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Competitive yield and economic benefits of cotton achieved through a combination of extensive pruning and a reduced nitrogen rate at high plant density

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A B S T R A C T

Plant density, nitrogen (N) fertilization rate and plant pruning are important measures used globally to cultivate cotton. A typical combination of 52,500 plants ha^{-1}, intensive pruning and 255 kg N ha^{-1} has been widely applied in the Yellow River Valley of China. The main objective of this study is to determine whether more beneficial combinations exist than the typical one for profitable cotton production in this region. Using a split–split plot design with four replications, we conducted a three-year field experiment to study the individual and interaction effects of plant density (52,500 and 82,500 plants ha^{-1}), plant pruning (intensive and extensive) and N fertilizer rate (195 and 255 kg N ha^{-1}) on yield, plant biomass and partitioning, N uptake and use efficiency, as well as input and output values. The results showed that cotton yield was affected by individual and interaction effects of the three agronomic factors. When planted at a moderate density (52,500 plants ha^{-1}), the seedcotton yield of intensively pruned cotton under a low N rate (195 kg N ha^{-1}) and of extensively pruned cotton under low and high (255 kg N ha^{-1}) N rates was reduced by 6.9, 6.7 and 5.4%, respectively, whereas the four combinations with high plant density (82,500 plants ha^{-1}) produced a yield value that was comparable to that of the typical combination, indicating a relatively stable yield at high plant density irrespective of pruning mode and N rate. Vegetative branches of the extensively pruned cotton accounted for 18.7–23.6% of the total biomass at moderate plant density compared with only 2.8–2.9% of the total biomass at high plant density. At moderate plant density, intensively pruned cotton exhibited a higher harvest index than the extensively pruned plants. By contrast, the harvest index for the four combinations with high plant density did not differ, suggesting a relatively stable harvest index among these combinations. There was no difference in the N biomass utility index (NBI) among all combinations. The combination of high plant density, extensive pruning and reduced N rate had a 6.7% lower nitrogen yield utility index (NYI) than the typical combination but a 5.4% higher NYI than the combination of high plant density, extensive pruning and high N rate. More importantly, the combination of high plant density, extensive pruning and reduced N rate produced comparable yield with less input, leading to 21.7% more net revenue than the typical combination. Our results support the use of high plant density, reduced N rate and extensive pruning to ensure profitable cotton production in the Yellow River Valley and other cotton-growing areas with similar ecologies.

1. Introduction

For decades, the Yellow River Valley in China has been one of the three major cotton production regions. In this region, cotton is usually planted at a moderate plant density (45,000–60,000 plants ha^{-1}) (Dong et al., 2006a) and is intensively managed using a number of agronomic practices such as plant pruning and the application of a high rate of nitrogen (N) fertilizer (225–270 kg N ha^{-1}) (Dai and Dong, 2014). Despite the moderate lint yield obtained, this intensive management system is currently being challenged with a reduction in the number of laborers in rural areas and the increasing costs and soil pollution associated with excessive fertilizer application (Dai and Dong, 2016; Feng et al., 2017). Therefore, it is necessary to improve or reform the traditional intensive system, in particular, labor and fertilizer inputs need to be reduced without a reduction in yield.

At moderate plant density, cotton plants usually have strong

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vegetative branches (VB) that grow from the main stem. These VB do not bear fruit directly, but they consume excessive nutrients, resulting in yield reduction (Dai and Dong, 2014; Dai et al., 2014). Thus, VB removal by hand has been adopted as a widely used plant pruning practice in the Yellow River Valley area (Dai and Dong, 2016). However, removal of these branches is labor intensive and inefficient. The retention of VB might be an alternative practice. It was reported that hybrid (F_1) cotton plants with VB at a low density of 22,500–30,000 plants ha^{-1} produced comparable cotton yield to those without VB at a moderate density (Dong et al., 2005). However, the fiber quality was slightly reduced because of the extended boll-setting period under such a low plant density and because of more seedcotton from VB (Dong et al., 2007; CRI (Institute of Cotton Research, Chinese Academy of Agricultural Sciences), 2013). It was also reported that VB growth was considerably inhibited as plant density increased as well as without yield reduction (Bednarz et al., 2000; Dai et al., 2014). In contrast to manual removal, a potential alternative for inhibiting VB is through a high plant density.

Nitrogen, as an essential macronutrient, is required most consistently and in larger amounts than other nutrients for cotton production (Hou et al., 2007, 2009; Chen et al., 2010). Nitrogen deficiency will lead to decreased boll production as a result of poor plant development and premature senescence (Dong et al., 2012). Nitrogen fertilization can enhance plant growth, lint yield, fiber quality and resistance to abiotic stresses such as salinity and drought; consequently, nitrogen is applied excessively by cotton growers (Bondada et al., 1996; Chen et al., 2010). Excessive application of N fertilizer is currently a serious problem in China. Approximately 270 and 450 kg N ha^{-1} are applied to cotton fields in the Yellow River Valley and the northwestern inland cotton regions in China, respectively (CRI (Institute of Cotton Research, Chinese Academy of Agricultural Sciences), 2013). An over-dose of nitrogen fertilization easily results in excessive vegetative development, soil degradation, low nitrogen use efficiency (NUE), greenhouse gas emissions and groundwater pollution risks (Hodges, 2002; Rochester et al., 2007; Geng et al., 2016). Thus, optimizing N fertilizer input to meet cotton requirements has been increasingly identified as a priority based on feedback from cotton growers. However, the N fertilizer rate and NUE are inevitably influenced by other agronomic practices such as plant density, pruning measures and planting system (Dong et al., 2010). Previous studies showed that an increased plant density could compensate for a reduced application of nitrogen without sacrificing cotton yield in a saline field (Dong et al., 2012). An in-depth analysis of plant density or plant pruning effects on N use efficiency is still important for cotton production.

Cotton yield is relatively stable within a certain plant density range (Siebert et al., 2006) through the manipulation of boll occurrence and boll weight under extensive management (Bednarz et al., 2000), as well as through dry matter accumulation and partitioning under intensive management (Dai et al., 2015). However, plant density is usually adjusted to avoid yield loss according to planting date (Wang et al., 2016; Dong et al., 2006a), soil fertility (Dong et al., 2010), plant pruning (Dong et al., 2005), or fertilizer application (Dong et al., 2012). This indicates that the optimization of an agronomic measure is usually affected by other factors, and in-depth analysis of interactions is more important than that of individual effects. The individual effects of plant density, plant pruning and nitrogen fertilizer rate on cotton growth and yield formation have been well documented. However, the interaction effects of these three factors have seldom been studied. Therefore, a three-year experiment was carried out to determine the interaction effects of plant density, N fertilizer rate and pruning modes on cotton growth, yield, nitrogen use efficiency and economic benefits and most importantly, the optimal combinations of plant density and N application rate for extensively pruned cotton plants in terms of yield and economic benefits.

2. Materials and methods

2.1. Experimental site and cultivar

The field experiment was conducted from 2013 to 2015 at the Experimental Station of the Shandong Cotton Research Center, Linqing (115°42′ E, 36°61′ N), Shandong, China. The soil (0–20 cm) characteristics of the experimental site were determined according to Dong et al. (2006b). Chemical analysis from soil samples before planting in 2013 showed that it was a sandy loam soil that contained 12.5 g kg^{-1} organic matter, 568 mg kg^{-1} total N, 35.2 mg kg^{-1} available P and 184 mg kg^{-1} available K. The climate is temperate and monsoonal with an average rainfall of approximately 600 mm, concentrated mainly in summer and early autumn. Cotton is usually sown in mid-April and is harvested at the end of October, with a growth and development period of 6 months.

K836, a high-yielding commercial Bt (*Bacillus thuringiensis*) transgenic cotton (*Gossypium hirsutum* L.) cultivar, developed by the Shandong Cotton Research Center and officially registered and released by the Shandong Crop Cultivar Evaluation Committee, was used in the experiment. Acid-delinted seeds treated with imidacloprid (Gaucho FS600, Bayer CropScience, Monheim, Germany) were kindly provided by the Luyi Cottonseed Company Ltd., Jinan, Shandong.

2.2. Experimental design

A split–split plot design with four replications was used in this study. The main plot was plant density (moderate density, 52,500 plants ha^{-1}; high density, 82,500 plants ha^{-1}), while pruning modes (intensive pruning and extensive pruning) and nitrogen fertilizer rate (high rate, 255 kg N ha^{-1}; low rate, 195 kg N ha^{-1}) constituted the sub- and sub-subplots. Each sub-subplot contained six rows of cotton, 10 m long with an inter-row spacing of 76 cm. Determination of the treatment levels was based on typical local practice, in which cotton is intensively pruned at a density of 52,500 plants ha^{-1}, with a split application of 255 kg N ha^{-1} through basal, early flowering and post-topping fertilization.

Intensive plant pruning involves plant topping, excising apical points of fruiting branches, and removal of vegetative branches (VB), old leaves, and empty fruit branches from squaring to maturity (harvest) (Dai and Dong, 2016), whereas here, extensive plant pruning only includes plant topping. For both pruning modes, plant topping was conducted in mid-July when there were approximately 12 fruiting branches per plant. In intensive pruning treatments, VB was removed at squaring (mid-June), and the apical points of fruiting branches, excess buds, old leaves, and empty fruit branches were continuously removed from squaring to maturity (harvest) according to local practice (Dai and Dong, 2014).

A compound fertilizer was applied to supply 81 kg N ha^{-1}, 81 kg P_2O_5 ha^{-1} and 81 kg K_2O ha^{-1} as a basal fertilizer before sowing, followed by 114 kg N ha^{-1} as urea (45% N) at early flowering for both N rate treatments, while an additional 60 kg N ha^{-1} was applied (post topping) in the high N rate (255 kg N ha^{-1}) treatment.

2.3. Field management

The soil was irrigated (1200 m^3 ha^{-1}) 20 days before sowing each year. A compound fertilizer as indicated above was applied to the soil as basal fertilization approximately 10 days after irrigation, and then the soil was ploughed and harrowed. Mechanical sowing, together with plastic film (0.008 mm) mulching, was simultaneously carried out on 25 April 2013, 28 April 2014 and 24 April 2015, with a 76-cm row–row distance for both plant density treatments, and hill–hill distances of 25.1 cm for the 52,500 plants ha^{-1} and 15.9 cm for the 82,500 plants ha^{-1} treatments.

Seedlings were freed from mulching at full emergence and thinned