Field Crops Research 215 (2018) 66–73

Contents lists available at ScienceDirect

Field Crops Research

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

Extending growing period is limited to offsetting negative effects of climate changes on maize yield in the North China Plain

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ARTICLE INFO

Keywords:
Corn
Cultivar
Climate change
Growing period
Plant density

ABSTRACT

Climate changes in temperature, solar radiation, and precipitation potentially interrupt progressive improvement in crop yield. Genetic and agronomic strategies to adapt climate changes were proposed in previous studies, but were rarely evaluated. In this study, meteorological data from 1954 to 2014 at one representative station in the North China Plain (NCP), model simulation of Hybrid-Maize, and a field experiment were combined together to detect climate change impacts on maize yield and to assess the adaptive effects of cultivars. Three maize cultivars with contrasting lengths of growing period were grown at three specific plant densities. Cultivar with a long growing period (LG) was grown at 67500 (optimal density), 82500, and 97500 plant ha^{-1}, medium-growing (MG) cultivar at 82500 (optimal), 97500, and 112500 plant ha^{-1}, and short-growing (SG) cultivar at 97500 (optimal), 112500, and 124500 plant ha^{-1}. During the past six decades, temperature increased and solar radiation decreased significantly in the total, vegetative, and reproductive growing periods of maize in the NCP with a slight decline in precipitation. These climate changes significantly reduced yield at a rate of 30.8, 31.3, and 25.0 kg ha^{-1} yr^{-1}, respectively, for SG, MG, and LG maize cultivars. Decline in growing degree days (GDD) use efficiency of LG cultivar with changing climate was one-fold slower than that of SG and MG cultivars. MG maize cultivar was estimated to produce the highest grain yield in NCP owing to its relatively long growing period and high tolerance of plant density. LG maize cultivar has a larger potential to adapt changing climate, but has a larger difficulty in improving yield because of lower tolerance of high plant density. Improvement of plant architecture in space and in time is expected to resolve the conflict between adapting climate changes and tolerating high plant density in maize.

1. Introduction

Climate changes retard the increase in global yield of many crops such as maize (Butler and Huybers, 2013), wheat (Hochman et al., 2017), and rice (Zhang et al., 2013) in the past several decades. The North China Plain (NCP), one of the most important agricultural production areas in China, is being confronted with an increasing challenge in enhancing crop yield due to the climate changes (Sun et al., 2007; Chen et al., 2010; Liu et al., 2010). Maize crop in NCP contributed more than 30% of China maize production, influencing food security for the millions of people in China and beyond (Tao et al., 2006; Wang et al., 2012).

Increased temperature and decreased solar radiation were estimated to reduce maize yield by 15–30% in some regions of NCP in 1981–2009, and the decreased precipitation likely further reduced maize yield by 3% (Xiao and Tao, 2016). The yield decline is attributed to the changes of maize phenology in relation to climate changes (Estrella et al., 2007; Xiao et al., 2016). Warming climate can advance flowering and maturity of maize and consequently shorten growing period (Tao et al., 2014). The shortened growing period can further reduce solar radiation accumulated in the maize season. Solar radiation deficit can reduce internode length in the vegetative growing period of maize (Fournier and Andrieu, 2000), and cause kernel losses at silking stage (Setter et al., 2001). Therefore, the decrease in the accumulated solar radiation is supposed to have more negative effects (Chen et al., 2013a; Xiao and Tao, 2016).

Adjustment of sowing time and cultivar shift were considered important mitigation strategies for climate changes (Howden et al., 2007; Liu et al., 2009; Deryng et al., 2011; Liu et al., 2013). Sowing earlier can partly offset the negative effects of climate change on maize yield (Rose et al., 2016). In the northeast China, per day extension of growing period by advancing sowing can increase maize yield by up to 4% in 1981–2007 (Liu et al., 2013; Zhao et al., 2015). Similar evidences were also found in NCP (Tao et al., 2014; Xiao and Tao, 2016), but the effects

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http://dx.doi.org/10.1016/j.fcr.2017.09.015
Received 12 June 2017; Received in revised form 3 September 2017; Accepted 9 September 2017
Available online 06 November 2017

of early sowing is supposed to be limited in this region because of the double cropping system of winter wheat and summer maize. Growing season of summer maize is restricted in a specific period ranging from June to early October in NCP (Sun et al., 2007). Sowing maize earlier would advance harvest of wheat, thus influencing wheat maturity and yield.

Cultivars with a longer growing period can extend the warming-shortened growing period of maize, increasing the utilization of potential thermal time as well as improving grain yield (Sacks and Kucharik, 2011; Tao et al., 2014; Zhao et al., 2015). Results of Tao et al. (2014) indicated that growing period of maize was significantly prolonged at around 40 out of 112 experimental stations across China in 1981–2009. Growing season of maize is extending in some regions where chilling stress is alleviated as a result of increased thermal time such as Central Europe (Rose et al., 2016) and Northeast China (Zhao et al., 2015). With these in mind, maize cultivars with a longer growing period would be favored in the context of warming climate.

In addition, increasing plant density is an important strategy to increase maize yield (Tokatlidis and Koutroubas, 2004; Testa et al., 2016) by changing plant architecture (Duvick, 2005; Lee and Tollenaar, 2007; Hammer et al., 2009). Plant phenotype is assumed to be related to plant growing period (Sultan, 2000), indicating that plant density tolerance is associated with growing period to some extent. Evidences for adapting changing climate are, however, particularly lacking when growing period and plant density tolerance of maize are both taken into account.

In view of the various factors considered, a field experiment, Hybrid-Maize Model simulation, and meteorological data from 1954 to 2014 were combined in this study. The Hybrid-Maize Model is able to estimate the potential yield of maize, climatic impacts on maize yield (Chen et al., 2013b), and varietal effects on offsetting climate change (Meng et al., 2016). The objectives of this study were (i) to detect responses of three maize cultivars with contrasting lengths of growing period (also referred to as contrasting plant sizes) to climate changes in the North China Plain in the past six decades, and (ii) to analyze the mechanisms to further improve maize yield in the context of changing climate.

2. Materials and methods

2.1. Study site and climate

The study was conducted in the Wuqiao experimental station (37°41′02″N, 116°37′23″E) of China Agricultural University in 2007, east part of North China Plain (NCP). In this site, soils were loams with soil pH of approximately 8.0. Soil of 0–20 cm depth contained 11.1 mg kg^{-1} organic matter, 0.7 mg kg^{-1} total N, 23.8 mg kg^{-1} available phosphorus (Olsen-P) and 146.7 mg kg^{-1} ammonium acetate extractable potassium (K). Meteorological data from 1954 to 2014 for Botou (38°05′N, 116°33′E, 50 km from Wuqiao) were obtained from the China Meteorological Data Sharing Service System (http://www.cdc.nmic.cn). Meteorological data collected from Wuqiao experimental station was not complete for Hybrid-Model simulation, and was not recorded in the China Meteorological Data Sharing Service System. The downloaded climate data include daily solar radiation, precipitation, relative humidity of the air, wind speed, and daily mean, maximum and minimum temperatures. The parameter growing degree days in the whole growing season (tGDD), vegetative (vGDD) and reproductive growing seasons (rGDD) of summer maize were calculated using a base temperature of 10 °C.

2.1.1. Experimental design

The field trial used three maize cultivars with contrasting growing periods, and each of them were planted in three densities and in three replicates. Maize hybrids CF008 has a short growing period (SG), ZD958 has a medium growing period (MG), and JH5 has a long growing period (LG). Plant densities of 97500, 112500, and 127500 plants ha^{-1} were used for CF008; 82500, 97500, and 112500 plants ha^{-1} for ZD958; and 67500, 82500, and 97500 plants ha^{-1} for JH5.

The plot size was 10 × 6 m (10 m long and 6 m wide) with a row spacing of 0.6 m. All the plots were provided with 36 kg ha^{-1} N (78 kg ha^{-1} urea), 105 kg ha^{-1} P_2O_5, 113 kg ha^{-1} K_2O, and 15 kg ha^{-1} $ZnSO_4$ before sowing; Extra 144 kg ha^{-1} N (313 kg ha^{-1} urea) in each plot was applied at 6-leaf stage (V6). Maize seeds of three cultivars were sown on the same day (June 16) in 2007, and were harvested on different days, depending on the maturity degrees of varieties (September 23 for CF008, September 25 for ZD958, and October 2 for JH5). To assure the expected plant densities, three seeds were sown per pit, and only one seedling was thinned left at the 3-leaf stage. Weeds, pests, diseases were well controlled in the whole growing season. To avoid drought stress, the field was irrigated shortly after sowing with 75 mm ha^{-1}.

2.1.2. Dry matter accumulation, translocation, and yield measurement

At 8-leaf, 12-leaf, silking, mid grain filling (about 25 days after silking) stage, and immediately before harvest, above-ground parts of three randomly selected plants were collected, from which leaves, stems, and/or grains were separated. The fresh samples were oven-dried at a temperature of 80 °C for 48 h, and were weighed to measure whole-plant dry matter (DM) accumulation (g plant^{-1}) above ground as follows,

DM accumulation per unit area (kg ha^{-1}) = whole-plant DM accumulation × plant density per unit area/1000.

To measure the potential grain filling rate, the kernels at the central position of five cobs sampled at each plot were dried, weighed, and were counted at 25 and 40 days after silking (DAS).

The potential grain filling rate (g kernel^{-1} day^{-1}) = (kernel weight/kernel number at 25 DAS − kernel weight/kernel number at 40 DAS)/(40 − 25).

Harvest was carried out when black layer was visible in 50% of the ears. At the central of each plot where no plants were sampled, all the ears in four adjacent rows 5 m long were harvested to determine grain yield and yield components. The grains were oven-dried at 80 °C to determine grain water content, and then was adjusted to 14% moisture. Kernel number per ear and 1000-kernel weight was measured.

DM translocation (DMT) was calculated as (Rajcan and Tollenaar, 1999)

DMT (kg ha^{-1}) = (DM at silking − DM in the stover at maturity) per plant × plant density/1000

The contribution of DMT to grain yield was as calculated as

DMT (%) = (DM at silking − DM in the stover at maturity)/(grain yield) × 100

Harvest index (HI, %) = whole plant grain yield at maturity/whole plant DW at maturity × 100

The calculation of potential climatic resource use efficiency (CRUE) was as follows

Potential CRUE in the whole growing season = potential yield/climatic variables during the whole growing season (such as total solar radiation, growing degree days, and precipitation). The potential yield was estimated by the Hybrid-Maize Model.

Potential CRUE in vegetative phase = potential yield/climatic variables during the vegetative phase (such as solar radiation, growing degree days, and precipitation from sowing to silking).

Potential CRUE in reproductive phase = potential yield/climatic variables during reproductive phase (such as solar radiation, growing degree days, and precipitation from silking to harvest).