Planting density affected biomass and grain yield of maize for seed production in an arid region of Northwest China (Postprint)

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Abstract

Field experiments were conducted from 2012 to 2015 in an arid region of Northwest China to investigate the effects of planting density on plant growth, yield, and water use efficiency (WUE) of maize for seed production. Five planting densities of 6.75, 8.25, 9.75, 11.25 and 12.75 plants/m2 were conducted in 2012, and a planting density of 14.25 plants/m2 was added from 2013 to 2015. Through comparison with the AquaCrop yield model, a modified model was developed to estimate the biomass accumulation and yield under different planting densities using adjustment coefficient for normalized biomass water productivity and harvest index. It was found that the modified yield model had a better performance and could generate results with higher determination coefficient and lower error. The results indicated that higher planting density increased the leaf area index and biomass accumulation, but decreased the biomass accumulation per plant. The total yield increased rapidly as planting density increased to 11.25 plants/m2, but only a slight increase was observed when the density was greater than 11.25 plants/m2. The WUE also reached the maximum when planting density was 11.25 plants/m2, which was the recommended planting density of maize for seed production in Northwest China.

Full Text

Preamble

Planting density affected biomass and grain yield of maize for seed production in an arid region of Northwest China

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Abstract

Field experiments were conducted from 2012 to 2015 in an arid region of Northwest China to investigate the effects of planting density on plant growth, yield, and water use efficiency (WUE) of maize for seed production. Five planting densities of 6.75, 8.25, 9.75, 11.25, and 12.75 plants/m^2 were implemented in 2012, and a planting density of 14.25 plants/m^2 was added from 2013 to 2015. Through comparison with the AquaCrop yield model, a modified model was developed to estimate biomass accumulation and yield under different planting densities using adjustment coefficients for normalized biomass water productivity and harvest index. The modified yield model demonstrated better performance, generating results with higher determination coefficients and lower error. The results indicated that higher planting density increased the leaf area index and biomass accumulation but decreased biomass accumulation per plant. Total yield increased rapidly as planting density increased to 11.25 plants/m^2, but only a slight increase was observed when density exceeded 11.25 plants/m^2. WUE also reached its maximum at a planting density of 11.25 plants/m^2, which represents the recommended planting density for maize seed production in Northwest China.

Keywords: planting density; yield model; biomass accumulation; grain yield; water use efficiency; Northwest China

1 Introduction

Planting density is one of the most important agronomic factors affecting crop grain yield and water use efficiency (WUE). Increased planting density usually improves seasonal interception of solar radiation, leading to enhanced canopy photosynthesis and biomass accumulation, and consequently higher grain yield and water productivity. However, grain yield tends to decline when planting density exceeds a certain level due to limited supply of carbon and nitrogen under intense interplant competition for intercepted radiation, soil nutrients, and water. This also increases barrenness and decreases kernel number. Consequently, an optimal planting density exists for maximizing utilization of available resources and achieving maximum yield per unit area by coordinating crop population and individual development.

Previous studies have reported that maize grain yield and WUE increased with planting density when below an optimum level. The optimal planting density of maize varies depending on varieties and microclimate conditions, ranging from 3.00 to over 9.00 plants/m^2. Under surface irrigation conditions, optimal planting density was found to be 5.00–5.60 plants/m^2 in Egypt, while another study observed an optimal density of 7.10 plants/m^2 under full irrigation.

In recent years, maize planting area has increased rapidly in China, with demand for maize seeds also rising significantly. Particularly in the arid region of Northwest China, natural isolation conditions and abundant light and heat resources are highly suitable for maize seed production, making it the main irrigated crop with rapidly expanding planting area. Unlike hybrid maize, seed production maize includes female and male parents of short inbred lines without heterosis. While numerous studies have examined planting density effects on common maize yield, few have investigated effects on seed production maize yield and WUE, particularly using yield models.

The AquaCrop model, recently developed by the Food and Agriculture Organization of the United Nations (FAO), assumes that aboveground biomass growth rate is linearly proportional to transpiration through biomass water productivity (WP), while yield is determined by harvest index (HI) multiplied by aboveground biomass. HI has been shown to increase with planting density but decline after reaching optimal density. To obtain conservative estimations for a given crop, WP should be normalized for climate by accounting for the ratio of transpiration to reference crop evapotranspiration. The normalized biomass water productivity (WP*) was found to be about 30-35 g/m^2 for C4 crops. However, it remains unclear whether WP* and HI in the AquaCrop yield model can be treated as constants under different planting densities for seed production maize, requiring further investigation.

The objectives of this study were to: (1) investigate effects of planting density on plant growth, yield, and WUE of maize for seed production; (2) modify WP* and HI in the AquaCrop yield model to improve estimation accuracy under different planting densities; and (3) determine the recommended planting density for maize seed production in the arid region of Northwest China.

2.1 Experimental Site

The experiments were conducted during the 2012–2015 growing seasons at the Shiyanghe Experimental Station of China Agricultural University (37°52 N, 102°50 E; 1581 m a.s.l.) located in Wuwei, Gansu Province, China. The station lies in a typical continental temperate climate zone, with mean annual precipitation of 164.4 mm, mean annual pan evaporation of 2000 mm, average groundwater table lower than 25 m below ground surface, mean annual sunshine duration over 3028 h, mean frost-free period of 150 days, and annual mean temperature of 8.8°C. Soil texture at the experimental station was light sandy loam with mean soil dry bulk density of 1.38 g/cm^3 and field water capacity of 0.29 cm^3/cm^3.

2.2 Experimental Design

Maize for seed production is normally planted at densities of 9.75-10.5 plants/m^2 in Northwest China. In 2012, experiments included five planting densities: 6.75, 8.25, 9.75, 11.25, and 12.75 plants/m^2 (designated D1, D2, D3, D4, and D5, respectively). From 2013 to 2015, a planting density of 14.25 plants/m^2 was added (D6). A randomized complete block design with three replicates per treatment was used. Experimental plots measured 9.6 m long and 6.0 m wide. In 2012, maize was sown in a pattern of one row of male parents with seven rows of female parents, changing to one male row with five female rows from 2013 to 2015. All treatments had the same row spacing of 40 cm, with six planting densities achieved through different within-row spacings: 37, 30, 25, 22, 20, and 18 cm for D1 through D6, respectively.

Before sowing, all plots received basal fertilizers of N (136 kg/hm^2), P O (240 kg/hm^2), and K O (50 kg/hm^2). After fertilization, soil surfaces were partially covered with 1.2 m wide plastic film, leaving 0.4 m bare soil between rows. Top-dressing with N (364 kg/hm^2) was applied on June 10, 2012, June 5, 2013, June 8, 2014, and June 8, 2015. Irrigation quota was 100 mm using border irrigation. Table 1 lists meteorological variables, irrigation, and planting times.

2.3.1 Meteorological Variables

Meteorological variables including solar radiation (Rs), precipitation (P), air temperature (Ta), and relative humidity (RH) during the 2012-2015 growing seasons were continuously monitored using a standard automatic weather station (Hobo, Onset Computer Corp., USA) located 100 m from the experimental plots. Thirty-minute averages of all variables were calculated and recorded using a data logger.

2.3.2 Leaf Area Index and Biomass Accumulation

Five female plants per plot were randomly selected for LAI and biomass accumulation measurements. Leaf length and maximum width were measured with a ruler at 7-10 day intervals after 15 days from sowing. Leaf area was determined by summing the rectangular area (length × maximum width) of each fully developed leaf, adjusted by a factor of 0.74. LAI was calculated by dividing leaf area per plant by ground area per plant.

Plant samples were collected at each growth stage. Total biomass accumulation was obtained after oven-drying leaves at 60°C until constant weight was maintained for three hours, then weighing with an electronic scale (precision 0.01 g).

2.3.3 Determination of Transpiration

Soil water content in the root zone was monitored using a Diviner 2000 system (Sentek Pty Ltd., Australia). Two PVC access tubes were installed below mulched and bare soil in each plot. Measurements were taken at 0.1 m intervals within 0-1 m soil depth every 5-7 days, as well as before and after irrigation and heavy rainfall events. Calibration was performed using the gravimetric method near the probe.

Evapotranspiration (ET, mm) was estimated through soil water balance analysis. Since the experimental plot was flat and rainfall was not intensive, surface runoff was neglected. Groundwater recharge was negligible as the water table was below 25 m. Measured soil water content at 90–100 cm depth showed no change before and after irrigation, so drainage was ignored. ET was estimated by:

$$ET = Pe + I - \Delta W$$

where Pe is effective precipitation (mm), I is irrigation amount (mm), and ΔW represents water content change (mm) in the root zone determined by:

$$\Delta W = W_{t2} - W_{t1}$$

where W_{t1} and W_{t2} represent mean water content (mm) in the root zone at times t_1 and t_2, respectively.

Soil evaporation (E, mm) was measured with two micro-lysimeters placed in bare soil between plastic films in each plot. The 20 cm high micro-lysimeter consisted of PVC tubes with inner and outer diameters of 10 and 11 cm, respectively. The outer cylinder was fixed in soil with its top level with the surface. The inner cylinder contained an intact soil core and was weighed daily at 19:00 LST using an electronic scale (precision 0.1 g). After measuring E, crop transpiration under different planting densities (Tr, mm) was calculated by:

$$Tr = ET - E$$

2.3.4 Grain Yield, Water Use Efficiency, and Harvest Index

Fifteen plants from the center of each plot were randomly selected for manual harvesting each season. Seeds were weighed after sun-drying to obtain grain yield (Y, t/hm^2). WUE (kg/m^3) was calculated by:

$$WUE = \frac{Y}{ET}$$

Harvest index (HI, %) under different planting densities was determined by:

$$HI = \frac{Y}{BA} \times 100\%$$

where BA is aboveground biomass accumulation (t/hm^2).

2.4 Estimation of Biomass Accumulation and Yield

In the AquaCrop model, BA is estimated using crop transpiration under different planting densities during the growing season (Tr) and normalized water productivity under standard crop management practice (WP*) as:

$$BA = \sum \left(\frac{Tr \times KS_b}{ET_0} \times WP^* \right)$$

where ET_0 is reference crop evapotranspiration calculated according to the FAO Penman-Monteith equation; KS_b is the air temperature stress coefficient (taken as 1 due to no temperature stress during the growing season); and WP* is normalized water productivity under standard practice, represented by a reference planting density of 11.25 plants/m^2 in the study area.

Harvestable yield (YA, t/hm^2) was then calculated from BA and HI under standard practice (HI_0) using:

$$YA = BA \times HI_0$$

The AquaCrop yield model was modified by introducing adjusted WP* under different planting densities (WP^*_{adj}) and adjusted HI (HI_{adj}). A linear relationship was assumed between relative WP* and relative planting density (D_{adj}/D_0):

$$\frac{WP^*_{adj}}{WP^*_0} = a + b \times \frac{D_{adj}}{D_0}$$

where D_{adj} is planting density (plants/m^2) and D_0 is reference planting density (11.25 plants/m^2). Coefficients a and b were fitted using measured transpiration and aboveground biomass data from 2012–2013, yielding values of 0.37 and 0.61, respectively.

HI_{adj} was calculated as:

$$HI_{adj} - HI_0 = c + d \times \frac{D_{adj}}{D_0}$$

where c and d were fitted using measured yield and biomass data from 2012–2013, yielding values of -0.18 and 1.29, respectively.

WP^*_{adj} and HI_{adj} can be calculated by:

$$WP^*_{adj} = WP^*_0 \times \left(a + b \times \frac{D_{adj}}{D_0} \right)$$

$$HI_{adj} = HI_0 + c + d \times \frac{D_{adj}}{D_0}$$

Aboveground biomass accumulation (B_d) and grain yield (Y_d) under different planting densities were then obtained using the modified model:

$$B_d = \sum \left(\frac{Tr \times KS_b}{ET_0} \times WP^*_{adj} \right)$$

$$Y_d = B_d \times HI_{adj}$$

2.5 Data Analysis and Model Performance Evaluation

SPSS 13.0 software (SPSS Inc., USA) was used for statistical analysis. Means were compared using Duncan' s multiple-range test at the 5% probability level. Model performance was evaluated based on linear regression between estimated (E_i) and observed (Q_i) yield values. Mean absolute bias error (MAE) and root mean square error (RMSE) were calculated as:

$$MAE = \frac{1}{N} \sum_{i=1}^{N} |Q_i - E_i|$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (Q_i - E_i)^2}$$

where N is the number of data samples.

3.1 Effect of Planting Density on LAI and Biomass Accumulation

Figure 1 [Figure 1: see original paper] shows LAI of maize for seed production under different planting densities across all seasons. Under each density, LAI increased rapidly from the shooting stage, peaked at heading, and declined at maturity due to leaf yellowing or wilting. During each season, LAI increased with planting density except at the seeding stage. Differences between densities reached maximum at heading, with maximum LAI differences of approximately 60% in 2012, 70% in 2013, 88% in 2014, and 80% in 2015 between D1 and the highest density.

Figures 2 and 3 present biomass accumulation and biomass per plant across densities and years. Both parameters showed logistic growth patterns, increasing gradually with plant growth regardless of density. Except at seeding, biomass accumulation increased rapidly up to 12.75 plants/m² (D5), with only slight increases beyond this density (Fig. 2 [Figure 2: see original paper]). However, higher density adversely affected biomass per plant in all seasons (Fig. 3 [Figure 3: see original paper]). Differences in biomass accumulation and biomass per plant between lowest and highest densities peaked at maturity. Compared to D1, the highest density increased biomass accumulation by 55% in 2012, 67% in 2013, 60% in 2014, and 67% in 2015, but decreased biomass per plant by 18% in 2012, 21% in 2013, 24% in 2014, and 21% in 2015, respectively. This occurred because aboveground biomass accumulation was associated with LAI, which increased with planting density. Higher LAI increased radiation interception proportion, leading to greater canopy photosynthesis and biomass accumulation. However, higher density intensified interplant competition, reducing biomass per plant. These results align with previous findings.

3.2 Effect of Planting Density on Yield and WUE

Table 2 presents yield and WUE results under different densities from 2012–2015. Results varied significantly among years due to microclimate differences. Yield per plant and grain yield were higher in 2012 than other years, with yield per plant declining with density in all years—consistent with previous research. This likely resulted from increased interplant competition at high densities reducing biomass per plant and thus yield per plant.

Grain yield showed different trends than yield per plant. It increased rapidly as density rose to 11.25 plants/m² (D4), with only slight increases beyond this threshold. Yield began decreasing when density exceeded 12.75 plants/m². This can be explained by the fact that under lower densities (D1-D4), interplant competition was minimal, so grain yield increased with radiation interception by leaf area during reproductive growth. However, when density was sufficient to intercept essentially all radiation at full canopy, further increases did not enhance yield. Moreover, higher densities may lead to fewer flower initials, poor pollination from tasseling-silking asynchrony, or kernel abortion after fertilization, consequently reducing grain yield.

WUE ranged from 1.84–2.46 kg/m³ in 2012, 0.90–1.19 kg/m³ in 2013, 1.13–1.39 kg/m³ in 2014, and 0.86–1.36 kg/m³ in 2015. Higher WUE in 2012 resulted from greater grain yield. However, density effects on WUE were similar across study periods. WUE increased significantly with density below 11.25 plants/m² (D4), but showed no significant increase beyond D4.

Table 2 showed significant decreases in grain yield and WUE when density was below 11.25 plants/m² or above 12.75 plants/m², indicating optimal densities of 11.25–12.75 plants/m² under these conditions. Previous studies reported optimal densities ranging from 4.80 to 10.00 plants/m² for various maize types. The optimal density in this study was significantly higher than for hybrid maize, primarily because seed production maize uses short inbred parent lines without heterosis, resulting in smaller interplant competition and greater tolerance of higher densities. WUE reached maximum at 11.25 plants/m², with no significant increase at higher densities. Moreover, higher densities resulted in greater evapotranspiration and LAI, leading to water resource waste and making agronomic practices more difficult. Therefore, the recommended planting density of 11.25 plants/m^2 is more economical for maize seed production in Northwest China.

3.3 Modification of Yield Model Under Different Planting Densities

Figure 4 [Figure 4: see original paper] compares estimated biomass accumulation and grain yield from the AquaCrop yield model (BA and YA) and modified yield model against measured values. The original AquaCrop model overestimated biomass and yield when density was below the reference density but underestimated when above it (Fig. 4). The determination coefficient (R^2), MAE, and RMSE were 0.78, 1.41, and 1.85 t/hm^2 for biomass accumulation, and 0.88, 0.62, and 0.50 t/hm^2 for grain yield, respectively (Table 3). This occurred because WP* and HI were treated as constants in the AquaCrop model, causing large estimation errors. In reality, they were not constant: WP* increased with density until reaching the optimum, while HI increased below the reference density but declined above it (Fig. 5 [Figure 5: see original paper]), consistent with other studies.

The modified AquaCrop yield model incorporated density effects on WP* and HI. Estimated biomass accumulation and grain yield from the modified model were closer to observed values (Fig. 4), with higher R^2 and lower MAE and RMSE compared to the original model (Table 3). Consequently, the modified AquaCrop yield model performed better in simulating biomass accumulation and grain yield under different planting densities for maize seed production.

4 Conclusions

Field experiments conducted from 2012–2015 examined impacts of planting density on biomass accumulation and yield of maize for seed production in Northwest China, and the AquaCrop yield model was modified to account for density effects on WP* and HI. Results indicated that increasing planting density enhanced LAI and aboveground biomass accumulation but significantly decreased yield and biomass per plant. Grain yield and WUE increased rapidly as density rose to 11.25 plants/m^2, with only slight yield increases beyond this density. Therefore, a recommended planting density of 11.25 plants/m^2 is more economical for maize seed production in Northwest China.

Within the experimental density range, the original AquaCrop yield model produced large errors, significantly overestimating biomass accumulation and grain yield when density was below the reference density and underestimating when above it. However, the modified model produced estimates closer to measured values, with higher determination coefficients and lower MAE and RMSE, indicating that the modified yield model accounting for density effects performed better in estimating biomass accumulation and grain yield of maize for seed production in the arid region of Northwest China.

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