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Effects of Saline Water Irrigation and N Application Rate on NH_3 Volatilization and N use Efficiency in a Drip-Irrigated Cotton Field

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Abstract Ammonia (NH_3) volatilization is one of the main pathways of N loss from farmland soil. Saline water irrigation can have direct or indirect effects on soil NH_3 volatilization, N leaching, and crop N uptake. This study was conducted to evaluate the effects of irrigation water salinity and urea-N application rate on NH_3 volatilization and N use efficiency in a drip-irrigated cotton field. The experiment consisted of three levels of irrigation water salinity: fresh water, brackish water, and saline water (electrical conductivities of 0.35, 4.61, and 8.04 dS/m, respectively). The N application rates were 0, 240, 360, and 480 kg/ha. The results showed that soil salinity and soil moisture content were significantly higher in the saline water treatment than in either the fresh or brackish water treatments. Irrigation water salinity significantly increased soil NH_4-N concentration, but NO_3-N concentration decreased as water salinity increased. The amount of N leaching varied from 5.0 to 25.5 kg/ha, accounting for 1.81 to 4.79 % of the urea-N applied under different water salinity and N application rate treatments. Both the amount of N leaching and the proportions of applied N lost through leaching significantly increased as water salinity increased. N application increased the amounts of N leaching, but the ratios of applied N were not affected by N application rate. Soil NH_3 volatilization increased rapidly after urea fertigation, and peaked at 1–2 days after N application, then decreased rapidly. The amount of NH_3 volatilization varied from 9.0 to 33.7 kg/ha, accounting for 3.2 to 3.8 % of the N applied in all treatments. Soil NH_3 volatilization was significantly higher in the saline water treatment than that in either the fresh or the brackish water treatments. Cotton N uptake increased significantly as N application rate increased, but decreased with irrigation water salinity increased. In conclusion, saline water irrigation with high N application rate induced high N leaching and NH_3 volatilization losses, thereby dramatically reducing the apparent N recovery (ANR) of cotton.

Keywords Saline water · N application rate · N leaching · NH_3 volatilization · Apparent N recovery · Cotton field

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1 Introduction

Ammonia (NH_3) is the most important and abundant alkaline constituent in the atmosphere, which contributes to aerosolised sulfate and nitrate in the atmosphere (Fu et al. 2015). It also becomes a secondary source of N_2O and NO (Fernández et al. 2015). In addition, the sinking of NH_3 into terrestrial and aquatic ecosystems can directly or indirectly cause soil acidification, eutrophication of water bodies, and decrease in biodiversity (Matson et al. 2002; Emmett 2007; Ellis et al. 2011). Agricultural activities including livestock production and fertilizer application are the main sources of NH_3

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emissions (Chen et al. 2015). Synthetic fertilizer application contributes about 20 % of the global NH_3 emissions and up to 45 % in Asia (Huo et al. 2015). Nitrogen (N) fertilizer is the most widely used fertilizer worldwide and the primary N input source in agroecosystems, which is used extensively to enhance crop production (Shan et al. 2015). The fate of N in field is an integrated consequence of crop N uptake, immobilization, and residues in the soil, and N losses to the environment, such as NH_3 volatilization, NO_X emissions, denitrification, N leaching and runoff (Jambert et al. 1997; Wu and Ma 2015). NH_3 volatilization is one of the major N loss pathways from N fertilizer application. The global N loss from fertilization through NH_3 volatilization accounts for 14 % of the annual nitrogen application rate (FAO and IFA 2001). The magnitude of NH_3 volatilization is influenced by many factors, including climatic conditions, soil properties, crop characteristics, and management practices (such as irrigation and N fertilization pattern).

Irrigation and fertilization are arguably the most important management factors in arid and semiarid climates, through which growers can manipulate crop yield and quality (Bar-Tal et al. 2015). Drip irrigation combined with split application of fertilizer nitrogen (N) dissolved in the irrigation water (i.e., fertigation) is commonly considered best management practice for water and nutrient efficiency (Abalos et al. 2014). Fertigation is an efficient strategy for controlling the placement, time, and rate of fertilizer N application, thereby increasing N use efficiency (Danso et al. 2015). Urea is the primary solid N fertilizer applied in drip irrigation system due to its high N content, water-soluble, and relatively low prices compared to other N fertilizers (Liu et al. 2006; Abalos et al. 2014). However, among synthetic fertilizers, potential NH_3 emissions are greatest for urea, of which cumulative losses can reach 50 % of applied N (Rochette et al. 2013a). The amount of volatilized NH_3 following urea application depends on soil properties, urea application rate, and method. Many researches addressed the response of NH_3 volatilization losses to urea application rate (applied by surface broadcasting or subsurface banding), with reports of decreasing, similar, and increasing proportional volatilization losses with increasing urea rates (White et al. 2002; Rochette et al. 2013b; Chen et al. 2015). The large variability in the results reported from previous studies has been due to the nonlinear response of the NH_3 to variation in pH and the availability of NH_3 in the soil (Ghaly and Ramakrishnan 2015). Since the transit time through the drip irrigation system is fast, urea is unlikely to be hydrolyzed to ammonium (NH_4^+) to a significant degree in the irrigation system even if the urease enzyme is present (Haynes 1985). Within the soil, the potential for NH_3 volatilization is high because of urea rapid hydrolysis to NH_4^+ and of the increased pH (Sommer et al. 2004). Some studies have reported that the appropriate combination of irrigation and fertilization management may minimize levels of NH_3 volatilization and nitrate (NO_3-N) leaching during agricultural practices (Jia et al. 2014; Peng et al. 2015). The order of potential N losses through NH_3 volatilization in irrigation systems is sprinkler > surface drip irrigation > subsurface drip irrigation (Bar-Tal et al. 2015). The influence of water management or combined water and nitrogen managements on NH_3 volatilization loss from agricultural fields has become a major concern in many regions (Liao et al. 2015). However, the research related to NH_3 emissions after application of urea in many regions is still limited (Ni et al. 2014).

In arid and semiarid regions, the scarcity of fresh water makes brackish water and saline water a valuable alternative water source for irrigation (Singh 2014). For example, irrigation water sources are often brackish or saline water in Xinjiang, northwest China. The salinity level for most of the shallow groundwater sources in this region is greater than 2 dS/m (Chen et al. 2010). Drip irrigation is the best method for applying saline water to crops (Shalhevet 1994; Dehghanisanij et al. 2006). In Xinjiang, saline water is increasingly used by drip irrigation in cotton (*Gossipium hirsutum* L.), a highly salinity tolerant plant (Chen et al. 2010). Saline water irrigation practices also have been implemented in multiple regions of the southwestern USA, and the irrigation of cotton with 1.5–5 g/L saline water produced cotton yields that are equal to or exceed those obtained with fresh water irrigation (Wang et al. 2016). In order to ensure the sustainability of saline water irrigation, the leaching of salts accumulated in soil profile is a requirement of saline water irrigation management, which can also produce N leaching (Merchán et al. 2015). Furthermore, the concentrations of Na^+ and Cl^- in saline water are high, making it different than ordinary fresh water. Even with careful management, saline water irrigation may cause some sort of salinity buildup in the rootzone and alter the physical, chemical, and biological properties of soil (Singh 2015; Min et al. 2016). This may lead to change the mineralization and nitrification processes of the N cycle and may also affect the NH_3 emissions from soils. Soil salinity has been reported to reduce urease activity (Tripathi et al. 2007; Pan et al. 2013; Singh 2015) and hence can be expected to affect the rate of urea hydrolysis. There have been numerous incubation and field studies on NH_3 volatilization from urea applied directly in saline soil, but there are conflicting reports about the effect of salt concentrations on NH_3 volatilization (McClung and Frankenberger 1985; Award EI-Karim et al. 2004; Akhtar et al. 2012). Quantification of actual NH_3 volatilization losses under a given set of soil and environmental conditions could seldom be achieved as it is governed by a multitude of factors (Liyanage et al. 2014). Different conditions and mechanisms may exert different influences on the processes of ammonia volatilization (Duan and Xiao 2000). However, relatively few researches combined application of urea with saline water irrigation management.

Saline water irrigation can directly or indirectly affect soil properties, which influence NH_3 volatilization and N use efficiency. Thus, nitrogen and water managements are important practices linked with NH_3 volatilization loss from the crop fields. The objectives of this experiment were to evaluate the effects of saline water drip irrigation and urea-N application rate on (1) soil inorganic N concentrations and leaching, (2) soil NH_3 volatilization, (3) cotton N uptake and N fertilizer use efficiency.

2 Materials and Methods

2.1 Site Description

The experiment was conducted at an agricultural experiment station of Shihezi University in Xinjiang Province, northwest of China (44°18′ N, 86° 02′ E). The region is classified as a temperate arid zone with a continental climate. The soil at the site is an alluvial, gray desert soil, classified as a Calcaric Fluvisol in the FAO/UNESCO System. The top 0–20 cm soil was a clay loam texture with bulk density of 1.33 g/cm^3. Some of the physical and chemical properties of the soil (0–20 cm depth) in 2009 are as follows: pH, 7.48; electrical conductivity (EC) in 1:5 soil:water extract, 0.13 dS/m; organic matter, 16.84 g/kg; total N, 1.08 g/kg; available P, 25.86 mg/kg; and available K, 253 mg/kg.

This experiment was part of a study that began at the site in 2009 to determine the effects of saline water irrigation and N application rate on soil physicochemical properties and cotton growth. The treatments described below had been applied to the same plots for six consecutive growing seasons when these measurements were made in 2014.

2.2 Experimental Design

The study consisted of a 3 × 4 factorial design with three irrigation water salinities and four N application rates. The EC of the irrigation water was 0.35, 4.61, or 8.04 dS/m. These treatments will be referred to as fresh water (FW), brackish water (BW), and saline water (SW), respectively, throughout the rest of the paper. The freshwater was obtained from a local well. Two water supply pools were built to prepare water for the BW and SW treatments. Each pool was equipped with an independent drip irrigation system, including one pump, one filter, and one pressure gauge. The water in the BW and SW treatments was produced by adding both NaCl and $CaCl_2$ (a mass ratio of 1:1) to fresh water. Nitrogen was applied as urea at rates of 0, 240, 360, and 480 kg N/ha, (abbreviated as N0, N240, N360, and N480, respectively). The 360 kg N/ha rate is commonly used by local farmers.

The 12 treatments were replicated three times in a randomized complete block design. Each plot was mulched with one sheet of transparent polyethylene film (1.2 m wide × 16 m long). The plastic film was held in place by burying the edges with soil. Two drip irrigation lines were installed under the plastic film. There was a 0.6-m-wide bare strip between each plot. Each plot had four rows of cotton plants. The cotton plants were sown at 10-cm intervals within each row. The plant population was 222,000 plants/ha. Cotton (*cv. Xinluzao No. 48*) was sown on 26 April 2014.

Water was applied by drip irrigation at a rate of 2.7 L/h per emitter. The emitters were 0.4 m apart. A flow meter was installed in each plot to control the irrigation amount. All plots were drip-irrigated with 30 mm fresh water at sowing to improve germination and seedling establishment. During the cotton growing season, 450 mm of irrigation water was applied. The plots were irrigated nine times (every 7 to 10 days) between June and August. These irrigation practices were similar to those used by local farmers. The plots were all irrigated on the same dates and with equal watering depths. To monitor leaching, a metal cylinder (0.4 m i.d.) was installed to a depth of 1 m in each plot prior to the start of the experiment. Leachate was collected in drainage tubes at the bottom of each cylinder.

Nitrogen fertilizer (urea) was applied through the drip irrigation system. The fertilizer was applied in five equal amounts 57, 64, 72, 80, and 95 days after planting. The urea fertilizer solution was stored in a 15-L plastic container and pumped into the irrigation system. All plots were fertilized with 105 kg P_2O_5/ha and 60 kg K_2O/ha before sowing.

2.3 Sampling and Measurement Methods

Volatilized NH_3 was collected using the closed chamber method. The trapping chamber consisted of a 10 cm high polyvinyl chloride tube (15 cm diam). The top of the tube was sealed. The open end of the tube was pressed against the soil surface. The chambers were positioned at three locations (i.e., cotton inter-row space and above the emitter) in each plot. An evaporating dish containing 20 ml 0.1 M H_2SO_4 was put on an iron stand inside each chamber. The distance between the bottom of the evaporating dish and the ground was 7 cm. Ammonia volatilization was dynamic, collection every day until the fourth day after fertilization and at other times for 7 to 10 days to collect at a time. The amount of NH_3 in the traps was determined using the indophenol blue colorimetric method. The amount of ammonia volatilization was calculated as:

$$T(NH_3) = 0.01M/A \quad (1)$$

where M is the amount (mg) of NH_3 collected by the PVC collector, A is the cross-sectional area (m^2) of the PVC collector.

Topsoil samples (0–20 cm depth) and ammonia volatilization were collected at the same time. Leachates were collected from each plot 5 to 6 days after each fertigation. Soil samples were also collected from the 0–20, 20–40, 40–60, 60–80, and 80–100 cm depths after cotton harvest. Soil moisture content, NH_4-N concentration, and NO_3-N concentration were measured using fresh soil. The remainder of each soil sample was dried at 105 °C for 24 h. Soil salinity, expressed as EC, was measured in 1:5 soil:water suspensions with a conductivity meter. Soil pH was measured in 1:2.5 soil:water suspensions with a pH meter. NH_4-N, NO_3-N was measured using a SmartChem 140 discrete autoanalyzer (Analytik Jena AG).

At boll-opening stage, the cotton plants were cut at the soil surface and partitioned into leaves, stems and bolls. Plant samples were dried at 105 °C for 30 min, and then at 75 °C to constant weight. The dry weight was recorded. The samples were then ground to pass through a 1-mm sieve before digestion with H_2SO_4-H_2O_2. Nitrogen concentrations were measured in each sample using an Auto-Kjeldal Unit (B-339, Buchi Labortechnik AG, Switzerland). The effect of N application rate on N use efficiency in each water salinity treatment was compared by calculating apparent N recovery (ANR) as follows:

$$\mathrm{ANR}(\%) = (\mathrm{NF\ uptake\text{-}NC\ uptake})/\mathrm{NF} \times 100 \quad (2)$$

where NF uptake is the total N uptake (kg/ha) of cotton plants receiving N fertilizer; NC uptake is the total N uptake (kg/ha) of unfertilized cotton plants; and NF is the total amount of N fertilizer (kg/ha) applied to the crop (Chen et al. 2010)

2.4 Data Analyses

The data were analyzed using SPSS statistical software v.11.0 (SPSS Inc., 1996) with a two-way ANOVA at a significance level of 0.05, with irrigation water salinity and N application rate as the independent variables. A Duncan multiple range test was carried out to determine if there were significant differences between individual treatments at $P < 0.05$.

3 Results

3.1 Soil Moisture

Soil moisture (0–20 cm) declined from about 20–25 % on day 1 after fertigation to about 11–15 % on day 7 (Fig. 1). Averaged across the 7 days, soil moisture was highest in the SW treatment, being 4.6 and 6.3 % higher than that in the BW and FW treatments. As the N application rate was increased from 0 to 240, 360, and to 480 kg/ha, the averaged soil moisture increased from 16.6 to 16.9 %, 17.6 %, and to 18.0 %, respectively.

Soil moisture during the cotton growing season (between 49 and 111 days after planting) was significantly affected by irrigation water salinity

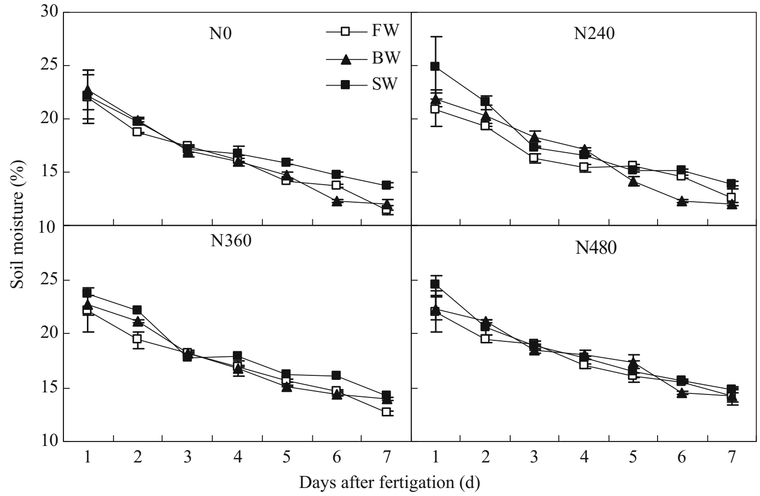

Fig. 1 Effects of irrigation water salinity and N application rate on soil moisture (0–20 cm depth) 1 to 7 days after fertigation. The symbols *FW*, *BW*, and *SW* represent irrigation water salinity of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates. The *bars* represent the SD

and N application rate (Fig. 2). Averaged across all four N fertilization rates, soil moistures in the SW treatment were 8.1 % and 13.2 % greater than those in the BW and FW treatments, respectively. In the N0 and N240 plots, the average soil moistures were 10.8–13.1 % greater in BW and 16.2-17.1 % greater in SW than in FW. In the N360 and N480 plots, the average soil moistures were 2.9-8.1 % greater in BW and 10.7-13.2 % greater in SW than in FW. There appears to be a compounded effect of N application rate and water salinity treatment. Soil moisture did not increase as much in the N360 and N480 plots as in the N0 and N240 plots.

3.2 Soil Salinity

Changes in soil salinity during 7 days after fertigation are shown in Fig. 3. Soil salinity ranged from 0.08 to 1.4 dS/m. Soil salinity was significantly increased as irrigation water salinity increased. The average soil salinity was highest in the SW treatment, being 31 % higher than that in the BW treatment and 80 % higher than that in the FW treatment.

Soil salinity during the cotton growing season was significantly affected by irrigation water salinity but not by N application rate (Fig. 4). Soil salinity in the FW treatments remained nearly stable across time. Depending on the N application rate, soil

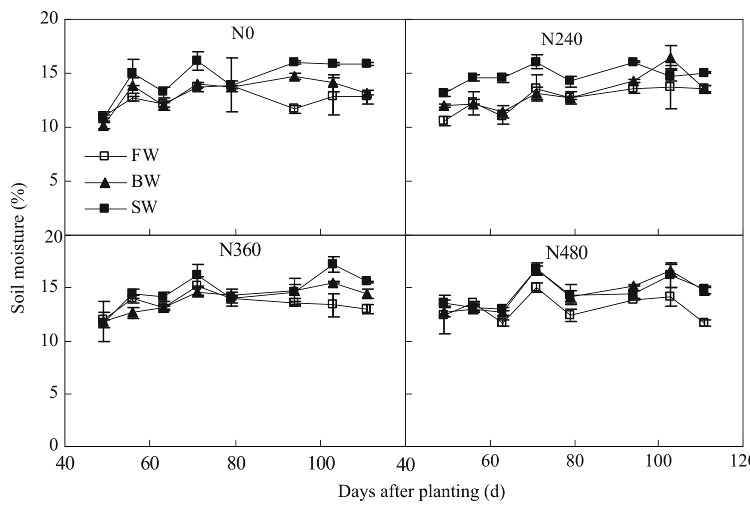

Fig. 2 Effects of irrigation water salinity and N application rate on soil moisture (0–20 cm depth) across the cotton growing season. The symbols *FW*, *BW*, and *SW* represent irrigation water salinity of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates. The *bars* represent the SD

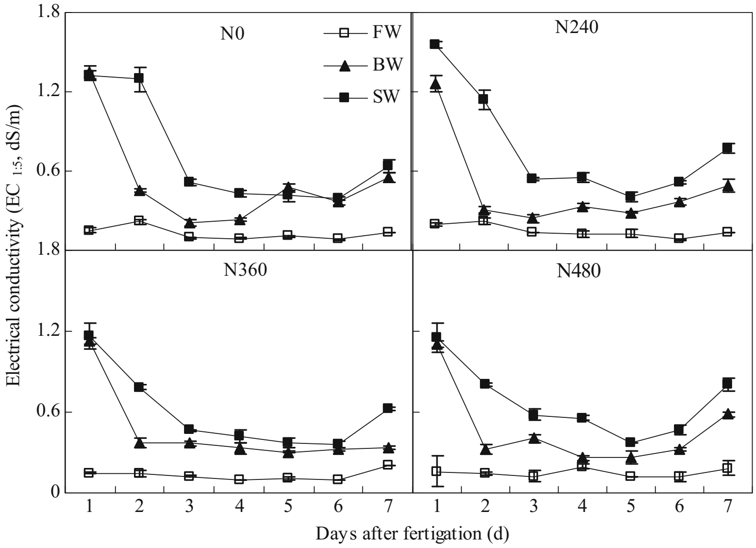

Fig. 3 Effects of irrigation water salinity and N application rate on soil salinity (0–20 cm depth) 1 to 7 days after fertigation. The symbols *FW*, *BW*, and *SW* represent irrigation water salinities of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates. The *bars* represent the SD

salinities in the SW treatments were 29.1 to 50.2 % greater than those in the BW treatments and 71.6 to 76.5 % greater than those in the FW treatments.

3.3 Soil NH_4-N Concentration

Soil NH_4-N concentrations (0–20 cm) were highest 1 day after fertigation and then decreased (Fig. 5). Soil NH_4-N concentrations were significantly influenced both by irrigation water salinity and by N application rate. Soil NH_4-N concentrations increased as N application rate increased. Soil NH_4-N concentrations were highest in the SW treatments, being 24.8 % higher than that in the BW treatment and 34.6 % higher than that in the FW treatment.

Changes in soil NH_4-N concentrations during the cotton growing season are shown in Fig. 6. Average NH_4-N concentrations in 0–20 cm soil depth increased in the order of N0 < N240 < N360, N480. Soil NH_4-N concentration was increased with irrigation water salinity increased. Average soil NH_4-N concentrations were 10.3 and 18.9 % higher in the SW treatment than those in the BW and FW treatments, respectively. However, with the water salinity increasing, the increase of soil NH_4-N concentrations in the N360 and N480 plots were higher than those in the N0 and N240 plots. In the N0 and N240 plots, the average soil NH_4-N concentrations were 4.0–

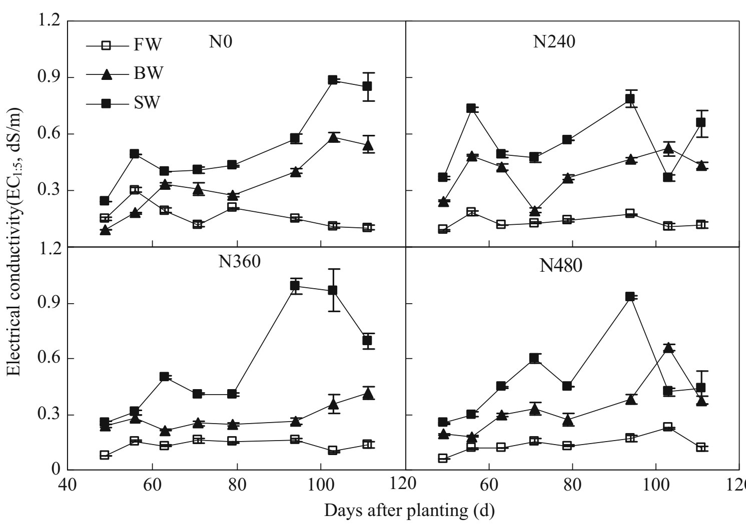

Fig. 4 Effects of irrigation water salinity and N application rate on soil salinity (0–20 cm depth) across the cotton growing season. The symbols *FW*, *BW*, and *SW* represent irrigation water salinities of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates. *Bars* represent the SD

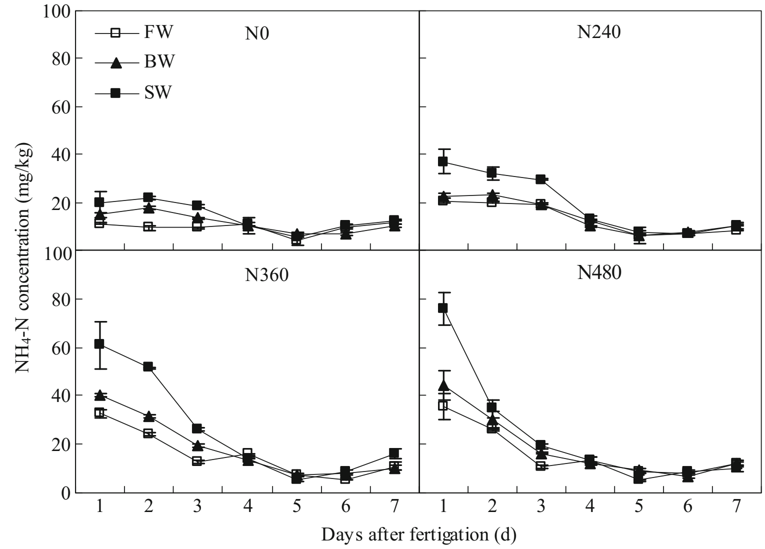

Fig. 5 Effects of irrigation water salinity and N application rate on soil NH_4-N concentration (0-20 cm) 1 to 7 days after fertigation. The symbols *FW*, *BW*, and *SW* represent irrigation water salinity of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates. The *bars* represent the SD

8.6 % greater in BW and 16.2–17.8 % greater in SW than in FW. In the N360 and N480 plots, the average soil NH_4-N concentrations were 10.5–15.2 % greater in BW and 22.5–31.5 % greater in SW than in FW.

Saline water irrigation and urea-N application significantly increased the concentrations of NH_4-N in the 1.0 m soil profile at harvest (Fig. 7). Generally, soil NH_4-N concentrations decreased with depth, with most of the NH_4-N being in the 0–40 cm depth. Averaged across all four N fertilization rates, the average NH_4-N concentrations in the 1.0-m soil profile were 24.0 % greater in BW and 45.7 % greater in SW than in FW. Compared with the N0 treatment, the average NH_4-N concentration in the 1.0-m soil profile was 25.8 % higher in the N240 treatment, 94.2 % higher in the N360 treatment, and 119.4 % higher in the N480 treatment.

3.4 Soil NO_3-N Concentration

Soil NO_3-N concentrations (0–20 cm) increased immediately after fertigation and then decreased (Fig. 8). Soil NO_3-N concentrations, which increased as N application rate increased, were significantly less in the SW treatment than in either the BW or FW treatments. The average soil NO_3-N concentration was highest in the FW treatment,

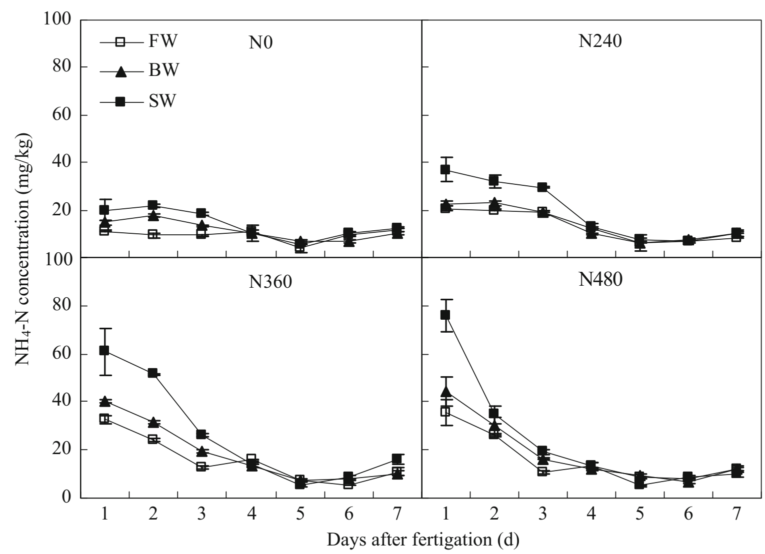

Fig. 6 Effects of irrigation water salinity and N application rate on soil NH_4-N concentration (0–20 cm depth) across the cotton growing season. The symbols *FW*, *BW*, and *SW* represent irrigation water salinities of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates. *Bars* represent the SD

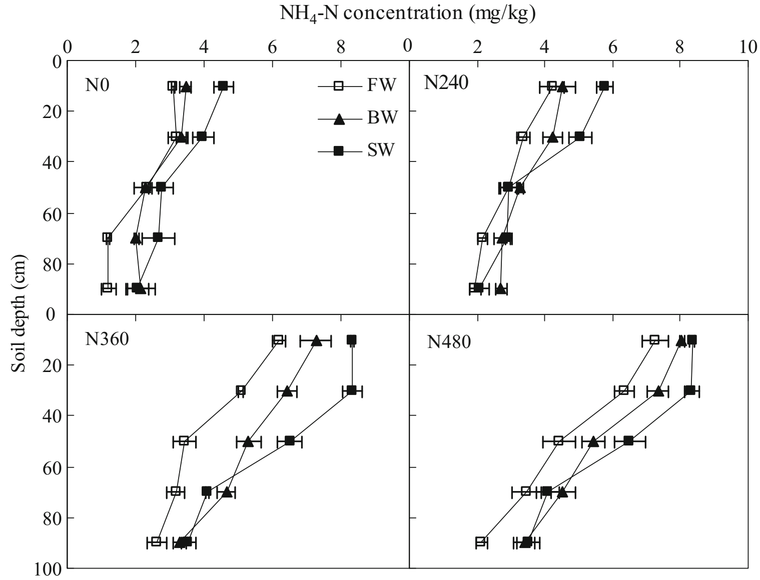

Fig. 7 Effects of irrigation water salinity and N application rate on distribution of NH_4-N concentration in the 1.0 m soil profile at harvest. The symbols *FW*, *BW*, and *SW* represent irrigation water salinities of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates. *Bars* represent the SD

being 20.7 % higher than that in the BW treatment and 30.4 % higher than that in the SW treatment.

Variations in soil NO_3-N concentrations in the 0–20 cm depth across the growing season are shown in Fig. 9. In general, the concentration of NO_3-N increased as N application rate increased, but decreased as irrigation water salinity increased. Compared with the FW treatment, the BW and SW treatment reduced the average NO_3-N concentrations by 20.7 and by 30.4 % (averaged across the four N application rates), respectively.

The distribution of NO_3-N concentrations in the 1.0 m soil profile at harvest was significantly affected by irrigation water salinity and N application rate (Fig. 10). Soil NO_3-N concentrations generally increased with depth, with most of the NO_3-N being in the 60–100 cm depth. The average NO_3-N concentration in the 1.0 m soil profile was increased sharply as N application rate increased. Compared with the N0 treatment, the average NO_3-N concentration in the 1.0-m soil profile was 221 % higher in the N240 treatment, 448 % higher in the N360

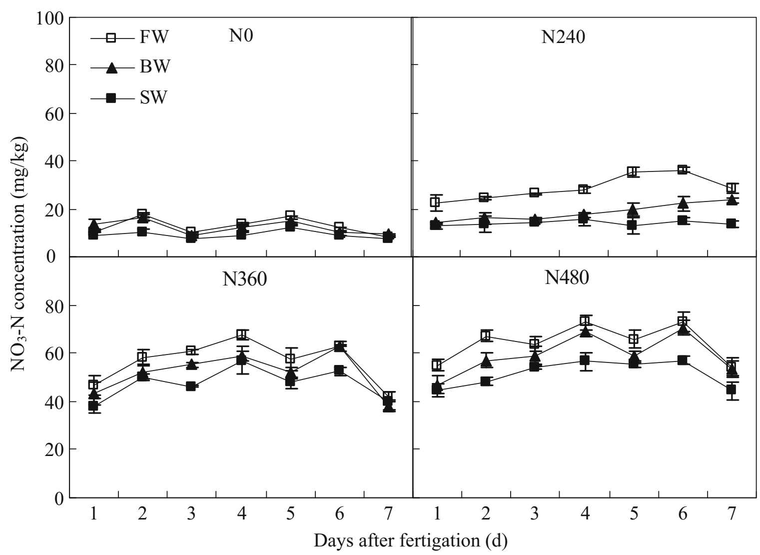

Fig. 8 Effects of irrigation water salinity and N application rate on soil NO_3-N concentration (0–20 cm) 1 to 7 days after fertigation. The symbols *FW*, *BW*, and *SW* represent irrigation water salinity of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates. The *bars* represent the SD

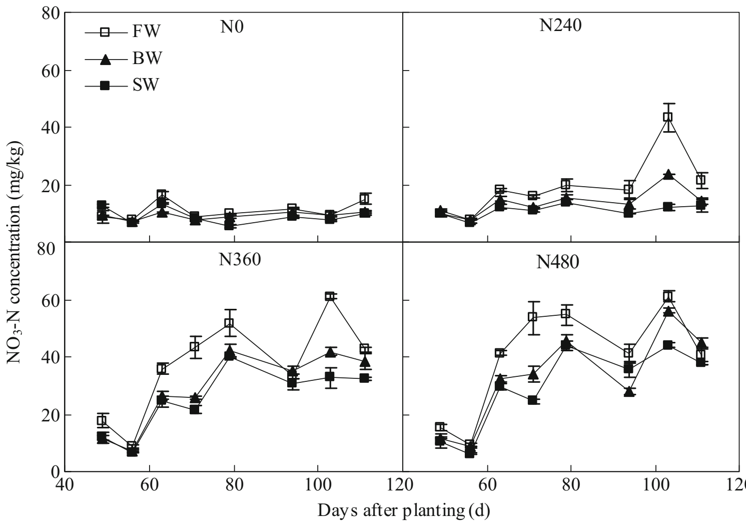

Fig. 9 Effects of irrigation water salinity and N application rate on soil NO_3-N concentration (0–20 cm depth) across the cotton growing season. The symbols *FW*, *BW*, and *SW* represent irrigation water salinities of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates. *Bars* represent the SD

treatment, and 700 % higher in the N480 treatment. NO_3-N concentration decreased significantly as irrigation water salinity increased. The average NO_3-N concentration in FW was 42.1 % higher than in BW and 98.7 % higher than in SW.

3.5 NH_4-N and NO_3-N Leaching

Water salinity, N application rate, and their interaction significantly influenced the leaching of both NH_4-N and NO_3-N (Table 1). The leaching of NH_4-N and NO_3-N increased as both water salinity and N application rate increased. N leaching losses (both NH_4-N and NO_3-N) were significantly greater in the SW treatment than in either the BW or the FW treatments. Irrigation water salinity and N application rate had significant interactive effects on (1) NH_4-N leaching in both the FW and BW treatments in the N480 plot and (2) NO_3-N leaching in both the BW and SW treatment under N0 plot. It was affected by water salinity and N application rate common action. The proportion of applied N lost through leaching was significantly greater in the SW treatment than in either the BW or the FW treatments. N

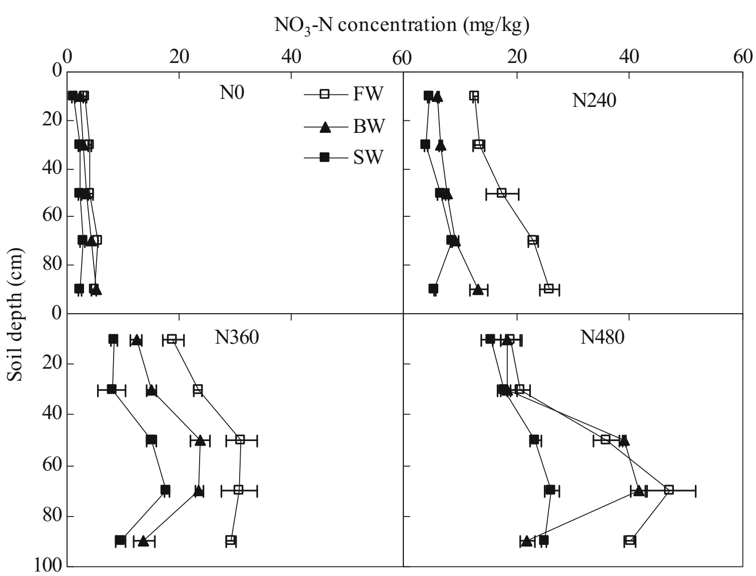

Fig. 10 Effects of irrigation water salinity and N application rate on distribution of NO_3-N concentration in the 1.0 m soil profile at harvest. The symbols *FW*, *BW*, and *SW* represent irrigation water salinities of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates. The *bars* represent the SD

Table 1 The effects of irrigation water salinity and N application rate on N leaching

N rate	Water salinity	N Leaching (kg N/ha)			% N lost as leaching of the applied N		
		NH_4-N	NO_3-N	Total	NH_4-N	NO_3-N	Total
N0	FW	0.02c[a]	0.63b	0.65c	–	–	–
	BW	0.08b	1.91a	1.99b	–	–	–
	SW	0.20a	2.31a	2.51a	–	–	–
	Mean[b]	0.10D[c]	1.61D	1.72D	–	–	–
N240	FW	0.06c	4.94c	5.00c	0.02b	1.80c	1.82c
	BW	0.12b	9.76b	9.88b	0.02b	3.27b	3.29b
	SW	0.37a	12.99a	13.36a	0.07a	4.45a	4.52a
	Mean	0.18C	9.23C	9.42C	0.03A	3.17AB	3.21AB
N360	FW	0.11c	7.76c	7.87c	0.03b	1.98c	2.01c
	BW	0.15b	11.40b	11.55b	0.02c	2.64b	2.66b
	SW	0.42a	17.98a	18.40a	0.06a	4.35a	4.42a
	Mean	0.23B	12.38B	12.61B	0.04A	2.99B	3.03B
N480	FW	0.14b	10.58c	10.72c	0.02b	2.07c	2.10c
	BW	0.14b	15.41b	15.55b	0.01b	2.81b	2.83b
	SW	0.53a	24.99a	25.52a	0.07a	4.73a	4.79a
	Mean	0.27A	17.00A	17.26A	0.03A	3.20A	3.24A
Analysis of variance (*P* value)							
Water salinity (S)		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
N rate (N)		<0.001	<0.001	<0.001	0.846	0.053	0.052
Interaction (S × N)		<0.001	<0.001	<0.001	0.003	0.005	0.005

FW fresh water, 0.35 dS/m; *BW* brackish water, 4.61 dS/m; *SW* saline water, 8.04 dS/m; *N0* 0 kg N/ha; *N240* 240 kg N/ha; *N360* 360 kg N/ha; *N480* 480 kg N/ha

[a] Different lowercase letters in the same column indicate significant differences at $P < 0.05$ level among different irrigation water salinity treatments

[b] Mean value for each N application rate

[c] Mean values with different capital letter are significantly different at $P < 0.05$ level between N application rates

application rate had no significant effects on the proportion of applied N lost through leaching.

3.6 Ammonia Volatilization

Similar temporal trends in soil NH_3 volatilization rates were observed for each treatment during the 7 days after N fertigation (Fig. 11). Averaged across all three water salinity levels, NH_3 volatilizations on the first day, the first 2 days, and the first 3 days in the unfertilized plots (N0) accounted for 26.9, 55.9, and 70.5 % of total NH_3 volatilizations over the 7 days, respectively, while the corresponding proportions in the fertilized plots (N240, N360, and N480) were 34.3–41.1 %, 69.5–80.6 %, and 84.2–91.1 %, respectively. Soil NH_3 volatilization rates were also significantly affected by water salinity and increased in the order FW < BW < SW.

Variations in soil NH_3 volatilization rates across the growing season are shown in Fig. 12. Both irrigation water salinity and N application rate significantly affected NH_3 volatilization. Averaged across all four N application rates, NH_3 volatilization rates were 26.2 % greater in SW and 16.5 % greater in BW than in FW. Soil NH_3 volatilization rates increased in the order N0 < N240 < N360 < N480.

The cumulative amount of NH_3 volatilization was significantly increased as water salinity increased (Table 2). Averaged across all four N application rates, the cumulative amount of NH_3 volatilizations were 40.4 % greater in SW and 17.7 % greater in BW than

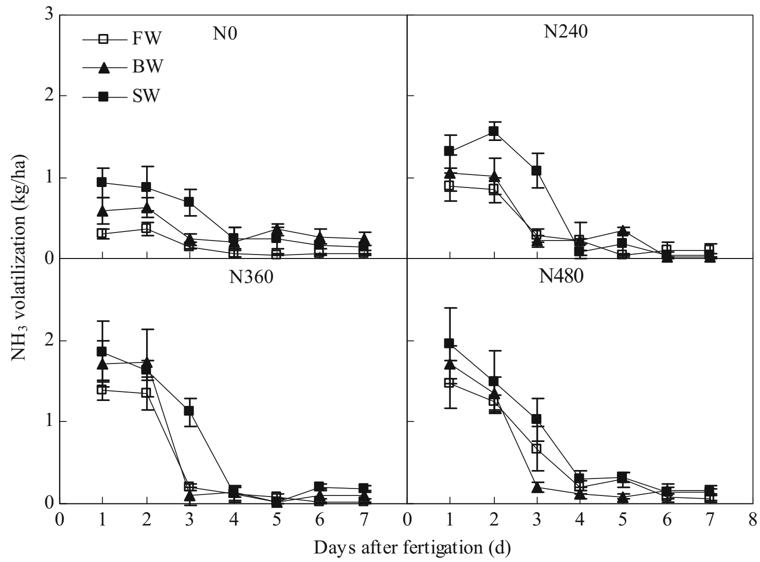

Fig. 11 Effects of irrigation water salinity and N application rate on soil NH_3 volatilization 1 to 7 days after fertigation. The symbols *FW*, *BW*, and *SW* represent irrigation water salinity of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates. The *bars* represent the SD

in FW. The cumulative amount of NH_3 volatilization was also affected by N application rate. Compared with the N0 treatment, the cumulative amount of NH_3 volatilization was 63 % higher in the N240 treatment, 101 % higher in the N360 treatment, and 132 % higher in the N480 treatment. The amount of NH_3 volatilization varied from 9.0 to 33.7 kg N/ha, accounting for 3.2 to 3.8 % of the urea-N applied. The proportion of applied N lost through NH_3 volatilization was not significantly affected by both irrigation water salinity and N application rate.

3.7 Nitrogen Uptake and Apparent N Recovery

Cotton N uptakes were significantly influenced by irrigation water salinity, N application rate, and the interaction (Table 3). In general, N uptake increased as N application rate increased. Compared with the N0 treatment, the total N uptake was 93 % higher in the N240 treatment, 122 % higher in the N360 treatment, and 138 % higher in the N480 treatment. The total N uptake in BW were similar or even higher than that in FW in the N0 and N240 pots,

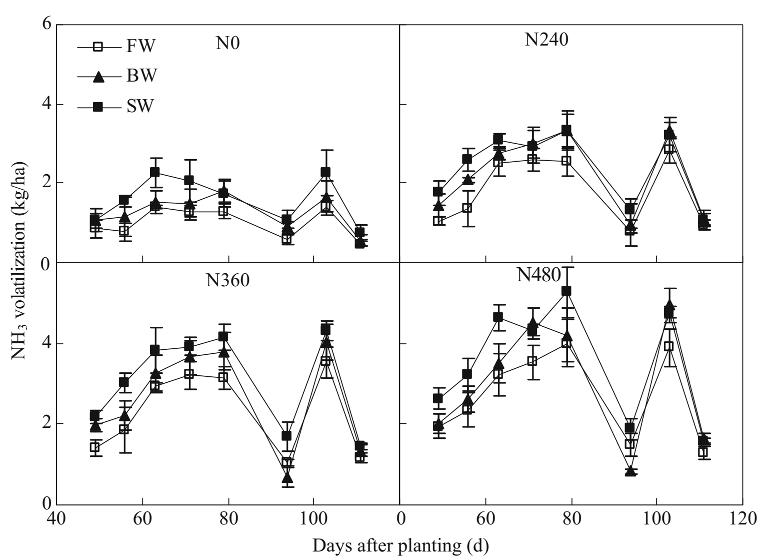

Fig. 12 Effects of irrigation water salinity and N application rate on soil NH_3 volatilization across the cotton growing season. The symbols *FW*, *BW*, and *SW* represent irrigation water salinity (EC) of 0.35, 4.61, and 8.04 dS/m, respectively. The symbols *N0*, *N240*, *N360*, and *N480* represent the 0, 240, 360, and 480 kg N/ha treatments, respectively. Values are the mean of three replicates, whereas *bars* represent the SD

Table 2 The effects of irrigation water salinity and N application rate on the cumulative amount of NH_3 volatilization and the proportion of applied N lost as NH_3 volatilization

N rate	Water salinity	Cumulative amount of NH_3 volatilization (kg N/ha)	% N lost as NH_3 volatilization of the applied N
N0	FW	9.04c[a]	–
	BW	12.69b	–
	SW	16.00a	–
	Mean[b]	12.58D[c]	–
N240	FW	17.09c	3.35a
	BW	20.82b	3.39a
	SW	23.58a	3.16a
	Mean	20.50C	3.30A
N360	FW	21.48c	3.46ab
	BW	24.82b	3.37b
	SW	29.69a	3.80a
	Mean	25.33B	3.54A
N480	FW	25.75c	3.48a
	BW	28.00b	3.19a
	SW	33.70a	3.69a
	Mean	29.15A	3.45A
Analysis of variance (*P* value)			
Water salinity (S)		<0.001	0.374
N rate (N)		<0.001	0.339
Interaction (S × N)		0.166	0.373

FW fresh water, 0.35 dS/m; *BW* brackish water, 4.61 dS/m; *SW* saline water, 8.04 dS/m; *N0* 0 kg N/ha; *N240* 240 kg N/ha; *N360* 360 kg N/ha; *N480* 480 kg N/ha

[a] Different lowercase letters in the same column indicate significant differences at $P < 0.05$ level among different irrigation water salinity treatments

[b] Mean value for each N rate

[c] Mean values with different capital letter are significantly different at $P < 0.05$ level between N rates

but were 14.3–15.0 % less than that in FW in N360 and N480 pots. In contrast, saline water irrigation (SW) significantly reduced the total N uptake in each N application rate.

The apparent N recovery (ANR) of the cotton ranged from 22 to 48 % (Table 3). ANR significantly decreased as N application rate increased. The average ANR decreased from 37.8 % in the 240 kg N/ha (N240) treatment to 32.9 % in the 360 kg N/ha (N360) treatment and 27.9 % in the 480 kg N/ha (N480) treatment. ANR was also significantly affected by water salinity, N240: FW > BW > SW; N360 and N480: FW > BW, SW.

4 Discussion

With increasing human population and rapid economic growth, the shortage of fresh water has become a fundamental and chronic problem for sustainable agriculture development, especially in arid and semiarid regions. Irrigation with saline water has become inevitable in arid and semiarid regions (Letey and Feng 2007). We observed that soil salinity and moisture content in the 0–20 cm depth were significantly increased as water salinity increased. This is in agreement with earlier findings that brackish or saline water irrigation could increase soil salinity and soil water content (Ben et al. 2012; Min et al. 2014).

Water salinity and N application rate affect soil salinity and moisture as well as N transformation. Generally, both NH_4-N and NO_3-N concentrations increased with N application rate increased. This is similar to the report by Malhi et al. (2003) who observed a significant increase in NH_4-N and NO_3-N concentrations increased with N application rate increased. Salinity affects soil N transformations by retarding several biological/microbial processes responsible for maintaining the NH_4/NO_3 balance (Lodhi et al. 2009). Our observations showed that soil NH_4-N concentrations increased as irrigation water salinity increased. In contrast, irrigation water salinity significantly decreased NO_3-N concentrations (Figs. 5, 6, 8, and 9). This is an agreement with observations that nitrification decreased as soil salinity increased, thereby resulting in an increase in NH_4-N and a reduction in NO_3-N (Akhtar et al. 2012). At harvest, the high NO_3-N concentrations were found in the deeper soil layers (60–100 cm), whereas NH_4-N accumulated in the surface soil layers (Figs. 7 and 10). Similarly, Ramos et al. (2012) reported that NH_4-N concentrations never increased at depths below 20 cm and relatively high NO_3-N concentrations were found below 65 cm of the root zone. This suggests that leaching of N occurred mainly in the NO_3-N form and saline water irrigation induce NO_3-N leaching in the deeper soil layers (Mai et al. 2010).

Studies have indicated that soil NO_3-N concentration and amount of subsurface drainage water (generated by irrigation) are two important factors controlling NO_3-N leaching (Jia et al. 2014). Both drip irrigation and higher splitting of N application rate have been proven to decrease NO_3-N leaching (Martínez-Alcántara et al. 2012). We observed that N leaching as NH_4-N (0.02–0.53 kg/ha) was far

Table 3 The effects of irrigation water salinity and N application rate on N uptake of cotton and apparent N recovery (ANR)

N rate	Water salinity	N uptake (kg N/ha)				ANR (%)
		Stem	Leaf	Boll	Total	
N0	FW	5.64b[a]	10.27c	66.71c	82.63c	–
	BW	10.08a	19.91a	84.42a	114.43a	–
	SW	5.25b	14.54b	75.00b	94.81b	–
	Mean[b]	6.99C[c]	14.91D	75.38D	97.29C	–
N240	FW	20.81a	24.49a	152.26b	197.56a	47.88a
	BW	16.66b	23.02a	158.77a	198.44a	35.01b
	SW	13.27c	23.34a	131.47c	168.08b	30.53c
	Mean	16.91B	23.61C	147.50C	188.03B	37.81A
N360	FW	17.14a	36.10a	195.03a	248.26a	46.01a
	BW	18.26a	25.98b	168.63b	212.86b	27.34b
	SW	16.31a	25.74b	144.39c	186.44c	25.45b
	Mean	17.23B	29.27A	169.356B	215.86AB	32.93B
N480	FW	25.19a	33.71a	207.96a	266.85a	38.38a
	BW	19.21a	24.38b	183.12a	226.71b	23.29b
	SW	22.46a	21.83b	155.38b	199.67b	21.85b
	Mean	22.14A	26.63B	182.15A	231.08A	27.87C
Analysis of variance (*P* value)						
Water salinity (S)		<0.001	0.002	<0.001	<0.001	<0.001
N rate (N)		<0.001	<0.001	<0.001	<0.001	<0.001
Interaction (S × N)		<0.001	<0.001	<0.001	<0.001	0.128

FW fresh water, 0.35 dS/m; *BW* brackish water, 4.61 dS/m; *SW* saline water, 8.04 dS/m; *N0* 0 kg N/ha; *N240* 240 kg N/ha; *N360* 360 kg N/ha; *N480* 480 kg N/ha

[a] Different letters in the same column indicate significant differences at $P < 0.05$ level among different irrigation water salinity treatments

[b] Mean value for each N rate

[c] Mean values with different capital letter are significantly different at $P < 0.05$ level between N rates

below as NO_3-N (0.63–25.0 kg/ha). The amount of N leaching varied from 5.0 to 25.5 kg/ha, accounting for 1.81 % to 4.79 % of the N applied under different irrigation water salinity and urea-N application rate treatments (Table 1). These leaching percentages were consistent with levels of 1.24–6.80 % reported by others for drip fertigation with urea (Hanson et al. 2006; Ajdary et al. 2007), but less than that reported by Phoga et al. (2014) and Wang et al. (2014). Both the irrigation water salinity and urea-N application rate had a significant effect on N leaching (Table 1). The amount of N leaching increased with increasing N application rate. It has been reported that N leaching has a positive relationship with N fertilizer input (Liu et al. 2014). Our result showed that NH_4-N and NO_3-N leaching increased as water irrigation salinity increased. This result is similar to the report by Bowman et al. (2006) who observed that saline water irrigation increased NO_3-N leaching. Our results also indicated that the proportion of applied N lost through leaching increased significantly with water salinity increased, but was not affected significantly by N application rate.

Ammonia volatilization is a physical process influenced by the concentration of NH_4-N in the soil solution (Bosch-Serra et al. 2014). In this study, soil NH_3 volatilization increased rapidly after urea fertigation, and peaked at 1–2 days after N application, then decreased rapidly (Fig. 11). Our results were consistent with others in the pattern of changes of NH_3 volatilization following fertilization, i.e., urea usually led to large NH_3 volatilization immediately after application, then reduced dramatically (Lin et al. 2012; Li 2013). In this study, the amount of NH_3 volatilization varied from 9.0 to 33.7 kg N/ha, accounting for 3.2 to 3.8 % of the urea-N applied (Table 2). These volatilization loss percentages were lower than those found (6–42 %) applying urea directly in soil (Ghaly and Ramakrishnan 2015). The lower percentages of NH_3 volatilization loss estimates in this study may have been a consequence of drip fertigation and higher splitting of urea-N application rate. Since urea is relatively mobile in soils and it is not strongly adsorbed by soil colloids, the deeper movement of applied urea via drip irrigation would tend to minimize NH_3 volatilization losses (Haynes 1985). Bar-Tal et al. (2015) also demonstrated that N loss through NH_3 volatilization from drip fertigation is usually low and can be minimized by proper management. Our results showed that urea-N application significantly increased the amount of NH_3 volatilization, the proportion of applied N lost through NH_3 volatilization, however, was not significantly affected by N application rate (Table 2). Soil NH_3 volatilization increased as the urea-N application rate increased, which was similar to previous reports (Wang et al. 2012; Han et al. 2014). Tian et al. (2001) also showed that the amount of N lost through NH_3 volatilization increased with increasing N application rate, but the ratio to applied N was not affected significantly by N application rate. We observed that saline water irrigation promoted NH_3 volatilization and the amount of NH_3 volatilization increased as irrigation water salinity increased. Akhtar et al. (2012) suggested that NH_3 losses increased as salinity because NH_4-N accumulation with increased salinity caused N losses in the form of NH_3 volatilization.

Most researchers believe that Na and Cl are primarily responsible for saline injury to plants (Flowers 2004; Ghanem et al. 2009; Munns et al. 2006). This is similar to our results N uptake decreased significantly as irrigation water salinity increased. However, in the unfertilized plot, N uptake decreased in the order BW > SW > FW. One explanation is that nutrient pools in the FW treatment had been depleted by previous crops. In contrast, long-term saline water irrigation inhibited nutrient uptake, with the result that available nutrient pools were greater in the BW and SW treatments than in the FW treatment. Our research shows that cotton N uptake increased significantly as N application rate increased, but decreased with irrigation water salinity increased. However, The ANR of cotton reduced as both N application rate and water salinity increased (Table 3). This result is similar to that of Min et al. (2014). Zhang et al. (2012) also reported that the N use efficiency decreased as N application rate increased under highly saline conditions. Our results suggest that saline water irrigation with high N application rate dramatically reduce the ANR of cotton. This is probably because saline conditions inhibited the growth and N uptake of cotton through osmotic stress, nutritional imbalance, and specific ion toxicity (Munns and Tester 2008).

Our research on the basis of 6 years saline water irrigation test and was dynamic observations ammonia volatilization under drip irrigation cotton. This experiment was conducted under field conditions and therefore affected by external environment factors. At the same time, various factors influence NH_3 volatilization. Therefore, the effects of saline water irrigation on NH_3 volatilization and its internal mechanism need further in-depth study.

5 Conclusion

Saline water drip irrigation with urea-N fertigation inevitably affects soil physicochemical properties and N transformations. Soil NH_4-N and NO_3-N concentrations increased as N application rate increased. In contrast, irrigation water salinity significantly decreased nitrification, resulting in an increase in NH_4-N and a reduction in NO_3-N. Irrigation water salinity induced NH_4-N accumulation and significantly promoted NH_3 volatilization. Both the amount of N leaching and the proportions of applied N lost through leaching significantly increased as water salinity increased. Urea application increased the amounts of N leaching and NH_3 volatilization, but the proportions of applied N were not affected by N application rate. Cotton N uptake increased significantly as N application rate increased, but decreased with irrigation water salinity increased. Overall, saline water irrigation with high N application rate induced high N leaching and NH_3 volatilization losses, thereby dramatically reducing the ANR of cotton.

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