Temporal and spatial changes of maize yield potentials and yield gaps in the past three decades in China

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ABSTRACT

The precise spatially explicit knowledge about crop yield potentials and yield gaps is essential to guide sustainable intensification of agriculture. In this study, the maize yield potentials from 1980 to 2008 across the major maize production regions of China were firstly estimated by county using ensemble simulation of a well-validated large scale crop model, i.e., MCWLA-Maize model. Then, the temporal and spatial patterns of maize yield potentials and yield gaps during 1980–2008 were presented and analyzed. The results showed that maize yields became stagnated at 32.4% of maize-growing areas during the period. In the major maize production regions, i.e., northeastern China, the North China Plain (NCP) and southwestern China, yield gap percentages were generally less than 40% and particularly less than 20% in some areas. By contrast, in northern and southern China, where actual yields were relatively lower, yield gap percentages were generally larger than 40%. The areas with yield gap percentages less than 20% and less than 40% accounted for 8.2% and 27.6% of maize-growing areas, respectively. During the period, yield potentials decreased in the NCP and southwestern China due to increase in temperature and decrease in solar radiation; by contrast, increased in northern, northeastern and southeastern China due to increases in both temperature and solar radiation. Yield gap percentages decreased generally by ~2% per year across the major maize production regions, although increased in some areas in northern and northeastern China. The shrinking of yield gap was due to increases in actual yields and decreases in yield potentials in the NCP and southwestern China; and due to larger increases in actual yields than in yield potentials in northeastern and southeastern China. The results highlight the importance of sustainable intensification of agriculture to close yield gaps, as well as breeding new cultivars to increase yield potentials, to meet the increasing food demand.

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1. Introduction

The global demand for food is expected to roughly double by 2050 (Godfray et al., 2010; Tilman et al., 2011), however yields of some important crops are reported to be stagnating in some regions around the world (Cassman et al., 2003; Brisson et al., 2010; Ray et al., 2012). Many irrigated cropping systems have yields at or approaching 80% of yield potential ceiling (Cassman, 1999; Lobell et al., 2009; Ramankutty, 2010; van Wart et al., 2013). This implies that yield gains in these regions will be small in the near future, and yields may even decline if yield potentials are reduced

because of climate change. In order to increase crop yields and meet the increasing food demand, it is critical to understand the magnitudes and causes of yield potentials and yield gaps (i.e., differences between yield potential and the actual yield achieved by farmers) (Cassman, 1999; Lobell et al., 2009). The precise spatially explicit knowledge about yield potentials and yield gaps is essential to guide sustainable intensification of agriculture (van Ittersum et al., 2013).

Since China is one of the major crop production and consumption countries, trends in actual yields and yield gaps for major crops in China have been of key concern (Cassman, 1999). Previous studies showed that although aggregate rice yields in China appeared to continue at a linear rate of increase established during the past several decades, yields were approaching the 80% yield potential threshold in several major rice production regions

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(Cassman et al., 2003; Licker et al., 2010; Mueller et al., 2012; Ray et al., 2012; Xiong et al., 2014; Zhang et al., 2014a). As the second largest maize producer and consumer, China accounts for more than 20% of total production annually in the world. Chinese maize harvest area and production amounted to 34.97 M ha and 1.65 M tones, respectively, in 2012 (FAO, 2013). Therefore, the changes in maize yields and yield potential in China have become a major research topic (Licker et al., 2010; Ray et al., 2012; Liang et al., 2011; Liu et al., 2012; Meng et al., 2013; Wang et al., 2014a). For examples, by comparing existing yields to climate-specific attainable yields, Licker et al. (2010) showed that maize in eastern China generally had high yield gaps although this region was heavily irrigated. Ray et al. (2012) showed that maize yields had stagnated across 52% of the maize-growing areas in China. Liang et al. (2011) showed that the aggregate yield for the wheat–maize double crops grown in the 2004–2005 season across the six counties in Hebei province of the North China Plain (NCP) was 72% of the average yield recorded from on-farm trials and 60% of the simulated average yield potential. By applying the APSIM-Maize model to estimate yield potential and yield gaps, Liu et al. (2012) showed that on-farm maize yields were, on average, only 51% of yield potentials in northeastern China. By comparing with the yield potentials simulated by the Hybrid-Maize Model at 50 representative sites, Meng et al. (2013) showed that the average farmer's maize yields attained 48–56% of the yield potentials in China. Wang et al.

(2014a), using APSIM model and long-term maize yield records (1981–2009) from 10 sites to investigate the changes in maize yield potentials and yield gaps in the NCP, showed that maize yield potentials had a general declining trend and maize yield gaps continued to shrink; at 2 of the 10 studied sites, the maize yield potentials had already been achieved. The inconsistencies in yield gap analyses in the literatures are mainly due to lack of consistency in yield potential estimations. Yield potentials can be estimated in a variety of ways including crop model simulation, field experiments and yield contests, and maximum farmer yields (Lobell et al., 2009). Model simulations are likely to provide the most accurate estimate of the yield potential ceiling for specific fields and for regions when information on spatial variation of model inputs is available, despite there are some shortcomings and uncertainties (Lobell et al., 2009). However, the uncertainties and variations in different crop models can result in different estimations (Asseng et al., 2013; Bassu et al., 2014). Moreover, site-specific and/or cultivar-specific estimation of yield potential can have poor representativeness at regional and national scales (van Wart et al., 2013). And the previous attempts to estimate yield potentials at a national level and global level have been too coarse and general (van Wart et al., 2013).

In this study, the process-based general Model to capture the Crop-weather relationship over a Large Area (MCWLA) for maize crop (MCWLA-Maize) (Tao et al., 2009a) was applied to estimate

Fig. 1. Maize cultivation fraction and cultivation zones in China.

maize yield potentials and investigate yield gaps at county scale across the major maize production regions of China. The ensemble simulation was applied to account for the uncertainties in the biophysical processes of the model, as well as the diverse varieties characteristics at county scale. We presented and analyzed the temporal and spatial patterns of maize yield potentials and yield gaps during 1980–2008 across the major maize production regions of China.

2. Material and methods

2.1. Study area

Maize is cultivated widely across China under diverse geographic and climatic conditions (Fig. 1). Based on the maize cultivation zones in China (Tong, 1992), the maize cultivation areas were divided into 6 zones: North China spring maize cultivation zone (Zone I), Huang-Huai-Hai plain (or North China Plain) maize cultivation zone (Zone II), Southwest China mountain and hill maize cultivation zone (Zone III), South China hill maize cultivation zone (Zone IV), Northwest China maize cultivation zone (Zone V), and Tibet maize cultivation zone (Zone VI) (Tong, 1992). The Zone V and Zone VI were not included in this study since maize cultivation fractions in these zones were quite small. The information on the dominant cropping system, typical sowing date and maturity date in each major maize production zone of China was presented in Table 1.

2.2. MCWLA-Maize model and its parameterization in each zone

The details on MCWLA-Maize model development, parameters optimization, and uncertainties analysis have been described in Tao et al. (2009a,b). Briefly, MCWLA-Maize simulates crop growth and development in a daily time-step. It is designed to investigate the impacts of weather and climate variability (change) on crop growth, development and productivity at a large scale. Growing degree-days provide the driving force for the processes of canopy development, flowering, and maturity. The daily growth of the crop leaf area is simulated by heat-dependent potential growth rate and stresses from water. MCWLA adopts the robust, process-based representation of the coupled CO₂ and H₂O exchanges. In the meantime, the impacts on yield due to factors other than weather (e.g., pests, disease and management factors) are modelled in a simplified way. Biomass is accumulated from the photosynthate and further transferred into crop yield by harvest index. The impact of extreme temperature on a crop is simulated by inhibited function limiting photosynthesis at low and high temperature. The water stress on yields is simulated through soil-moisture stress on daily leaf area index (LAI) development and transpiration, and subsequently on root development, photosynthesis, and canopy conductance (Tao et al., 2009a).

The Bayesian probability inversion and a Markov chain Monte Carlo (MCMC) technique to the MCWLA have been applied to

analyze uncertainties in parameter estimation and model prediction and to optimize the model (Tao et al., 2009a). Shuai et al. (2014) further calibrated and validated the model, selecting 10 optimal sets of parameters for each of the four maize cultivation zones. Using the selected 10 optimal sets of parameters, MCWLA-Maize ensemble hindcasts can simulate both mean and interannual variability of maize yield fairly well in each zone (Shuai et al., 2014). As shown in Shuai et al. (2014), in 9 from the 18 provinces, the correlations between modeled and observed yields from 1963 to 2008 were highly significant ($P < 0.01$). In 5 from the 18 provinces, the correlations were significant ($P < 0.05$). The root mean square errors in 16 of the 18 provinces were less than 1000 kg/ha. The selected 10 optimal sets of parameters for each zone by Shuai et al. (2014) were applied in the current study.

2.3. Data

Time series of actual maize yields (Y_a) by county from 1980 to 2008 were obtained from the Agricultural Yearbook of each province (autonomous region or municipality) in China (China Agriculture Press, Beijing 1980–2009 (annual)) and some unpublished data from county-level census bureau. A preliminary quality check was conducted, and observations were flagged as outliers when they fell outside the range of biophysical attainable yield records. As in Tao et al. (2012), we finally used time series of maize yield data from 1980 to 2008 for 2111 counties across the major production regions.

The MCWLA-maize requires at least four meteorological variables, including daily mean temperature (T_{mean}), vapor pressure (V_{pr}), solar radiation (S), and total precipitation (P). The monthly data for T_{mean} , V_{pr} , S , P and wet days (W_{et}) were obtained from the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn/>). The monthly means of temperature, vapor pressure, and solar radiation, were interpolated to daily values using spline interpolation (Press et al., 1992). Monthly precipitation was interpolated to daily values using a weather generator, with monthly total precipitation and wet days as inputs, after Gerten et al. (2004). Previous studies have shown that the simulations using the interpolated daily data and observed daily data have quite similar results (Tao et al., 2009a,b). T_{mean} , V_{pr} , P , and W_{et} were obtained from 755 weather stations all over China for the period 1963–2008. Since only 122 out of them stations had S records, S was calculated from sunshine duration (Yang et al., 2006), which was available in all the 755 stations. In our study, the MCWLA-maize model was run at each $0.5^\circ \times 0.5^\circ$ grid with maize cultivation fraction (the ratio between maize cultivation area and total area in a grid) ≥ 0.0 across the study area (Fig. 1). There were a total of 1879 grids in China. As the inputs of MCWLA-maize model, all the 755 stations' meteorological data have been interpolated into $0.5^\circ \times 0.5^\circ$ grid using nearest method. The maize sowing dates for each of 120 agrometeorological stations during 1991–2008 were also obtained from the China Meteorological Data Sharing Service System. The average sowing date during the period

Table 1
The dominant cropping system, typical sowing date and maturity date in each major maize production zone of China.

Zones	Dominant cropping system	Sowing date	Maturity date
Zone I	Spring maize or rice	April 30th	September 20th
Zone II	Rotation between summer maize and winter wheat	June 10th	September 20th
Zone III	Spring maize	March 30th	August 1st
Zone IV	Rotation between spring cereals and summer maize	May 15th	September 10th
	Rotation between rice and spring maize	April 1st	July 15th
	Rotation between rice and maize	July 1st	October 1st

at each station was interpolated into $0.5^\circ \times 0.5^\circ$ grid. The soil texture and hydrological properties data were obtained from the FAO soil dataset (FAO, 1991; Zobler, 1986), as in previous studies (Tao et al., 2009a,b; Tao and Zhang, 2010).

2.4. Estimates of climate potential yield (Y_p), water-limited climate potential yield (Y_{pw}), yield gaps (Y_{gp}) and evapotranspiration (ET) using ensemble simulations

Using the selected 10 optimal sets of parameters for each zone, MCWLA-maize model was firstly run at each $0.5^\circ \times 0.5^\circ$ grid without water and nutrient limitations from 1980 to 2008. In each year, ensemble mean of simulated yield and ET was computed to represent the Y_p and ET for each $0.5^\circ \times 0.5^\circ$ grid, respectively. Then the area-weighted mean of Y_p and ET for all the $0.5^\circ \times 0.5^\circ$ grids in each county in each year were computed to get Y_p and ET for each county in each year from 1980 to 2008. Likewise, MCWLA-maize model was run again at each $0.5^\circ \times 0.5^\circ$ grid without nutrient limitations but under rainfed conditions from 1980 to 2008 to get Y_{pw} and ET in each county in each year from 1980 to 2008. Then, together with Y_a , Y_{gp} and yield gap percentage (Y_{gpp}) for each county in each year were computed as:

$$Y_{gp} = Y_p - Y_a$$

$$Y_{gpp} = \left(1 - \frac{Y_a}{Y_p}\right) \times 100\%$$

In comparison with previous studies, in this study, the estimations of Y_p and Y_{gp} for each county were based on ensemble simulations at each $0.5^\circ \times 0.5^\circ$ grid in the county, which represented better the diverse climate, soil and varieties information in each county. Particularly, the ensemble simulation, which used 10 sets of optimal parameters, was applied to represent better the uncertainties in biophysical processes, as well as the diverse varieties characteristics in each county.

2.5. Analyses

Time trends in Y_a , Y_p , Y_{pw} - Y_{gp} and Y_{gpp} during 1980–2008 in each county were investigated using the linear regression method. For comparisons, trends in Y_a during 1980–2008 in each county were also analyzed via parsimoniously choosing among regression models of increasing order, i.e., an intercept-only method, a linear model, a quadratic model and a cubic model, after Ray et al. (2012). Yield trends were then classified into six categories based on model parameters, which were ‘yields never improved’, ‘yield stagnated’, ‘yield collapsed’, ‘yield increasing rapidly’, ‘yield increasing moderately’ and ‘yield increasing slowly’ (Ray et al., 2012).

3. Results

3.1. Spatial patterns of mean and trend in Y_a during 1980–2008

During 1980–2008, mean of Y_a ranged from less than 3000 kg/ha in southern China to more than 6000 kg/ha in the NCP and northeastern China (Fig. 2a). Based on the linear regression method, the results showed that Y_a increased generally from less than 100 kg/ha to 300 kg/ha per year, however had a decreasing trend in some counties (Fig. 2b). Based on the method of Ray et al. (2012), the results showed that maize yield was increasing rapidly, moderately and slowly, respectively, at 10.0%, 25.4% and 16.3% of maize-growing areas, mainly in major maize production regions such as the NCP, northeastern China and southwestern China.

Fig. 2. Mean (a) and trend (b) in actual maize yields by county during 1980–2008.

Fig. 3. Trends in maize actual yields during 1980–2008 by county based on the method of Ray et al. (2012).

However it was never improved at 7.0%, stagnated at 32.4%, and collapsed at 8.9% of maize-growing areas (Fig. 3). The results suggested that maize yields became stagnated at quite a large area although had an increasing trend at about half of maize-growing areas during 1980–2008.

3.2. Spatial patterns of mean and trends in Yp and Ypw during 1980–2008

During 1980–2008, mean of Yp ranged generally from less than 5000 kg/ha in southwestern China to 11000 kg/ha or so in northern China (Fig. 4a). Yp in the NCP and in northeastern China ranged generally from 7000 kg/ha to 11000 kg/ha. During the period, Yp increased most by about 100 kg/ha per year in northern and northeastern China, however had a decreasing trend in the NCP and southwestern China (Fig. 4b).

During 1980–2008, mean of Ypw ranged generally from less than 5000 kg/ha in southern China to 11000 kg/ha in northern and northeastern China (Fig. 4c). Ypw in the NCP and in northeastern China ranged generally from 5000 kg/ha to 11000 kg/ha. During the period, Ypw increased generally by ~ 100 kg/ha per year in northern and northeastern China, however had a decreasing trend in the NCP and southwestern China (Fig. 4d).

3.3. Spatial patterns of mean and trends in Ygp and Ygpp during 1980–2008

In the major maize production regions, i.e., northeastern China, the NCP and southwestern China, mean of Ygp during 1980–2008 was generally less than 4000 kg/ha and less than 2000 kg/ha in some areas (Fig. 5a); Ygpp was generally less than 40% and less than 20% in some areas. By contrast, in northern and southern

China, where Ya was relatively lower, Ygp was generally larger than 4000 kg/ha, and Ygpp was generally larger than 40% (Fig. 5b). The area with Ygpp less than 20% and less than 40% accounted for 8.2% and 27.6% of maize-growing area, respectively.

During the period, Ygpp decreased generally by $\sim 2\%$ per year across maize-growing areas in China, although it increased in some areas in northern and northeastern China (Fig. 5c).

4. Discussion

4.1. Ygp is shrinking due to the relative changes in Ya and Yp

The methods to estimate Yp and Ygp applied in this study have better representativeness at regional and national scales than those based on site-specific and/or cultivar-specific estimation and those based on 'climatic potential yield' (e.g., Licker et al., 2010) in many previous studies. Based on the estimations, we found that Ygp and Ygpp were shrinking at most of maize-growing areas across China. The shrinking of Ygp and Ygpp can be ascribed to increase in Ya and decrease in Yp in the NCP and southwestern China, and to larger increase in Ya than in Yp in northeastern and southeastern China. Increase in Ya can be ascribed to use of modern high-yielding varieties, chemical fertilizers, irrigation, and weed and pest control, which is known as the 'green revolution'. In the 1960s, double-cross hybrids were dominant. Since the 1970s, double-cross hybrids have been extensively replaced by single-cross hybrids. The breeding strategies to increase maize yield potential include disease-resistant gene selection, plant canopy architecture improvement, stay green, and late-maturing (Li and Wang, 2009; Fan et al., 2012). The increasing uses of the medium-late maturity varieties in the NCP and northeastern China have greatly increased maize yield in the past few decades (Liu et al., 2012; Chen et al., 2013). In addition, planting technologies have shifted from individual techniques to technical integration. For example, maize planting density increased generally in the past three decades (Liang et al., 2011); chemical fertilizer types were used from sole nitrogen in the 1970s to nitrogen and phosphorus in the 1980s, and even to the combination of nitrogen, phosphorus and potassium in the 1990s and 2000s. Chemical fertilizer rate has also greatly increased since the 1990s (Li and Wang, 2009; Fan et al., 2012).

Yp and Ypw decreased in the NCP and southwestern China due to increase in temperature and decrease in solar radiation. As shown in Fig. S1, the temporal and spatial change patterns of Yp and Ypw were quite similar to those of temperature (Fig. S1a) and solar radiation (Fig. S1c), suggesting that decreases in Yp and Ypw should be ascribed to increase in temperature and particularly decrease in solar radiation. By contrast, in northern, northeastern and southeastern China, Yp and Ypw increased due to increases in solar radiation and temperature, which improved light and heat resources in these regions (Chen et al., 2011b; Wang et al., 2014b; Zhao et al., 2014). Changes in precipitation were quite small and insignificant, which had less impact on trends in Ypw. The results are consistent with previous studies on maize and other crops (Tao et al., 2012; Liu et al., 2012; Wang et al., 2014b; Zhang et al., 2014b).

Among other things, maize yield stagnation can be ascribed to changes in climate and agronomic management. The spatially explicit impacts of climate change on Yp and Ypw consequently on Ya, are due to the relationship between climate conditions and maize productivity in each region (Tao et al., 2012). Change in agronomic management is closely related to national and local policy and economy such as food price, labors and fertilization (Brisson et al., 2010; Fan et al., 2012).

In comparison with rice and wheat in China, in general, maize yields have larger increasing potentials than rice and wheat yields. For example, previous studies showed that rice yields were

approaching the 80% yield potential threshold in several major rice-producing regions (Defeng, 2000; Cassman et al., 2003; Licker et al., 2010; Mueller et al., 2012; Ray et al., 2012; Zhang et al., 2014a). Based on yield potentials simulated using EPIC model at 43 representative sites, Lu and Fan (2013) showed that wheat yield gaps were between 600 kg/ha and 5300 kg/ha (or 7–69% of yield

potentials) across the NCP. Based on yield potentials simulated using APSIM model at 16 representative sites, Li et al. (2014) showed that wheat yield gaps were estimated to be 1140–6810 kg/ha or 15–80% of yield potentials during 1981–2010 across the NCP. The improvements of on-farm yields have substantially contributed to spatio-temporal variations in yield gaps. As a result, the yield

Fig. 4. Mean (a, c) and trend (b, d) in potential yield (a, b) and water-limited potential yield (c, d) by county during 1980–2008.

Fig. 5. Mean yield gap (a) and yield gap percentage (b), as well trend in yield gap percentage (c) by county during 1980–2008.

gap decreased from 4200 kg/ha (56%) in 1981–1990 to 3000 kg/ha (35%) in 2001–2010 at a rate of 69 kg/ha per year. Yields were stagnating at 32.3% of wheat-growing areas.

4.2. Closing yield gaps by adopting advanced water, soil and integrated agronomic management technologies

Water stress is one of major limitations for maize growth and productivity in northern and northeastern China (Tao and Zhang, 2010). Moreover, maize production is increasingly suffered from droughts with climate change in the past three decades (Zhang et al., 2014b). We found that the differences between Yp and Ypw were less than 1500 kg/ha in southwestern China, from 1000 to 2500 kg/ha in the NCP, however more than 3000 kg/ha in northern and northeastern China (Fig. 6a). To increase maize yields from Ypw to Yp, water use, as represented by evapotranspiration (ET), will increase by less than 20 mm in the NCP and in southwestern

China, by 20–40 mm in southern and northeastern China, and by more than 40 mm in northern China (Fig. 6b). Therefore, water availability and improvement of irrigation infrastructure is essential to increase yield and close yield gap, suggesting considerable investment in agriculture is needed to close yield gap and meet increasing demand for food.

Ya had a spatially explicit pattern across China. It was generally lower in southern China for a number of reasons. For examples, the soil quality and fertility was relatively poor and soil erosion was severe. The agronomic management for maize was generally poor, maize production was paid much less attention to in comparison with rice production. Maize was usually cultivated in hill rainfed cropland with poor irrigation facility and agronomic management, the new cultivation technologies and varieties were not easily accessed by farmers (Tong, 1992). The main limitations for low-yielding croplands include low organic matter, low and unbalanced nutrient concentrations, soil acidification, soil salinization,

Fig. 6. Difference between potential yield and water-limited potential yield (a), and the corresponding changes in evapotranspiration by county during 1980–2008.

desertification, soil hardening, soil gleyization, erosion and severe droughts (Zeng et al., 2014). By contrast, Ya was generally higher in the NCP and northeastern China because the soils, irrigation facility, agronomic management, cultivation technologies and cultivars were relatively better. Therefore, integrated agronomic management technologies on soil improvement, fertilization, tillage and cultivation, should be applied (Chen et al., 2011a), together with new varieties and disease and insects control. Finally, the social-economic policy should be made to encourage farmers' initiative to improve agronomic management and further to close Ygp. The programmes for agricultural technology training, extension and service should be enhanced, and subsidies to help farmers to access the new technologies and facilities should be increased.

5. Conclusion

In recent decades, maize consumption has increased sharply and maize cultivation area has become the largest among the major crops in China. However maize is generally cultivated in low-yielding croplands suffering frequently from droughts, regions difficult to access to new varieties and advanced cultivation and agronomic management technologies. Maize yield is relatively lower and its interannual variability is relatively higher in comparisons with developed countries such as USA. Yield is stagnated at 32.4% of maize-growing areas. The areas with Ygpp less than 20% and less than 40% account for 8.2% and 27.6% of maize-growing areas, respectively. There are still large potentials to increase both maize yield and maize maize-growing areas in China, particularly in northern and southern China.

To further increase crop yield, one way is to develop sustainable intensification of agriculture to close Ygp and the other is to increase crop Yp using advanced breeding technologies. For the former, context dependent policies and agricultural development programs must address drivers of yield limitation such as droughts, difficulties in accessing to new cultivars, new cultivation and tillage technologies. Integrated agronomic management technologies should be stressed. Subsidies for farmers should be increased and policy should be made to increase farmers' initiatives to improve agronomic management. For the latter, new technologies must be developed to accelerate breeding new cultivars.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.agee.2015.04.020>.

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