Agricultural and Forest Meteorology 243 (2017) 33–42

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Effects of jointing and booting low temperature stresses on grain yield and yield components in wheat

Hongting Ji, Liujun Xiao, Yumin Xia, Hang Song, Bing Liu, Liang Tang, Weixing Cao, Yan Zhu*, Leilei Liu*

National Engineering and Technology Center for Information Agriculture, Key Laboratory for Crop System Analysis and Decision Making, Ministry of Agriculture, Jiangsu Key Laboratory for Information Agriculture, Jiangsu Collaborative Innovation Center for Modern Crop Production, Nanjing Agricultural University, Nanjing, Jiangsu 210095, China

ARTICLE INFO

Keywords:
Jointing
Booting
Low temperature stress
Grain yield
Yield components
Wheat

ABSTRACT

Climate change has brought more low temperature events and posed an increasing risk to the global wheat production. In order to evaluate the effects of low temperature at jointing and booting stages on wheat grain yield and its components, two years of environment-controlled phytotron experiments were carried out with two wheat cultivars under different low temperature levels and durations. Low temperature level and its interaction with low temperature duration had negative effects on the observed grain yield in two cultivars. Moreover, wheat yield was more sensitive to low temperature at booting than at jointing stages. Compared with the control treatment ($T_{min}/T_{max}/T_{mean}$ of 6 °C/16 °C/11 °C, T1), 4.6%–56.4% and 3.1%–44.6% decreases of grain yield per plant (YPP) were observed under low temperature at jointing in Yangmai16 (spring wheat) and Xumai30 (semi-winter wheat), and 13.9%–85.2% and 3.2%–85.9% decreases under low temperature at booting in Yangmai16 and Xumai30, respectively. The spike number per plant (SNPP) and grain number per spike (GNPS) were more sensitive to low temperature at jointing and booting stages than 1000-grain weight (TGW). Furthermore, significant negative linear relationships were observed between the accumulated cold degree days (ACDD) and YPP, SNPP, GNPS and TGW in both cultivars. The contribution of GNPS to the variation of YPP was greater than SNPP and TGW at the mild low temperature level ($T_{min}/T_{max}/T_{mean}$ of -2 °C/8 °C/3 °C, T3) in both cultivars. However, at the extreme low temperature level ($T_{min}/T_{max}/T_{mean}$ of -6 °C/4 °C/-1 °C, T5), the major variation of YPP was caused by SNPP of Yangmai16 and GNPS of Xumai30. In general, the decreased YPP under low temperature condition was mainly from the decreased grain number per plant (GNPP = SNPP × GNPS) in both cultivars and treatment stages, thus maintaining a high GNPP is very important for compensating the yield losses caused by low temperature at jointing and booting stages.

1. Introduction

Wheat is the food crop with the third highest yield in the world and the staple food for approximately 60% of the world's population. By 2020, wheat production in developing countries is expected to increase by 1.6% per annum worldwide to meet the growing food demand due to population growth and economic development (Ortiz et al., 2008). China is currently the world's largest wheat-producing country, which produced more than 17.6% of the global wheat production (FAO, 2013). Therefore, wheat production has an important role in ensuring food security in China as well as the world.

Climate change has resulted in a continuous increase in the frequency, intensity, and duration of extreme low temperature events (Augspurger, 2013; Kodra et al., 2011; Rigby and Porporato, 2008; Vavrus et al., 2006). In addition, global warming has accelerated the process of wheat growth and development, resulting in significant advancement of the low temperature sensitive stage of wheat, thereby increasing the probability of cold or frost injury in wheat (Gu et al., 2008; Zheng et al., 2015, 2012). During the last several decades, low temperature has caused serious losses in wheat production in Australia (Barlow et al., 2015; Crimp et al., 2016), the United States (Gu et al., 2008; Shroye et al., 1995), Europe (Peings et al., 2013; Trnka et al., 2014) and China (Zhong et al., 2008). For example, in Queensland and northern New South Wales of Australia, gross yield reductions of 10% was associated with frost damage (Frederiks et al., 2004), which resulted into more than AUD$100 million economic losses (Frederiks et al., 2008). Between 1955 and 2010, in Kansas, USA, 41 cold stress events occurred, resulting in an annual wheat yield losses of more than

---

* Corresponding authors.
E-mail addresses: yanzhu@njau.edu.cn (Y. Zhu), liuleilei@njau.edu.cn (L. Liu).

http://dx.doi.org/10.1016/j.agrformet.2017.04.016
Received 2 November 2016; Received in revised form 21 April 2017; Accepted 24 April 2017

8 bushels/acre (Holman et al., 2011). In China, the frequency of freezing stress events for wheat in Henan Province increased from 40% before the 1970s to approximately 50% in the 1980s, and reached more than 78% in the 1990s (Zhong et al., 2007). From 2000 to 2008, freezing stress events occurred in 8 years in Shandong Province and more than 10% of the wheat planting area was damaged in five growing seasons during this 9-year period. Moreover, the total frost injury area between 2000 and 2008 in Shandong Province was more than 2.92 million ha (Wang et al., 2011). However, due to the increasing global mean temperature during the last several decades, the majority of studies have been well concerned with heat stress on crop production (Liu et al., 2014; Sun and Huang, 2011; Zhou and Ren, 2011). Low temperature injury on corps, which includes both cold and freezing injury, has been usually ignored (Ding et al., 2010; Rigby and Porporato, 2008).

Low temperature affects wheat production mainly by reducing photosynthetic rate (Allen and Ort, 2001), leaf area, dry matter accumulation (Valluru et al., 2012), grain number (Thakur et al., 2010) and grain filling rate (Cromey et al., 1998), and finally results in grain yield losses. Subedi et al. (1998b) investigated the effects of cold stress from booting to flowering on wheat yield and found that the grain number per spike was significantly reduced under cold stress (2 °C/8 °C), resulting in 35%–78% decreases of grain yield, compared to the control. Subedi et al. (2001) reported that the grain set of wheat decreased with increasing cold duration (0, 3, 6 and 12 days) under 2 °C/10 °C treatment after ear emergence. Whaley et al. (2004) found that freezing temperature between −8 °C and −9 °C during stem elongation restricted internode extension, killed spikelet and reduced dry matter accumulation and grain yield. Fuller et al. (2007) exposed two wheat cultivars at the vegetative growth stage to a freezing temperature at 0, −3, −5, −7, −9 and −13 °C for 2 h in a convective freezing chamber. They found that flag leaves and ears of both cultivars were damaged at the treatment of −3 °C for 2 h, and damage increased as low temperature declined to −5 °C and −7 °C, resulting 10%–100% grain yield loss. Venzhik et al. (2011) investigated the effects of low temperature on the resistance and functional activity of the photosynthetic apparatus (PSA) of wheat under 4 °C at seedling stage. They reported that the activity of PSA decreased along with an increase in resistance in the first hour of cold. While after one to four days of cold, when resistance reaches its maximum, the leaf photosynthetic and the rate of electron transport are stabilized and the chlorophyll content complex increased. Li et al. (2015) found that spring freeze (8 °C lower than ambient temperature) at jointing significantly decreased gas exchange rates and maximum quantum efficiency of photosystem II in wheat leaves, causing 5%–14% grain yield reduction. Previous studies mostly focus on the effects of low temperature at a certain growth stage of wheat (Cromey et al., 1998; Marcellos and Single, 1984; Subedi et al., 1998a), whereas comparison of low temperature effects at different growth stages has rarely been reported. In addition, previous studies mostly investigated the effect of either low temperature level or low temperature duration alone on wheat production (Al-Issawi et al., 2013; Fuller et al., 2007; Subedi et al., 2001), with less focus on the combined effects of low temperature level and duration. Furthermore, temperature regimes in most of the previous studies were based on the fixed daytime/nighttime temperature treatments (Chakrabarti et al., 2011; Langer and Olugbemi, 1970; Wu et al., 2014), which were not consistent with the daily natural temperature dynamic. In actual production, the impact of low temperature on crop growth and development is often affected by the combination of low temperature level and duration under the daily temperature variation pattern (Shimono et al., 2007).

Cold degree days (CDD, °C d), which considered the duration and intensity of low temperature, had been employed to quantify the effects of low temperature on the growth, development and yield formation of crops (Ma et al., 2003; Shimono et al., 2005; Uchijima, 1976). Yajima et al. (1989) used CDD to build quantitative relationship between low temperature stress and the sterility of paddy rice at different ecological sites in Japan ($r^2 = 0.67$, $n = 22$). Godwin et al. (1994) introduced CDD into CERES-Rice model to improve the simulation accuracy under low temperature environment, suggesting that CDD could quantify the chilling injury effect greatly in an extensive field experiment. Roel et al. (2005) used CDD to analyze the effects of the water layer temperature on grain yield during the rice growing season in different years in California, USA, and found that 84% of the variation of the rice yield was induced by low water temperature. Shimono (2011) employed CDD to quantify the effects of low temperature at booting on rice yield in northern Japan between 1961 and 2010, and found that for every 1 °C d increase in CDD, rice yield was predicted to decline by 0.86% ($r = 0.511$, $p < 0.001$). Although several studies have been carried out to quantify the effects of low temperature on rice yield with CDD, few similar studies have been conducted on wheat crop.

In this study, two years of environment-controlled phytotron experiments were conducted with different wheat cultivars, low temperature levels and durations at two growth stages. Our main objectives were to: (1) analyze the impacts of low temperature levels and durations at jointing and booting stages on grain yield and its components, (2) quantify the comprehensive effects of low temperature levels and durations on wheat yield and its components with CDD, (3) investigate the relative contribution of yield components to the variation of wheat grain yield under low temperature condition.

2. Materials and methods

2.1. Experimental design

Environment-controlled phytotron experiments were conducted during the 2013–2015 growing seasons in the experimental station of National Engineering and Technology Center for Information Agriculture (NETCIA), which was located in Rugao city, Jiangsu province, China (120°45′ E, 32°16′ N). Two wheat cultivars, Yangmai16 (spring wheat) and Xumai30 (semi-winter wheat), were planted in plastic pots, with a planting density of 10 plants per pot. The height and inside diameter of pots were 30 cm and 25 cm. Each pot was filled with sieved yellow brown soil with available nitrogen content, available phosphorus content, available potassium content and organic matter content of 150.41 mg kg^{-1}, 57.84 mg kg^{-1}, 96.32 mg kg^{-1}, and 24.60 mg kg^{-1}, respectively. Sowing dates in the two growing seasons were November 4 of 2014 and November 3 of 2015, respectively. Before sowing, 0.9 g N, 0.5 g P_2O_5 and 0.9 g K_2O per pot were applied as base fertilizer, and an extra 0.9 g N per pot, was top-dressed at jointing stage. All other cultivation practices such as irrigation and pesticide application were carried out according to the local standard of wheat cultivation to make sure wheat was grown without water and disease or pest stresses. Wheat was grown in pots in a normal ambient environment before and after low temperature treatments. Once developed into the jointing (*Zadoks* 31) and booting stages (*Zadoks* 45), wheat was transferred into phytotrons to be exposed to different low temperature conditions.

The low temperature treatments were conducted in four - independent phytotrons, with a size of 3.4 m × 3.2 m × 2.8 m (length × width × height). The air temperature and relative humidity in the phytotrons were controlled using air conditioners and bubbling system. Two fans in each phytotron were employed to keep the CO_2 concentration consistent with ambient environment. Temperature and humidity in the phytotrons were controlled precisely to simulate the daily changing patterns of temperature and humidity observed under field conditions. EM50 data loggers (Decagon Devices, Inc. Washington, USA) were used to record temperature and relative humidity every 5 min during the treatment periods. Fig. 1 shows the daily temperature dynamics followed a similar pattern of ambient temperature. Supplemental light was applied by halogen lamp to ensure enough radiation for wheat growth in the phytotrons. The light intensity in the phytotron