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Assessing the contribution of weather and management to the annual yield variation of summer maize using APSIM in the North China Plain

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ABSTRACT

Long-term field experimental data provides a good opportunity to evaluate the effects of different management practices and weather factors on maize yield. An 11-year field experiment (2003–2013) with the same maize cultivar and two short-term experiments including different sowing dates and plant densities were conducted at Luancheng Agro-ecological Experimental Station in the North China Plain (NCP). The measured pheonological development, biomass and grain yield were used to calibrate and validate the APSIM-maize model. The results showed that APSIM-maize model could capture the biomass and grain yield of summer maize under the various management practices and weather conditions. After calibration and validation, five scenarios were simulated using the APSIM model. The simulated results showed that weather factors including sunshine hours and the diurnal temperature range during the grain fill stage had the positive effects on maize yield. For different management practices, plant density was the most important factor which affected the maize yield. The optimal plant density was approximate 8.6 plants/m^2. Maize yield would be decreased with the sowing dates delayed after the middle of June. Meanwhile, earlier sowing before the end of May also reduced the grain production. The optimized sowing date and plant density could reduce the seasonal yield variation of maize caused by the weather factors. The findings of this study suggest that the maize plant density should be properly increased and sowing time should be optimized according to the harvesting of its previous crop.

1. Introduction

The North China Plain (NCP) is one of the major maize production areas in China. It produces more than one-third of the cereals in China and around 6.7% of global maize grains (FAO, 2012). Therefore, NCP plays a very important role in securing food production in China and globally. In the past three decades, maize yield in NCP have increased continuously (Chen et al., 2012; Liang et al., 2011; Meng et al., 2013), but this increase was slowed down since 1995 when it reached 5 Mg ha^{-1} and the annual increase thereafter was less than 1% (Meng et al., 2013). In addition, maize yield has been fluctuating greatly in recent years. Therefore, there is a need to understand and quantify how weather factors and management practices affect the yield variations of maize for developing better management strategies.

Previous studies showed that the large yield gap between potential and actual yield was mainly attributed to poor agronomic practices and climate variability (Chen et al., 2010; Grassini et al., 2011; Wang et al., 2012; Meng et al., 2013; Tsimba et al., 2013; Ren et al., 2016). For management practices, plant density and sowing date are two major factors to influence maize yield. Planting density of maize varies from 50,000 to 60,000 plants ha^{-1} in China and have gone from 6000 plants ha^{-1} in 1995 to 75,000 plants ha^{-1} in 2012 in USA (Lobell et al., 2014; Li et al., 2015). The lower planting density in China is likely a result of inherited habits by farmers who are used to plant low density maize in the past under lower inputs or for the purpose of reducing the risk of lodging. Investigations have been conducted to determine the optimal planting density of maize, and results showed that the optimal density ranged from 80,000 to 120,000 plants ha^{-1} depending on the growing conditions of the crop and the characters of the cultivars (Liu et al., 2010b; Wang et al., 2014). The optimized density is much higher than the density used by the local farmers.

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In the NCP, the prevailing cropping system is the winter wheat and summer maize, forming the annual double cropping system. Normally, maize was planted immediately after winter wheat harvest in the middle of June. Due to the variation in seasonal weather, the timing of wheat harvest could change up to 15 days (Wang et al., 2013), which significantly affected the sowing time of its following crop, the summer maize (ranging from 10th to 23rd June) and the subsequent maize yield. The delayed sowing time would lead to a shortened growing duration and resulted in premature harvest for the summer maize (Liang et al., 2011; Zhao et al., 2016). Sowing date significantly affected the performance of the summer maize in the NCP.

Maize productivity is also strongly dependent on the local climate conditions. Extensive studies had been conducted to investigate the impacts of climate change on maize yield and yield gap (Wang et al., 2014; Kim et al., 2015; Zhao et al., 2015). The key weather factors limiting the climate-induced yield were varying in the different regions. Studies have shown that radiation, rainfall and temperature are the major weather factors which greatly contribute to the variation in maize yield in the NCP. Under the current climate change background, the average temperature during the maize growing season was increased at the rate of 0.36 °C per decade during the past 30 years in the NCP (Meng et al., 2016). The temperature increase was mainly related to the increase in the minimum temperature which reduced the diurnal temperature range (DTR). Significant decreases in solar radiation were also observed for the region. Meng et al. (2016) simulated the weather driven yield of maize using the Hybrid-Maize model and found that yield was decreased by 10-11% due to the decrease in solar radiation and DTR in the NCP. The trend in future climate change might further negatively affect the yield of maize in this region. Developing management strategies to mitigate the negative effects of climate change would become more important.

Thus, the objectives of this study were to combine field measurements and crop modeling to evaluate: (1) impacts of weather factors, planting density and sowing time on grain yield of summer maize in the NCP; (2) how seasonal weather variation affected the influences of planting density and sowing dates on the yield of maize; (3) deciding the optimal planting density and sowing date for maximizing the yield of maize.

2. Materials and methods

2.1. Study site

A field experiment was conducted for 11 years from 2003 to 2013 at the Luancheng Agro-Eco-Experimental Station (37°53 N, 114°40 E; 50 m above sea level) of the Chinese Academy of Science. At the study site, the annual rainfall ranged from 362 to 601 mm, with 269–555 mm in the maize growing season. Annual daily temperature ranges from 23.9 to 26.1 °C. The soil is classified as silt loam. Table 1 showed the bulk density and hydraulic parameters in different soil layers in the 2 m soil profile.

Table 1
Soil characteristics at the study site, including soil bulk density (BD), saturated volumetric water content (SAT), drained upper limit (DUL) and 15 bar lower limit (LL15) in different soil layers.

Soil depth (cm)	Bulk density (g/cm^3)	SAT (v/v)	DUL (v/v)	LL15 (v/v)
0-20	1.30	0.457	0.344	0.100
20-40	1.41	0.395	0.336	0.126
40-60	1.46	0.342	0.329	0.137
60-80	1.49	0.365	0.329	0.14
80-100	1.44	0.365	0.329	0.143
100-120	1.44	0.332	0.318	0.145
120-140	1.41	0.345	0.321	0.125
140-160	1.46	0.360	0.321	0.115
160-180	1.55	0.390	0.380	0.130
180-200	1.54	0.410	0.400	0.180

2.2. Long-term experiment (2003–2013)

The long-term experiment was carried out from 2003 to 2013, involving six irrigation treatments. For this study, the maize data from the treatment under full irrigation was used to analyze how maize yield changed in response to weather fluctuation and management practices under the conditions of sufficient water and nutrient supply. The typical cropping system at the experimental site is annual rotation of winter wheat–summer maize. The growing season for winter wheat is from October to the earlier June next year. The growing season for maize is from the middle of June to the end of September. The soil at the experimental site is loamy soil with a deep soil profile. Soil organic matter was 17 g kg^{-1}, total N was 1.11 g kg^{-1} and available N, P and K were 80, 21 and 120 mg kg^{-1}, respectively, for the top tillage soil layer.

Table 2
The sowing and harvesting dates, plant density and irrigation water applied during the experiment period from 2003 to 2013 for the maize cultivar Zhengdan 958.

Year	Sowing date (day/month)	Harvesting date (day/month)	Plant density (plants/m^2)	Irrigation amount (mm)
2003	17/06	23/09	4.6	202
2004	06/06	04/10	5.2	71
2005	16/06	29/09	6.9	200
2006	11/06	26/09	5.0	141
2007	12/06	26/09	5.2	220
2008	10/06	24/09	6.7	150
2009	10/06	23/09	5.8	71
2010	23/06	04/10	4.8	170
2011	11/06	28/09	6.1	225
2012	14/06	03/10	5.9	150
2013	17/06	30/09	5.5	85

During the study, the same variety "Zhengdan 958" was used. Table 2 shows the planting and harvesting dates, plant density and irrigation applications each season. The sowing dates during the 11 years varied from 6th June to 23th June, as a result of varying harvest dates of the previous wheat crop. The plant densities ranged from 4.6 to 6.9 plants/m^2.

The phenological development, plant density, biomass and grain yield were measured each season using the conventional methods. Soil water contents were regularly monitored down to 2 m depth with an interval of 20 cm increment using a neutron probe (503DR, CPN International Inc., USA). Seasonal evapotranspiration (ET) was calculated based on the water balance method according to Zhang et al. (2008). Water use efficiency (WUE) was calculated as grain yield divided by seasonal ET.

2.3. Short-term experiments with varying planting densities and sowing dates

A field experiment was conducted for two years in 2003 and 2004 to investigate the impacts of varying planting densities on maize yield. The same maize cultivar "Zhengdan 958" was sown on the same sowing dates, but with five plant densities, i.e., 5.2 plants/m^2, 6.0 plants/m^2, 6.7 plants/m^2, 7.5 plants/m^2 and 8.2 plants/m^2. Another field experiment was carried out in 2007 to assess how sowing dates affected maize yield. Maize cultivar Zhengdan 958 was sown at the same plant density of 6.8 plants/m^2, but on six sowing dates, i.e., 25th May, 30th May, 4th June, 9th June, 14th Juneand 19th June.

Apart from the planting densities and sowing dates, other managing practices were similar to those of the long-term field experiment. Each treatment had four replicates with plot area of