Field Crops Research 212 (2017) 126–134

Contents lists available at ScienceDirect

Field Crops Research

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

Adjusting maize plant density to different climatic conditions across a large longitudinal distance in China

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ARTICLE INFO

Keywords:
Maize
Plant density
High yield
LAI
Climate

ABSTRACT

Climatic conditions, including temperature range and solar radiation, are closely linked to maize (*Zea mays* L.) growth and development. Adjusting plant density is one of the most effective measures for maximizing maize yield under different climatic conditions. The objectives of this study were (1) to determine the optimum plant density as well as the corresponding leaf area index (LAI) and yield in different maize producing regions in China and (2) to learn how climatic conditions influence maize growth and grain yield. The 3-year (2013–2015) field experiment used a hybrid maize cultivar ('Zhengdan 958') with six plant density treatments: 4.5, 6, 7.5, 9, 10.5, and 12 plants m^{-2}. Three different ecological regions were chosen for the study: Gongzhuling (Jilin Province, China), Yinchuan (Ningxia Hui Autonomous Region, China), and Qitai (Xinjiang Uygur Autonomous Region, China). Comparing the same plant density treatment at different sites, grain yield and dry matter accumulation decreased in the order Qitai > Yinchuan > Gongzhuling. The optimum plant densities (i.e., treatments with greatest yield) were 12 plants m^{-2} at Qitai, 10.5 plants m^{-2} at Yinchuan, and 7.5 plants m^{-2} at Gongzhuling. At the optimum plant density, the LAIs at silking and physiological maturity were, respectively, 8.94 and 4.27 at Qitai, 7.50 and 1.85 at Yinchuan, and 6.18 and 1.67 at Gongzhuling. Climatic factors, especially solar radiation and diurnal temperature range, exerted significant influences on maize yield. These observations will be useful for determining best management practices for maize production under different climatic conditions across large areas and for providing helpful suggestions for maize breeders.

1. Introduction

As population increases, shortages in food and energy at a global scale are becoming more prominent. Increased maize (*Zea mays* L.) yield will play a key role in alleviating these shortages (Cassman and Liska, 2007; Cassman et al., 2003; Grassini et al., 2011). China is the second largest maize producer in the world (Ci et al., 2012). The area that China devotes to maize production (37 million ha in 2014) is larger than that of any other crop (National Bureau of Statistics of China, 2015). The main maize planting areas in China are divided among four to six zones (Qiu et al., 2003; Li and Wang, 2010) with dramatically different climatic conditions. For example, in the north spring maize region, the largest maize production region in China, the annual accumulated temperature above 10 °C ranges between 2000 and 2900 °C, the total sunshine hours ranges between 2100 and 2900 h, and the total precipitation ranges between 400 and 800 mm (Li and Wang, 2010; Liu et al., 2013a,b; Hou et al., 2014). Previous studies have shown that climatic conditions, especially solar radiation, have great influence on maize growth and population structure (Liu et al., 2015b; Iizumi and Ramankutty, 2015). The maize plant density in China varies depending on climatic conditions, particularly solar radiation. Therefore, determining the optimum plant density under different climatic conditions across different regions would be helpful for maize cultivation in China and other countries around the world.

Crop production depends on plant population; therefore, an appropriate canopy structure is vital to attain high yield (Casal et al., 1985). Proper plant density is the most critical factor for establishing an optimum canopy structure. In the United States, the country with the greatest maize production in the world, the maize plant density is typically 82, 230–92, 100 plants ha^{-1} (Grassini et al., 2011). In contrast,

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http://dx.doi.org/10.1016/j.fcr.2017.05.006
Received 19 March 2017; Received in revised form 4 May 2017; Accepted 4 May 2017
0378-4290/

the plant density is much more complicated in China where plant densities range from 49,850 plants ha^{-1} in the Huang-Huai-Hai Plain to 65,180 plants ha^{-1} in the northwest spring maize area. These values are much lower than the U.S. average (Meng et al., 2013; Li et al., 2016). Because China is a large country, climatic conditions, especially solar radiation, and maize plant densities change significantly across longitudes. However, the optimal crop plant density for different climatic conditions across longitudes remains unclear.

Researchers have sought for many years to elucidate how plant density is related to yield, leaf area, leaf area index (LAI), and photosynthesis (Tetio-Kagho and Gardner, 1988; Begna et al., 1997; Echarte et al., 2000; Amanullah et al., 2007; Liu et al., 2015a; Xue et al., 2015). These studies have shown that LAI increases as plant density increases. However, it is possible for LAI to become too high, causing self-shading and possibly yield loss (Liu et al., 2015a; Srinivasan et al., 2017). In previous studies, our research group observed that LAI and yield both increased gradually as plant density increased. In some high-yielding maize stands the LAI was greater than 10 (unpublished data). However, Kiniry et al. (2004) reported that the optimum LAI for maize was 6. Therefore, clarifying the critical LAI under optimum plant densities across different regions is of great significance for the management of closely planted stands and for improving light use efficiency to increase yield.

The light extinction coefficient (k) is an important indicator that reflects a crop's ability to attenuate light within the crop canopy. The k value is influenced by crop canopy structure, especially leaf area and leaf azimuthal orientation (Flans et al., 1996; Maddonni et al., 2001), both of which are affected by plant density. In a simulation study, Flans et al. (1996) observed an exponential relationship between LAI and light interception by the crop. In this study we defined the "optimum plant density" as the one that produced the highest yield. The corresponding k value was the "optimum k value" for a given region. Thus, we determined the optimum LAI and plant density under given solar radiation conditions.

We conducted experiments in three different ecological regions spanning a large east-west distance in China: Gongzhuling (Jinlin Province, 43°30′ N, 124°50′ E), Yinchuan (Ninxia Province, 38°13′ N, 106°14′ E), and Qitai (Xinjiang Province, 43°50′ N, 89°46′ E). The climatic conditions vary significantly among these regions. The objectives of this study were (1) to determine the optimum maize plant density for these regions as well as the corresponding optimum LAI and yield under these plant densities and (2) to elucidate the influence of climatic conditions on optimum plant density across a large longitudinal distance in China. The findings of this study should be helpful not only for maize producers in regions with different climatic conditions but also for plant breeders as they develop new maize lines.

2. Materials and methods

2.1. Experimental design

Field experiments were conducted from 2013 to 2015 at the Qitai Farm (Qitai, Xinjiang Uygur Autonomous Region), the Ninxia University Farm (Yinchuan, Ningxia Hui Autonomous Region), and the Gongzhuling Experimental Station, Institute of Crop Sciences, Chinese Academy of Agricultural Sciences (Gongzhuling, Jinlin Province) (Fig. 1). The first two sites are in China's northwestern irrigated spring maize region. The third site is in the north spring maize region. Table 1 shows the geographical positions of the sites and their average climatic conditions during the maize growing season. Qitai Farm and Yinchuan are located in the regions with an arid continental climate. Sunshine is abundant during the maize growing season and the diurnal temperature range is large. Compared with Qitai and Yinchuan, Gongzhuling receives less solar radiation and has a smaller diurnal temperature range. The daily mean temperatures are similar at the three sites.

The maize cultivar in this study, 'Zhengdan 958' (ZD958), is widely grown in all three regions. The maize was planted in a randomized complete block with three replicates at six densities: 4.5, 6, 7.5, 9, 10.5 and 12 plants m^{-2} (respectively referred to as D1–D6). All six treatments were used at Qitai and Yinchuan in all three growing seasons. At Gongzhuling, treatments D1–D4 were used in 2013 and 2014, whereas treatments D1–D6 were used in 2015. Maize was sown by hand from early April to early May and harvested from late September to early October at all three sites.

The crop management practices were selected so as to obtain the highest possible yields at each site. Soil nutrient tests were conducted and then the following fertilizer rates were determined based on recommendations in previous studies: 225–500 kg N ha^{-1}, 100–150 kg P_2O_5 ha^{-1}, and 75–112 kg K_2O (Hou et al., 2012; Li et al., 2015). All three sites were irrigated. Weeds, diseases, and pests were controlled in the plots.

2.2. Sampling and measurements

Silking was defined as the date when 60% of the ears showed silk emergence. Physiological maturity was the date when the black layer appeared. The meteorological data (i.e., daily temperature, mean temperature, and precipitation,) was obtained from the meteorological station nearest each site (CMA Archives, 2010). The distance between the meteorological stations and the sites ranged from 3 to 39 km.

Twenty ears were collected from the middle four rows of each plot at physiological maturity. The number of kernels was counted on each ear. Ear number, grain moisture content, and final yield were also determined for each plot. The grain yield and 1000-kernel weight were expressed at 14% moisture. The grain moisture content was determined with a portable moisture meter (PM8188, Kett Electric Laboratory, Tokyo, Japan). Aboveground dry matter at silking and physiological maturity was measured using random five plants from each plot with border rows removed. The grain was separated from the other plant parts and then all of the plant samples were dried at 80 °C to constant weight.

The number of growing degree days (GDD) was calculated using the equation $GDD = \Sigma\ [(T_{max} + T_{min})/2 - T_{base}]$, where T_{max}, T_{min}, and T_{base} are the maximum, minimum, and 10 °C base temperatures, respectively (McMaster and Wilhelm, 1997; Yang et al., 2004). The upper threshold temperature was 30 °C.

The leaf area was measured for five plants per plot and then averaged to obtain one value. The length (L) and maximum leaf width (W) were measured and then leaf area (S) was calculated according to the formula: $S = 0.75 \times L \times W$ (Montgomery, 1911).

The k value was calculated according to the following formula (Maddonni et al., 2001):

$$k = -\ln(TPAR/IPAR)/LAI \quad (1)$$

where intercepted photosynthetically active radiation (IPAR) was calculated from photosynthetic active radiation (PAR) above the canopy and transmitted PAR (TPAR) at the bottom of the canopy. The reflection of light in the canopy was not considered in this study. Photosynthetic photon flux density (PPFD) was measured between 13:00 and 15:00 (solar noon, the time difference among the three experimental sites was considered) on seven successive clear days using a 1-m line quantum sensor (SUNSCAN, Delta, UK). At least five measurements of PPFD were made in each plot at silking.

According to the Mosi-Formula (Monsi and Saeki, 2005) and the definition of the optimum leaf area index (Hu, 1992) we developed the following formula to calculate the optimum LAI (LAI_{opt}) at silking:

$$LAI_{opt} = A \times \left(-\frac{1}{k} \times lnE\right) \quad (2)$$

where A is a constant closely related to the solar radiation intensity. The *E* value is the ratio of the light intensity at which the light compensation