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Selecting traits to increase winter wheat yield under climate change in the North China Plain

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ABSTRACT

To mitigate the possible yield reduction of winter wheat under climate change in the North China Plain (NCP), cultivars with traits that could offset the negative effects of several deteriorating weather factors in the future should be developed. This study used 16 recently certified cultivars of winter wheat each season for five seasons from 2011 to 2016 under three irrigation treatments (I0: without irrigation; I1: moderate irrigation; and I2: well water supply) to examine the agronomic traits of winter wheat that may be able to reduce the negative effects of abiotic stress. Yield variation up to 32% was observed during the five seasons, indicating the significant effects of seasonal weather conditions. The yield difference among the cultivars reached 33%, indicating the benefit of selecting a better cultivar to minimize the negative effects of weather and water deficit. Cultivars with higher seed numbers per area and greater biomass usually gave better grain production under all three water supply conditions. Under good water supply conditions, sunshine duration during the vegetative growth stage significantly affected the spike numbers per area and seed numbers per spike. Diurnal temperature range (DTR) during the grain-fill stage was positively related to the seed weight. Cultivars with higher leaf photosynthetic rates and earlier anthesis dates had an advantage to relieve the influence of climate change and produced higher yield. Due to the reduced rainfall and increased atmospheric evaporation potential under the climate change background, for winter wheat grown under limited water supply, cultivars with a higher kernel Δ^{13}C, a lower canopy temperature and a larger root system usually produced a higher yield. In general, for winter wheat grown under good water supply conditions, cultivars that had higher efficiency in dry matter assimilation and allocation performed better. Under dry conditions, cultivars with a high ability to use the soil water stored before sowing had an advantage that allowed them to produce a higher yield.

1. Introduction

Winter wheat is one of the most important crops in the world (Braun et al., 2010). The demand for wheat is projected to increase at a rate of approximately 1.7% per annum (p.a.) until 2050 (Rosegrant and Agcaoili, 2010). However, providing an adequate supply of food will be difficult in the face of a steadily increasing population and the diminishing availability of fertile land (Hawkesford et al., 2013). Moreover, the impacts of climate change on agricultural production further challenge the food security (Piao et al., 2010; Tripathi et al., 2016). The Earth's climate has warmed by approximately 0.6 °C over the past 100 years. Higher temperatures can reduce net carbon gain by increasing plant respiration more than photosynthesis (Högy and Fangmeier, 2008), change the crop phenology (Estrella et al., 2007), and even lead to the invasion of weed, diseases and pest (Baker et al., 2000). Numerous studies about changing climate resulting in considerable reduction in crop yield have been reported worldwide (e.g., Asseng et al., 2011; Licker et al., 2013; Morgounov et al., 2013). Water is one of the most essential resources for agriculture, and it will also be further affected by climate change (Barnett et al., 2005; Semenov, 2009).

The North China Plain (NCP) is one of the most productive and intensively cultivated agricultural regions in China and supplies more than 50% of China's wheat production (Wang et al., 2012). Several studies have found that the climate has become warmer and drier since the late 1970s and across the NCP (Tao et al., 2006;

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Fu et al., 2009). You et al. (2009) showed that a 1 °C increase during the wheat growing season reduced wheat yield by approximately 3–10%. The results from Liu et al. (2009) showed that the warming mainly occurred during the vegetative growth stage. Zhang et al. (2013) suggested that the diurnal temperature range (DTR) was declining in the NCP. In addition, there has been a significant decrease in sunshine hours since the 1960s (Che et al., 2005). The changing climatic trend may further negatively affect winter wheat yield in the future (Zhang et al., 2013). The production of winter wheat in the NCP also faces water shortage problems. Rainfall during the winter wheat growing season, ranging from 60 mm to 150 mm, could only meet 25–40% of water requirements (Fang et al., 2010). To achieve high grain yields, supplemental irrigation is essential (Zhang et al., 2008). However, irrigation also caused a rapid decline in the groundwater table, which threatens sustainable agricultural development. Moreover, a decline in seasonal rainfall and increased durations of days without rain were observed, which further deteriorated the water shortage situation (Zhang et al., 2017).

It is important to maintain or increase crop productivity under conditions of climate change and changes in the supply of natural resource. Historically, cultivar renewal contributed to yield increase by 12.2–22.6% during 1980–2009 in China (Xiao and Tao, 2014). Many studies showed that the considerable increases in wheat yields were attributed mainly to the increase in harvest index (HI) and biomass (Zhang et al., 2010). The biomass contributed more to the grain yield improvement than HI (Zhang et al., 2013). Different cultivars have different contribution of biomass and HI (Álvaro et al., 2008). Under climate change, new crop varieties should be developed to have physiological or agronomic traits that are suited to future conditions.

Improving agronomic management practices such as fertilizer, pesticide utilization and soil organic matter content; changing cropping patterns; adjusting sowing dates; and better water management could potentially mitigate the negative impacts of climatic change (e.g., Huang et al., 2007; Franks et al., 2007; Waongo et al., 2014; Waongo et al., 2015; Kalra et al., 2008; Falloon and Betts, 2010; Laux et al., 2010; Maltais-Landry and Lobell, 2012). Due to the importance of genetic contribution to the increased crop yield, adoption of new crop varieties can be seen as a useful method to offset the unfavorable effects of climatic change (Morgounov et al., 2013). Ludwig and Asseng (2010) demonstrated that cultivars with higher specific leaf area could increase grain yield under future climate change in the Mediterranean. Extending the length of the grain-fill stage could lead to a stable or increased yield of winter wheat in China (Liu et al., 2009). Kernel numbers per area had the highest correlation with grain yield and contributed the most to its genetic gains (Donmez et al., 2001). Iqbal et al. (2016) showed that the grain yield increase was positively correlated with days to maturity and kernel weight. However, Gummadov et al. (2015) demonstrated that there was no clear tendency of changes in yield components and the new high-yielding cultivars may have different ways to reach their yield potentials. Fischer et al. (1998) suggested that carbon-13 isotope discrimination (Δ^{13}C) was positively associated with yield progress. Amani et al. (1996) and Zhang et al. (2016) used canopy temperature depression to select the yield traits of wheat under dry conditions. Lower canopy temperature genotypes tended to partition more assimilates to deeper roots. A deep rooting system was an alternative strategy for adapting to drought stress (Lopes and Reynolds, 2010). Therefore, the responses of modern cultivars toward climatic changes are important factors to be taken into account when solving the negative influences of climate change (Howden et al., 2007; Mondal et al., 2014).

Thus, the aims of this study were to examine (i) the influence of weather and soil water conditions on the performance of different winter wheat cultivars, and (ii) the beneficial traits of winter wheat cultivars for future winter wheat breeding under climate change.

2. Materials and methods

2.1. Study site

The field experiment was conducted at Luancheng Agro-Eco-Experimental Station of the Chinese Academy of Sciences from 2011 to 2016 during five growing seasons of winter wheat. The station is located in the northern part of the NCP at the base of Mt. Taihang (37°53′N, 114°40′N; 50 m above sea level). The soil is a moderate well-drained loamy with an average water holding capacity of 38% (v/v) and a wilting point of 13% (v/v) for the top 2 m soil profile (Zhang et al., 2010). The soil nutrient contents for the top tillage layer were 18 g/kg for organic matter, 21 mg/kg for available P, 80 mg/kg for available K and 92 mg/kg for available N and 1.2 g/kg for total N.

2.2. Experimental design

During the five growing seasons of 2011/2012, 2012/2013, 2013/2014, 2014/2015, 2015/2016 for winter wheat, 16 recently certified cultivars that were purchased from the local seed markets were used for the test. Some of the cultivars were renewed each season. The including of new certificated cultivars each season could ensure the characters of new developed cultivars being considered. There were two cultivars (KN 199 and SX828) grown during all the five seasons for analyzing the weather factors on seasonal yield variation. A total of 47 cultivars were used during the five seasons. The cultivars were grown following the conventional management practices of local farmers, except for the irrigation management. Approximately 1 ha land was used with the field being divided into three parts for three irrigation treatments. Each part was planted with 16 cultivars in a randomized plot design with four replicates, and each plot was 4 m × 6 m. Planting occurred around 10th of October and was performed by a hand-operated sowing machine. Row spacing was 20 cm, and seeding rates were adjusted for each cultivar to achieve a density of 300 viable seeds m^{-2}. From planting to the end of November is the seedling stage of winter wheat. December to early March of the next year is the long winter dormancy period, and at the end of the dormancy in March, winter wheat begins to recover. The heading and flowering stages occur at the end of April and the first ten days of May, respectively. Harvesting typically occurs around the 10th of June. The grain-fill duration lasts 30–35 days. After winter wheat harvesting, summer maize is sown, and the straw of the maize is incorporated into the soil by cultivating before sowing the winter wheat. Together they form the annual double cropping system.

The three irrigation treatments were no irrigation (I0, defined as dry condition), one irrigation at the jointing stage (I1, as moderate deficit condition), and two irrigations at the jointing and anthesis stages (I2, well-irrigated condition) for the five seasons based on previous studies at the same site (Zhang et al., 2008). In the 2014–2015 season, a pre-sowing irrigation was applied due to the previous dry summer. The irrigation amount was approximately 60–90 mm/application. It was conducted with a plastic hose connected to the outlet of a low pressure water transportation system that obtained water from a well. A water meter was installed in the system to control the water applied to each plot. Except for the irrigations, other field management practices were the same for all the treatments. Before planting, diammonium phosphate at 450 kg ha^{-1}, urea at 150 kg ha^{-1} and potassium chloride at 150 kg ha^{-1} were broadcasted and incorporated into the soil during tillage. An additional 150 kg ha^{-1} of urea was top-dressed