Narrowing the Agronomic Yield Gaps of Maize by Improved Soil, Cultivar, and Agricultural Management Practices in Different Climate Zones of Northeast China

Zhijuan Liu and Xiaoguang Yang*

College of Resources and Environmental Sciences, China Agricultural University, Beijing, China

Xiaomao Lin

Department of Agronomy, Kansas State University, Manhattan, Kansas

Kenneth G. Hubbard

School of Natural Resources, University of Nebraska–Lincoln, Lincoln, Nebraska

Shuo Lv

College of Resources and Environmental Sciences, China Agricultural University, Beijing, China

Jing Wang

College of Resources and Environmental Sciences, China Agricultural University, Beijing, and Ningxia Institute of Meteorological Sciences, Yinchuan, China

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* Corresponding author address: Xiaoguang Yang, College of Resources and Environmental Sciences, China Agricultural University, No. 2 Yuanmingyuan West Rd., Haidian District, Beijing 100193, China.

E-mail address: yangxg@cau.edu.cn

ABSTRACT: Northeast China (NEC) is one of the major agricultural production areas in China, producing about 30% of China's total maize output. In the past five decades, maize yields in NEC increased rapidly. However, farmer yields still have potential to be increased. Therefore, it is important to quantify the impacts of agronomic factors, including soil physical properties, cultivar selections, and management practices on yield gaps of maize under the changing climate in NEC in order to provide reliable recommendations to narrow down the yield gaps. In this study, the Agricultural Production Systems Simulator (APSIM)-Maize model was used to separate the contributions of soil physical properties, cultivar selections, and management practices to maize yield gaps. The results indicate that approximately 5%, 12%, and 18% of potential yield loss of maize is attributable to soil physical properties, cultivar selection, and management practices. Simulation analyses showed that potential ascensions of yield of maize by improving soil physical properties PAY_s, changing to cultivar with longer maturity PAY_c, and improving management practices PAY_m for the entire region were 0.6, 1.5, and 2.2 ton ha^{-1} or 9%, 23%, and 34% increases, respectively, in NEC. In addition, PAY_c and PAY_m varied considerably from location to location (0.4 to 2.2 and 0.9 to 4.5 ton ha^{-1} respectively), which may be associated with the spatial variation of growing season temperature and precipitation among climate zones in NEC. Therefore, changing to cultivars with longer growing season requirement and improving management practices are the top strategies for improving yield of maize in NEC, especially for the north and west areas.

KEYWORDS: Geographic location/entity; Asia; Variability; Climate variability; Applications; Crop growth

1. Introduction

Maize accounts for more than one-third of Chinese cereal production and cereal is the largest food crop in China [Food and Agriculture Organization (FAO) 2012]. Northeast China (NEC) is one of the largest maize production areas in China, and the production of maize in NEC accounted for more than 30% of the nation's total [National Bureau of Statistics of China (NBSC) 2008, 2009, 2010]. Therefore, it is widely realized that the productivity of maize in NEC must be substantially improved if the growing demand of food continues because of the population increases in China. Potential yield is the ceiling of the yield for a certain place, which is largely determined by the particular combination of solar radiation, temperature, soil, and plant density at a specific location (van Ittersum and Rabbinge 1997). However, actual farmers' yields in a region or country are smaller than potential yields because the latter requires nonlimiting management throughout the crop growth cycle (Lobell et al. 2009). Hence, a large exploitable gap exists between current yields and what is theoretically achievable under ideal management. The demonstration of yield gaps between potential yield and actual farmers' yield for cereal crops provides an essential framework within which to prioritize research and policy efforts aimed at reducing these gaps (Abeledo et al. 2008; Neumann et al. 2010; Laborte et al. 2012; Mueller et al. 2012). It is acknowledged that yield gaps cannot be reduced to zero because of widespread practical and economic constraints present in commercial farming. Even so the gaps can be narrowed by identifying the most important factors relating to the

crop, soil, and management now limiting farm yields (Fischer et al. 2009; van Ittersum et al. 2013).

According to the nature of yield gaps and the degree to which factors contribute to yield gaps (de Bie 2000), these factors are classified as noncontrollable, agronomic, and socioeconomic factors. The yield gap between potential yield and attainable yield is mainly due to noncontrollable factors that include various environmental conditions and technologies available at research stations for the farmers' field. This component of the yield gaps therefore cannot be narrowed or exploitable further in the current technologies (Van Tran 2001). On the other hand, the yield gap between attainable yield and potential farmers' yield is mainly due to differences in agronomic factors. This gap exists because farmers use suboptimal doses of inputs and cultural practices, which can be narrowed by improving management practices. The yield gap between potential farmers' yield and actual farmers' yield is caused by socioeconomic factors. This gap exists because farmers use inputs or practices that result in lower yields than those possible on their farms. Why farmers are not using the inputs or cultural practices that would result in higher yields may be due to farmers' traditions and knowledge, family size, household income/expenses/investment, lack of large-scale irrigation projects, and so on (Dedatta et al. 1978).

Crop simulation models deal with interactions of crop growth with climatic conditions, soil conditions, and agronomic management practices; therefore, the crop simulation can be used to estimate the limitations on crop growth and yield (Rockström and Falkenmark 2000; van Ittersum et al. 2003; Nelson et al. 2010; Liu et al. 2015). The Agricultural Production Systems Simulator (APSIM) has proven to be an effective tool to simulate the effects of cultivar selection, soil, and management practices on crop growth, development, and yield (Keating et al. 2002; Peake et al. 2008; Lv et al. 2015; Yang et al. 2015). In a previous study (Liu et al. 2016), the mean magnitude of yield loss due to suboptimal agronomic factors was about 40% of the potential yield and varied considerably among climate zones (CZs; 25% ∼ 46%). It should be noted that the greater values (>40%) were located in climate zones (Figure 1) with the positive crop water deficit (CZs 1, 3, 5, 7, and 9), especially to the west of Heilongjiang and Jilin Provinces. These results indicate maize yield could be increased in these areas if the optimal agronomic practices were applied. Moreover, the agronomic factors mainly include soil physical properties, cultivar selection, and management practices. Therefore, the objectives of this study are to 1) determine maize yield gaps caused by soil physical properties, cultivar, and management practices in different CZs under the changing climate in NEC; and 2) clarify how much the yield would increase with improved soil condition, higher-yielding cultivar, and better management practices at the CZs in the NEC.

2. Materials and methods

2.1. Study sites and classification of climate zones

The mean maximum temperature for the entire maize-growing season ranged from 23.1°C in the north to 28.0°C in the south. Similarly, the mean minimum
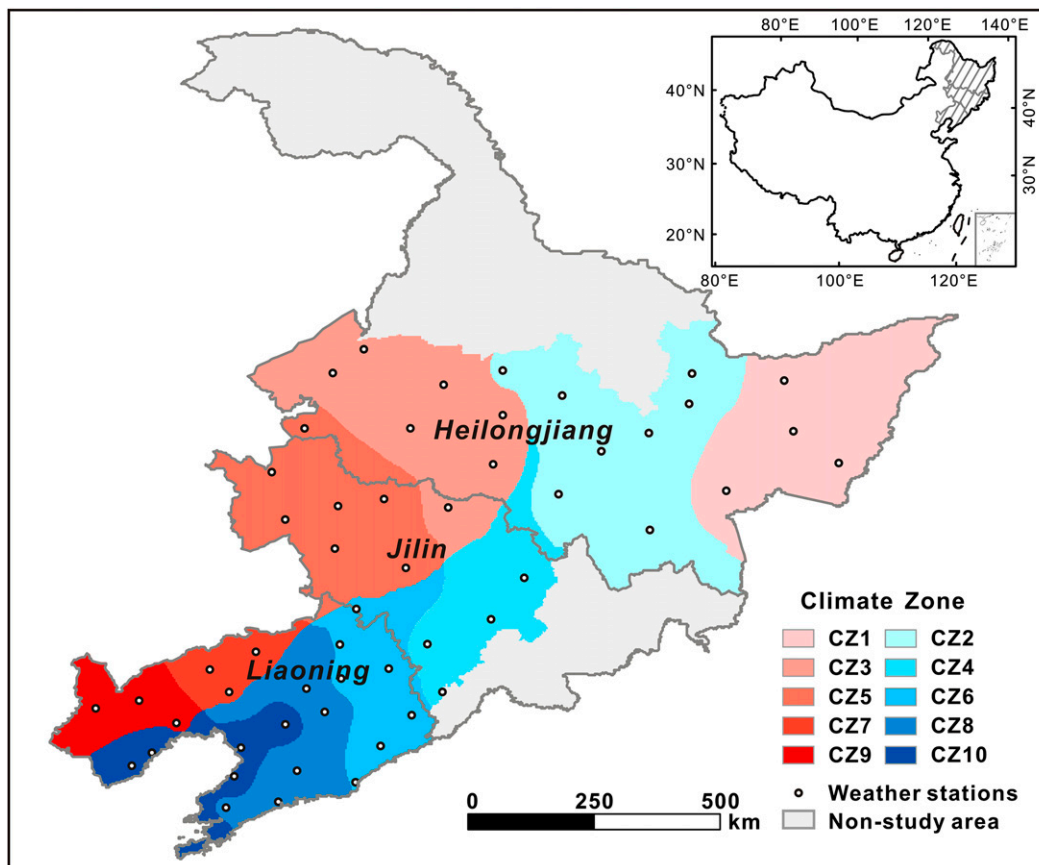
Figure 1. The locations and climate zones selected for simulation of maize potential yield, potential farmers' yield, and potential farmers' yield with recommended soil, cultivar, or management practices in NEC. The open circles indicate locations used for simulating yield. The gray shading indicates nonstudy areas in NEC. The colorful shadings indicate the climate zones in NEC. Provinces are named in italics, and their boundaries are shown in gray lines.

temperature for the entire growing season ranged from 12.6°C in the north to 18.0°C in the south. Total precipitation for the maize growth season ranged from 325 mm in the northwest to 864 mm in the southeast. Moreover, the maximum and minimum temperatures during the maize-growing season have been increased, and the total precipitation decreased in most of the selected locations but not significantly (Liu et al. 2012).

According to the growing degree-days (GDD) and a crop water deficit K, the major maize-growing areas in NEC were classified into 10 CZs (Liu et al. 2016) shown in Figure 1. For the CZs with odd numbers (areas shaded in red), the precipitation during maize-growing season cannot meet the water requirement of maize, while for the CZs with even numbers (blue shading), the amount of

precipitation during maize-growing season can meet the water requirement of maize (see Figure 1 for climate zone names and spatial patterns for CZs).

2.2. Climate, crop, soil, and management data

Climatic information includes daily maximum and minimum temperatures, sunshine hours, and precipitation from 1961 to 2010 at each climate station. Sunshine duration was converted into daily solar radiation using the Ångström formula (Black et al. 1954; Jones 1992).

The experiment data on maize phenology (sowing, emergence, flowering, and maturity dates), cultivar type, yields, and management practices are obtained from local agrometeorological experimental stations (AESs) in NEC, which have been well maintained by the Chinese Meteorological Agency. The maize parameters in the APSIM-Maize model are identified based on field-measured phenology, total aboveground dry matter, and grain yield of maize in each AES by optimizing the model performance with a trial-and-error method (Chen et al. 2010). More detailed information on the model calibration and validation is provided in Liu et al. (2012). In this paper, we selected two cultivars in each climate zone in order to determine the constraint of cultivar selection on maize yield; the two cultivars were the major cultivar that local farmers' planted and a high-yielding cultivar.

The soil data used in our study include the soil bulk density (BD), saturated volumetric water content (SAT), drained upper limit (DUL), and 15bar lower limit (LL15) in different soil layers. These data were from local experiment station datasets and data from the China Soil Scientific Database (CSSD; http://www.soil.csdb.cn). According to soil information from CSSD, the major soil types in which maize is grown were determined; the simulation model was then used to determine the optimal soil (OS) in which the maize can get the highest yield for each climate zone.

2.3. Crop modeling and simulation

APSIM was developed by the Agricultural Production Systems Research Unit in Australia (Keating et al. 2003). It is a process-based crop model that simulates daily crop development, growth, biomass production, and soil water and nitrogen dynamics as affected by the climate, cultivar selection, soil, and management practices. APSIM has been widely used to simulate cropping systems around the world. APSIM-Maize has been calibrated and used in northeast China for simulating the growth and yield of maize. The previous results indicated that APSIM-Maize can be successfully used for simulating growth and yield for maize in NEC. For the days of flowering and maturity, the R^2 values were 0.89 and 0.86 and the D values were 0.99 and 0.99 (Liu et al. 2016), respectively, indicating that the model-predicted maize growth stages reasonably well in NEC. In addition, simulated yields compared well with observed yields ($R^2 = 0.85$; D value $= 0.97$); more details are available in Liu et al. (2012, 2016). In this study, we rely on the previous model validation work for model performance.

According to Wang and Li (2010) for maize production in NEC, there are three major agronomic factors responsible for local yield loss of maize, including soil

Table 1. The design for different level of yield (potential farmers' yield, yield with recommended soil, cultivar, or management practices); L indicates local and R indicates recommended.

Simulation	Soil	Cultivar	Management practices		
			Density (plant ha^{-1})	Irrigation (mm)	Fertilizer (kg ha^{-1})
PF	L	L	50 000	0	200
PF+OS	R	L	50 000	0	200
PF+HYC	L	R	50 000	0	200
PF+OMPs	L	L	70 000	200	300

physical properties, cultivar selection, and management practices. The other limiting factor was pests (pathogens, insects, rodents, weeds, etc.). Management factors that have constrained the yields include applications of fertilizer, irrigation, and lower plant densities. Therefore, in this study, we designed four runs to separate the constraints of soil physical properties, cultivar selection, and management practices using APSIM-Maize model. These simulations include potential farmers' (PF) simulation, potential farmers' simulation but with optimal soil (PF+OS), high-yielding cultivar (PF+HYC), and optimal management practices (PF+OMPs), as defined in Table 1.

At each weather site, we first simulated potential farmers' yield Y_{pf} with local cultivar (LC) of maize planted in the local soil (LS) type with the average local farmer's management practices (LMPs) when sowing date, sowing density, and other management practices were kept constant throughout the simulation period (1961–2010; see Table 2). The soil bulk density of different layers of local soil for each climate zone and optimal soil across NEC is summarized in Table 2. For the runs PF+OS, PF+HYC, and PF+OMPs, we only changed the soil, cultivar, and management practices from local to recommended levels, while all other variables were not changed (Table 2). On average, over NEC, 200 kg ha^{-1} nitrogen and no irrigation for maize were applied during our simulation (Gao et al. 2010). According to average records of AESs the planting density was set as 50 000 plants per hectare. Therefore, these values were used as the average LMPs to simulate the potential farmers' yield. Optimal management practices were based on the results from the maize high-yield research projects conducted in NEC (Chen et al. 2009); the technology and management we fixed were nitrogen (300 kg ha^{-1}), irrigation (200 mm, with 100 mm applied at both jointing and flowering stage), and sowing density (70 000 plants per hectare). These conditions serve as the "best currently available management practices" during APSIM simulations in our study.

2.4. Data analyses

In our analysis, we define potential farmers' yield Y_{pf}, potential farmers' yield with optimal soil Y_{pf+OS}, high-yielding cultivar Y_{pf+HYC}, or optimal management practices $Y_{pf+OPMs}$. Therefore, the yield gaps caused by soil YG_s was calculated as the difference between potential farmers' yield with optimal soil and potential farmers' yield, which indicates the yield loss due to suboptimal soil physical properties. The yield gaps caused by cultivar YG_c were calculated as the difference between potential farmers' yield with high-yielding cultivar and potential farmers'

Table 2. Soil bulk density of different layers of soil for each CZ and optimal level in northeast China (g cm^{-3}).

Soil depth (cm)	0–10	10–20	20–30	30–50	50–70	70–90	90–110
CZ1	1.26	1.29	1.31	1.33	1.38	1.49	1.56
CZ2	1.22	1.26	1.27	1.32	1.37	1.46	1.52
CZ3	1.07	1.26	1.23	1.21	1.30	1.35	1.31
CZ4	1.38	1.48	1.48	1.40	1.45	1.46	1.42
CZ5	1.50	1.38	1.46	1.47	1.51	1.51	1.51
CZ6	1.45	1.37	1.24	1.37	1.37	1.37	1.37
CZ7	1.30	1.29	1.35	1.42	1.37	1.37	1.37
CZ8	1.48	1.37	1.26	1.38	1.38	1.39	1.39
CZ9	1.32	1.30	1.36	1.41	1.39	1.39	1.39
CZ10	1.45	1.38	1.26	1.37	1.37	1.37	1.37
Optimal	1.04	1.14	1.14	1.15	1.28	1.33	1.38

yield with LC. The yield gaps caused by management practices YG_m were the difference between potential farmers' yield with optimal management practices and potential farmers' yield. These three yield gaps caused by soil physical properties YG_s, cultivar selection YG_c, and management practices YG_m are expressed as the percentage of potential yield Y_P:

$$YG_s = \frac{Y_{pf+OS} - Y_{pf}}{Y_p} \times 100\%, \tag{1}$$

$$YG_c = \frac{Y_{pf+HYC} - Y_{pf}}{Y_p} \times 100\%, \quad \text{and} \tag{2}$$

$$YG_m = \frac{Y_{pf+OMPs} - Y_{pf}}{Y_p} \times 100\%. \tag{3}$$

The potential ascension of yield by improving soil physical properties PAY_s, changing cultivar PAY_c, and management practices PAY_m were calculated using Equations (4), (5), and (6):

$$PAY_s = Y_{pf+OS} - Y_{pf}, \tag{4}$$

$$PAY_c = Y_{pf+HYC} - Y_{pf}, \quad \text{and} \tag{5}$$

$$PAY_m = Y_{pf+OMPs} - Y_{pf}. \tag{6}$$

The average simulated yields and yield gaps are scaled from the site level to the CZs, and the entire region levels by weighting with the area in each county dedicated to maize crop.

3. Results

Previously (Liu et al. 2016), we found the regional yield loss due to suboptimal agronomic factors was about 40% of potential yield in NEC and varied considerably among CZs (25% ~ 46%). Therefore, in the following three sections, we presented our results from separating the influences of soil physical properties, cultivar selection, and management practices to maize yield in different CZs and in NEC.

3.1. Yield gap caused by soil physical properties

The orange bars in each chart in Figure 2 show the maize yield gaps caused by soil physical properties in 10 CZs and in NEC as a whole. At the regional scale, the area-weighted mean YG_s was 5% of Y_p averaged from 1961 to 2010. There were significant year-to-year variations of yield gaps caused by soil physical properties, ranging from 0.2% to 14.8% during past five decades (Figure 3). The year-to-year variations may be due to differences in recharge and soil water storage being limiting for some years and not for others. The probability of a low YG_s (less than 5%) is about 60% of all years in this study. For about 10% of the years, the YGs are more than 8.5%. This is similar to the results reported by Wang and Li (2010), which indicated that soil physical properties were not the main cause for reduction in yield. Within our study, CZs and YG_s varied from 1% to 7%, depending on local soil physical properties.

3.2. Yield gap caused by cultivar selection

Because of the large range of the heat resources ($1460° \sim 2370°C\ day^{-1}$; here we use GDD as the index, as mentioned in the previous subsection), several maturity types of maize (early maturing, midmaturing, late maturing, and so on) were commonly planted in NEC (Liu et al. 2013; Zhao et al. 2014). Therefore, selecting the optimal cultivars in certain climate zones is vital for maize production in NEC.

Figure 4 shows the differences of durations for the vegetative growing period (VGP), reproductive growing period (RGP), and whole growing period (WGP) between the LC and the high-yielding cultivar (HYC) in each CZ and in NEC as a whole. In CZs 1 ~ 5, the duration of WGP for HYC was 14 to 18 days longer than LC. However, in the southern areas (CZs 6 ~ 10), the duration of WGP for HYC was 1 to 3 days longer than LC. Upscaling these differences to regional scale based on the harvested area around simulation stations, the regional difference of the duration of WGP for HYC and LC is about 9 days. Further, compared with the durations of VGP and RGP between HYC and LC, our results show that the duration of WGP of HYC was longer than LC, especially for the duration of RGP, which affords more thermal time to transfer dry matter to grain for the HYC.

Averaged from 1961 to 2010, the area-weighted mean YG_c was 12% of Y_p at the regional scale. Considerable temporal variability in YG_c of maize was observed in the NEC, ranging from 6.5% to 20.9% (Figure 3); moreover, in 38% of
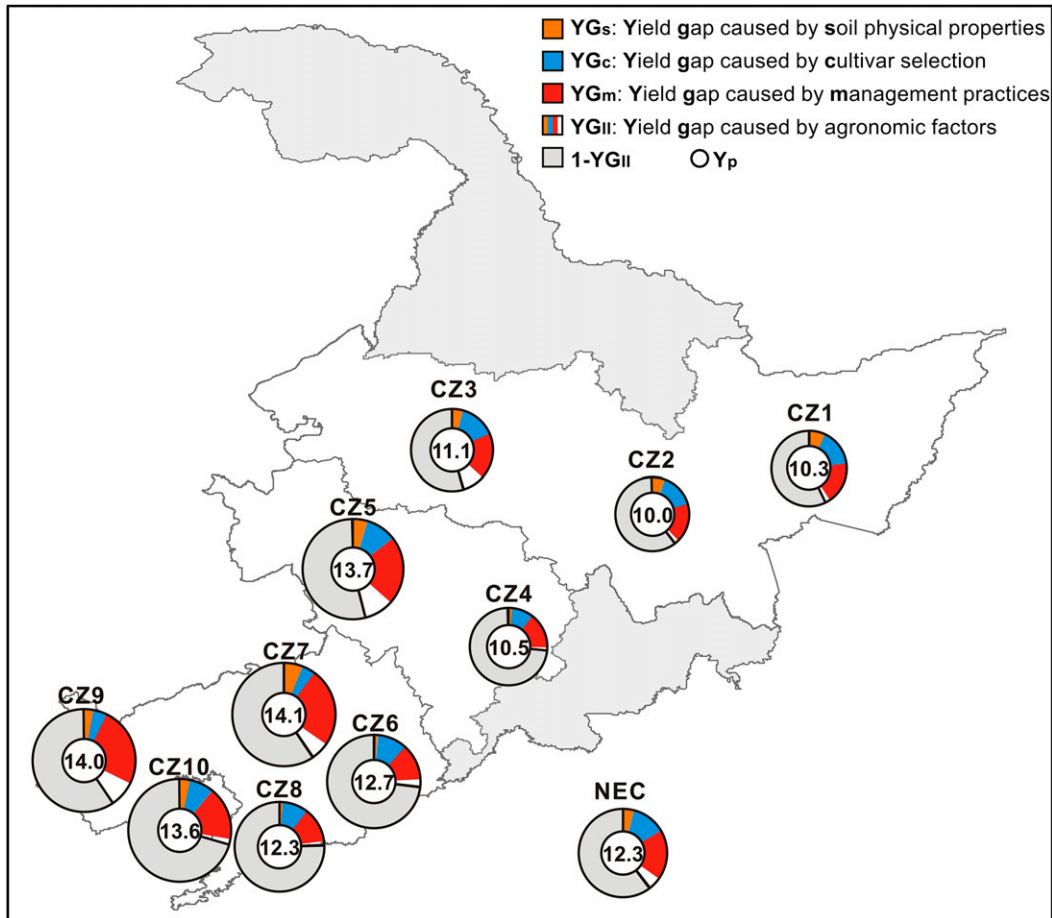
Figure 2. Yield gaps expressed as percentage to Y_P (%) of maize caused by soil physical properties YG_s (orange shading), cultivar selection YG_c (blue shading), and management practices YG_m (red shading) for 10 climate zones and the entire region in NEC. The size of the pie is proportional to the average simulated potential yield over the past five decades, and the values were labeled in the center of the pie. The shading areas including orange, blue, red, and white colors indicate the yield gap caused by agronomic factors YG_{II}, as shown in our previous research (Liu et al. 2016). The location of each pie chart represents the climate zone, and the pie chart for the entire region (NEC) is located below the map.

the years, YG_c was less than 12%. Averaged from 1961 to 2010, the area-weighted mean YG_c varied from 4% to 16%, depending on cultivar planting among 10 CZs. The greater YG_c (higher than the regional average 12%) was found in CZs 1, 2, and 3, which indicated that more than 12% of the yield gap was caused by suboptimal cultivar in Heilongjiang Province. The lowest YG_c of maize are distributed in CZs 7 and 9 (blue bars in Figure 2). On the one hand, the
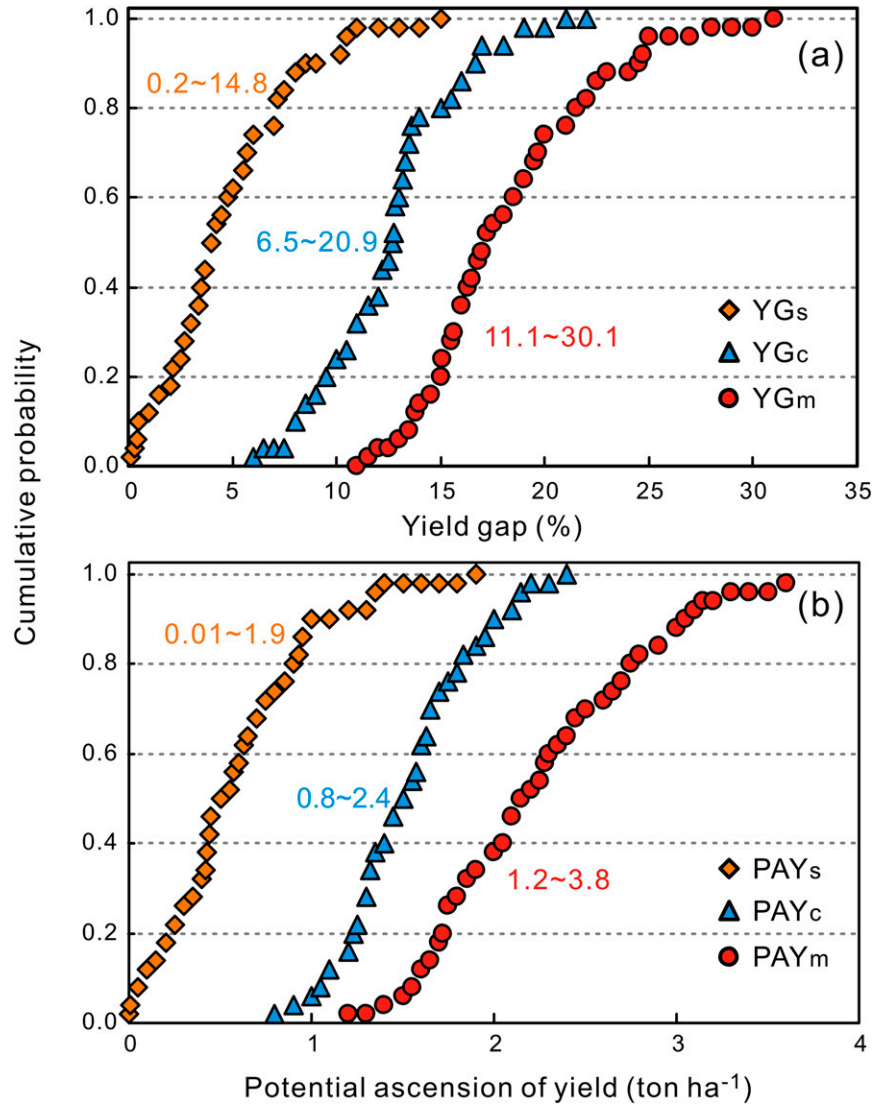
Figure 3. Cumulative probability distributions of (a) yield gaps expressed as percentage to Y_P (%) of maize caused by soil physical properties YG_s, cultivar selection YG_c, and management practices YG_m and (b) potential ascension of yield (ton ha^{-1}) of maize by improving physical properties PAY_s, changing cultivar PAY_c, and management practices PAY_m for the entire region in NEC during the period from 1961 to 2010. The numbers in each subfigure are the ranges of each variable.

durations of the WGP of local cultivar have been close to the high-yielding cultivar in the current situation (Figure 4). On the other hand, however, because of the limitation of precipitation in the semiarid areas of western NEC, the advantages of the high-yielding cultivars were stymied.
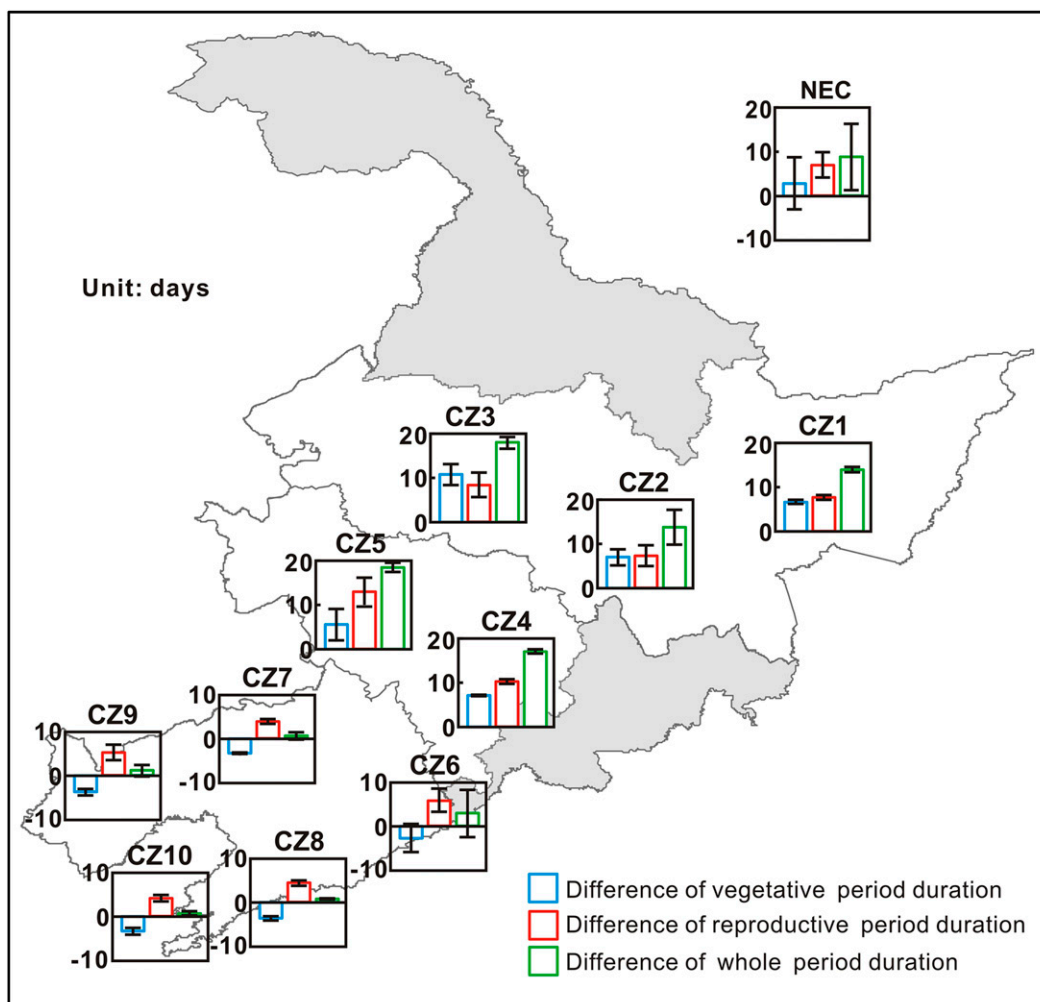
Figure 4. The changes of days in the length of vegetative growing period (color in blue), reproductive growing period (color in red), and whole growing period (color in green) between local and recommended high-yielding cultivars of maize for 10 CZs and the entire region in northeast China (days). Positive (or negative) days indicate the length of period of recommended high-yielding cultivars was longer (or shorter) than local cultivars. The error bars represent one standard deviation of the location average. The location of each bar chart represents the CZ, and the bar charts in the top indicate the entire region (NEC).

3.3. Yield gap caused by management practices

The red bars in each chart in Figure 2 show the maize yield gaps caused by management practices in 10 CZs and on NEC as a whole. Averaged from 1961 to 2010, the mean magnitude of yield loss due to suboptimal management practices (YG$_m$) was about 18% of potential yield and varied considerably among CZs (12% $\sim$ 25%). Considerable temporal variability in YG$_m$ of maize was observed in the NEC,
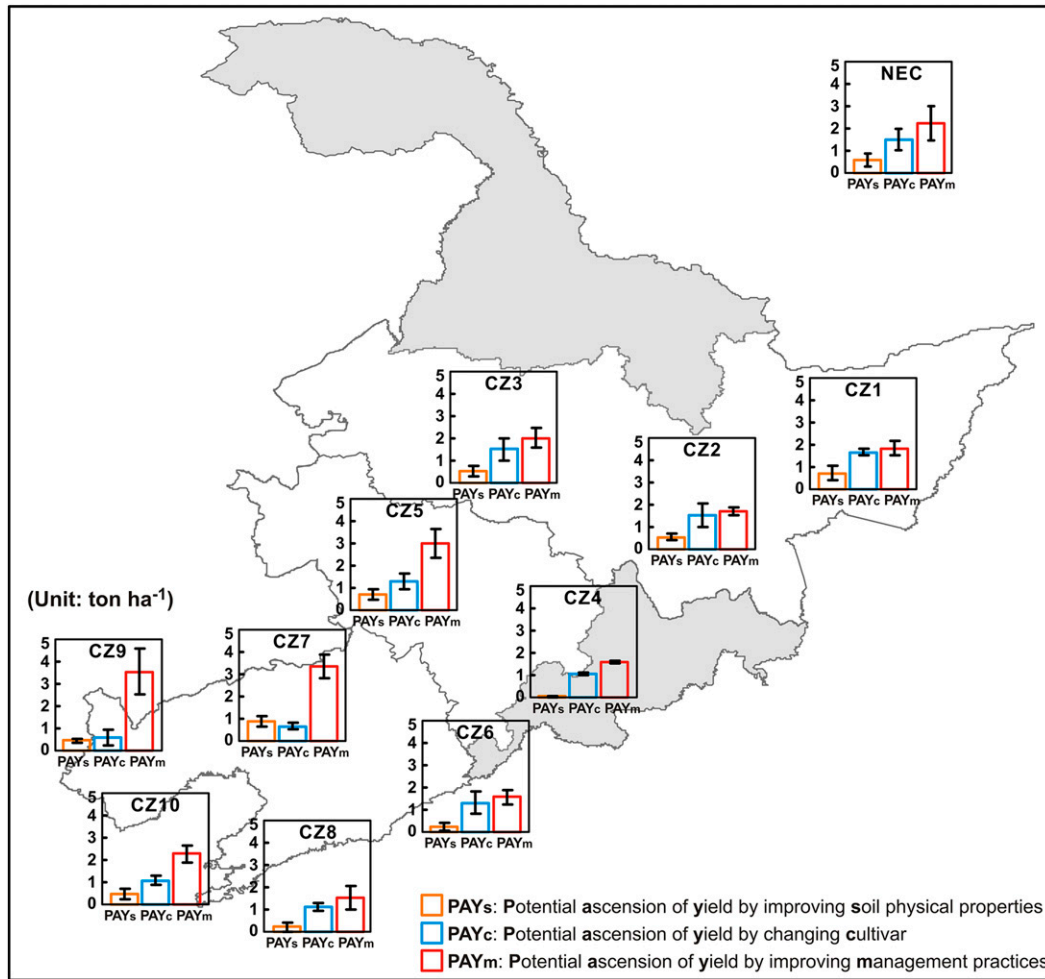
Figure 5. Potential ascension of yield (ton ha^{-1}) of maize by improving soil physical properties PAY$_s$ (orange), changing cultivar PAY$_c$ (blue), and management practices PAY$_m$ (red) for 10 CZs and the entire region in NEC. The error bars represent one standard deviation of the location average. The location of each bar chart represents the CZ, and the bar chart in the top indicates the entire region (NEC).

ranging from 11.1% to 30.1% (Figure 3); moreover, in 56% of all years, YG$_m$ was less than 18%. It should be noted that the greater values (higher than the regional average 18%) were located in climate zones with the positive crop water deficit (CZs 1, 3, 5, 7, and 9). These results quantify the magnitude of increase to be realized if the optimal management practices were applied.

3.4. Potential ascension of yield by improving soil physical properties PAY$_s$

In Figure 5, the potential ascension of yield of maize by improving soil physical properties PAY$_s$, changing cultivar PAY$_c$, and improving management practices
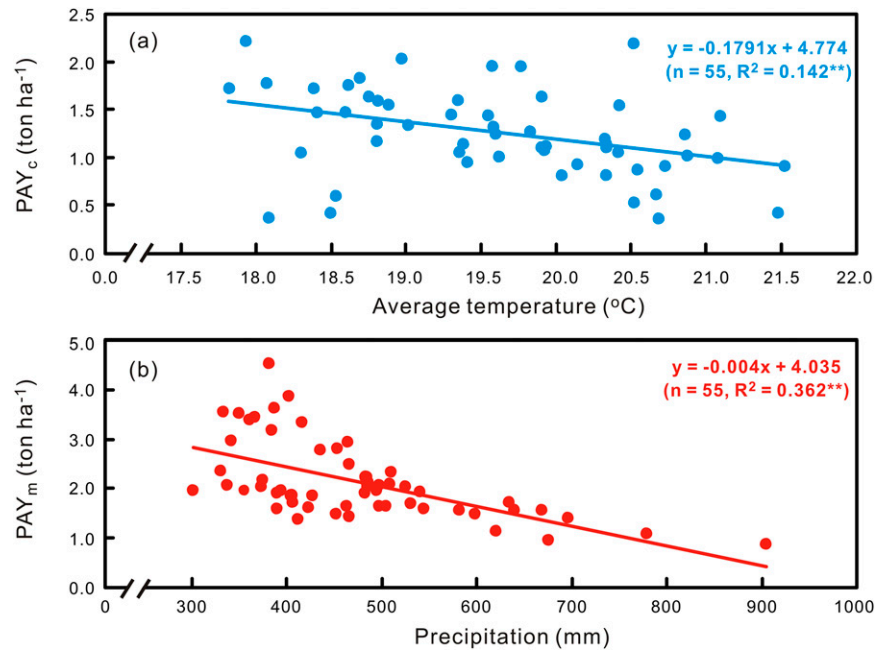
Figure 6. The relationship (a) between potential ascension of yield (ton ha^{-1}) of maize by changing cultivar PAY$_c$ and growing season average temperature, and relationship (b) between potential ascension of yield (ton ha^{-1}) of maize by improving management practices PAY$_m$ and growing season precipitation for 55 weather stations in NEC. Straight line is the linear regression line against year among weather stations. The double asterisks (**) indicate significant at $p < 0.01$.

PAY$_m$ for 10 CZs and for the NEC are shown. At the regional scale, the 50-yr mean magnitude of PAY$_s$, PAY$_c$, and PAY$_m$ were 0.6, 1.5, and 2.2 ton ha^{-1}, which indicate that potential farmers' yield would be increased 9%, 23%, and 34% by improving soil physical properties, changing cultivar, and improving management practices. Relatively larger temporal variability in PAY$_s$, PAY$_c$, and PAY$_m$ of maize was also observed in the NEC, ranging from 0.01 to 1.9, 0.8 to 2.4, and 1.2 to 3.8 ton ha^{-1}, respectively (Figure 3).

Among the locations, 50-yr mean PAY$_s$ ranged from an equivalent 0.3 to 1.1 ton ha^{-1}. Upscaling from location to CZs, all five CZs with the positive crop water deficit (CZs 1, 3, 5, 7, and 9) were relatively higher PAY$_s$ than the CZs with negative crop water deficit in the same growing degree-days.

3.5. Potential ascension of yield by changing cultivar PAY$_c$

The 50-yr mean PAY$_c$ was ranged from 0.4 to 2.2 ton ha^{-1}, and PAY$_c$ has a negative relationship with growing season average temperature in NEC (Figures 5, 6), which suggests that in areas of lower growing season average temperature (CZs in the north area) a relatively larger yield can be realized by changing to longer

growing season cultivars compared to other areas (e.g., CZs are located in the south area). Moreover, 29% locations of their PAY$_c$ were about 1.5 ton ha^{-1} or higher, which was distributed in Heilongjiang Province. According to this analysis, in CZs 1 ∼ 5, the cultivars with duration of WGP 14 to 18 days longer than LC were recommended to increase maize yield. On the other hand, in the south areas (CZs 6 ∼ 10), the cultivars with duration of WGP 1 to 3 days longer than LC were recommended to increase maize yield.

3.6. Potential ascension of yield by improving management practices PAY$_m$

The 50-yr mean PAY$_m$ varied considerably from location to location (0.9 to 4.5 ton ha^{-1}; Figure 5). The relationship between maize PAY$_m$ and growing season precipitation are shown in Figure 6. The highest values of PAY$_m$ were found in the locations where growing season precipitation were higher [PAY$_m$ (ton ha^{-1}) = −0.004 × precipitation + 4.035]. Note that we did not find any significant relationships between PAY$_m$ and temperatures. At about 300 mm of growing season precipitation, maize yield would be increased by improving management practices by about 2.8 ton ha^{-1}; PAY$_m$ was only about 2.0 ton ha^{-1} until the growing season precipitation reaches 500 mm. When growing season precipitation exceeds 700 mm, PAY$_m$ could be as low as 1.2 ton ha^{-1}. If improvement of current management practices is feasible, our results suggest that development of irrigation systems might start first in the northwest areas of NEC (CZs 5, 7, and 9) where the greatest PAY$_m$ exists (Figure 5). Based on the results shown (Figure 5), approximately 18%–56% more maize could be produced if the recommended management practices (including applying nitrogen of 300 kg ha^{-1}, irrigation of 200 mm, and sowing density of 70 000 plants per hectare) could be implemented in the maize planting areas in 10 CZs.

4. Discussion and conclusions

Yield gaps have been estimated in previous studies with either a global or local focus. Whereas global simulation methods for yield gaps generally provide a coarse coverage, local studies are based on location-specific environmental conditions and management, which give more detailed suggestions to local farmers and scientists (van Ittersum et al. 2013). Many crop, genetics, and environmental factors affect the magnitude of yield loss due to suboptimal agronomic factors (Grassini et al. 2011). In spite of the above, there is little evidence relating the quantification of constraints of crop yield gaps, especially for this important maize production area in China (NEC). From our definition, potential yield is the yield ceiling of the crop for a given variety in a given location. Average farm yields in a region or country are inevitably lower than potential yields because achieving yield potential requires near-perfect management of crop and soil factors that influence plant growth and development throughout the crop growth cycle. Therefore, the total yield gap of crop was the yield difference between potential and actual farmers' yield. According to the constraints, yield gaps can be broken down further into three components. The first component of yield gaps (potential yield and

attainable yield) is mainly due to noncontrollable factors, the second component of yield gaps (attainable yield and potential farmers' yield) is mainly due to differences in agronomic factors, and the third component of yield gaps (potential farmers' yield and actual farmers' yield) was caused by socioeconomic factors. We have quantified the constraints of noncontrollable factors, agronomic factors, and socioeconomic factors for maize yield in our previous study Liu et al. (2016). In addition, according to Wang and Li (2010), for maize production in NEC there are three major agronomic factors responsible for local yield loss of maize, which are soil physical properties, cultivar selection, and management practices. In this study, we have focused on soil physical properties, cultivar selection, and management practices and their roles in improving yields of maize in different CZs of NEC. In our study, approximately 5%, 12%, and 18% of potential yield loss was due to soil physical properties, cultivar selection, and management practices in NEC. For yield gap analyses, studying the constraints that limit crop production is more important for crop producers and decision-makers. The ability of simulation models to separate the constraints of crop production in more details is potentially invaluable for understanding yield constraints in many agricultural regions.

The yield gap due to limitations in soil physical properties were first estimated, and the results showed the area-weighted mean YG_s was 5% of Y_p, averaged from 1961 to 2010 at the regional scale, and PAY_s was 0.6 ton ha^{-1}, indicating that potential farmers' yield would be increased 9% if soil physical properties were improved in NEC. Our results of maize YG_s in NEC were consistent with recent findings in Wang and Li (2010), a study based on participatory rural appraisal surveys, which indicated that soil physical properties were not the main cause for reduction in maize yields. In NEC, long-term continuous cropping is dominated by small-sized four-wheeled tractors; because of the overexploitation of the soil as well as improper mechanical manipulation of the soil, the effective plow layer has gradually decreased and the plow pan layer has thickened (approximately 5–10 cm; Liu et al. 2008). The average effective plow layer depth is only 15.1 cm in NEC (against an average of 16.5 cm in China), much shallower than that in the North America, which usually reaches 35 cm on average (Cai et al. 2014). The shallow and compacted topsoil not only restricts the root development of plants but hinders their absorption of nutrients and water. The poor soil properties also reduce their tolerance to abiotic stress, especially resistance against natural disasters (Zhang and Li 2010; Cai et al. 2014). To improve the situation farmers should follow recommendations of agronomists to increase the health of the soil by incorporation of crop residue and appropriate tillage.

Because of the widespread adaptation of high-yielding cultivars, and introduction of new high-yielding management practices (Chen et al. 2011; Liu et al. 2012), actual farmers' yield in NEC increased at the rate of 1.27 ton ha^{-1} decade^{-1} since 1961, and this has caused reductions in total yield gap (potential yield and actual farmers' yield) over time according to our results (Liu et al. 2016). A similar time trend of total yield gap was also found for winter wheat in the North China Plain (Li et al. 2014) and rice in China (Zhang et al. 2014). Compared among the locations, regions in Heilongjiang Province (CZs 1, 2, and 3) presented YG_c of 14%–16% of the potential yields and a higher PAY_c (1.5–1.7 ton ha^{-1}). Because the temperature warming trend in Heilongjiang Province was faster than other locations due to relatively high latitudes, this province can now switch to a cultivar

with a longer growing season, thus realizing a higher yield (Liu et al. 2012). The increase in T_{min} in September leads to more optimal conditions during grain filling and reaching maturity in a timely manner to avoid damage by early frost (Chen et al. 2011). We also observed lower PAY_c of maize (approximately 5%) in western Liaoning Province (CZs 7 and 9) because the current recommended cultivars for this location do not fully utilize the heat resources (Zhao et al. 2015); thus, breeding new, longer growing season cultivar might be a solution for improving maize yields in terms of existing thermal conditions.

In this study, the constraints of soil physical properties, cultivar, and management practices were quantified to assess the relative impact on the yield gap between attainable yield and potential farmers' yield. Further effort is required to identify more specific effective solutions to narrow down the local yield gaps in the low yield regions. First, the effects of the incorporation of crop residue and the appropriate tillage on the maize yield for different soil types in each climate zone should be cleared. Second, the other cultivar genetic advances (leaf angle, drought tolerance, more tolerance to stresses due to higher plant density, etc.) were not considered in this study; therefore, a subsequent study should quantify maize yield gains of higher-yielding modern cultivars in more detail. Third, effective management practices should be selected to reduce yield gaps. Last, the constraints of other agronomic factors, including pests (insects, weed infestation, disease management, and weed control; Cassman 1999; Boling 2007), were relatively small for most of the regions; however, these factors should be accounted for in future studies.

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