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Declining yield potential and shrinking yield gaps of maize in the North China Plain

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ABSTRACT

Quantifying the changes in crop potential yields and yield gaps is essential to determine the yield-contributing and yield-limiting factors and enhance crop productivity. Here we combine simulation modeling and long-term maize yield records (1981–2009) from 10 sites to investigate the changes in maize yield potential, actual yield and yield gaps in the past three decades in the North China Plain (NCP). The cultivar parameters in the APSIM-maize model were derived based on the recorded flowering and maturity dates at each site, and the simulation results of calibrated model was able to explain >63% of the variations in recorded maize grain yield across the 10 sites. Potential maize yield simulated under sufficient water and nitrogen supply showed a general declining trend, significantly ($P < 0.01$) at half of the study sites. This was mainly caused by the declining radiation together with increasing temperature, particularly during the pre-flowering period. Continuous adoptions of new maize varieties helped to maintain the pre-flowering periods at some sites and to extend post-flowering periods at most sites. This, together with increasing planting density, led to continuous increase in maize yields. As a result, maize yield gaps continued to shrink ($P < 0.05$) at all the sites except for Zhengzhou, with a rate ranging from −116.8 kg/ha a to −356.5 kg/ha a across sites. At two of the studied sites, the maize potential yield had already been achieved. While application of irrigation and nitrogen fertilizers has been managed at near optimal level already, other new technological breakthroughs will be needed for future advance of maize yield.

1. Introduction

Maize, one of most important food crops worldwide, accounts for more than 34% of global cereal production (FAO, 2012). In order to meet the needs of the population growth, the global maize production is expected to increase by more than 450 million tons during 2000 to 2050 (Hubert et al., 2010). China's maize production occupies 17% of global maize production (Xiong et al., 2009). As the largest agricultural production area in China, the North China Plain, supplies more than 33% of nation's maize production (Wang et al., 2008). Advancing maize productivity of NCP will play an important role in ensuring China's and global food security (Meng et al., 2013). However, this will be a big challenge under the warming future climate (Liu et al., 2010). Previous studies showed that the warming and dimming trend since the 1980s in the North China Plain had negative impact on crop potential yield (Chen et al., 2010b; Liu et al., 2010; Tao et al., 2006; Wang et al., 2012).

Quantifying maize potential yields and yield gaps could help identify the yield-limiting factors and develop adaptive management practices for future climate change (Aggarwal and Kalra, 1994; Bhatia et al., 2008). Yield gaps have been intensively investigated in the past decades at different production levels (Liang et al., 2011; Liu et al., 2012b; Meng et al., 2013; Neumann et al., 2010; Penning de Vries et al., 1989). Crop modeling is considered as the most effective means to estimate crop yield potential because it allows the assessment of the interactive impacts of climate, cultivar and crop management on crop growth and development. Crop simulation models are widely used to quantify the potential yield, water-limiting or nutrient-limiting yields and the yield gaps across regions (Grassini et al., 2009; Liu et al., 2012b; Meng et al., 2013). However, few studies have explored the change trend in yield gaps caused by climate, cultivar and crop managements in China. Quantifying the historical change in potential yields and yield gaps of maize can help understand the changes in the yield-contributing

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and yield-limiting factors and provide scientific basis for developing adaptive strategies under future maize production. This is particularly relevant in the North China Plain, where the climate (radiation and temperature), crop cultivars and management input have had significant changes in the past decades.

In this study, we will attempt to quantify the changes in maize yield gaps in the last three decades at 10 sites across the North China Plain by combining analysis of historical data and simulation modeling. The farming systems model APSIM (Keating et al., 2003; Wang et al., 2002) will be used to reproduce the long-term change in maize phenology, biomass and yield and to help disentangle the impact of climate, cultivar and crop management changes. The contribution of these changes to the changes in yield potential and yield gaps are analyzed.

2. Materials and methods

2.1. Study sites, climate, crop and soil data

Ten sites were selected for this study, which are roughly uniformly distributed across NCP (Fig. 1, Table 1). The winter wheat–summer maize double cropping system is the dominant crop rotation at all sites. During the maize growing season (June–September), average maximum and minimum temperature ranged from 29.2 to 31.1 °C and from 19.7 to 22 °C, respectively, and total precipitation ranged from 366 to 534 mm across the sites. Maize varieties have changed frequently at most sites in the past decades. However, at the Huanghua site only one maize variety (Luyuandan_4) was planted continuously during a 12-year period from 1981 to 1992. The 12 years of data provides a unique opportunity to calibrate and test the APSIM model to investigate whether the simulated phenology, biomass and yield of a single maize cultivar followed the observed change.

Historic daily weather data at the study sites were available from China Meteorological Administration, including daily average (T_{aver}), maximum (T_{max}) and minimum (T_{min}) temperatures, precipitation (P), and sunshine hours (S). Daily solar radiation (R_s) was estimated from daily sunshine hours based on the Angstrom equation (Wang et al., 2008).

Crop data including maize varieties, major phenological stages, total above-ground biomass, grain yield and yield components, and management practices were recorded at the agro-meteorological experimental station close to the weather station at each site. Periods of available data are shown in Table 1. Planting density was estimated from observed effective spikes per m^2 and ear number per plant. Table 2 summarizes the maize varieties planted at the study sites and number of planting years for each variety. Irrigation, fertilizer applications and other management practices were also recorded. Usually, 90–225 kg/ha N fertilizer was applied at sowing or in two splits (basal at sowing and top-dressings before rapid growth) depending on the rates. 45–120 mm of irrigation water was applied during maize growth period depended on seasonal rainfall. In general these management activities were representative of those by local farmers. The timing of five maize growth stages was recorded each year, including sowing, stem elongation, flowering, milking and maturity. Therefore, the changes in climate conditions during, and the length of, the four phases and the whole growing period were analyzed, i.e., sowing to stem elongation (MS1); stem elongation to flowering (MS2); flowering to milking stage (MS3); milking to maturity (MS4), and sowing to maturity (MS).

Soil data for each site, including the soil bulk density, saturation water content, drained upper limit, permanent wilting point, and soil types, soil organic carbon contents and soil pH values in different soil layers, are obtained from National, Soil Survey Data (Chen et al., 2010b; National Soil Survey Office, 1993, 1998).

2.2. APSIM validation and derivation of cultivar parameters

The Agricultural Production System Simulator (APSIM, version 5.3) (Keating et al., 2003; Wang et al., 2002, 2004) was used to simulate the phenology, biomass and yield of maize during the study period. APSIM has been previously tested and applied in the NCP (Chen et al., 2010a; Wang et al., 2007, 2012, 2013). In general, these previous work showed that the model was able to explain the variation in maize biomass and yield in response to the change in climate, variety, water and nitrogen inputs observed in short-term experiments at selected sites.

Here, we further test the performance of APSIM in simulating the phenology, biomass and yield of maize against the long-term continuous observation data before we conduct simulations for yield potential and yield gaps. Firstly, data from the Huanghua site for a single maize variety from 1981 to 1992 was used to evaluate APSIM's ability to simulate a single cultivar across years. The data was split into two consecutive periods of 1981–1985 and 1986–1992. Data from 1981–1985 was used to calibrate the model for simulating observed phenology, biomass and yield. Data from 1986 to 1992 was used as independent data to test the calibrated model for simulating the same cultivar. Simulating trial-and-error method was used for model calibration. Two phenology parameters, i.e., thermal time from emergence to end of juvenile stage (tt_emerg_to_endjuv, °C d) and thermal time from flowering to maturity (tt_flower_to_maturity, °C d), were adjusted to achieve a good match between observed and simulated emergence, flowering and maturity date (using days after sowing, DAS). The maximum specific leaf area (sla_max, mm^2/g) was slightly adjusted to improve the simulation of above ground biomass. The maximum grain number per head (head_grain_no_max, kernels per head) and grain-filling rate per day (grain_gth_rate, g/kernel d) were adjusted based on yield component records and for getting a good match between observed and simulated grain yield. Thereafter, the calibrated model was run against the data from 1986 to 1992 at Huanghua and the model performance was evaluated for both calibration and validation periods (Table 4).

For all the other sites and the period from 1993 to 2009 at Huanghua, cultivars changed frequently and we had to adjust the phenology and grain growth parameters for each cultivar for simulating phenology and grain yield. For crop cultivars used in two and more years, data from one growth season was used to calibrate the model and data from other growth seasons were used to test the model. For crop varieties used only in one year, the variety parameters were tuned to match the simulated and observed phenology and yield only in this growth season. This process ensures the minimum calibration of the model. The final comparison across all sites between simulated and observed phenology (Fig. 2), biomass (Fig. 3) and grain yield (Fig. 4) represents the model performance with model calibration as minimum as possible.

2.3. Modeling the impact of climate variability, sowing date and variety changes on phenology

Two sets of simulations were performed for analyzing the impact of climate variability, sowing date and variety changes on maize phenology. Assuming no varietal and sowing date changes in the past, the simulated change in phenology would reflect only the impact of climate variability. The first set of simulations were conducted with a single maize cultivar used in 1981 and one sowing date as the average sowing date of the whole studied period at each site. The changes in the simulated growth durations from sowing to flowering, sowing to maturity and flowering to maturity were analyzed to investigate the climate variability impact only. The second set of simulations was performed by still using the single cultivar but with the recorded sowing dates each year at each