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Effects of reduced nitrogen rate on cotton yield and nitrogen use efficiency as mediated by application mode or plant density

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ABSTRACT

Nitrogen (N) fertilization plays an important role in yield formation of field-grown cotton (*Gossypium hirsutum* L.), but little is known of its interaction with mode of application or plant density under irrigated production. Our objective was to determine the effects of N application rate on cotton yield, leaf senescence and N use efficiency as mediated by mode of application and plant density. To achieve this goal, two field experiments which were conducted from 2015 to 2016 using a split-plot design in randomized complete blocks. In the first experiment, the main plots were assigned to N application modes (conventional application and drip fertigation) and the subplots to N rates (375, 319, 264 and 0 kg N/ha). In the second experiment, the main plots were assigned to plant density (12 plants/m^2-low density and 19.5 plants/m^2-high density) and the subplots to N rates (330, 264 and 0 kg N/ha). The N rate of 264 kg/ha under drip fertigation or high plant density did not reduce cotton yield. Agronomic nitrogen use efficiency (aNUE) and nitrogen recovery efficiency (NRE) were the highest at 264 kg N/ha under drip fertigation and high plant density. Although a reduced N rate increased boll load, fertigation or high plant density relatively reduced boll load and delayed late-season leaf senescence as indicated by the increased photosynthetic rate and chlorophyll content as well as the reduced malondialdehyde concentration compared to conventional application or low plant density. The yield stability across N rates (264–375 kg N/ha) was probably due to the delayed leaf senescence and improved N use efficiency. The results suggest that the N rate could be reduced to 264 kg/ha, or 20–30% from the traditionally recommended rate, without sacrificing yield under high plant density or drip fertigation. These results are beneficial to the formulation of a scientific and rational use of N fertilizer for sustainable cotton production and environmental health.

1. Introduction

The northwest inland is currently the largest cotton-growing area in China (Dai and Dong, 2014). Holding abundant sunshine and large temperature difference between day and night, this inland is an arid area with irrigated agriculture, where drip irrigation under plastic mulch has been widely adopted for cultivation of cotton (Cao et al., 2012). Despite being one of the most dominant cotton growing areas with relatively high yield and fine quality in China, low N use efficiency resulting from irrational N application have imposed a great challenge to sustainable cotton production in the area (Ju et al., 2009; Li and Zhang, 2013; Zhang et al., 2014). Therefore, it is necessary to explore the agronomic factors affecting fertilizer use efficiency in the area, so as to reduce fertilizer inputs without yield reduction.

Nitrogen is an essential macronutrient, required most consistently and in larger amounts than other nutrients for cotton production (Hou et al., 2007). Its application can enhance canopy area, photosynthesis, lint yield, fiber quality and resistance to abiotic stresses such as salinity and drought (Bondada et al., 1996; Chen et al., 2010). Thus, N nutrition is one of the most pivotal facets of cotton production (Bondada and Oosterhuis, 2001). Deficient N levels could lead to decreased boll production due to poor plant development and premature senescence (Dong et al., 2012). Consequently, N fertilizer is often applied excessively in the northwestern inland cotton regions (Mao, 2013). However, an over-dose of N will promote excessive vegetative development and delay maturity (Hodges, 2002). Studies in Australia have

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shown that about 20% of the N fertilizer inputs can be reduced without a reduction in yield (Rochester et al., 2009). Our study also suggested that N fertilizer can be used at a moderately lower rate and more efficiently than has been traditionally used in China (Dong et al., 2010). Reports from other countries further suggested that N inputs can be reduced and N use efficiency (NUE) increased, although the optimum N rate and use efficiency are affected by a number of factors like soil fertility, field management and yield potential (Boquet, 2005; Clawson et al., 2008; Janat, 2008; Kumbhar et al., 2008). There are several measures of NUE. Agronomic nitrogen use efficiency (aNUE) and nitrogen recovery efficiency (NRE) are the two most common measures. The NRE is the proportion of the applied N fertilizer that is taken up by the crop, expressed as a percentage of that applied. It indicates how well a crop uses the N fertilizer that has been applied (Rochester et al., 2007). The aNUE is defined as the increase in (seedcotton) yield per unit of fertilizer N applied (Novoa and Loomis, 1981). Maximal aNUE leads to a maximal value: cost ratio, an important economic indicator evaluating the investment benefits since both parameters are linearly related for specific input and output prices (Vanlauwe et al., 2011).

It has been widely recognized that drip fertigation can increase water and nutrient use efficiency through improvement in crop yield per unit volume of water and nutrients (Bar-Yosef, 1999; Patel and Rajput, 2011). Drip fertigation not only results in good crop growth and yield advantage due to stable water content maintained near the root zone but also has the additional advantage as the water-soluble fertilizers can be injected in precise amounts (Ayyadurai and Manickasundaram, 2014). In the northwest inland of China, drip irrigation under plastic mulching, which saves water and increases water use efficiency as compared to furrow irrigation, is widely used (Hou et al., 2009). Compared with furrow irrigation, N use efficiency increased by 20–30% and cotton yield significantly increased due to increases in biological yield and leaf area index under drip fertigation (Li et al., 2004). The highest N recovery efficiency occurred at a lower N rate and cotton yield decreased significantly compared with high N rate under drip fertigation (Li et al., 2015). Consequently, an optimum N application rate under drip fertigation is important for achieving high cotton yield in the northwest inland of China.

Cotton has perennial and indeterminate growth habit, consequently, it is exceedingly sensitive to environmental conditions and agronomic practices such as plant density (Darawsheh et al., 2009). The effects of plant density on cotton yield have been well documented (Bednarz et al., 2005; Feinerman, 1983; Keren et al., 1983). Although final lint yields in cotton were relatively stable across a wide range of plant densities through manipulation of boll occurrence and boll weight (Bednarz et al., 2000), the maximum lint yield can be achieved only at an optimum plant density (Feinerman, 1983), which depends on N application rate and other management practices (Zhang et al., 2011). Reports have indicated a significant interaction between plant density and N rate in the Yellow River Valley of China. Increased plant density is beneficial to cotton yields under low N rate and the yield increase due to plant density, N rate or their combinations was attributed to increases in boll number or boll weight (Dong et al., 2010). In the northwest inland of China, a new cultivation system of “short-dense-early” combined with drip fertigation has been well adopted (Tian, 2016), however, the effects of N rate, plant density and their interactions have been rarely studied under the new pattern. Thus it is necessary to clarify the effects of plant density and N fertilization rate on yield and N use efficiency, and most importantly, determine the optimum N rate for northwest inland of China.

It has been widely believed that plant density, N rate and drip irrigation are three important agronomic factors for keeping high yield and sustainable development of cotton production in the northwest inland of China. A number of studies on rain-fed cotton in the Yellow River and Yangtze River valley regions have proved that the N rate can be reduced without reducing economic yield by appropriately increasing plant density in cotton (Dong et al., 2010; Mao, 2013; Wang et al., 2012). Other studies in these regions have also indicated that fertigation can reduce the N input without sacrificing yield (Yan et al., 2015; Ma et al., 2016). Reports have indicated that drip fertigation can reduce N application rate and increase N use efficiency in cotton (Bar-Yosef, 1999; Jayakumar et al., 2014). Therefore, we hyphotesized that a moderate reduction in N rate under high plant density or drip fertigation would not affect the yield of irrigated cotton in the northwest inland of China. The objectives of the present study were to determine: a) The effects of N rate on cotton growth, yield, yield components and nitrogen use efficiency as mediated by mode of application or plant density and b) If the rate of N application can be reduced without yield reduction under irrigated agriculture.

2. Materials and methods

2.1. Experimental sites and cultivars

Two field experiments were carried out at different sites in the Northwest inland of China during the growing seasons of 2015 and 2016. The first experiment was located in southern Bayingolin city (39°51′N, 79°3′E), Xinjiang, China. The average annual sunshine duration is 4400 h with 225 d of frost-free crop growth season. Daily average temperature steadily above 10 °C starts in late March and ends in late October with a period of 210 d. Relative humidity during summer months is 40–50%, with an annual precipitation of 100.3 mm. The soil is sandy loam (the typical Xinjiang gray desert soil) with pH 8.0, organic matter 10.01 g/kg, total N 0.93 g/kg, available P 10.8 mg/kg and available K 295 mg/kg. CRI 49, a dominant cotton cultivar in the local area, was used in the experiment.

The second experiment was located in Dafeng Town (44°68′N, 87°12′E), Hutubi County, Xinjiang, China. The experimental area is in a warm-temperate arid zone with a continental climate, an average annual precipitation of 150–200 mm and an evaporation of 1600–2200 mm. Annual effective accumulated temperature is 3400–3584 °C. The soil is sandy loam (similar to the soil in the first experiment) with pH 8.0, organic matter 9.87 g/kg, total N 0.87 g/kg, available P 11.5 mg/kg and available K 308 mg/kg. Xinluzao 66, a dominant cotton cultivar in the local area was used in the experiment.

2.2. Experimental design and field management

A split-plot design in randomized complete blocks with three replications was used for the first experiment. The main plots were assigned two N application modes (conventional application-30% N fertilizer plus all P and K fertilizers basally applied, and the balance 70% N applied at early flowering and drip fertigation −30% N, and all P and K used as basal fertilizer and the balance 70% N applied through drip fertigation with 15% at squaring, 27.5% at flowering and 27.5% at boll-setting). Subplots were assigned four N fertilizer (in the form of urea) rates: 375, 319, 264 and 0 kg N/ha, hereafter referred to N_{375}, N_{319}, N_{264}, and N_0. The N_{375} is the recommended rate in local high-yielding cotton fields (Tian, 2016), while the N_{319} and N_{264} are rates reduced by 15 and 30% relative to N_{375}. Each subplot was 60 m^2 (13.3 m × 4.51 m) and contained 6 rows with a plant population density of 18 plants/m^2. The experiment was performed in 2015 and repeated in 2016.

The second experiment was arranged into the same design as the first but the main plot was plant density (12 and 19.5 plants/m^2), while N rates (0, 264 and 330 kg/ha) constituted the subplots, hereafter referred to N_0, N_{264}, and N_{330}. As in the first experiment, 30% N fertilizer, and all P and K fertilizer were used as basal fertilizer and the balance 70% N fertilizer was applied through drip fertigation with 15% at squaring, 27.5% at flowering and 27.5% at boll-setting. Each subplot was 60 m^2 (13.3 m × 4.51 m) and contained 6 rows at a plant population density of 12 or 19.5 plants/m^2.

The cotton cultivar, CRI 49 was used for experiment 1 while Xinluzao 66 was used for experiment 2; both were sown on 14–17th