Agricultural and Forest Meteorology 260–261 (2018) 1–8

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

# Effect of freezing temperature and duration on winter survival and grain yield of winter wheat

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ARTICLE INFO

*Keywords:*
Winter wheat
Freezing stress
Freezing degree days
Winter survival
Grain yield

ABSTRACT

Climate change has already increased the occurrence of extreme temperature events, which has restricted the production and development of winter wheat. To evaluate the effects of freezing temperature and duration on winter wheat survival and grain yield, two years of controlled freezing experiments were conducted under different freezing temperatures and durations. Three freezing temperatures (T1, T2 and T3) were implemented in these experiments, and soil minimum temperatures of −14 °C, −17 °C and −20 °C were designated for T1, T2 and T3, respectively. The freezing durations were designed as 2, 4, 6, 8 and 10 days under T1, 1, 2, 3, 5, 6, 7, 8 and 9 days under T2, and 1, 2, 3, 4, 5, 6 and 8 days under T3. The effects of freezing duration on the mortality of plants and tillers, as well as its effects on the grain yield per pot (GYPP), were much more serious under lower temperature. For every 1-day increase in freezing duration, GYPP decreased by 3.3% and 8.4% under T1 and T2, respectively, while the spike number per pot (SNPP) decreased by 4.4% and 21.6% under T1 and T2, respectively. When analyzing the combined effects of freezing temperature and duration, we introduced freezing degree days (FDD), which uses soil minimum temperatures below a threshold of −12 °C to represent the magnitude of the exposure to freezing temperature and duration. For every 1 °C·d increase in FDD, the mortality of plants and tillers increased by 1.0% and 1.4%, respectively. The interaction between freezing temperature and duration had a great effect on GYPP (0.5–1.2%/°C·d), while SNPP was more sensitive to freezing stress than GYPP and decreased at a rate of 2.3–2.9%/°C·d. An increasing trend in grain number per spike (GNPS) was clearly observed as FDD increased in 2014–2015, while freezing stress during the overwintering period had no direct influence on thousand-grain weight (TGW). The variation in GYPP was mainly caused by the grain number per pot (GNPP = SNPP × GNPS). The contribution of SNPP to the variation in GYPP was greater than that of GNPS or TGW under mild temperature, while GNPS contributed more under severe temperature. The results of this study provide data support for the improvement of crop models when simulating the effect of temperature stress on grain crops, and they can be consulted to predict freezing injury during winter wheat production.

## 1. Introduction

Wheat is the third-largest crop in the world; it grows on more than 200 million hectares of cropland worldwide and annually produces over 600 million tons (FAO, 2013). China is currently the largest wheat-producing country in the world, as it is responsible for more than 17.6% of global wheat production (FAO, 2013). Winter wheat, which represents more than 90% of wheat produced in planting areas in China (National Bureau of Statistics of China, 2017), is exposed to climatic vagaries for longer periods during overwintering periods, which can potentially have negative impacts on winter survival, crop vigor, and hence final yields (Holmer, 2008; Licker et al., 2013; Peltonen-Sainio et al., 2011; Reinsdorf and Koch, 2013; Vico et al., 2014). In many areas where winter wheat is grown over large areas, this crop frequently suffers freezing injury of varying severity, resulting in significant yield losses (Andrews et al., 1974; Li et al., 2005; Skinner, 2012). Therefore, it is important to evaluate the responses of winter wheat to freezing stress during overwintering periods.

*Abbreviations:* CDD, cooling degree days; FDD, freezing degree days; GNPP, grain number per pot; GYPP, grain yield per pot; $LD_{10}$, the number of freezing days required for 10% mortality; $LD_{20}$, the number of freezing days required for 20% mortality; $LD_{50}$, the number of freezing days required for 50% mortality; $LT_{50}$, the temperature at which 50% of plants are killed by freezing; SNPP, spike number per pot; TGW, thousand-grain weight

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https://doi.org/10.1016/j.agrformet.2018.05.011
Received 1 November 2017; Received in revised form 2 May 2018; Accepted 11 May 2018

The mean surface air temperature of the Earth has increased by 0.86 °C from the Industrial Revolution to recent years (Abbas et al., 2017; IPCC, 2014). Under global warming, higher winter temperatures have caused winter wheat to extend northward and westward in China and have changed the cropping system and cultivated varieties in winter wheat-planting regions (Hao et al., 2001; Li et al., 2013; Ren et al., 2005; Sun and Liu, 2008 Tan et al., 2009; Yang et al., 2011). However, climate change has already increased the occurrence of extreme climate events, especially extreme temperature (IPCC, 2014), which has influenced the stability of crop production and caused severe reductions in yield, thus restricting the development of wheat production (Lobell et al., 2011; Xiong et al., 2005; Zheng et al., 2012).

Experimental evidence has suggested that the freezing injury of winter wheat is influenced by extreme freezing temperatures (of both air and soil) and freezing durations under milder, subzero temperatures during winter and that these two factors exert different degrees of influence (Gusta et al., 1997; Roberts, 1985; Skinner and Garland-Campbell, 2008; Taylor and Olsen, 1985; Vico et al., 2014). For example, air temperature of −23 °C for one day resulted in 50% mortality of plant for Norstar, while 13 freezing days at the air temperature of −15 °C caused 50% mortality (Gusta et al., 1997). The relationships between freezing soil temperature and winter wheat mortality have been established in controlled freezing experiments, and $LT_{50}$ (the temperature at which 50% of plants are killed by freezing) has been determined using these relationships (Mu et al., 2015; Zhao and Liang, 1987 Zheng, 1981). In addition, mathematical models have been built to represent the relationship between freezing duration and winter wheat mortality at particular temperatures (Gong et al., 1982; Zheng, 1981).

Freezing injury also has a great influence on grain yield and yield components. The effect of freezing injury of different degrees on grain yield has also been assessed in previous studies. Different responses of grain yield and yield components were observed at varying degrees of freezing injury. When winter wheat plants were slightly injured, grain numbers per spike increased and thousand-grain weight decreased slightly. For plants whose main stem froze to death, spike number, thousand-grain weight and grain yield per plant decreased by 12.3%, 7.8% and 10.2%, respectively, whereas grain number per spike increased by 11.3%. For plants whose main stem and strong tillers both were killed by freezing, the spike number, grain number per spike, thousand-grain weight and grain yield decreased by 49.2%, 17.7%, 14.6%, and 64.3%, respectively (Zheng et al., 1989). For winter wheat fields, freezing injury during winter mainly reduced spike rate and number thus decreasing yield, but with little effect on the grain number per spike and thousand-grain weight (Barlow et al., 2015; Huangfu et al., 1996). However, previous studies have mostly investigated the effect of either freezing temperature or freezing duration alone on winter wheat survival, with less focus on the combined effects of temperature and duration. In addition, the quantitative impact of freezing temperature and duration on grain yield and yield components has rarely been reported.

Cooling degree days (CDD), a factor that combines low temperature and duration, has been employed to quantify the effects of low temperature on the growth, development and yield formation of crops (Ji et al., 2017; Ma et al., 2003; Roel et al., 2005; Shimono et al., 2005, 2011). However, these studies mostly focused on the effect of low temperatures above 0 °C on yield formation during reproductive stages. Few studies have been conducted to evaluate the combined effect of freezing temperature below 0 °C and freezing duration on winter wheat survival and grain yield during overwintering periods. Freezing degree days (FDD), was used in here to define the degree and duration of cold during the overwintering period of winter wheat. The previous study reported that the crown is considered the organ most crucial for winter survival of winter wheat, as a viable crown is required for the regeneration of other plant organs damaged by freezing injury (Persson et al., 2017). The soil temperature around the wheat crown commonly determines whether a wheat crop will suffer a freezing injury during the winter (Persson et al., 2017). Therefore, the soil temperature was used here to calculate FDD.

In this study, two years of controlled freezing experiments were conducted using different freezing temperatures and durations during winter. The objectives were to: (1) establish the relationships between freezing duration and mortality and grain yield at different freezing temperatures, (2) quantify the combined impacts of freezing temperature and duration on winter survival and grain yield using FDD, and (3) explore the contribution of yield components to variations in grain yield at different freezing temperatures during overwintering periods.

## 2. Materials and methods

### 2.1. Experimental materials and management

The experiments were conducted during 2014–2016 at China Agricultural University, which is located in Beijing, China. Winter wheat cultivar Jing411 (strong-winter type) was used in these experiments. This wheat is widely cultivated in the northern area of the Huang-Huai-Hai region due to its strong hardiness. Winter wheat was planted in 23 cm (diameter) × 22 cm (deep) plastic pots on September 28 (2014–2015) and September 30 (2015–2016). Prior to sowing, the pots were filled with 7.5 kg of sandy loam soil that had been dried in the sun and 2.0 g (N:P:K = 15:15:15) fertilizer per pot as base fertilizer and then watered to water-holding capacity. Twenty seeds were sown at a depth of 2.5 cm in each pot and the seedlings were subsequently thinned to 10 per pot at the three-leaf stage. The pots were buried in the experimental field after sowing so that the plants could grow and acclimate under natural conditions before the freezing treatments were applied. An application of 1.0 g N per pot was conducted at the time of regrowth after the freezing treatments. Other cultivation practices, such as irrigation and pesticide application, were carried out as required, so that the experimental plants grew without stress from water, disease or pests.

The meteorological conditions during November and December in the experiment years in the experimental field, including daily air minimum temperature, daily soil minimum temperature at 2.5 cm depth and solar radiation (which influence the hardening levels of winter wheat), are shown in Fig. 1. The average air minimum temperature was 1.8 °C in November and −3.7 °C in December in the year 2014, while the average air minimum temperature was 1.3 °C in November and −2.4 °C in December in 2015. The average soil minimum temperature was 2.0 °C in November and −3.8 °C in December in 2014, while the average soil minimum temperature was 2.6 °C in November and −1.8 °C in December in 2015. The controlled treatments were conducted during late December to next January. The air and soil minimum temperatures were −3 °C to −6 °C respectively, in the experimental field before the treatments.

### 2.2. Controlled freezing treatments and observations

The experimental process is shown in Fig. 2. In order to expose the winter wheat cultivar to freezing injury of different degrees, three freezing temperature regimes (T1, T2 and T3) representing different freezing temperature levels were implemented and soil minimum temperatures ($T_{min}$) for T1, T2 and T3 were −14 °C, −17 °C and −20 °C, respectively. The mortality of plants was 0%, 5% and 30% under T1, T2 and T3 for one day, respectively (Mu et al., 2015). Once the targeted minimum temperature was established, the diurnal temperature range and the rate of cooling were adjusted. The respective soil maximum temperatures ($T_{max}$) for T1, T2 and T3 were established at −5 °C, −8 °C and −11 °C, in order to ensure that there were no death of plants and tillers due to the soil maximum temperatures and the diurnal temperature range. Experimental plants that had acclimated outside were moved to the freezing chamber for controlled freezing