European Journal of Agronomy 99 (2018) 106–115

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Constraints on maize yield and yield stability in the main cropping regions in China

Jin Zhao, Xiaoguang Yang*, Shuang Sun

College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China

ARTICLE INFO

Keywords:
Maize
Yield gap
Stability
High-stable zones

ABSTRACT

Understanding the distributions of zones of high/low and stable/unstable recorded maize (*Zea mays* L.) yield, and identifying the constraints on yield and yield stability, is essential for optimized crop distribution and agricultural management to mitigate limitations and improve maize production under climate change. In this study, we collected recorded maize yields and simulated three levels of yield potentials (radiation-temperature yield potential Y_p, climatic yield potential Y_{pw} and soil-climatic yield potential Y_{pws}) with the Agricultural Production Systems sIMulator (APSIM-Maize) from 1981 to 2010 in the three main cropping regions in China [the North China spring maize region (NCS), the Huanghuaihai summer maize region (HS), and the Southwest China mountain maize region (SCM)]. The distributions of four categories of maize yield and yield stability zones, and limitations by precipitation, soil and technology & management on average yield, yield stability and total production were analyzed. The county-level average recorded yields during the period under study were 4624.26 kg ha^{-1}, 4718.32 kg ha^{-1} and 3880.44 kg ha^{-1} in NCS, HS and SCM, respectively. Coefficients of variations (CV) for recorded yields were 0.40, 0.30 and 0.27 in NCS, HS and SCM, respectively. Based on comprehensive analysis of both average yields and CV values, we divided the main maize cropping areas into four zone categories: those with high and stable yields (high-stable zone), those with high and unstable yields (high-unstable zone), those with low and stable yields (low-stable zone), and those with low and unstable yields (low-unstable zone). Comparison of Y_p, Y_{pw}, Y_{pws} and Y_a at the county level, among the three regions, revealed that precipitation was the most important limiting factor on both averages (56%, 9436.97 kg ha^{-1} and 53%, 8114.21 kg ha^{-1}) and CVs (0.42 and 0.39) of yield in all four zone types in NCS and HS. On the other hand, technology & management was the most important limiting factor in SCM (39%, 3934.87 kg ha^{-1}). Total maize productions were reduced by 47.6% and 52.7% by precipitation in NCS and HS, respectively. Nevertheless, the limiting effect of soil was lower than that of technology & management in NCS, while it was higher in HS. In SCM, technology & management was the most important limiting factor (1295.72×10^4 t and 39.3%), followed by precipitation (613.80×10^4 t and 18.6%) and soil (219.62×10^4 t and 6.7%). In the three main cropping regions, the limiting effect of each factor on total productions in high-stable zone was the highest among all four zone types. Our results could be used to provide a theoretical basis for targeted climate change adaptation policies to improve maize yield and yield stability in China. In addition, our results may serve as a reference for other maize cropping regions in the world.

1. Introduction

China is the second largest maize (*Zea mays* L.) producer and consumer in the world, accounting for 19.15% and 21.42% of total harvest areas and production in the world in 2014 (FAO, 2014). Between 2004 and 2012, maize planting areas and total production increased in a near-linear fashion by 45.2% and 79.7%, respectively (Zhao and Wang, 2013). Therefore, it is strategically important to promote maize production for ensuring China's national food security (Meng et al., 2013; Zhao and Wang, 2013). However, statistical analysis has shown that climate change is increasingly affecting maize yields worldwide (Challinor et al., 2014; Gabaldón-Leal et al., 2016; Lobell et al., 2011; Rose et al., 2016), and effects of climate change on maize yields have also been reported in China (Liu et al., 2012; Tao et al., 2015; Wang et al., 2014a, 2014b). Because of differences between local environmental and productive conditions, it is essential to clarify the constraints by different limiting factors on maize yield in each region, and make targeted adaptations to meet future food demands.

* Corresponding author.
E-mail address: yangxg@cau.edu.cn (X. Yang).

https://doi.org/10.1016/j.eja.2018.07.003
Received 14 August 2017; Received in revised form 9 July 2018; Accepted 10 July 2018

Under current agricultural production systems, crop yield is dependent on solar radiation, precipitation, temperature, soil physical properties and fertility, and management decisions such as hybrid selection, planting date, and inputs (fertilizers and irrigation) (Kucharik, 2008). Yield gaps between yields under different limiting factors and the recorded yield reflect the limiting effects by the corresponding factors (Cassman et al., 2003; Liu et al., 2016a). The radiation-temperature yield potential (Y_p) is the yield limited only by solar radiation and temperature under optimal soil conditions and management, and without yield losses due to biotic and abiotic stress. Y_p should be the maximum yield which could be reached by a crop variety in any given environments, because the solar radiation and temperature are difficult to control under field conditions (Evans and Ficsher, 1999; Grassini et al., 2011). Accurate estimates of Y_p are essential for assessing regional crop production capacity on existing farmland, given the best management practices and possible improvements in the future (Liu et al., 2017, 2016a). However, potential conditions cannot be realized in the field for the perfect management of crop and soil factors that influence plant growth and development throughout the crop growth cycle (Lobell et al., 2009). Moreover, between Y_p and farmers' recorded yield (Y_a), there may be several yield levels due to one or more limiting factors. Yield potential under water-limited conditions (climatic yield potential Y_{pw}, maximum yield with no other manageable limitation than water supply) and actual soil physical condition (climatic-soil yield potential, Y_{pws}) are two important yield potential levels, since most maize fields are rain-fed and abundant in soil physical properties in China (Liu et al., 2017). Comparing the limiting factors on yield potentials and actual yield (Table 1), the yield gaps between Y_p and Y_{pw}, Y_{pw} and Y_{pws}, Y_{pws} and Y_a can reflect the limitations of precipitation, soil and technology & managements on maize yield.

Crop modeling is an effective tool to simulate yield potentials and to analyze yield gaps, which has been applied in previous studies on maize in China. Liu et al. (2016a,b) investigated the maize yield gaps between potential yields, attainable yields, and potential farmers' yields simulated by the APSIM-Maize model, and recorded farmers' yields in Northeast China, and identified yield gaps caused by non-controllable, agronomic, and socioeconomic factors under conditions of climate change. Meng et al. (2013) compared maize yield potential simulated by the Hybrid-Maize model and recorded maize yields published in the literature from field experiments and farm survey data in the four maize agro-ecological regions of China. Liu et al. (2017) used the agro-climatic zones and the reference weather stations buffer zones, together with the Hybrid-Maize model to estimate maize Y_p in the four maize-growing-regions of China under both irrigated and rain-fed conditions. In addition, farm surveys (Liang et al., 2011) and remote sensing (Zhao et al., 2015a,b) were used to estimate the yield potential and yield gaps in maize cropping regions in China.

In addition, increased probability, frequency, and severity of possible extreme events or disasters can also cause considerable damage to crops and food systems infrastructure (Lesk et al., 2016). Maize yield stability would also influence food security (Liu et al., 2005). Therefore, it is also necessary to understand yield-stability gaps caused by different factors (Guan et al., 2017; Katz and Brown, 1992; Rosenzweig et al., 2001). However, most previous studies have focused on the average yield gap; while, few studies have researched yield-stability gaps and total productions. In this study, the recorded county-level maize yields and cropping areas were collected in the main cropping regions from 1981 to 2010. In addition, three levels of yield potentials under different limiting factors (Y_p, Y_{pw}, and Y_{pws} in Table 1) (Ma, 1988; Wang, 1987) were simulated using the Agricultural Production Systems sIMulator (APSIM-Maize). The objectives of this study were to: (1) investigate the distributions of four types of maize recorded yield and yield stability zones and (2) quantify the constraints of precipitation, soil and technology & management on maize yield, yield stability and the total production in each region during the study period. The results of this research could be used to provide a theoretical basis for targeted climate change adaptation policies to improve maize yield and yield stability in China. In addition, our results may serve as a reference for other maize cropping regions in the world.

Table 1
The yield gradations and their limiting factors.

Yield level	Limiting factors
Radiation-temperature yield potential (Y_p)	Radiation, temperature
Climatic yield potential (Y_{pw})	Radiation, temperature, precipitation
Climatic-soil yield potential (Y_{pws})	Radiation, temperature, precipitation, soil
Actual yield (Y_a)	Radiation, temperature, precipitation, soil, technology & management

2. Materials and methods

2.1. Study areas and climate data

In China, the North China spring maize region (NCS), the Huanghuaihai summer maize region (HS), and the Southwest China mountain maize region (SCM) account for more than 90% of the maize growing areas (Wang and Li, 2010). In the three main cropping regions, quality controlled historical climate data from 364 meteorological stations from 1981 to 2010 were obtained from the China Meteorological Administration climate data-sharing service system. Annual growing degree-day (GDD) was calculated for each station. We used the inverse distance weighting (IDW) method in ArcGIS software to interpolate GDD within the 20th percentile for stations across the three regions. Areas with a growth degree-day greater than 2100 °C·d (maize can be planted) (Gong, 1988; Liu et al., 2010) were selected as study areas in Fig. 1. In total, 331 meteorological stations were located in the research area and listed in Fig. 1, which were used to simulate the three levels of yield potentials (Y_p, Y_{pw} and Y_{pws}).

2.2. Recorded yields and cropping areas

The recorded maize yields and cropping areas in each county were collected from the 'Agricultural Statistical Yearbook' maintained by the Ministry of Agriculture of China in the main cropping regions in China from 1981 to 2010. Because the recorded yield was the average value of all the fields in each county, it was used as the county-level average yield in this study. And the region-level average yield was the average value of all the county-level average yield in each region.

2.3. Simulation of yield potentials

The APSIM-Maize model (http://www.apsim.info/apsim/), which can successfully capture interactions between soil water and nutrient dynamics, crop growth, climate, and farm management (Gaydon et al., 2017; Keating et al., 2003), was used to simulate maize yield using historical climate data (1981–2010) under three levels of potential conditions in the main maize cropping regions (Table 1). Maize trial data were collected from 14 Agrometeorological Experimental Stations (6 in NCS, 5 in HS, and 3 in SMC) (Fig. 1) operated by the China Meteorological Administration. Based on the phenological data (including sowing, flowering, and physiological maturity dates), cultivars, soil physical properties in the trial fields, yields, management practices, and climate data from the nearest meteorological stations, APSIM-Maize model was validated for its ability to successfully predict maize growth stages (flowering and maturity) in the three main cropping regions. In addition, simulated yields matched observed yields with a high degree of acceptability (Zhao and Yang, 2018). Depending on the availability of data, one cultivar was selected and calibrated for one/two provinces to obtain province-specific crop coefficients for subsequent model