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Impacts of heat stress on leaf area index and growth duration of winter wheat in the North China Plain

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ABSTRACT

Impact of high temperature stress on crop growth and productivity is one key concern with respect to crop production and food security under climate change. Due to the complexity and diversity of crop characteristics and farmers' management practices, as well as the difficulties in quantifying those agronomic management practices at reasonable temporal and spatial scales, crop responses to heat stress at a regional scale have not been properly assessed yet. In this study, we used remote-sensing data to investigate the responses of growth duration and leaf area index (LAI) of winter wheat to extreme high temperature during reproductive growing stage in the North China Plain from 2001 to 2008. Growing degree days above 0 °C (GDD) from heading to maturity was used to represent average temperature of growing environment, and the extreme temperature (> 34 °C) degree days (EDD) was used as an indicator for heat stress. We detected statistically significant shortening of reproductive growing duration due to increase in GDD and EDD at both site and regional scales. We also found acceleration of leaf senescence under warmer environment, as well as considerable damages to leaf area by extremely high temperatures according to LAI values from remote-sensing data. Our results present the explicit patterns of crop responses to heat stress at different spatial scales and periods, indicating the complexity of the impacts of extreme events. Moreover, we highlighted that exposure, vulnerability and adaptation all should be considered in evaluating the impacts of extreme events. In addition, our findings suggest great potential for improving regional crop growth monitoring and yield prediction through assimilating remote-sensing data into mechanistic crop simulation models.

1. Introduction

As one of the most widely grown crop around the world, winter wheat is now cultivated on approximately 220 million hectares of cropland, accounting for 21% of world's food consumption (http://www.fao.org/faostat/en/#data/QC). The growth of winter wheat is generally threatened by high temperature during post-heading stages (from anthesis to maturity) which are the warmest periods during the growing season of this crop that rather prefers cool temperatures (Wardlaw and Wrigley, 1994; Porter and Gawith, 1999). The major influence of higher average temperature during this period is shortening of the grain filling duration (Zhao et al., 2007; Lobell et al., 2012; Garg et al., 2013). Furthermore, exposure to extreme high temperature may damage the leaf photosynthetic apparatus of winter wheat and lead to more rapid senescence or even forced maturity (Porter and Gawith, 1999; Zhao et al., 2007; Gupta et al., 2010). Because of the high sensitivity of crop growth to temperature, global warming has already led to critical threats for winter wheat production throughout the world (Lobell et al., 2011; Tao et al., 2012a,b; Trnka et al., 2014; Asseng et al., 2015; Chen et al., 2016; Liu et al., 2016). In addition, predicted warming trend in future climate scenarios suggests increasing risk of heat stress for winter wheat growth, especially for regions with currently favorable environment (Ortiz et al., 2008; Gourdji et al., 2013; Tao and Zhang, 2013; Teixeira et al., 2013; Asseng et al., 2015), highlighting the importance of understanding, estimating and coping with the impacts of heat stress.

The impacts of temperature change on wheat growth and yields are complex and diverse (Siebert and Ewert, 2014). Although some basic knowledge of high temperature effects, such as accelerating senescence and shortening growing season, have been investigated in various

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experimental set-ups including field trials, the detailed mechanisms responsible for negative impacts at different scales are still imperfectly understood, especially for impacts at large spatiotemporal scales (Asseng et al., 2011; Rötter et al., 2011; Hakala et al., 2012; Tao and Zhang, 2013; Barlow et al., 2015; Fan et al., 2015). Additionally, the quantification of actual impacts of unfavorable and extreme temperature conditions on crop growth under field conditions is also confronted with uncertainties because farmers will undoubtedly adjust their crop varieties and management methods to cope with typical threats from weather conditions (Reidsma et al., 2010; Farooq et al., 2011; Tao et al., 2015). These issues have resulted in substantial errors in estimating the influence of climate change on agricultural production, which have been highlighted in previous studies that focused on the performance of crop models (Rötter et al., 2011). Although crop models have been increasingly regarded as effective tools to estimate the responses of crop to climate changes, their ability to capture the impacts of extreme events such as heat stress is still limited (Tao et al., 2015), and their performance under high temperature scenarios are weaker than that under normal environment (Asseng et al., 2015). These deficiencies have limited the application of crop models in yield prediction for large areas (Rötter et al., 2011; Siebert and Ewert, 2014).

In order to better understand the detailed responses of crops to extreme temperature under different climatic regimes, a substantial number of suitable experiments are obviously needed (Rötter, 2014). Besides, with the development of remote-sensing technology, satellite images have been utilized as data sources for indicating the growth status of crops for large areas (Doraiswamy et al., 2003; Launay and Guerif, 2005). This led to the idea of investigating the relationship between climate factors and crop growth under actual planting practices. With the help of phenology data derived from remote-sensing data, Lobell et al. (2012) presented a study on the impacts of high temperature on growing season length of winter wheat in India. In current study, our main aim is to evaluate the impacts of high temperature on leaf area index and growth duration of winter wheat in the North China Plain. The results will provide not only knowledge on the impacts of extreme events, but also suggestions for crop model improvement.

2. Method and data

2.1. Study area and data sources

The study area covered main planting area of winter wheat in four provinces (Hebei, Shandong, Henan and Anhui) in North China Plain (Fig. 1). The North China Plain is an intensive wheat cultivation area and the field generally has a large size. The winter wheat is cultivated in this area between the October and the May of the following year, and its growing season is generally followed by the cultivation of maize. The study period comprised of the growing seasons of winter wheat from 2001 to 2008. Climate data, phenology data, weather disaster records, and remote-sensing data across the research area from 2001 to 2008 were used. Daily maximum temperature (Tmax), minimum temperature (Tmin) and total precipitation were observed and collected from 86 ground meteorological stations in research area. The phenology data and disaster records were observed and collected from 68 agro-meteorological stations with records of winter wheat cultivation in research region (Fig. 1). These datasets at station scale were obtained from China Meteorological Data Sharing Service System (http://data.cma.cn/). The remote-sensing data used in this study was an MODIS-based LAI product with spatial resolution of 1 km and temporal frequency of 8 days (Xiao et al., 2014). The product provided higher-quality data series of LAI values with spatial completion and temporal continuity than original MODIS LAI products (Xiao et al., 2014). The remote-sensing data was used for two objectives. Firstly, we used the data to estimate complete phenology data for 2001–2008 to investigate the responses of reproductive growing duration (RGD) to weather conditions. Secondly, the temporal changes of LAI were used to assess the responses of winter wheat growth status to actual weather conditions and severity of agro-meteorological disasters.

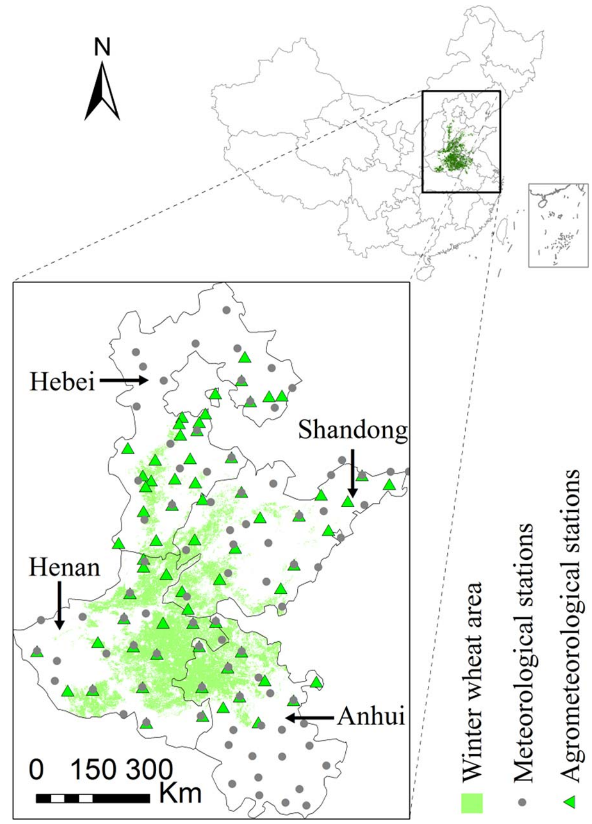

Fig. 1. Study area, retrieved winter wheat planting area, and locations of agrometeorological stations and meteorological stations.

As for the remote-sensing data in each 1 km grid, cubic spline interpolation in time was applied for generating continuous LAI curves over growing seasons. These curves were then used to determine grids with winter wheat cultivation. The LAI curve of winter wheat was identified through an inflection point in time of green-up stage (around February) and a peak value point during time of heading stage (around April). In all eight years, the same grids with these identifiable indicators were regarded as the main cultivation region and used in further research. In total, we selected 138, 842 grids as study area (Fig. 1).

2.2. Identifying crop phenological dates and reproductive growth duration (RGD) of winter wheat using remote-sensing data

The RGD is defined as the duration between heading date (ZADOKS growth scale 59) and maturity date (ZADOKS growth scale 91). The heading date was retrieved according to the peak value in LAI curve. Many criteria have been used to identify crop maturity date (Sakamoto et al., 2010). In this study, we used senescence speed and threshold as indicators to retrieve crop maturity date. The senescence speed of LAI value was indicated by the first derivative (d_1) of the curve. The day of year (DOY) with the maximum senescence speed was labeled as DOY_{speed}. The threshold was defined as a certain value between the maximum and minimum LAI value in LAI curve. The peak LAI value during heading stage was the maximum LAI value (LAI_{MAX}), and the minimum value (LAI_{MIN}) was defined as the value after harvest. Because of the rotations of winter wheat and maize in the North China Plain, a distinct trough in LAI curve between two growing seasons could be observed. This trough is the indicator for harvest of winter wheat, and maturity stage is generally started several days before harvest.