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Review

Combating salinity stress effects on cotton with agronomic practices

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Excessive salts in the soil lead to a series of metabolic disorders in cotton plants mainly due to osmotic effects (dehydration), nutritional imbalance and toxicity of salt ions (Na^+ and Cl^-). The metabolic disorders may finally reduce cotton growth and lint yield, particularly, in moderate to highly saline soils. Although, an improvement in the salinity tolerance of cotton through genetic breeding is believed to be potentially useful for combating salinity stress and agronomic practices that improve at least part of the root-zone environment and is currently considered as more practical options for reducing salinity effects. This review highlighted agronomic practices like furrow seeding, plastic mulching, increased plant density and fertilizer management; and how they reduce salinity effects on cotton. Further research should focus on understanding the supply and uptake characteristics of water and fertilizer, and the development of new products for cotton growing in saline soils.

Key words: Cotton, soil salinity, salinity stress, agronomic practices, root zone.

INTRODUCTION

Soil salinity is a major constraint limiting agricultural productivity on nearly 20% of the cultivated area and half of the irrigated area worldwide (Zhu, 2001; Lobell et al., 2007; Haque, 2006). Although, cotton is classified as one of the most salt-tolerant major crops and considered a pioneer crop in reclamation of saline soils (Maas, 1990), its growth and development as well as yield and fibre quality are adversely affected by excessive soil salinity (Maas and Hoffman, 1977; Qadir and Shams, 1997; Higbie et al., 2010). Soil salinity is usually expressed by electrical conductivity of a saturated paste extract (ECe), and soils with ECe more than 4 dS/m at 25°C are considered saline (Richards, 1954). ECes of 4 - 8, 8 - 12 and ≥ 12 - 16 dS/m are referred to as low, moderate and high salinity levels, respectively (El-Swaify, 2000). Salinity stress usually delays and reduces germination and emergence rates, decreases cotton shoot growth and may finally lead to reduced seed cotton yield and fibre quality (Khorsandi and Anagholi, 2009). However, salinity effects on plant growth and yield vary with salinity levels, and cotton yield was decreased by 10, 25 and 50% at ECes of 10, 12 and 16 dS/m, respectively (Chen et al., 2010; Maas and Grattan, 1999). Over the last thirty years, a number of studies have been conducted to find ways and practices to reduce salinity effects. Progress has been made in all aspects of soil salinity-cotton plant (Ashraf, 2002; Ahmad et al., 2002; Lubbers et al., 2007; Gorham et al., 2009). This review covers research work on control of salinity effects on cotton growth and yield, with a focus on comprehensive utilization of agronomic practices.

EFFECTS OF SALINITY STRESS ON COTTON

An understanding of salinity effects on cotton is the first step in dealing with soil salinity. Although, salinity effects occur at almost all growth stages, including germination, seedling, vegetative and maturity stages of field-grown cotton, it is generally believed that emergence and young seedling stages are more sensitive to salinity stress than other stages (Ahmad et al., 2002). Seed germination and emergence of cotton are generally delayed and reduced by high soil salinity levels (Qadir and Shams, 1997). Biological or economic yield reduction is the final result of salinity stress at the whole-plant level, and is usually attributed to various physiological and biochemical processes at the cellular or even molecular levels (Meloni et al., 2003; Nawaz et al., 2010). Soil salinity stress reduces plant growth and cotton yield mainly through three pathways- osmotically induced water stress, specific ion toxicity due to high concentration of sodium and chloride, and nutrient ion imbalance due to high level of Na^+ and Cl^- which reduces the uptake of K^+, NO_3^-, PO_4^{3-}, etc (Greenway and Munns, 1980).

In saline soils, too much salt in the soil environment lowers the osmotic potential of the soil solution so that cotton cannot take up enough water (Khan et al., 2004), finally leading to reduced plant growth and development as a result of osmotic effects. Both cellular and metabolic processes involved in osmotic stress due to salinity are similar to those due to drought (Tang et al., 2007).

The rate at which new leaves are produced depends largely on the water potential of the soil solution, in the same way as for a drought-stressed plant (Nawaz et al., 2010). Reduced leaf and root growth rates are probably due to factors associated with water stress (Munns, 2002). The degree of growth inhibition due to osmotic stress depends on the time and scale of the response, the particular tissue and species in question, and whether the stress treatments are imposed abruptly or slowly (Ashraf, 1994; Munns et al., 2002).

Transcript-profiling of plants subjected to drought and salt suggests that plants perceive and respond to these stresses by quickly altering gene expression in parallel with physiological and biochemical alterations and this occurs even under mild to moderate stress (Nawaz et al., 2010).

It is apparent that both stresses of salinity and drought lead to down-regulation of some photosynthetic genes, with most of the changes being small, possibly reflecting the mild stress imposed. When compared with drought, salt stress affected more genes and more intensely, possibly reflecting the combined effects of dehydration and osmotic stress in salt-stressed plants (Chaves et al., 2009).

There are 12 main soluble salts made up of cations (Na^+, Ca^{2+} and Mg^{2+}) and anions (CO_3^{2-}, HCO_3^-, Cl^- and SO_4^{2-}) in saline soils (Maas and Hoffman, 1977). Uptake and accumulation of certain toxic ions from the saline soil or irrigation water can lead to toxicity.

These toxic constituents include mainly sodium, chloride and sulphate (Maas, 1990). Although, chloride and sulphate are essential elements, their content in the saline soil is far more than required for normal growth of plants. The salt taken up by plants concentrates in the old leaves (Munns, 2002), and its transportation continues into transpiring leaves over a long period of time which eventually results in very high Na^+ and Cl^- concentrations that causes the leaves to die (Munns, 2005). The cause of the injury is probably due to the salt load exceeding the ability of the cells to compartmentalize salts in the vacuole. Salts then would rapidly build up in the cytoplasm and inhibit enzyme activity (Gouia et al., 1994). Alternatively, they might build up in the cell walls and dehydrate the cell (Munns, 2005). The Cl^- is more toxic than Na^+ in a number of plant species including cotton (Luo et al., 2002, Tavakkoli et al., 2010). Concentrations of Na^+ and Cl^- in cotton roots, xylem sap and leaf increased with increasing concentration of NaCl in the soil environment (Hirayama, 1987); a large quantity of Na^+ and Cl^- poured into the cells destroys the ion balance in the cytoplasm, particularly the Ca^{2+} balance. High concentrations of Na^+ can replace bound Ca^{2+} in the plasma membrane and cell membrane system, increasing the ratio of Na^+/Ca^{2+} and finally, damaging the membrane structural integrity and function. As a result, there is a dramatic increase in free cytoplasmic Ca^{2+} impaired cellular metabolism (Hirayama, 1987).

Salinity may result in the disturbance of uptake and utilization of essential nutrients due to competition and interactions of soluble salts with mineral nutrients (Rathert, 1982; Gouia et al., 1994). Ionic imbalance occurs in the cells due to over accumulation of Na^+ and Cl^- and reduced uptake of other mineral nutrients, such as K^+, Ca^{2+}, and Mn^{2+} (Karimi et al., 2005). High sodium to potassium ratio due to accumulation of high amounts of sodium ions inactivates enzymes and affects metabolic processes in plants (Booth and Beardall, 1991). It is believed that Ca^{2+} plays a key role in alleviating salinity damage by protecting the cell membrane structure of cotton. Cramer (1987) reported that salt stress severely inhibited root absorption, transportation and distribution of Ca^{2+} and K^+ in cotton. As an essential nutrient, Mg^{2+} participates in the formation of chlorophyll components. Thus, reduced uptake of Ca^{2+} and Mg^{2+} by soil salinity would have adverse effects on growth and development of the cotton plant (Yeo, 1998). Potassium plays an important role in cotton growth, nutrient distribution and resistance to pests and diseases. Since K^+ and Na^+ have similar physical and chemical structure, Na^+ can partially replace K^+ to promote plant growth in low-K soil (Zhang et al., 2006). But at higher NaCl concentration, the selectivity of potassium for cotton plant will fall greatly. When the Na^+ concentration exceeds a certain threshold, Na^+ will be competing with K^+ transport and binding sites, leading to potassium depletion (Yeo, 1998). Potassium deficiency in cotton leaves can reduce chlorophyll and photosynthesis, while excessive absorption of the Cl^- can reduce uptake of NO_3^- and $H_2PO_4^-$ (Gong et al., 2009). According to Brugnoli and Bjorkman (1992), nitrogen content in cotton leaves decreased with increases in salt

Table 1. Effects of unequal salt distribution on plant growth, Na^+ and chlorophyll (Chl) concentrations, and net photosynthetic (Pn) rate in the 3rd main-stem leaves from terminal at 6 weeks after salt stress (flowering).

Item	NaCl treatment (mM/mM)	Dry mass ($g•plant^{-1}$)	Pn ($μmol\ CO_2•m^{-2}•s^{-1}$)	Na^+ ($mg•g^{-1}$)	K^+ ($mg•g^{-1}$)	K^+/Na^+	Chl ($mg•g^{-1}$)
Unequal salt distribution	100/100	25.5^c	23.6^b	11.3^c	7.90^b	0.699^b	16.2^c
	200/200	20.8^d	20.9^{bc}	12.8^b	7.34^c	0.573^c	15.1^d
	300/300	15.2^e	15.9^d	14.5^a	7.04^d	0.486^d	14.1^e
Equal salt distribution	50/150	33.1^a	25.5^a	10.2^d	8.33^a	0.817^a	20.9^a
	100/300	28.2^b	25.4^a	11.2^{cd}	7.82^b	0.674^b	20.3^a
	100/500	25.2^c	22.3^c	12.4^{bc}	7.78^b	0.627^b	17.5^b

Within a column, means with different letters differ significantly ($P<0.05$).

concentration. They also found that under high salinity stress, cotton would reduce the absorption of ^{15}N, while at low salinity there was no significant impact on absorption (Pessarakli and Tucker, 1985). Under NaCl stress, the NO_3-N uptake was seldom affected, but the NO_3-N accumulation was significantly decreased, and the absorption of NH_4^+-N was greatly inhibited (Pessarakli, 2001). Using ^{32}P labelling technique, Martinez and Läuchli (1991) found that under low P conditions, salt stress inhibited the absorption of phosphorus in cotton seedlings. At moderate salinity, ^{32}P transportation from cotton root to shoot was reduced, such that old leaves of cotton contained more P than new leaves.

AGRONOMIC PRACTICES FOR COMBATING SALINITY STRESS

High soil salinity decreases cotton growth and yield. Osmotic stress, ion toxicity and nutritional imbalance are the main causes of such decreases in saline soils. Therefore, reducing the salt content in the vadoze zone and creating a more suitable soil environment for cotton growth are the main ways to combat salinity stress.

Ways of improving root-zone environment

Salinity and the resulting stress originate from the root-zone soil environment. Theoretically, any practice that improves at least part of the root-zone environment can alleviate salt damage. The root-zone environment can be improved by reducing soil salinity and increasing soil moisture and temperature.

Unequal salt distribution

In a split-root experiment, Dong et al. (2010b) confirmed that unequal salt distribution in the root-zone can alleviate salt damage to cotton plants (Table 1). Potted cotton plants were grown in a split-root system in the green-house and half of each root was irrigated with either the same or two concentrations of NaCl. When the entire root system was exposed to the same concentration of NaCl, shoot dry weight, leaf area, plant biomass, leaf chlorophyll (Chl), photosynthesis (Pn) and transpiration (Tr) were significantly reduced relative to the NaCl-free control. Significant reductions in biological and economic yields were noticed at harvest. However, when only half of the root system was exposed to low-salinity, the inhibition effect of salinity on growth and yield was significantly reduced. Plant biomass and seed cotton yield were significantly increased compared to equal salt distribution. The results indicated that non-uniform salinity in the root zone improves cotton growth relative to uniform salinity.

In another experiment, Dong (2012) established a new split-root system through grafting to simulate uniform (100/100 mM NaCl) and non-uniform (0/200 and 50/150 mM NaCl) salinity treatments and determined the effects of non-uniform salinity on cotton biomass, leaf Pn and water use as well as Na^+ and K^+ accumulation in leaves and Na^+ recirculation from shoot to root (Kong et al., 2011). The fluxes of Na^+ and H^+ in roots were also investigated using the scanning ion-selective electrode technique. Water use of the 0/200 and 50/150 treatments were 2.1 and 1.4-fold higher under the non-uniform salinity treatments than the uniform salinity control. Non-uniform root zone salinity also decreased Na^+ content and increased K^+ content in leaves; Na^+ in the “0” side of roots in the 0/200 treatment was much higher than in either side of roots in the 0/0 control 7 days after treatment, but root Na^+ content greatly decreased in the “0” side of hypocotyl–girdled plants. The increased Na^+ accumulation in the “0” side roots was possibly due to transportation of foliar Na^+ to roots through the phloem. After only 24 h, plants under non-uniform salinity extruded more Na^+ from the root than those under

Table 2. Effects of soil water content on emergence and growth of cotton under salinity stress.

Item	Soil water content (%)	Soil salinity (dS/m)							
		2.5	3.0	4.0	5.5	7.0	8.0	9.0	10.0
Emergence rate (%)	12	92.4^{a}	85.4^{b}	72.7^{c}	50.1^{b}	20.3^{c}	0^{c}	0^{b}	0^{a}
	16	93.2^{a}	92.1^{a}	85.4^{b}	50.2^{b}	45.8^{b}	20.2^{b}	0^{b}	0^{a}
	20	91.5^{a}	92.4^{a}	90.2^{a}	78.9^{a}	65.4^{a}	36.7^{a}	14.8^{a}	0^{a}
Fresh mass (g•plant^{-1})	12	2.65^{c}	2.17^{b}	1.57^{c}	0.95^{c}	0.21^{c}	0^{c}	0^{b}	0^{a}
	16	3.57^{b}	3.21^{a}	2.09^{b}	1.64^{b}	0.75^{b}	0.47^{b}	0^{b}	0^{a}
	20	3.91^{a}	3.35^{a}	2.24^{a}	1.85^{a}	0.86^{a}	0.65^{a}	0.28^{a}	0^{a}

Emergence rate and fresh mass per plant were determined at 14 and 30 days after seeding. Within a column, means with different letters differ significantly ($P<0.05$).

Table 3. Effects of soil temperature on emergence and stand establishment of cotton under 0.25% salinity stress in a pot experiment.

Sowing date (Y-M-D)	Soil Temperature (℃)	No. of days to emergence (days)	No. of days to full emergence (days)	Emergence rate (%)	Dead plant rate (%)	Stand establishment (%)
2007-03-10	15±2	15^{a}	25^{a}	70.5^{c}	20.3^{a}	50.2^{d}
2007-03-15	20±2	12^{b}	20^{b}	78.5^{a}	15.0^{b}	63.5^{b}
2007-05-10	25±2	9^{c}	15^{c}	75.5^{b}	7.7^{c}	67.8^{a}
2007-05-15	30±2	8^{cd}	12^{d}	65.8^{d}	7.0^{c}	58.8^{c}
2007-05-15	35±2	7^{d}	12^{d}	60.9^{e}	13.8^{b}	47.1^{d}

Within a column, means with different letters differ significantly ($P<0.05$).

uniform-salinity and this trend was consistent after 7 days of NaCl treatment. Root Na^+ efflux from the non- or low-salinity side under non-uniform salinity was greatly enhanced by the higher-salinity side. However, the NaCl-induced Na^+ efflux and H^+ influx in roots were inhibited by amiloride (a Na^+/H^+ antiporter inhibitor) and sodium orthovanadate (a plasma membrane H^+-ATPase inhibitor). The Na^+ extrusion in cotton roots was probably due to an active Na^+/H^+ antiport across the plasma membrane. The results indicated that the improved plant growth under non-uniform root-zone salinity was attributed to increased water use, decreased leaf Na^+ content, transport of excessive foliar Na^+ to the low-salinity side of roots and enhanced efflux of Na^+ from the low-salinity side due to higher salinity in the other side (Kong et al., 2012).

Increasing soil moisture and temperature

Dong (2012) found that seed emergence and seedling growth could be improved through increasing soil moisture and temperature under salinity stress in two greenhouse experiments. In the first experiment, cotton seeds were raised on potted soils with different salinity levels and water content (12, 16 and 18%) in a greenhouse. The soils were sampled from saline fields in the Yellow River Delta. It was found that increased soil water content was beneficial to emergence and seedling growth at each given salinity level. Improved emergence and seedling growth were attributed to decreased osmotic stress and salt accumulation in leaves as a result of "dilution effect" (Table 2). In the second experiment, cotton seeds were sown in potted saline soils at varied dates to determine soil temperature effects. It was found that soil temperature up to 20 to 30°C was beneficial to seedling emergence and growth under salinity stress (Table 3).

Mulching and furrow seeding

Proper management of cotton with rational cultivation techniques like mulching, furrow seeding, fertilization and irrigation can alleviate salt damage to cotton plants in saline fields (Dong et al., 2010b; Dong, 2012).

Since cotton plants at emergence and seedling stages are more sensitive to salt stress than at other stages of growth, poor stand establishment and seedling growth are often encountered in saline soils. Because good stand establishment is a prerequisite for a bumper harvest of cotton, more attention should be paid to emergence and stand establishment during field management.

During periods of high evapotranspiration, especially in spring and summer, there is a tendency for the leached salts to return to the soil surface (Abrol et al., 1988). Soil salinization is particularly high when the water table is shallow and the salinity of groundwater is high. Practices that reduce evaporation from the soil surface and/or encourage downward flux of soil water will help to control root zone salinity. Sandoval and Benz (1966) and Benz et al. (1967) studied soil salinity changes under bare soil and straw mulching over three years. Their results showed that mulching reduced soil salinity. Fanning and Carter (1963) reported a significant reduction in root zone salt concentration in plots where cotton-burr mulch was applied at 90 t/ha. It was also reported that periodic sprinkling of mulched soils resulted in greater salt removal and therefore higher leaching efficiency than did flooding or sprinkling of bare soil (Carter and Fanning, 1964). Dong et al. (2010b) compared cotton raised on furrow-beds in saline fields with those raised on flat beds as controls and found that furrow-bed seeding induced unequal salt distribution in saline fields resulting in significantly improved plant growth, yield and earliness. The improvement in yield and earliness was mainly due to unequal distribution of salts in the root zone. Reduced Na^+ accumulation and increased K^+/Na^+ ratio, as well as improved transpiration and photosynthesis are possible escape mechanisms against salinity stress (Dong et al., 2008).

Row covering with polyethylene film (plastic mulching) is a common practice in many countries because it permits early sowing with lower risk of failure. In China, this practice has become one of the most popular techniques for cotton production since the 1980s. Plastic mulching enhanced plant growth by increasing soil temperature, thus increasing cotton lint yield (Dong et al., 2007). Some other benefits of plastic mulching include water conservation, salinity control in the root zone and weed control. Plastic mulching also resulted in unequal salt distribution in the saline soil, in which part of the root system developed in relatively low-saline soil, and salt damage was thus reduced (Bezborodov et al., 2010). Further study by Dong et al. (2008) showed that the integration of plastic mulching with furrow seeding could more effectively enhance stand establishment, earliness, yield, and yield components of cotton than mulching or furrow seeding alone. These improvements were due to the unequal salt distribution and elevation of soil temperature and moisture in the root-zone soon after seeding. As a result, the Na^+ uptake by roots and leaves was reduced, peroxidation of lipids in cotton tissues was decreased, and Pn improved. The integration of plastic mulching with furrow bed seeding is a promising cotton production technique in saline areas (Dong et al., 2008).

Row covering is conventionally applied after sowing, but pre-sowing evaporation in spring would cause accumulation of salts and moisture loss in the surface layer of saline soils, especially, in areas without pre-sowing irrigation (Dong et al., 2009). Row mulching with plastic film can be done 30 days before sowing (early mulching) in saline fields. Although, both conventional and early mulching could effectively improve stand establishment, plant growth, earliness and lint yield of cotton, early mulching was more beneficial to stand establishment, plant growth and yield. The increased benefits of early mulching were due mainly to the better control of root-zone soil salinity, elevation of soil temperature and reduction of moisture loss (Dong, 2012). As a result, the Na^+ accumulation in leaves and peroxidation of lipids in cotton tissues decreased, and pn improved. Mulching was more costly, but the increased yield by mulching was enough compensate for the cost increase. Early mulching is also a promising cotton production technique in the saline areas (Dong et al., 2009b).

Late planting of short season cotton

Normal planting of full-season cotton in saline fields in temperate areas is faced with poor stand establishment, late maturity, and increasing cost of inputs (Dong et al., 2007). Dong et al. (2010a) showed that late planting of short-season cotton significantly improved seed emergence and seedling growth due to increased temperature and reduced Na^+ concentration in cotton tissues relative to normal planting. The yield from late-planted short-season cotton and normal-planted full-season cotton was comparable, but the former performed better in earliness and required less input than normal planting. Therefore, the net revenue from late-planting of short-season cotton was greater than that from normal-planting of full-season cotton. Late planting of short-season cotton is a promising system for growing cotton in saline areas of the Yellow River delta and probably in other cotton growing areas with similar ecologies (Dong et al; 2010a).

Fertilizer management

Soil application

Under salt stress, plant growth, nutrient absorption and metabolism, protein synthesis and water absorption were greatly altered, making it difficult for plants to fully utilize nutrients (Pessarakli, 2001; Ella and Shalaby, 1993). Therefore, proper fertilizer management will improve the salt tolerance of cotton and reduce the adverse effects of salinity. Chen et al. (2010) studied the influence of different N fertilization rates and soil salinity levels on the growth and nitrogen uptake of cotton. They found that cotton growth was significantly affected by the interaction of soil salinity and N but not by N alone. At low to moderate soil salinity, the growth inhibition was alleviated by fertilizer application. At low to medium soil salinity, N uptake increased with N fertilization. At higher salinities, N uptake was independent of N rates and was mainly influenced by soil salinity. The uptake of K decreased with soil salinity. The concentration of Na, Cl and Ca in plant tissues increased with soil salinity with the highest concentrations in cotton leaves. Applying nitrogen at the beginning of an irrigation cycle enhanced yield and fertilizer use efficiency (Hou et al., 2009).

Keshavarz et al. (2004) indicated that application of K improved the growth and yield of cotton, especially, in saline soils. Modifications in the evaluation of soil K and in the fertilizer recommendation will be necessary. The critical level of K in saline soils (240 mg kg^{-1}) is more than in non- saline soils (210 mg kg^{-1}). Also, K sufficiency range in saline soils is smaller than non-saline soils. Therefore, increasing K fertilizer in this condition should be done with caution. Rate of K application is almost equal in saline and non-saline soils even though cotton yield is lower in saline condition.

In a saline field experiment, Xin et al. (2010) planted cotton in high-, medium-, and low-salinity soils under NPK, NP, or NK fertilization. Compared to the non-fertilization controls, the NP and NPK treated cotton had much higher nutrient uptake levels and significantly lower levels of Na^+ uptake, especially under the NPK treatment. The nutrient use efficiency of cotton treated with NPK was the highest among treatments regardless of salinity level. The agronomic N use efficiencies were 0.20, 1.95, and 2.07 kg lint kg^{-1} under the low, medium, and high salinity level, respectively; the agronomic P use efficiencies were 0.87, 8.35, and 8.71 kg lint kg^{-1}, respectively while the agronomic K use efficiencies were 0.26, 2.89, and 3.77 kg lint kg^{-1}, respectively. The NPK treatment also maintained higher leaf area, chlorophyll content, and Pn than other fertilization treatments. The NPK treatment also had the highest biomass and lint yield, and the lint yields were enhanced by 2.53, 28.67, and 30.47% in the low, medium, and high salinity soils, respectively. The effect of NPK was more obvious in the middle or high salinity fields. The results suggest that proper fertilizer management was beneficial to yield increase under salinity stress (Xin et al., 2010).

Foliar application

Jabeen and Ahmad (2009) investigated the response of cotton grown at high salinity supplemented with foliar application of KCl (500 mg/L) and NH_4NO_3 (500 mg/L) alone and in mixture. Soil salinity was maintained through irrigation with saline water. Plant growth parameters were reduced significantly at high salinity but the detrimental effects were alleviated by foliar spray with NH_4NO_3 or KCl. Foliar spray with a combination of NH_4NO_3 and KCl showed better result than spraying with either fertilizer material alone. The performance trends at the vegetative and reproductive growth stages under non-saline and saline conditions were same and varied in the order: Non-spray < water spray < KCl < NH_4NO_3 < NH_4NO_3 + KCl. Foliar nutrient spray was beneficial to both vegetative and reproductive parameters in cotton under saline environment (Jabeen and Ahmad, 2009).

Combination of foliar and soil application

Dong (2012) conducted a pot experiment to study the effects of soil application (S), foliar application (F) and a combination of both (S + F) with labelled nitrogen (^{15}N) on plant growth, nitrogen uptake and translocation under salinity stress (ECe = 12.5 dS/m) in a greenhouse. Plant biomass, leaf area, leaf chlorophyll (Chl) content, leaf net photosynthetic (Pn) rate, levels of ^{15}N and Na^+ and K^+/Na^+ ratio in plant tissues were determined at 3, 7, 14 and 28 days after application. Salinity stress inhibited the uptake of ^{15}N from soil and translocation to leaf when N was applied to the soil. Although, ^{15}N uptake and translocation from leaves to roots was less inhibited under foliar application than under soil application, it did not maintain a long-term nutrient supply and fair distribution of N across tissues. Foliar application enhanced an accumulation of leaf nitrogen, soil application favoured N accumulation in roots nitrogen, while combined application ensured balanced nitrogen accumulation in all tissues under salinity stress. Either soil or foliar application of nitrogen significantly reduced leaf Na^+ concentrations, and foliar application was more effective in reducing the accumulation of Na^+ in leaves. Although, combined application had no advantage over foliar or soil application in reducing leaf Na^+ concentration, it significantly increased the K^+ and ratio of K^+/Na^+ in tissues than either method alone. It was therefore concluded that improved plant growth and salinity tolerance with a combination of foliar and soil fertilization was attributed to increased total uptake of nitrogen, balanced distribution of N across tissues through quick uptake and accumulation in both leaves and roots, and increased ratio of K^+/Na^+. These findings may be of significance for nitrogen management for cotton in highly saline soils.

Plant density management

High salinity causes reductions in plant growth rate as a result of reduced ability to take up water, along with a suite of effects identical to those caused by water stress (Khan et al., 2004). If excessive amounts of salt enter the plant, they will eventually rise to toxic levels in older transpiring leaves, and reduce the photosynthetic capacity of the plant. Salinity can therefore reduce growth through altered water relations, hormonal balance, or carbon supply, the relative importance of each process depends on the time scale of the response (Munns, 2002). Many studies have indicated a yield increase in cotton with increased plant density under salinity stress (Francois, 1982; Feinerman, 1983). This is because excessive salts in the soil usually reduce plant size. The smaller plant size left a significant space between plant canopies which could support additional plants (Francois, 1982). It has been reported that increasing population also enhanced cotton earliness (Fowler and Ray, 1977). In a recent field experiment, Dong et al. (2012) found that seed cotton yield was greatly improved with increased plant density under strong salinity conditions. It is suggested that increased plant density would be necessary for enhancing yield and earliness in highly saline fields.

SUMMARY

About 23% of the world’s cultivated lands are saline (Tanji, 1990). Thus, there is a great potential for cotton production in saline lands, but this potential depends largely on the technological advances and research achievements in cotton grown in saline soils. Although, improvement in salinity tolerance of cotton through genetic breeding is believed to be a potentially useful approach to combating salinity stress, agronomic practices that improve at least part of the root-zone environment are more practical options to reduce salinity effects. Currently, full utilization of agronomic practices like furrow seeding, plastic mulching, increased plant density and proper fertilizer management will significantly enhance cotton productivity in saline soils.

Further research should focus on two aspects: The first is to further explore and understand the supply and uptake characteristics of water and fertilizer, and to explore new alternatives to improve uptake and use efficiency of nutrients and water in saline soils. The second is to develop new products for cotton growing in saline soils, including new foliage fertilizer, specific slow-release fertilizer and commercial plant growth regulators. It should be noted that some agronomic practices like furrow seeding and plastic mulching are capital- and labor-intensive. Reducing these limitations by developing new corresponding machinery would certainly increase the overall benefits of this integrated production system.

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