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Limits to maize productivity in the North China Plain: A comparison analysis for spring and summer maize

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ABSTRACT

Assessing the constraints to maize productivity and narrowing the yield gap between yield potential and actual farmers' yield in intensive maize production are essential to meeting future food demand with finite resources. A 6-year experiment that compared spring and summer maize was conducted to illuminate the limiting factors to maize productivity in the North China Plain (NCP). Drought stress in 2015 and overcast and rainy stress at the critical stage (15 d pre-silking to 15 d post-silking) in 2009, 2010 and 2016 reduced the kernel number in spring maize, and the overcast and rainy stress around silking in 2009, 2010, 2013 and 2016 led to poor pollination and low kernel number in summer maize, i.e., environmental stress at the key stage bracketing silking severely restricted the kernel number of spring and summer maize. The main limits to spring maize weight were that there was a low filling rate during the early stage and that the abundant solar and thermal resources after silking were not efficiently utilized due to heat stress; the limiting factor for summer maize weight was that the filling rate declined rapidly during the late stage because low temperature and solar radiation at late September reduced the filling rate.

1. Introduction

Yield potential is defined as the yield of a crop cultivar when grown in a condition to which it is adapted, with non-limiting nutrients and water and effectively controlled pests and diseases (Evans, 1993). In recent years, crop yield gaps have been assessed widely in the world (Neumann et al., 2010). Also, these studies have received abounding attention in China (Meng et al., 2013; Tao et al., 2015). The evaluation of yield potential and yield gaps can help estimate restrictive factors and develop strategies to increase crop grain yield (Aggarwal and Kalra, 1994). Moreover, years of field experiment would offer more opportunities to catch the limiting factors to crop yield.

Maize (*Zea mays* L.) is one of the most broadly grown crops in the world and is not only a staple food for people and animals but is also a crucial industrial material for fuel and many other uses. To meet the increasing consumption demand of an exploding population, maize grain yield must grow substantially (Cassman et al., 2003). Maize has been the largest cereal food crop in China since 2013. The maize grain yield was 2.15×10^8 t in 2014, which accounted for more than one third of the cereal yield in China, which represents 21% of the global maize output (FAO, 2016). The North China Plain (NCP), one of the most pivotal agricultural production areas in China, supplies approximately 33% of the country's maize production (Wang et al., 2012). However, the average yield in the NCP (include Beijing, Tianjin, Hebei Province, Henan Province and Shandong Province) is 5.7 Mg ha^{-1} (China Statistical Yearbook, 2016), which is far lower than the highest recorded yield (19 Mg ha^{-1}) in Shangdong Province (Li and Wang, 2009). Yield potential in the NCP, simulated by the Hybrid-Maize Model, was 17.6 t ha^{-1} and 13.4 t ha^{-1} for irrigated and rainfed maize, respectively (Meng et al., 2013). Liu et al. (2017) reported that the average yield potential of irrigated and rainfed maize was 13.3 and 11.1 t ha^{-1} in the NCP from 1985 to 2014, respectively. This means that a huge yield gap could be narrowed in maize production in the NCP, so assessing constraints to maize productivity is essential to meeting the future food demand.

Two cropping systems dominated in the NCP: winter wheat followed by summer maize, or a single spring maize. The summer maize is often planted directly into the stubbles of wheat immediately after its harvest in early to mid-June and is harvested in late September to early October. The single spring maize is mainly sowed in April to May and

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harvested in late August to mid-September. The visible differences in temperature, active radiation and precipitation between spring maize and summer maize growth seasons lead to different growth conditions and yield potentials. Studies attempting to identify the maize yield potential and its variation in relation to meteorological factors have advertised the predominant role of solar radiation and temperature (Muchow, 1989; Cirilo and Andrade, 1994a; Otegui et al., 1995, 1996). However, in all of these studies, maize yields were estimated against average climatic factors for the whole growth season rather than for specific growing periods that are most susceptive to environmental restriction (Otegui and Bonhomme, 1998). To determine the limiting factors for maize production in the NCP, we want to quantify yield potentials of spring and summer maize by using the Hybrid-Maize Model and record the solar radiation, temperature and rainfall in experimental site, and to assess the meteorological factors in the crucial stage for maize yield formation (15 d pre-silking to 15 d post-silking), and to compare the filling rate and discover the limits to grain filling. The primary objectives of this work were to (i) reveal the main limiting factors for reduced kernel number in the NCP and (ii) compare spring and summer maize in regard to their grain filling rate and detect the limiting factors to the process. Results of this study would help make a recommendation for simple and effective management practices for spring and summer maize production in the NCP.

2. Materials and methods

2.1. Experiment site and planting detail

In 2009, 2010 and 2013–2016, a field experiment was conducted at Wuqiao Experimental Station of China Agricultural University (Hebei Province, China, 37°41′02″N, 116°37′23″E). Zhengdan 958, a common maize cultivar in China, was sown in this experiment. The conventional irrigation quantity in Wuqiao County, 75 mm, was irrigated at the sowing and tasseling stage. Surface flood method, through plastic pipe, was used if visible drought stress occurred at these two stages. Given groundwater overdraft problems and labor costs, other stages when maize suffered a water deficit were generally neglected. The plant density and irrigation treatment in each growth season were shown in Table 1 and the planting date and growth stage were shown in Table 2. In addition, to find out the suitable sowing date, a sowing date experiment was conducted from 4 April to 13 June with 14 days interval in 2009 and 2010. There were three replications with a random complete block design in present experiment. Each plot area was 50 m^2 (5 m × 10 m) in 2009–2010 and 80 m^2 (8 m × 10 m) in 2013–2016 with a 2-m buffer zone between plots. In 2009–2010, 750 kg ha^{-1} compound fertilizer (N-P_2O_5-K_2O: 15-15-15) was applied before sowing, and 138 kg N ha^{-1} (urea) of fertilizer was top-dressing at V12. In 2013–2016, fertilizer containing 72 kg N ha^{-1} (urea), 105 kg P_2O_5 ha^{-1} (diammonium phosphate) and 120 kg K_2O ha^{-1} (potassium sulphate) was applied before sowing, and 108 kg N ha^{-1} (urea) of fertilizer was top-dressing at V12. There were no weeds or pests stresses in this experiment.

Table 1
The plant density and irrigation management in each growth season.

Year	Sowing season	Plant density (plant ha^{-1})	Experimental irrigation		Simulative irrigation	
			Irrigation date DAP	Irrigation amount	Irrigation date DAP	Irrigation amount
2009	Spring	70500	−8	75 mm	45, 54, 76, 87	128 mm
	Summer	70500	–	–	–	–
2010	Spring	72500	−8, 72	150 mm	56, 59, 71, 79	128 mm
	Summer	72500	0	75 mm	–	–
2013	Spring	–	–	–	–	–
	Summer	70000	–	–	–	–
2014	Spring	72000	−8, 72	150 mm	47, 67, 109	96 mm
	Summer	75000	0, 59	150 mm	–	–
2015	Spring	72000	−8, 73	150 mm	50, 54, 69, 82, 88	160 mm
	Summer	75000	0	75 mm	–	–
2016	Spring	72000	−8, 72	150 mm	48	32 mm
	Summer	75000	–	–	–	–

DAP, day after planting. -8 indicated 8 days before sowing. Each irrigation amount was 75 mm and 32 mm for experimental irrigation and simulative irrigation, respectively.

Table 2
The phenology stage of spring and summer maize in different growth seasons.

Year	Sowing season	Phenology stage				
		Sowing	V6	V12	R1	R6
2009	Spring	18 Apr.	28 May.	17 Jun.	29 Jun.	9 Sep.
	Summer	13 Jun.	13 Jul.	29 Jul.	11 Aug.	9 Oct.
2010	Spring	18 Apr.	28 May.	17 Jun.	29 Jun.	9 Sep.
	Summer	13 Jun.	8 Jul.	24 Jul.	4 Aug.	8 Oct.
2013	Spring	–	–	–	–	–
	Summer	17 Jun.	18 Jul.	5 Aug.	17 Aug.	7 Oct.
2014	Spring	22 Apr.	2 Jun.	22 Jun.	3 Jul.	7 Sep.
	Summer	15 Jun.	13 Jul.	1 Aug.	13 Aug.	4 Oct.
2015	Spring	16 Apr.	26 May.	16 Jun.	28 Jun.	2 Sep.
	Summer	14 Jun.	16 Jul.	30 Jul.	12 Aug.	2 Oct.
2016	Spring	22 Apr.	2 Jun.	21 Jun.	3 Jul.	1 Sep.
	Summer	13 Jun.	8 Jul.	24 Jul.	5 Aug.	28 Sep.

The spring maize in 2013 was not planted.

2.2. Sampling and measurements

2.2.1. Weather

Daily weather data (rainfall, temperature, sunshine hour, wind speed and relative humidity) between sowing and harvest were obtained from the automated weather station at Wuqiao Experimental Station. The growing-degree days (GDD, °Cd.) after sowing was calculated during different growth periods as Tsimba et al. (2013):

$$GDD = \sum \left(\frac{T_{max} + T_{min}}{2} - T_b\right)$$

where T_{max} and T_{min} were daily maximum and minimum air temperature, respectively, and T_b was base temperature and defined as 10 °C.

The daily total solar radiation (SR) was calculated according to the formula by Prescott (1940) and Zuo et al. (1963).

$$Q = Q_0\,(a + b\,S/S_0)$$

where Q is the daily total solar radiation (MJ m^{-2}), Q_0 is the astronomical radiation (MJ m^{-2}), S is the actual sunshine hours (h), S_0 is the possible sunshine hours (h), S/S_0 is the proportion of sunshine, and a and b are correction coefficients, which are 0.25 and 0.5, respectively (Allen et al., 1998).

2.2.2. Biomass, leaf area index and grain filling

At V6, V12, R1 and R6 (Abendroth et al., 2011), three representative plants (aboveground) were sampled in each plot in 2014–2016. To calculate the leaf area, the length (L) and maximum width (W) of each leaf were measured. Leaf area (LA) and leaf area index (LAI) was calculated according to the formula (Ren et al., 2016):

$$LA = 0.75 \times W \times L,$$

$$LAI = \text{total leaf area per hectare / per hectare}$$

Then the maize plant was divided into four sections (leaf, stem, kernels and cob + bractea) to be dried at 80 °C for 48 h to invariable weight.

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