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Estimating spring frost and its impact on yield across winter wheat in China

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ABSTRACT

Frost events in spring pose a serious threat to wheat production in China. These events coincide with late vegetative stages and reproductive development, which are sensitive to frost stress. To understand the spatio-temporal pattern of spring frost and its impact on winter wheat yield, we calculated the accumulated frost degree-days (AFDD) as an index for frost risk affecting yield. Additional indices to characterize the spring frost risk included accumulated frost days and temperature-drop-rate. These indices were calculated for the growth period from stem elongation to flowering with historical data collected from 161 stations across the main winter wheat growing area in China from 1981 to 2009. Frost risk is smaller in the cooler northern and warmer southern regions than in the central winter wheat growing region of China. Huang-Huai Subregion (HHS) has the greatest frost duration, intensity and suffers the largest yield losses due to spring frost. Frost risk during stem elongation to flowering has not been significantly decreased in the winter wheat-growing regions of China under climate warming. While rising temperature reduces frost events in general, it also accelerates wheat phenology which increases the risk of spring frost. Quantifying future trends and impacts of spring frost damage on wheat production will be critical for developing appropriate adaptation and mitigation strategies for food availability in China and other regions of the world affected by frost.

1. Introduction

Extreme climate events and agricultural disasters have increased in the past decades (IPCC, 2012). Frost disaster is one of the extreme events characterized by a short duration of freezing air that is destructive to crop growth and production (Crimp et al., 2016; Frederiks et al., 2015). Frost events in spring occur frequently in many regions of the world, such as China (Li et al., 2015a; Zhong et al., 2008), United State of America (Holman et al., 2011; Whaley et al., 2004), and Australia (Zheng et al., 2015, 2012). For instance, despite a warming trend of 0.17 °C per decade since 1960, frost season length has still increased by 26 days across southern Australia and frost-related production risk has increased by as much as 30% across much of the Australian wheatbelt (Crimp et al., 2016). The relationship between a warming climate and increasing spring frost damage to crops seems like a paradox (Crimp et al., 2016; Gu et al., 2008; Li et al., 2016b). The underlying reasons are as follows: Firstly, a higher temperature accelerates vegetative development, and shifts frost-sensitive reproductive stages ahead in spring (Chen et al., 2014; Saeidi et al., 2014; Shimono, 2011; Wang et al., 2013); Secondly, complicated warm-cold fluctuations in spring may increase the uncertainty of spring frost events (Gu et al., 2008); And thirdly, the tissues and organs of winter habit cereals which experienced a warm winter are more susceptible to low temperature stress in the spring (Li et al., 2015b, 2016b).

Winter wheat (Triticum aestivum L.) is a winter habit crop which requires a low temperature to complete vernalization and can survive from some low temperature conditions during early vegetative stages (Fowler and Carles, 1979; Fowler et al., 1996). Frost tolerance of winter wheat can be acquired via freeze hardening during winter, however, it decreases rapidly through frost dehardening after crops resumed growth in spring (Bergjord et al., 2008; Frederiks et al., 2012, 2015; Fuller et al., 2009, 2007; Majláth et al., 2012). As stem extension pushing the apex above the insulating soil surface at stem elongation stage, floret primordium differentiation commences and the apex switches to the production of reproductive primordia (Whaley et al., 2004; Zhong et al., 2008), winter wheat becomes more sensitive to frost damage at this stage (Single, 1984). Spring frost damage occurs when canopy temperature fall below 0 °C or Stevenson screen air temperatures below 2 °C (Frederiks et al., 2015; Zheng et al., 2015). Rapid temperature-drop-rate can cause more severe frost damage than slow

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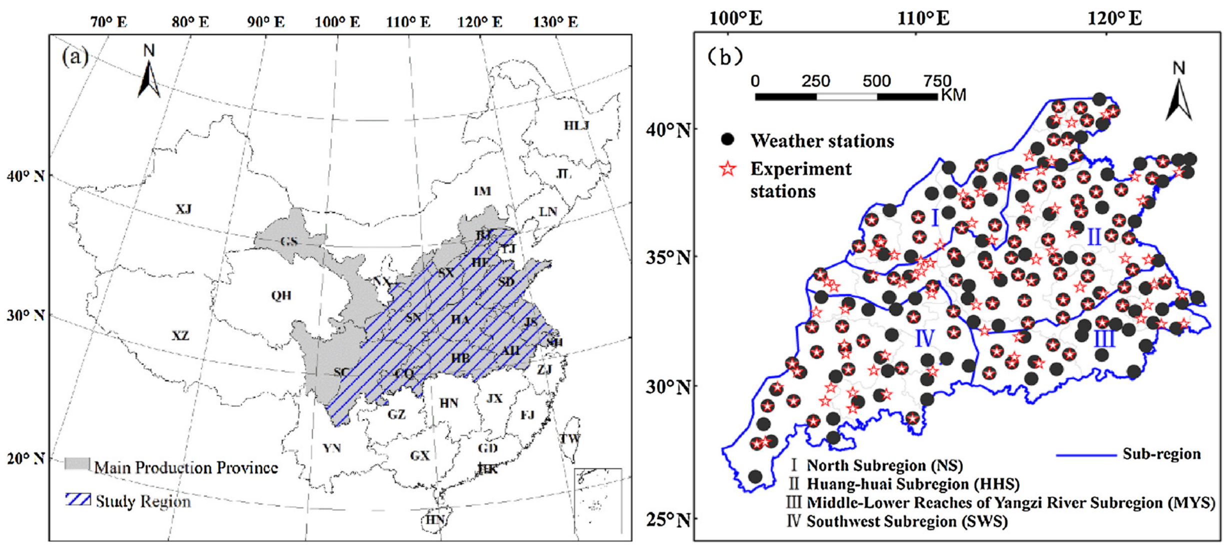

Fig. 1. (a) Map of China with main winter wheat-growing region and study region, and (b) locations of weather stations (black dots) and agro-meteorological experimental stations (red stars).

temperature-drop-rate because crops cannot acclimate to a sudden cold condition (Al-Issawi et al., 2013; Bergjord et al., 2008; Li et al., 2014). A sudden frost event at the sensitive post-stem elongation stage can cause severe yield loss (Al-Issawi et al., 2013; Fuller et al., 2007; Li et al., 2015c; Zhong et al., 2008). The spring frost stress-induced yield loss is highly correlated with the reduction of tiller and spike number, which are associated with a restriction on stem extension, specific leaf area and photosynthetic capacity (Li et al., 2015c; Valluru et al., 2012). As shown in the field experiment (2010–2011) by Li et al. (2015c), the reduction of spike number was 8%–15% and the yield loss was 5%–14% with a 5-day spring frost episode (with daily minimum temperature in the range of 0 to 4 °C) at the elongation stage. The yield loss increases with lower temperature (Wu et al., 2014). 1 °C minimum temperature drop below threshold temperature during reproductive stage could increase wheat damage from 10% to 90% (Marcellos and Single, 1984).

Winter wheat is a major staple food crop in China, accounting for more than 15% of total crop planting area and more than 20% of total crop production of China in recent years (2010–2014) (National Bureau of Statistics of China, 2015), which makes China the largest producer of wheat in the world (FAO, 2016) (last visited 11 May 2018). Winter wheat is typically sown in autumn, growing through winter and harvested in the following summer in China (Jin, 1996). Previous studies have been widely concerned with the spatio-temporal patterns of spring frost in China in recent decades (Li et al., 2015a; Yue et al., 2016; Zhong et al., 2007a,b). Spring frost widely distributes in about 85% of the total winter wheat planting area in China (Yue et al., 2016). It usually occurs in March and April during the immature ear and early ear emergence period, nevertheless, the frost damage to winter wheat after flowering is uncommon (Li et al., 2015a; Wu et al., 2014). Huang-Huai winter wheat growing region (110 °E-118 °E and 34 °N-36 °N) suffers the most severe spring frosts in China (Feng et al., 1999). In this region, the probability of spring frost has been increasing since the 1970 s (Zhong et al., 2007b). In eastern China, spring frost events are frequent in the north of Huaihe river valley (31 °N–36 °N) and the historical occurrence cycles of the spring frost is 22 years, 11 years, 4 years and 2 years depending on different stations (Bao et al., 2012). The average wheat grain yield variations caused by single spring frost in each decade during 1961–2000, ranged between -20.87% and 3.43%, based on six agro-meteorological stations in Eastern China (Li et al., 2015a). Previous studies have characterized the spatio-temporal distribution of extreme temperature events, drought events, and their impacts on wheat yield in different areas (Liu et al., 2014; Tao et al., 2015; Wang et al., 2016; Zhang et al., 2014). Heat stress and drought could occur after spring frost events, which would further aggravate the negative impacts on grain yield (Zheng et al., 2012). However, few studies have quantified the impacts of both types of climatic variables, and separate the spring frost impact from other climatic stress impacts on winter wheat production using long-term historical climate and yield records at a large spatial scale. Furthermore, the advancement of the elongation and heading stages caused by climate warming has played an important role in increasing the risk of spring frost (Gu et al., 2008; Zheng et al., 2012). Previous frost risk assessments often used fixed wheat growth seasons among different years and less considered actual temporal phenology variation among different ecological regions (Yue et al., 2016; Zhong et al., 2007a). Therefore, using historical observed phenology dates and climate records to analyze the spatio-temporal variability of spring frost, and separate its impacts from other extreme climate conditions on wheat yield in China is critical for preparing adaptation strategies to minimize the impacts of frost on food supply and regional food availability.

In this study, the main objectives are the following: 1) to calculate frost indices from daily minimum temperature records between stem elongation and flowering stage across the main winter wheat-growing region of China; 2) to analyze the spatial and temporal variation of frost during 1981–2009; and 3) to investigate the relationship between agro-climatic variation and grain yield variability, and separate the impact of spring frost on winter wheat yield from other climate factors.

2. Materials and methods

2.1. Study region and data source

The study region is located in the main winter wheat-growing region of China (26°13′-40°68′N, 100°83′-121°87′E), which contributes to more than 83% of the total wheat planting area and 88% of total wheat production in China (National Bureau of Statistics of China, 2015) (Fig. 1a). The whole region includes 14 main winter wheat production provinces and municipalities. Spring wheat-growing regions (Fig. 1a grey) were removed according to Chinese wheat planting regionalization (Jin, 1996). The whole study region is divided into four sub-regions (Fig. 1b) based on geographical environment and climate condition, including two northern sub-regions, the North Subregion (NS) and the Huang-Huai Subregion (HHS), and two southern sub-regions, the Middle-Lower Reaches of Yangzi River Subregion (MYS) and the Southwest Subregion (SWS) (Jin, 1996), which are the same as Liu et al (2014).