Field Crops Research 217 (2018) 75–81

Contents lists available at ScienceDirect

Field Crops Research

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

Localized ammonium and phosphorus fertilization can improve cotton lint yield by decreasing rhizosphere soil pH and salinity

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ARTICLE INFO

Keywords:
Localized fertilization
Ammonium sulfate
Cotton
Rhizosphere processes
Salinity
pH

ABSTRACT

Soil salinity affects crop production, especially in arid regions such as Central Asia, by inhibiting cotton (*Gossypium hirsutum* L.) root growth and thus capacity to scavenge phosphorus (P) from soil. We hypothesized that acidifying rhizosphere pH would reduce salinity in rhizosphere soil and improve plant growth and P nutrition. A 2-year experiments was conducted in a drip-irrigated cotton field in Xinjiang, China, the largest oasis-type agricultural region in Central Asia, to test six combinations of localized nitrogen (N) and P applications. The cotton was drip-irrigated every 10–15 days after the early bud stage (60 days after sowing). The localized supply of superphosphate and ammonium sulfate as starter fertilizers decreased the pH from 7.6 to 7.4 and salt content from 2.1 to 1.7 g/kg in the cotton rhizosphere soil at the seedling stage, thereby increasing P uptake and aboveground biomass compared to the control (conventional farmers' practice of broadcast fertilization). Furthermore, fertigation with ammonium sulfate at the flowering stage further decreased rhizosphere soil pH and increased P uptake, aboveground biomass. Thirdly, the lint yield was increased by around 15% by the fertilizer management of the localized supply of superphosphate and ammonium sulfate compared with the control. We conclude that localized ammonium sulfate and superphosphate may be an effective soil amelioration measure to improve cotton production in highly saline soils in dry regions.

1. Introduction

Soil salinity is a major problem in agriculture as it affects at least 20% of the irrigated land (Pitman and Läuchli, 2002), and more than half of the existing irrigation systems are associated with salinization in arid zones (Szabolcs, 1994). The improvement and management of soil quality in arid areas are important in addressing the problem of soil salinity. Because of severe water shortage caused by continuously increasing population and global climate change, the traditional approach (irrigation-drainage balance to ensure salt leaching), particularly in arid zone in northwest China (located in central Asia, the world's largest drip-irrigation area), is becoming increasingly difficult to put into practice (Sun et al., 2012). Hence, the biggest challenge in these farming systems is how to increase crop production with water-saving irrigation and without leaching out the salts from the profile. Therefore, development of novel approaches to alleviate salt stress on plants by redistributing salts in the root zone or by manipulating rhizosphere processes is required to underpin sustainable agriculture in the arid zone.

The previous studies have suggested some ways of changing salt distribution in the root-zone and promoting plant growth without an additional irrigation water input. For example, Wadleigh and Fireman (1949) suggested that furrow irrigation causes salt accumulation in the ridges; Kang et al. (2000) found that the fixed-furrow irrigation maintained higher grain yield (with up to 50% reduction in the irrigation amount) compared with the conventional-furrow irrigation methods in an arid zone.

The effects of rhizosphere manipulation in alleviating soil salinity on crop growth have attracted increasing attention in recent years. Zhang et al. (2005) found that soil salinity as well as soil pH decreased

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https://doi.org/10.1016/j.fcr.2017.12.011
Received 2 November 2017; Received in revised form 8 December 2017; Accepted 11 December 2017

in the rhizosphere of *Puccinellia ciliata* Bor regardless of whether the rhizoboxes were flushed with water or not. Arbuscular mycorrhizal fungi or plant-growth-promoting rhizosphere bacteria can improve crop yield in saline soils by improving nutrient uptake, decreasing sodium-to-potassium ratio in plants (Dodd and Perez-Alfocea, 2012; Liu et al., 2016) or regulating plant hormonal balance (Pérez-Alfocea et al., 2010; Sheng et al., 2011).

There is a correlation between salt concentration and soil pH (Richards, 1969), with a pH decrease accompanying salt leaching from the soil profile (Liu et al., 2016). Decreased pH in the rhizosphere may be beneficial for crops. For example Ma et al. (2013) showed that localized supply of P fertilizer with ammonium-based N fertilizer enhanced P uptake and grain yield of maize grown in a calcareous (non-saline) soil. Therefore, we hypothesized that rhizosphere acidification (induced by supplying ammonium sulfate together with localized supply of P fertilizer) would alleviate the negative effects of salinity on the growth and improve N and P uptake efficiency of drip-irrigated crops in salt-affected soils, by increasing the rhizosphere P availability and reducing the area of root-salt interaction.

Cotton (*Gossypium hirsutum* L.) is the main source of natural fiber worldwide and is an important cash crop in China, India, Pakistan, and USA. For example, in Xinjiang province where has the most cotton-planting area in China, about one-third (1.23×10^6 ha) of the total farmland suffer from salinity (Hou et al., 2007). Cotton, even though one of the most salt-tolerant crops (Maas, 1986), can be negatively influenced by soil salinity (Chinnusamy et al., 2005; Rodriguez-Uribe et al., 2011). Particularly in the seedling stage, cotton roots are sensitive to salt stress (Waisel and Eshel, 2002), which can significantly limit cotton yield later in the season. Recent studies suggested that cotton roots have relatively poor capacity to forage for P in soil compared with wheat (*Triticum aestivum* L.) and white lupin (*Lupinus albus* L.), because cotton has weak capacity to release root exudates (e.g. carboxylates) to mobilize sparingly-soluble soil P under conditions of low P availability (Wang et al., 2008, 2010). Cotton plants frequently suffer from P deficiency in saline soils (Parida and Das, 2004). Enhancing P availability in the rhizosphere of cotton may alleviate the adverse effects of soil salinity. The objectives of this study were (1) to quantify the changes in the rhizosphere in terms of salt content, pH, P availability, and P uptake; and (2) to characterize the optimal rhizosphere manipulating strategy (amount of localized vs broadcast fertilizer as well as fertilizer timing) that can improve cotton growth, nutrient uptake and yield in the salt-affected soil.

2. Materials and methods

2.1. Sites

The study site is located at the Cotton Experimental Station (44°17′57″N, 86°22′6″E, 400 m a.s.l.) of Xinjiang Academy of Agricultural Sciences in Manasi County, Xinjiang, northwestern China. The annual average temperature is 7.2 °C, and total annual rainfall is 180–270 mm. The total annual evaporation is 1000–1500 mm. The groundwater table was more than 3 m below ground, and salt concentration of the irrigation water pumped from deep belowground (more than 30 m) was 0.14–0.34 g L^{-1}. According to the FAO soil classification, the soil in our experimental field is the desert soil (Gypsisols), clay loam to sandy clay. The average proportions of sand, silt and clay in the 0–100 cm layer were 8%, 64% and 28%, respectively (Lu et al., 2011). Based on the total soluble salt concentration (1:5 soil:water), the saline strength of a soil is classified as none (< 3 g kg^{-1} DW soil), slightly (3–6 g kg^{-1} DW soil), moderately (6–10 g kg^{-1} DW soil), highly (10–20 g kg^{-1} DW soil) and extremely high saline (> 20 g kg^{-1} DW soil) in this region (Abuduwaili et al., 2012). We used moderately saline soils in our studies.

This saline desert was converted to arable land in 2005. Since then, cotton has been grown as pioneer crop in the newly cultivated lands under drip irrigation with plastic film mulching. Such approach can leach most salts from the topsoil layer to 100 cm deep, resulting in a relatively low salt concentration in the root zone (see Wang et al., 2010; Liu et al., 2016). The total amount of irrigation for cotton per growing season was 5250 m^3 ha^{-1}, supplied in 8–10 portions during the growth season, and every time there was 655–525 m^3 ha^{-1} of irrigated water for cotton. The total amount of irrigation in this study was the same as the local farmer's practice. Drip irrigation was applied after the seeds were sowed to improve seedling emergence. During the seedling stage, the plants were not irrigated. After the bud emergence stage, plants were irrigated once every 10–15 days, in total 8–10 times during the whole growth period. Our previous studies showed the salt content in the 0–20 cm layer can be decreased to 6–10 g kg^{-1} DW soil (conductivity 0.8 mS cm^{-1} on average) after 15 years of cultivation (classifying soil as moderately saline, see Liu et al., 2016). To improve soil organic carbon content, cotton straw was crushed and returned to the field at the end of every cotton-growing season.

The field experiments were conducted at two adjacent sites at the Cotton Experimental Station in 2012 and 2015. Before sowing, the initial soil samples were taken from the topsoil (0–30 cm). The basic soil properties (mean ± SE) in 2012 (2015) were as follows: electrical conductivity (EC, 1:5, soil:water) 0.66 ± 0.08 (0.65 ± 0.05) mS cm^{-1}, soil salt content 3.6 ± 0.20 (3.6 ± 0.09) g kg^{-1}, pH (1:5, soil:water) 7.8 ± 0.09 (8.5 ± 0.09), organic matter 6.3 ± 0.74 (12.4 ± 0.24) g kg^{-1}, and Olsen-P 7.4 ± 0.54 (4.2 ± 0.21) mg kg^{-1}. For more details on the measurements see Section 2.4.

2.2. Experimental design

Field experiments were conducted to characterize the effects of localized P supply in combination with ammonium sulfate on cotton root growth and nutrient uptake in saline farmland. The sowing times were April 18th, 2012, and May 2nd, 2015. The previous crop was cotton at both sites. The experiment was set up in completely randomized block design (4 replicates) with six treatments:

(1) C: farmers' conventional fertilization practice (broadcast 7.5 kg N (as urea) ha^{-1} and 180 kg P_2O_5 (as superphosphate) ha^{-1} just before sowing);

(2) UP_{30}: localized 7.5 kg N (as urea) ha^{-1} and 30 kg P_2O_5 (as superphosphate) ha^{-1} with broadcast 150 kg P_2O_5 (as superphosphate) ha^{-1} just before sowing;

(3) AP_{30}: localized 7.5 kg N (as ammonium sulfate) ha^{-1} and 30 kg P_2O_5 (as superphosphate) ha^{-1} with broadcast 150 kg P_2O_5 (as superphosphate) ha^{-1} just before sowing;

(4) UP_{60}: localized 7.5 kg N (as urea) ha^{-1} and 60 kg P_2O_5 (as superphosphate) ha^{-1} with broadcast 120 kg P_2O_5 (as superphosphate) ha^{-1} just before sowing;

(5) AP_{60}: localized 7.5 kg N (as ammonium sulfate) ha^{-1} and 60 kg P_2O_5 (as superphosphate) ha^{-1} with broadcast 120 kg P_2O_5 (as superphosphate) ha^{-1} just before sowing.

For these five treatments, 138 kg N (as urea) ha^{-1} was applied as top-dressing by drip irrigation at 105 days after sowing.

(6) AP_{60}/A: localized 7.5 kg N (as ammonium sulfate) ha^{-1} and 60 kg P_2O_5 (as superphosphate) ha^{-1} with broadcast 120 kg P_2O_5 (as superphosphate) ha^{-1} just before sowing, and 138 kg N (as ammonium sulfate) ha^{-1} applied as top-dressing by drip irrigation at 105 days after sowing.

All broadcast fertilizer was plowed in (30 cm) after application (just before sowing). Banding fertilizer was localized 10 cm deep and 5 cm to the side of the sowing row.

Cotton was grown by drip irrigation combined with the plastic film mulching technique. The film was 2.3 m wide. The seeds were sowed 2 cm deep, with six rows in each film sheet (row spacings of 10 cm, 20 cm, 55 cm, 20 cm, 55 cm, 20 cm and 10 cm; see Fig. 1). The film remained for the whole cotton growth stage until harvesting. After