Agricultural and Forest Meteorology 205 (2015) 1–10

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Yield gap simulations using ten maize cultivars commonly planted in Northeast China during the past five decades

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ARTICLE INFO

Article history:
Received 9 November 2014
Received in revised form 29 January 2015
Accepted 8 February 2015

Keywords:
Maize
Yield gaps
APSIM
Cultivars
Climate change

ABSTRACT

Northeast China (NEC) is one of the most important agricultural production areas in China and is one of the most sensitive areas in the country to climate change, particularly during the last five decades when strong climate warming occurred. Thus, a better understanding of the potential, attainable, and farm yields and yield gaps of spring maize under climate change is necessary with respect to historical cultivars improvements. Ten spring maize cultivars commonly planted from the 1960s to the 2000s were selected for a two-year field experiment in Lishu, NEC. The APSIM-maize model was used to simulate the potential and attainable yields of spring maize from 1961 to 2009 using real-time cultivar calibration and validation during the past five decades. Our results indicated that the yield gap between the potential and farm yields was 9.7 t ha^{-1}, or 66.2% of the potential yield; the yield gap between the attainable and farm yields was 5.6 t ha^{-1}, or approximately 54% of the attainable yield. Climate change from 1961 to 2009 led to a reduction in the potential yield by 2.1% and a reduction in the attainable yield by 8.0%. Improved cultivars and agricultural practices have led to an increase of 62.2% and 80.5% in potential and attainable yields, respectively. Therefore, the combined impact of climate change and improvements in cultivars and agricultural practices increased potential and attainable yields 53.3% and 70.3%, respectively, for the period 1961–2009 relative to the yields of the cultivar planted in the 1960s. In conclusion, improvements in cultivars and agricultural practices for spring maize in NEC played a dominate role for the increase of yield, and the persistent large yield gap between farm and attainable or potential yields provides farmers an opportunity to increase their agricultural production.

1. Introduction

Northeast China (NEC) is an important grain production region, where the maize yield is approximately 50 million t yr^{-1}, which is approximately 30% of the nation's commercial food grain (maize) (Editing Committee of China Agricultural Yearbook, 2009). The maize area accounts for more than 30% of the total crop area in NEC. Hence, NEC plays an important role in food security. The average farm yield of maize during the past five decades in NEC has increased as a result of the green revolution, namely through the use of high-yielding cultivars, effective fertilizer, and pesticides (Chen et al., 2013; Matson et al., 1997). Nevertheless, further increase in the farm yield of maize in NEC is possible according to the determined potential yields, particularly when compared with the maize yields in other developed countries (Grassini et al., 2011; Liu et al., 2012; Lobell et al., 2009). Therefore, the exploitable gaps of spring maize yields, which are a key component for food security in China, should be quantified during the past five decades (Liu et al., 2012).

Recent effort has been made to estimate the impacts of improved crop varieties, management and climate change on crop yields and yield gaps using crop modeling (Martína et al., 2014) and empirical–statistical methods (Angulo et al., 2013; Ewert et al., 2005). Although yield gaps and yield constraints of spring maize have been studied in NEC, the understanding of trends and variations of the potential yield and yield gaps described in previous studies (Liu et al., 2012; Wang et al., 2012) remain uncertainties because of taking fixed cultivars and consistent agricultural practices in their crop simulations. Notable evidence suggests that plant

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http://dx.doi.org/10.1016/j.agrformet.2015.02.008
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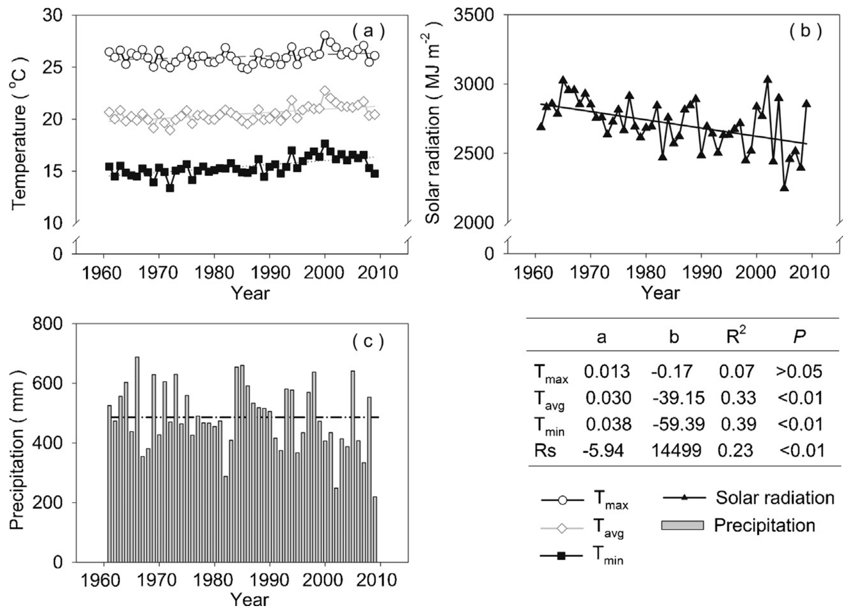

Fig. 1. Trends in (a) maximum temperatures (T_{max}), minimum temperature (T_{min}), and average temperature (T_{avg}), (b) solar radiation, and (c) precipitation during maize growing season in Lishu, Northeast China over 1961–2009.

breeding and improved agricultural practices have explained much of the historical yield improvement (Duvick, 2005). New maize cultivars in the 2000s have contributed to 53% of the increased on-farm yields in China relative to the cultivar yields in the 1970s (Ci et al., 2011). Consequently, improved cultivars and agricultural practices are indispensable when studying the long-term trends of yields and yield gaps. However, it still remains a challenge to evaluate the long-term yields (especially the potential yield) and yield gaps with improvements in cultivars and agricultural practices and climate change.

Air temperatures have increased over recent decades but the solar radiation has decreased in NEC due to increases of cloudiness and air pollution (Xia et al., 2006; Yang et al., 2009; Liu et al., 2013). Meanwhile, climate change could have a crucial impact on crops and crop yields because crop growth and development are directly affected by climatic drivers, including temperatures, solar radiation, and precipitation (Liu et al., 2012; Yang et al., 2007). Such climate change impacts on crop production can be further analyzed for each crop growth stages, crop management (Grassini et al., 2009; Liu et al., 2010), and new cultivar breeding applications (Mendelsonhn et al., 1994). A few studies have illustrated the long-term impact of climate change on crops in NEC during the past few decades, e.g., Chen et al. (2013) suggested that climate change in the 2000s led to a decrease of the potential yield by an average of 12.9% across different dominate hybrids in NEC compared with the yield in the 1970s. However, Chen et al. (2013) limited their study to the 2000s and ignored the climate change during the 1980s and 1990s. In this study, ten spring maize cultivars commonly planted from the 1960s to the 2000s in NEC were replanted for a two-year field experiment in Lishu, NEC. Crop, soil, and climate observations from our two-year experiment were for calibrating and validating the Agricultural Production Systems Simulator (APSIM). The APSIM model was then used to simulate potential and attainable yields based on these ten spring maize cultivars to further quantify the impacts of climate change and improvements in cultivars and agricultural practices according to the approach in Lobell and Burke (2008). The objectives of this study were to (1) estimate the yield gaps of spring maize from 1961 to 2009 and (2) jointly and separately evaluate long-term yield impacts of cultivars, agricultural practices, and climate change during the past five decades in NEC.

2. Materials and methods

2.1. Study site

The study was conducted in Lishu, Jilin Province, in the Golden Maize Belt of China, which is a high maize production zone with proper agricultural management. The maize area accounts for approximately 70% of the total crop area in Lishu, and the soil types in Lishu include the typical soil type (black soil according to the Chinese soil classification) in NEC. Therefore, the study area is representative of the high maize production zone in NEC. We examined the climate data during the growing season of spring maize from 1961 to 2009 in NEC. The maximum, minimum, and average temperatures (T_{max}, $T_{min,}$ and T_{avg}, respectively.) in Lishu (43°16′47″N, 124°26′9″E) increased 0.13, 0.38, and 0.30 °C decade^{-1}, respectively, in the growing season (Fig. 1a). The cumulated solar radiation during the growing season in Lishu decreased by 59.4 MJ m^{-2} decade^{-1} (Fig. 1b). The average total precipitation during the maize growing season was 484 mm (Fig. 1c). The climatic trends, variations, and climatology in Lishu shown in Fig. 1 agreed with the regional climate changes observed in NEC (Chen et al., 2011; Liu et al., 2012), indicating that our experiment site was representative of the climate change and climatology in NEC. Additionally, the experiment site was located in a rain-fed area that accounts for approximately 94% of the maize planting area in NEC (Liu et al., 2012).

2.2. Field experiment design

The field experiment was designed as a split-plot with three replicates with N fertilizer treatments as the main plots and maize cultivars as the subplots. Ten spring maize cultivars released and planted between the 1960s and the 2000s were selected (Table 1), and the field experiment was conducted in 2010 and 2011 in Lishu, NEC. The soil type is black soil (according to the Chinese soil classification; it is typic hapludoll in the USDA soil taxonomy). The sowing dates were May 8, 2010, and May 4, 2011. The sowing density was 6.0×10^4 plants per hectare, with a row spacing of 0.6 m. Applications of 85 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1} were completed each year before sowing. Two nitrogen (N) fertilization treatments were employed in 2010 and 2011, including no N fertilization and 240 kg