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Modeling the effects of plant density on maize productivity and water balance in the Loess Plateau of China

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ABSTRACT

Loess Plateau of China is an area with serious soil evaporation and large inter-annual rainfall variations. Water stress is the major limiting factor for crop production in local area. Optimizing plant density is one crucial management in semi-arid dry land areas where crop growth is constrained by precipitation and a high evaporative demand. The Agricultural Production System Simulator (APSIM) was parameterized and tested with two years datasets, and then used to investigate long-term rainfed maize productivity and water balance with the historical weather records. Model application showed that water use and yield were varied because of the plant density and the inter-annual variability of precipitation. Plant density presented no influence on the evapotranspiration (ET) in extremely dry years, dry years and mild wet years but a significantly ($P < 0.05$) influence in normal and extremely wet years. In extremely dry years, the grain yield and (WUE) were all significantly ($P < 0.05$) decreased when plant density increased. The grain yield and WUE showed a parabolic relation with the plant density except extremely dry years. On average, the maximum yield and WUE were 6715 kg ha^{-1} and 1.81 kg m^{-3} at 52500 plants ha^{-1} (D_2) in dry years, 7857 kg ha^{-1} and 1.92 kg m^{-3} at 67500 plants ha^{-1} (D_3) in normal years, 8937 kg ha^{-1} and 2.19 kg m^{-3} at 67500 plants ha^{-1} (D_3) in mild wet years, and 9713 kg ha^{-1} at 82500 plants ha^{-1} (D_4) and 2.25 kg m^{-3} at 67500 plants ha^{-1} (D_3) in extremely wet years, respectively. However, no significant difference was obtained for average yield or WUE when compared traditional density of 52500 plants ha^{-1} (D2) with higher plant density. Compared with the traditional plant density of 52500 plants ha^{-1} (D_2), the increase of plant density significantly ($P < 0.05$) reduced soil evaporation, only with the exception of extremely dry years. In order to get long term average benefits in the study area and similar agro-ecological zones, plant populations should not exceed 32500 plants ha^{-1} (D_1) in extremely dry years, indeed, lower may be better. A plant density of 52500 plants ha^{-1} (D_2) in dry years and 67500 plants ha^{-1} (D_3) in normal years, mild wet years and extremely wet years are recommended as the optimum value, respectively.

1. Introduction

China is the second largest maize (*Zea mays* L.) producer in the world, with an annual sowing area of approximately 37 million ha and production of 215.6 million t (National Bureau of Statistics of China (NBSC), 2015). Northern China has a large region of dryland farming, which accounts for about 55% of the nation's total cultivated land area (Xin and Wang, 1999). Precipitation is the main resource for the crop and shows a large inter-annual variability. Dryland maize is one of the most widely grown grain crops on Loess Plateau where a typical semi-humid region dominated by rainfed farming. In the past few decades, on-farm yield has risen without pause owning to the high tolerance of the newer hybrids at higher plant densities (Duvick, 2005). As a result, plant density has been one of important cultural practices impacting grain yield in the Corn Belt for several decades (Sangoi, 2001). Several investigations demonstrate that the relationship between yield components and plant densities is parabolic (Holliday, 1960; Sangoi et al., 2002; Tokatlidis et al., 2011). Potentially, high plant density has higher yield due to a large number of small ears. But higher plant density resulting in a reduction in grain yield per plant by intensive competition for the resources such as incident radiation, water, and nutrients (Sangoi et al., 2002). In addition, it will accelerate the rate of leaf senescence (Borrás et al., 2003) and increase the risk of lodging (Tollenaar et al., 1997). On the other hand, low plant density result in low production due to the limited ears per unit area.

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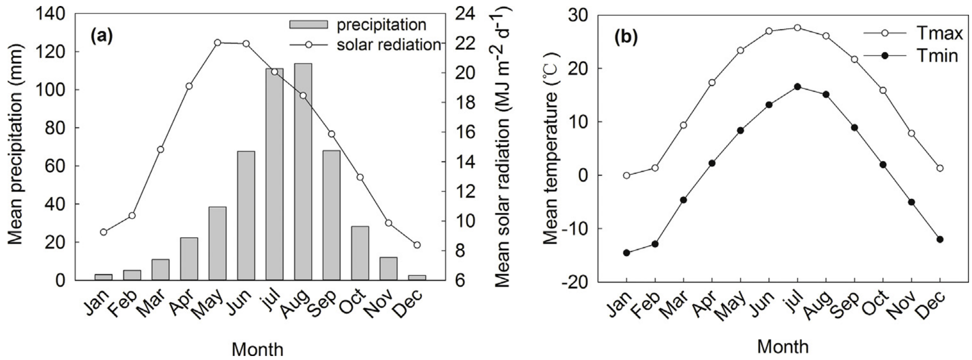

Fig. 1. (a) mean monthly solar radiation and precipitation and (b) mean monthly maximum, minimum temperature.

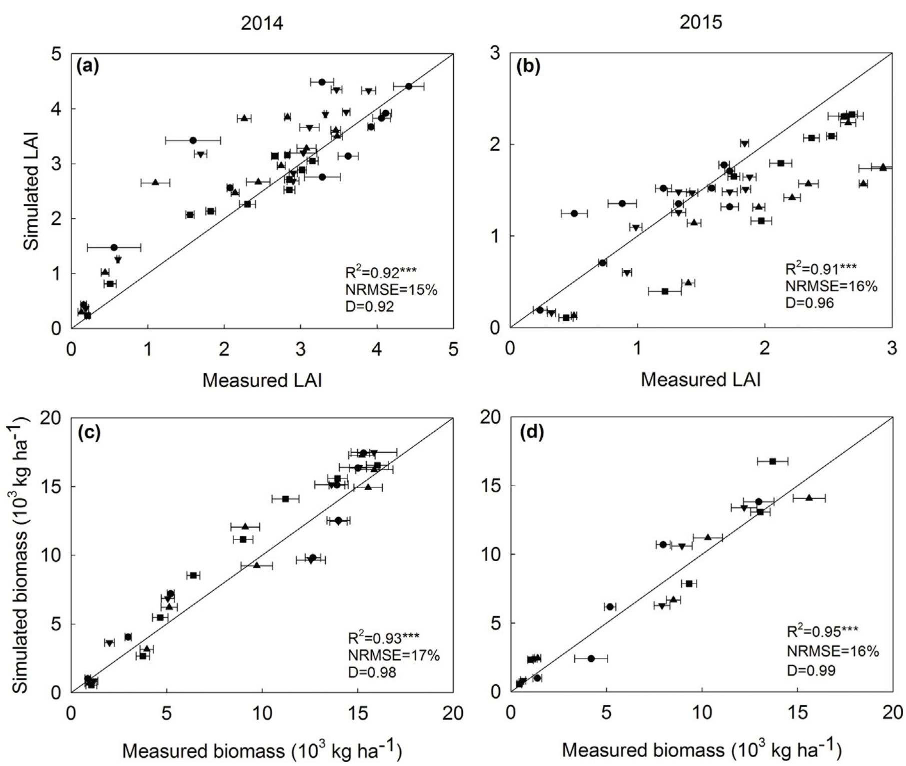

Fig. 2. Comparisons of measured LAI (a and b), above-ground biomass (c and d). a and c were used to calibrate the model, b and d were used to validate the model. "■" is 52500 plants ha^{-1}, "▲" is 67500 plants ha^{-1}, "▼" is 82500 plants ha^{-1}, and "●" is 97500 plants ha^{-1}, respectively. The solid line is 1:1 line. Error bars of the measured data are standard error of the mean. *** indicates significance at $P < 0.001$.

More seriously, many modern maize hybrids do not tiller effectively and then produce only one ear per plant under low density (Gardner et al., 1985). Additionally, increasing plant population can increase the amount of soil water transpired relative to the soil-water evaporated directly from the soil surface and to the total soil-water extracted (Persaud and Khosla, 1999).

As a matter of fact, determination of the optimum plant population density necessary for optimal yield is a major agronomic goal especially where water is a limiting factor (Ren et al., 2016). Since optimum plant densities are related to soil water availability, it is important to understand the probability of various water-limited yield potentials and profitability at different sowing density for the large variability of rainfall in Loess Plateau. Many investigations have been conducted to determine the optimum plant densities for maize on Loess Plateau of China. A maximum WUE of 2.52 kg m^{-3} was achieved at plant density of 75000 plants ha^{-1} in normal and wet years in Shanxi province (Zhang et al., 2014). The optimum plant density for different cultivars to get maximum yield and WUE was different. For example, cultivar "nongda 108" get the maximum yield and WUE at density 57000 plants ha^{-1} but cultivar "zhengdan 958" get the maximum at 97000 plants ha^{-1} (Liu et al., 2010). The optimal plant density for a given field depends on each year's varying growing conditions. Because of the large variability of the rainfall on the Loess Plateau in China, it will cost long time and resource to determine the optimum density according to field experiments in this site.

In recent years, the farming systems models such as CERES-maize and AquaCrop were used to investigate relation between the plant density and production (Piper and Weiss, 1990; Nyakudya and Stroosnijder, 2014). The Agricultural Production Systems Simulator (APSIM) has been used to investigate the effect of plant density and irrigation strategies on maize yield (Peake et al., 2008) and frequently used in China to investigate agricultural management impacts on crop productivity (Chen et al., 2008, 2010), however, there is still a lack of comprehensive analysis how the yield of rainfed maize and soil water balance are affected by the plant