 15.1 mg kg^{-1} and 146.1 mg kg^{-1} in Xuchang; 7.3, 20.0 g kg^{-1}, 2.2 g kg^{-1}, 42.9 mg kg^{-1} and 55.4 mg kg^{-1} in Xuzhou; and 7.2, 28.3 g kg^{-1}, 3.1 g kg^{-1}, 15.5 mg kg^{-1} and 57.7 mg kg^{-1} in Danyang.

2.1.2. Field experiment design and warming facility

Two treatments i.e. nighttime warming (warmed) and unwarmed control (unwarmed) were applied during the entire growth period of winter wheat at each site. The experimental design was the same at all sites, using a completely randomized design with three replicates. Each replicate plot was 4 m × 5 m in size, and the distance between adjacent plots was 10 m to avoid heating contamination. Wheat was also sown in the field between the adjacent plots, and no obvious heating contamination was found on wheat plants in the field between the plots.

A novel passive nighttime warming (PNW) facility was employed in accordance with previous studies (Beier et al., 2004; Zeiher et al., 1994). The warmed plots were manually covered with a curtain from sunset to sunrise (around 19:00–06:00) daily, from sowing to harvest except for the rainy or snowy days. The unwarmed control was kept open without curtain covering. To minimize the impact of the curtain on air exchange in the field, the spacing between the curtain and wheat canopy was kept constant at 25–30 cm by weekly adjusting the curtain suspension height according to plant height. The curtain material consisted of 0.25-mm-wide aluminum foil knitted into a fiberglass cloth (Jiangyin Zhongchang Fiberglass Composite Material Co., Ltd., China). This curtain can reflect 97% of the direct and 96% of the diffused radiation, allows transfer of water vapor, and is opaque to visible radiation. Thus, the curtain reduces the loss of infrared radiation from the field surface and increases the air temperature around wheat canopy during the night. This PNW facility is energy and cost saving and can be widely used in fields where power is not available.

Air temperature around the wheat canopy in each treatment was monitored automatically at an interval of 20 min for the entire growth period using a digital temperature monitor (ZDR–41, Hangzhou Zheda Electronic Instrument Co., Ltd., China Our previous studies have demonstrated that the PNW facility is reliable for warming at nighttime under field conditions(Chen et al., 2014). Based on field monitoring, this facility can increase wheat canopy air temperature by about 0.8–1.3 °C at nighttime (Table 1), which was the warming level during last decades in the test areas and is the predicted range by the next 20–30 years (IPCC, 2007).

2.1.3. Crop management

Wheat (*Triticum aestivum L.*) cultivars, Liangxin 99, Yumai 7036, Yanfu 188 and Yangmai 11 were grown at Shijiazhuang, Xuchang, Xuzhou and Danyang sites, respectively. Since wheat is sown during winter in the study area, it is called as winter wheat or winter-sown wheat in China. The type and length of vernalization of the four cultivars are listed in Table 2. The cultivars grown at each site are dominant in their respective regions. Wheat seeds were manually sown in October at a density of 225 plants m^{-2}, with 20 cm row spacing, at all

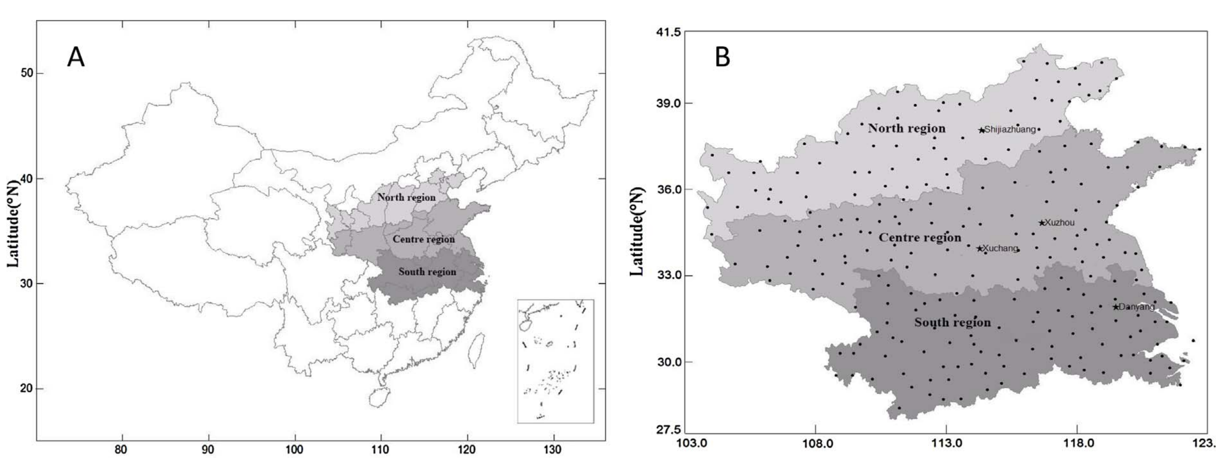

Fig. 1. The locations of major Chinese winter wheat cropping regions (The filled area) (A) and the distributions of meteorological stations and field warming experimental sites (B). Each black dot represents a meteorological station; each star represents a field warming experiment site.