Effects of drip irrigation and cropping on soil salinity, ionic composition and waxy corn production in a severely saline and calcareous and gypsiferous soil

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Abstract: Drip technologies have been suggested as practical for irrigation under conditions of high salinity and for reclamation of saline soils. Drip irrigation triggered by soil water potential thresholds was applied to both reclaim a severely saline calcareous gypsiferous soil and irrigate a waxy corn crop (*Zea mays* L. sinesis Kulesh). However, there is a lack of knowledge on the sustainability of reclamation of saline soils with drip irrigation and the changes in soil salinity and salt ion composition during the amelioration process. Therefore, effects on soil salinity, its ionic composition, and on crop growth and yields were evaluated in an experiment conducted in the Yinchuan Plain, northwest China. Treatments included fields in their first to fourth years of the drip irrigation reclamation-cropping scheme and adjacent native, non-cropped or irrigated saline-sodic land as control. Yield of waxy corn increased and days of growth to maturity decreased as a function of time and reclamation management. The improvement in crop performance could be largely credited to the reduction of soil salinity and changes in salt composition under the drip-irrigated reclamation protocols. The drip irrigation regime created a region of low salinity proximal to the emitters conducive to germination and plant growth. Deleterious ions for crop growth such as Na^+ and Cl^- were reduced while Ca^{2+} and Mg^{2+} concentration increased, especially in the upper 40 cm of soil. After only a single season of drip-irrigated waxy corn production, both Cl^-/SO_4^{2-} ratios and sodium adsorption ratio (SAR) decreased dramatically. The results suggested that drip irrigation is an effective technology for reclamation of severely saline-affected soils, such as those widely distributed over the Ningxia Plain in China and that this or similar reclamation strategy could be appropriate for reclamation of other hard to manage calcareous and gypsiferous soils.

Keywords: soil salinity, calcareous, gypsiferous, ion composition, leaching, salt transport
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1 Introduction

Soils covering some 1 billion ha in more than 100 countries, concentrated in arid and semi-arid regions around the globe, are estimated to be negatively affected by salinity[1] . Some 99 million hm^2 of Chinese land resources can be characterized as “saline wasteland”, a general term for land that has for the most part not been utilized due to various salt and alkali problems[2,3]. The reclamation of such wastelands for agricultural use has become a national priority to replace arable land lost to agriculture due to occupation of industry and urbanization, and therefore to resolve China’s food problem[3]. The Yellow River Irrigation District of Ningxia is one of China’s largest irrigation areas and an important food production base in northwest China. However, the region’s lands irrigated with water from the Yellow River have long been plagued by soil salinity. This salinity can be attributed to a number of factors, including: shallow groundwater tables with high concentrations of salts caused by over-irrigation, inadequate drainage systems, and flat, difficult-to-drain terrain[4]. Practices applied in the region to prevent soil salinization and reclaim salt-affected soils include leaching salts from the soils with excess water, building drainage systems, and reducing the area of flooded paddies[5]. Due to these practices, the proportion of salt-affected soil in the region was reduced from 67.4% in 1962 to 33.5% in 2007[6]. However, there remain clay soils with low water infiltration rates

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that tend to waterlog and in which salt leaching is inefficient[7]. For example, a cohesive soil locally known as "red sticky salty soil", widely distributed over the Ningxia Plain, has proven difficult to ameliorate of salts with traditional flood irrigation.

Drip irrigation has been suggested as potentially practical for irrigation under conditions of high salinity and for reclamation. The precise control of emitter flow rate and irrigation water amount provided by drip irrigation allow a favorable environment for crops including adequate soil water and air in the root zone. In heavy soils, waterlogging is minimized by drip due to partial wetting of the soil surface and the low flow rates. For the same reasons, the non-saturated conditions maintained by drip may also be more suitable for leaching salts compared to other irrigation techniques[8]. Drip irrigation has been shown in the literature to be an effective measure for reclamation of salt-affected soils and irrigation under conditions of soil and water salinity. Wan et al.[9] used drip irrigation on raised beds to ameliorate severely saline soils and in Ningxia plain, northwest of China. Wang et al.[10] demonstrated drip irrigation for reclamation of severely saline soils in Xinjiang in an arid climate. Li et al.[11] and Sun et al.[12,13] combined drip irrigation and other strategies such as installation of a gravel-sand layer to reclaim saline-sodic soils in coastal region.

The key to successful reclamation of salt-affected soils with drip irrigation is to supply enough water to transport salts out of the root zone either by continuous leaching by maintaining soil water at amounts greater than the requirements of evapotranspiration or by periodic leaching with large amounts of water. Soil water under drip irrigation can be managed through measurement of soil matric potential (SMP) with tensiometers[14-17]. SMP-based drip irrigation scheduling has previously been applied for reclamation of saline wasteland[9-11,13,18]. According to the previous literature, suitable SMPs for some crops were less than –20 kPa in non-salt affected soils. For example, –35 kPa SMP for radish[14], –50 kPa for tomato in North China Plain[15], and –30 kPa in northwest China[19]. However, the corresponding SMPs usually were above –20 kPa in saline soils. In saline soils, an optimum SMP of –10 kPa was reported for waxy corn grown in average soil (0-20 cm depth) with salinity of 19.4 g/kg[20], *L. barbarum* L. with rootzone (0-20 cm) soil electrical conductivity (EC) of a saturated paste extract (*ECe*) of 15.1 dS/m[18] and for cotton with *ECe* of 45.3 dS/m in the 0-30cm soil layer in Xinjiang[10] for irrigation was –10 kPa. An even higher threshold of -5 kPa was found to be preferable for less salt-tolerant vegetation species such as hibiscus, redleaf cherry plum and Chinese glossy privet[12] and Chinese Rose[11]in coastal saline soils with initial soil *ECe* of 24.6 dS/m. Most of the previous research focused on effects of SMP on crop growth and salinity distribution. An interesting finding was observed by Zhang et al.[18], SMP of –10 kPa as a threshold for drip irrigation for the first two years for *Lycium barbarum* L. with an initial *ECe* of 15.1 dS/m in the 0-20 cm soil layer and then a decrease to –20 kPa from the third year in Ningxia Plain. Wan et al.[9] also found that the response of waxy corn growth and yield characteristics to SMP became less pronounced with prolonged cultivation. What caused changes in the appropriate SMP and the response of maize growth and yield to SMP during saline soils reclamation? What changes in the dynamic process of salinity and ionic composition during the reclamation of saline soils? No information is currently available regarding the sustainability of reclamation of saline soils with drip irrigation based on regulation of SMP.

The dynamics of soil salinity is the result of weather conditions, fluctuations of ground water table, cultivation patterns, and irrigation management. Multi-seasonal studies of soil reclamation and changes in soil salinity and its chemical components over time attempt to evaluate the effectiveness of leaching management and response of crops. Unfortunately, differences in meteorological conditions and groundwater tables in the different years make it difficult to isolate the irrigation scheduling and cropping measure variables, and therefore, these studies remain without vigorous conclusions. That said, it remains necessary to understand the changes of soil salinity and crop yield over time in order to develop sustainable methods of reclamation and utilization of salt-affected soils.

The objectives of this study were to evaluate changes of soil salinity, salt chemical composition and pH in soil profiles and to measure the response of waxy corn yield during multi-season reclamation of a severe saline and calcareous-gypsiferous soil.

2 Materials and methods

2.1 Experimental site

Field experiments were carried out at the Qingtongxia Agriculture Integrated Development Experimental Station, Ningxia Hui Autonomous Region of China. The station (latitude: 37°36'N; longitude: 105°39'E; 1156 m a.s.l.) is located in the middle part of Yinchuan irrigation district, which diverts water from the Yellow River (Figure 1). The location has a typical mid-temperate continental climate with a mean annual temperature of 8.5ºC, a mean annual precipitation of 185 mm, most of which occurring in summer, and a potential annual evaporation of 2085 mm.

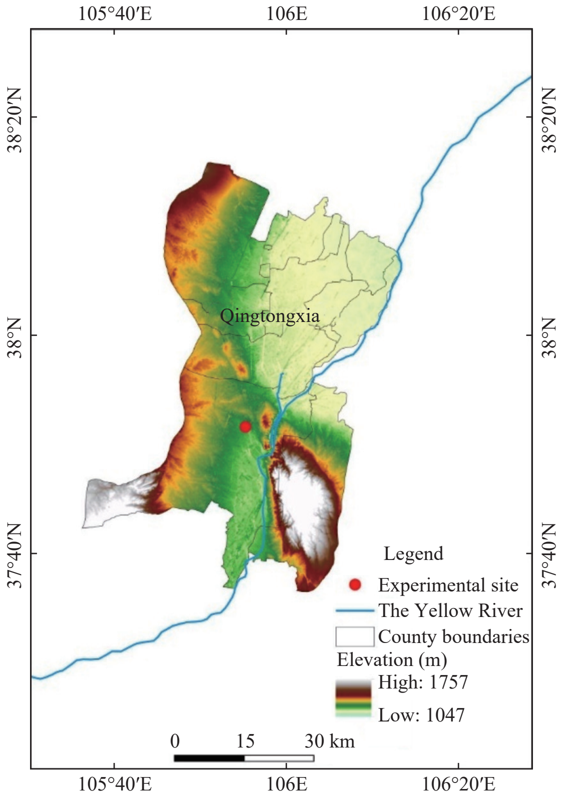


Figure 1 Study area map

Average groundwater table at the experimental site was approximately 1.2-1.5 m before sowing and rose up to about 1m during the cropping season. The EC and sodium adsorption ratio (SAR) of irrigation water diverted from the Yellow River were 0.50 dS/m and 2.8 $(mmol/L)^{0.5}$, respectively. The ionic compositions of irrigation water and ground water are given in Table 1.

Table 1 Ionic composition of ground water and irrigation water

	pH	ECw/dS·m^{-1}	Anions/mmol·L^{-1}				Cations/mmol·L^{-1}				SAR/(mmol·L^{-1})$^{0.5}$
			CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+	
Ground water	7.4	4.7	0.2	4.1	18.9	12.9	7.8	12.0	9.4	0.3	2.9
Irrigation water	7.1	0.5	0.0	2.4	2.3	0.2	0.7	0.5	2.2	0.2	2.8

The soil at the experimental site is an Aridsol according to USDA soil taxonomy, locally known as “red sticky salty soil”. This is a silt loam containing low initial levels of macronutrients and organic matter. The pre-reclamation soil suffered from heavy salinization with high chlorides and sulfates and a total dissoluble salt content of 23.4 g/kg in 0-40 cm soil layer. Some principal chemical-physical properties of 0-120 cm layers at the beginning of the experiment are listed in Tables 2-4. The soil was both calcareous and gypsiferous (Table 3).

Table 2 Physical properties of the initial soil profile

Depth/cm	Soil texture	Particle size distribution/%			Soil bulk density/g·cm^{-3}	Field capacity/m^3·m^{-3}
		Clay	Silt	Sand		
0-20	Silt loam	3.6	61.8	34.6	1.47	0.39
20-40	Silt loam	2.6	67.9	29.5	1.64	0.38
40-90	Sandy loam	1.5	35.9	62.6	1.68	0.36
90-120	Sand	4.5	1.0	94.5	1.78	0.25

Table 3 Macro-nutrients in the initial (non-reclaimed) soil profile

Depth/cm	Total N/g·kg^{-1}	Total P/g·kg^{-1}	Available N/mg·kg^{-1}	Available P/mg·kg^{-1}	Available K/mg·kg^{-1}	Organic matter/g·kg^{-1}	$CaCO_3$/g·kg^{-1}	$CaSO_4$/g·kg^{-1}
0-10	0.19	0.51	34.0	0.10	103.5	2.2	87.3	34.7
10-20	0.22	0.37	25.0	0.20	90.8	2.7	106.3	19.3
20-30	0.26	0.55	18.0	0.29	99.3	1.8	113.7	22.7
30-40	0.24	0.42	17.0	0.20	73.1	1.9	121.1	26.2
40-60	0.11	0.16	11.0	0.21	87.8	1.3	141.3	24.9
60-80	0.10	0.12	9.0	0.16	76.9	1.1	139.6	24.1
80-100	0.10	0.21	7.0	0.13	85.5	1.5	120.6	23.3
100-120	0.09	0.28	7.0	0.89	46.8	0.8	103.4	25.8

Note: N, nitrogen; P, phosphorus; K, potassium.

Table 4 Salinity and chemical composition of the initial soil profile

Depth/cm	Composition of soil: water 1:5 (w/v) extract (mmol/L)								$SAR^a_{1:5}$/(mmol·L^{-1})$^{0.5}$	$pH^a_{1:5}$	$EC^a_{1:5}$/dS·m^{-1}	ECe^b/dS·m^{-1}
	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+				
0-10	0.03	0.89	39.92	14.58	11.10	2.30	40.58	0.43	15.68	7.3	6.0	28.7
10-20	0.03	0.85	23.94	15.10	10.73	2.06	28.98	0.34	11.46	7.3	5.6	26.7
20-30	0.03	0.82	32.68	21.52	14.66	2.54	41.70	0.34	14.22	7.2	6.1	29.3
30-40	0.03	0.70	43.32	25.40	14.49	2.32	58.83	0.31	19.71	7.2	7.4	35.8
40-60	0.00	0.72	38.37	24.69	14.75	2.69	53.22	0.26	18.02	7.2	7.4	35.4
60-80	0.00	0.72	28.17	20.29	14.10	4.32	32.33	0.26	10.62	7.0	6.6	31.9
80-100	0.00	0.72	19.89	16.46	13.06	5.03	17.12	0.23	5.69	7.0	4.6	22.0
100-120	0.00	0.66	11.55	15.52	13.70	3.25	9.02	0.26	3.10	7.0	4.0	19.1

[a] The $pH_{1:5}$, $SAR_{1:5}$, and $EC_{1:5}$ means the pH, SAR and EC of soil: water 1:5(w/v) extracts, respectively.

[b] The *ECe* means the EC of saturated paste extract, calculated from the relationship between *ECe* and $EC_{1:5}$.

2.2 Experimental design

An experiment was conducted in 2007 on four adjacent plots situated in a single large field with generally homogeneous properties. The plots were incrementally annually drip-irrigated and planted over four years. The 1st year plot was reclaimed starting in 2007, the 2nd year plot was reclaimed starting in 2006, the 3rd year plot from 2005 and the 4th year plot reclaimed since 2004. The 1st-3rd year plots were located on three sides of the 4th year plot to minimize any influence due to spatial variability. All plots were reclaimed with mulch-drip irrigation and cropped with waxy corn under identical agricultural management. Plot areas were at least 144 m^2. The length and width of the plots were 45 m×4.0 m, 52 m×4.8 m, 56 m×6.4 m and 45 m×3.2 m for the 1st year, the 2nd year, the 3rd year and the 4th year, respectively. Three sub-plots of 48 m^2 in each were used as replicates for data collection and measurements. Non reclaimed wasteland adjacent to the experimental plots was considered as year 0. The relative location of different treatments and sampling areas were shown in Figure 2.

Each plot had an independent drip irrigation system including valves, pressure gauges, a water flow meter, a screen filter, and a fertilizer tank. Thin wall drip tapes (Beijing Lvyuan Co.), with emitters spaced 0.2 m apart and emitter discharge of 0.75 L/h at an operating pressure of 0.03 MPa, were placed in the center of the bed, which was covered with a white 0.038 mm polyethylene film.

2.3 Agronomic practices

Before sowing, 225 kg/hm^2 compound fertilizer (diammonium phosphate: 18% N, 46% P_2O_5, 1.5% SO_4^{2-}) and 150 kg/hm^2 K_2SO_4 were uniformly applied to each field as base fertilizer. During the waxy corn growth, a total of 300 kg/hm^2 urea and 75 kg/hm^2 dipotassium hydrogen phosphate were top-dressed to the fields accompanying the drip irrigation. The experimental fields were ploughed and prepared with raised beds. Each bed was 0.4 m wide and 0.15 m high, and the distance between two bed centers was 0.8 m (Figure 3). Waxy corn (*Zea mays* L. sinesis Kulesh) is a popular fresh-food corn, which is one of the widely cultivated crops in the Ningxia Plain. Also, it is a salt-tolerant crop. One row of waxy corn

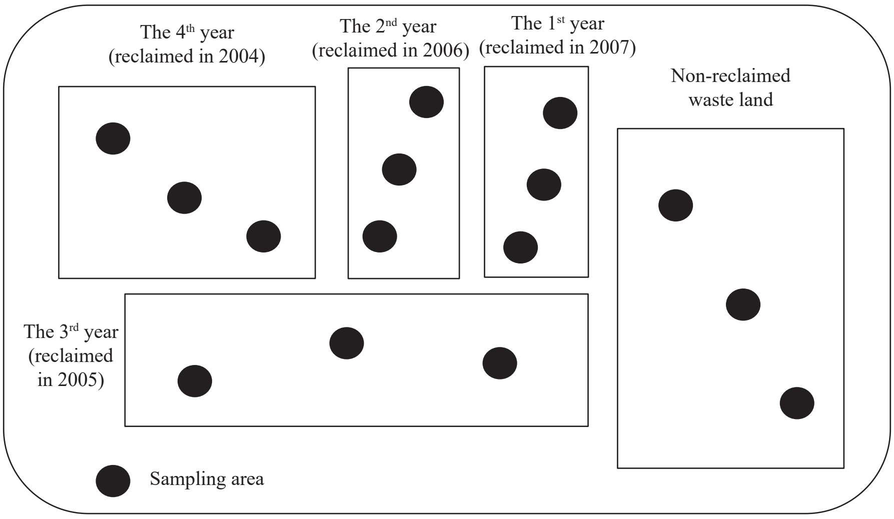


Figure 2 Schematic diagram of relative location of treatments and sampling areas.

(*Zea Mays* L. ceratina Kulesh, Zhongnuo No.1) was sown on the bed tops manually with seeds planted at 0.2 m interval. Waxy corn was sown on 17 May, however the harvest date was different due to disparity in maturity, the 4th year field was on 20 August, the 2nd and 3rd year fields on 31 August, and the 1st year plot on 10 September.

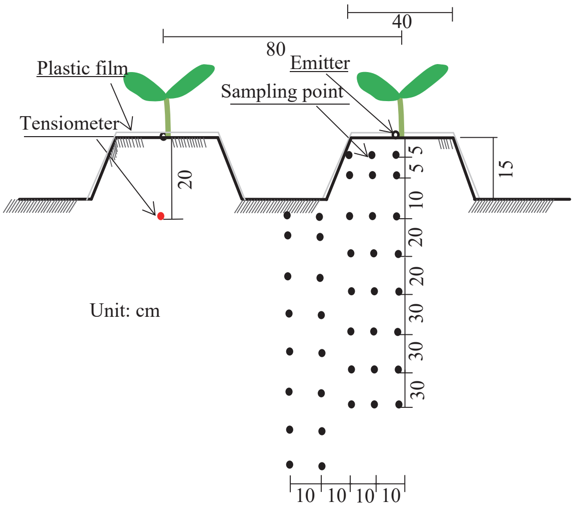


Figure 3 Dimensions of beds and positions of the tensiometer and soil sampling

2.4 Soil matric potential and irrigation

Two manually read vacuum gauge tensiometers (Beijing Aote Sida Technology Co., Ltd.) were installed at 0.2 m depth directly under emitters (Figure 3) in each treatment to measure SMP and to trigger irrigation events. Tensiometer readings were recorded three times daily at 08:00, 14:00 and 18:00 during the crop season.

Immediately after sowing, 40 mm was irrigated to leach accumulated salts in the upper soil layer and support seed germination. Subsequently, irrigation was applied according to soil moisture in the direct vicinity of the seeds. From germination until the fourth leaf stage, an irrigation event of 3 mm was given whenever soil water potential decreased for 2-3 times. After crop establishment, irrigation was triggered based on SMP threshold, that is, when the SMP at 0.2 m directly under drip emitters was lower than –10 kPa, an irrigation event was initiated. The amount of irrigation per event was 5 mm at the seedling stage and 10 mm at the heading and filling stages.

2.5 Measurements

2.5.1 Soil salinity, major ions and pH

Soil samples were obtained in three replications from each plot with auger (4.0 cm in diameter and 15 cm high) before sowing, after the first irrigation and at the end of experiment. Before sowing, samples were taken with three soil cores at random locations in each sub-plot from the depths of 0-5, 5-10, 10-20, 20-40, 40-60, 60-90, 90-120 and 120-150 cm. The other two times, samples were taken at 0, 10, 20, 30 and 40 cm distance from the drip emitter at the same depths (Figure 3). Triplicate soil samples were mixed into one sample per position and depth for salinity and major ion analysis.

Soil samples were air-dried and passed through a 1 mm sieve. Electrical conductivity ($EC_{1:5}$) and pH ($pH_{1:5}$) were measured in 1:5 (weight: volume) soil: water extracts by a conductivity meter (DDS-11A, Shanghai Rex Instruments, China) and a pH meter (PHS-3C, Shanghai Rex Instruments, China). After ending the experiment, the relationship between *ECe* and $EC_{1:5}$ was determined according Agriculture Handbook No.60[20] and used to convert $EC_{1:5}$ to *ECe* for all soil samples[9]. The relationship is as follows.

$$ECe = 4.81EC_{1:5}(R^2 = 0.90) \tag{1}$$

Concentrations of major ions including Na^+, Ca^{2+}, Mg^{2+}, Cl^- and SO_4^{2-} were also determined based on the 1:5 extract of soil to water. Chloride was measured by silver nitrate titration, SO_4^{2-} by indirect complexometric titration, Ca^{2+} and Mg^{2+} by EDTA titration, and Na^+ by flame photometer[21].

2.5.2 Average soil salinity (*ECe*), concentrations of ions and $pH_{1:5}$

A section of soil 40 cm wide and 40 cm deep, centered on the bed, was considered as root zone in this study, assuming typical water and root dynamics expected under high-frequency drip irrigation[22]. Average *ECe*, concentration of each ion and $pH_{1:5}$ in root zone and the larger 0-150 cm soil profile were calculated by the weighted mean method, e.g., average *ECe* on date *i* (*ECe*(*i*)) of 0-150 cm soil profile was calculated from *ECe*(*j, k*) and S(*j, k*) data (*j*=0, 10, 20, 30, 40; *k*=5, 10, 20, 40, 60, 90, 120, 150)[23].

$$ECe(i) = \frac{\sum_{\substack{j=0,10,20,30,40 \\ k=5,10,20,40,60,90,120,150}} ECe(i,j,k)S(j,k)}{\sum_{\substack{j=0,10,20,30,40 \\ k=5,10,20,40,60,90,120,150}} S(j,k)} \tag{2}$$

where, *ECe* (*i, j, k*) is the *ECe* value of date *i*, *j* is the horizontal distance to the drip tape and *k* is the depth to soil surface. S(*j,k*) is the representative area of the soil sample.

Seasonal average root zone ECe ($\overline{ECe}$) was integrated to take into account both spatial and temporal variation.

$$\overline{ECe}=\frac{ECe(f)+ECe(n)}{2} \tag{3}$$

where, $ECe(f)$ and $ECe(n)$ refer to the spatial weighted average value of the root zone after the first irrigation and at the end of experiment, respectively.

2.5.3 Rainfall and evaporation

Meteorological data including rainfall, wind speed, temperature and relative humidity were automatically recorded by a weather station located at the experimental site. Daily evaporation (*Ep*) was measured by a 20 cm diameter pan installed 0.7 m above the soil surface in a standardized meteorological station at the experimental station.

2.5.4 Yields

Twenty contiguous plants were harvested in one of the middle rows in each sub-site for yield analysis. Harvest was timed according to when kernels in the middle part of the ear were thickened to a doughy consistency. Total fresh corn ears were weighed and grain yield and above-ground biomass were measured.

2.6 Statistical analysis

Surfer (ver. 14, Golden Software, USA), SAS (ver.8.0, SAS Institute, USA), and Excel 2016 (Microsoft, USA) were used for data analysis and to create figures. *ECe*, ion concentration, and yield components were analyzed with one-way analysis of variance (ANOVA) and multiple comparisons were performed for significant effects among different reclaimed years with Duncan's test. The ANOVA analysis was based on three sites in each treatment and was performed at p=0.05 and p=0.01 levels of significance.

3 Results

3.1 Rainfall, evaporation and irrigation

The cumulative rainfall and pan evaporation during waxy corn growing season in 2004-2007 are shown in Figure 4. From the Figure 4, the cumulative rainfall was more than 100 mm except in 2005 and the pan evaporation was about 700 mm during the waxy corn growing season at the experimental site.

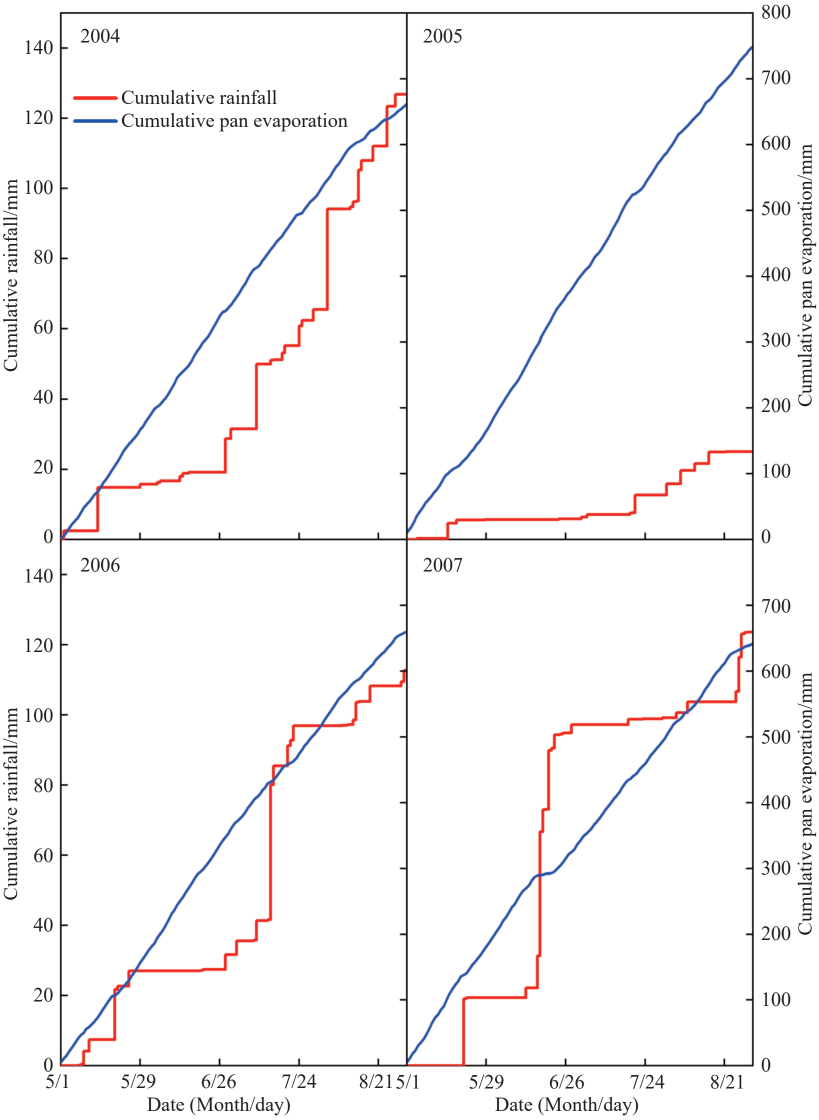


Figure 4 Total rainfall and pan evaporation during the growth period of waxy corn in 2004-2007

During the waxy corn growing season in 2007, total rainfall was 134.1 mm, concentrated in June, July and August, representing 35%, 28% and 18%, respectively, of total annual rainfall. Daily rainfall reached more than 10 mm seven times. Total pan evaporation during the growing season was 826.6 mm in 2007 (Figure 4).

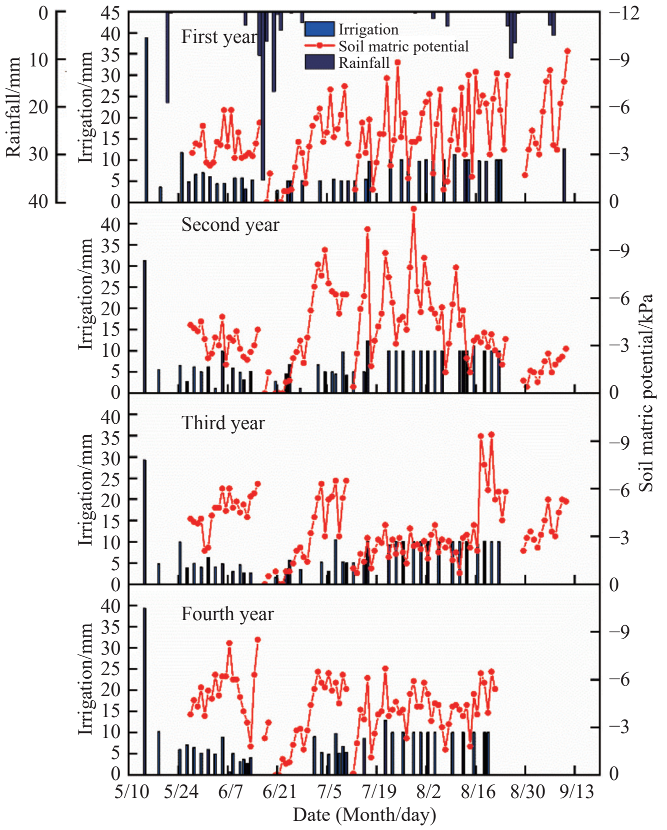
The amounts of irrigation water for the fields of the 1st and 2nd reclaimed year were more than those for the fields of the 3rd and 4th reclaimed year (Table 5), accounting for only 89% and 91.5% of the amount of 2nd year, respectively. The 4th year field also had a smaller number of irrigation events with 6 fewer irrigation events (36 times) compared to in the 2nd year (41 times). In the 1st and 3rd reclaimed year fields 39 irrigation events were applied. The differences in irrigation amount and times could be attributed to discrepancy of waxy corn growth and days to maturity among the treatments.

Table 5 Irrigation amounts and times, and date of last irrigation for different treatments in 2004-2007

Treatments	Irrigation Amount/mm	Irrigation times	Date of last irrigation
1st year (reclaimed in 2007)	318	39	10-Sep
2nd year (reclaimed in 2006)	317	41	23-Aug
3rd year (reclaimed in 2005)	286	39	23-Aug
4th year (reclaimed in 2004)	291	35	20-Aug

3.2 Soil matric potential (SMP)

The temporal variations of SMP at 20 cm depth immediately under the emitters for different reclaimed years are presented in Figure 5. The SMP at 20 cm depth for each treatment was fairly well maintained at the target value, i.e., the SMP was higher than –10 kPa over most of the growing period. It is therefore reasonable to hypothesize that no drought stress was experienced during the growth period.



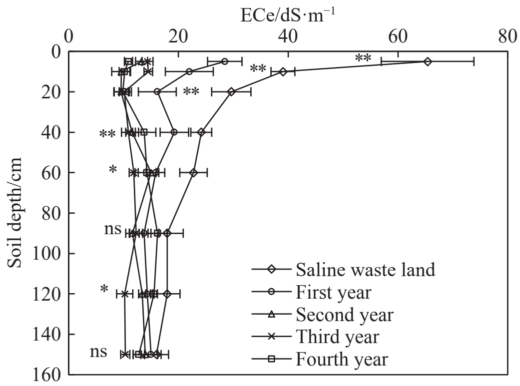
Note: The red scatter line stands for the soil matric potential, and the blue bar means the irrigation amount every time.

Figure 5 Soil matric potential at 20 cm depth immediately under the emitters and irrigation events for different reclaimed years during the growing period of waxy corn in 2007

3.3 Soil salinity

3.3.1 Before sowing

Figure 6 shows soil salinity profiles measured following winter and spring fallow and prior to sowing. Salts in non-reclaimed wasteland accumulated on the soil surface while the *ECe* of the 0 to 150 cm soil profile in the planted and drip-irrigated fields was rather low, indicating that the effect of leaching by drip irrigation persists even after winter fallow.



Note: Error bars show standard errors, ** represents significant differences at $p<0.01$, * stands for significant differences at $p<0.05$ and ns, not significantly.

Figure 6 Vertical distribution of *ECe* (electrical conductivity of the saturated paste extract) at the beginning of the experiments in different reclaimed years

Compared to the non-reclaimed wasteland, the *ECe* of the 0-40 cm soil layer in the planted and drip-irrigated fields decreased greatly. There were no significant differences in the root zone *ECe* between the fields of different reclamation duration. For example, the weighted average *ECe* in the 0 to 40 cm soil layer in non-reclaimed soil (and the yet-to-be reclaimed 1st year), the 2nd year, the 3rd year and the 4th year were 32.54, 11.02, 11.59 and 11.98 dS/m, and those in 40-150 cm soil layer were 18.28, 13.37, 11.11 and 14.73 dS/m, respectively, indicating that the salts in the upper soil could be significantly reduced by drip irrigation without resulting in salt buildup in the lower soil layer.

3.3.2 After the first irrigation

Figure 7a shows spatial distribution of *ECe* in the vertical transect perpendicular to the drip tapes for each treatment after the initial 40 mm irrigation event designed to leach, germinate and establish the crop. This initial irrigation created an obvious low salinity zone surrounding the emitter (within 20 cm distance from the drip emitter at 0-20 cm soil depth) for all treatments and accumulation of salts on the edges of beds and furrows (20 to 40 cm distance from emitters). Averaged *ECe* values of the low-salinity zone were 15.62, 16.06, 13.41 and 9.60 dS/m in the 1st, 2nd, 3rd, and 4th year, respectively, which were 43%, 41%, 51.5% and 65% lower compared with the corresponding 27.65 $dS.m^{-1}$ in non-reclaimed soil. In addition, we found that salinity decreased with the number of years of reclamation, both in the low salinity zone and in the 0-20 cm depth.

The salinity distribution pattern of the whole 0-150 cm soil profile (Figure 7a) clearly indicates higher *ECe* values in the top 0 to 40 cm soil compared to in the deeper 40-150 cm soil for the 1st year and the 2nd year treatments and equal or less salinity in the top 0 to 40 cm soil compared to the deeper soil for the 3rd year and the 4th year reclamation treatments. The patterns in the 1st and 2nd year were similar to non-reclaimed wasteland. The vertical distribution of salinity shifted from higher in the upper soil layers to mostly uniform in the soil profile and then to higher in the lower soil layers as a function of increasing period of reclamation and cropping.

The ANOVA (Table 6) showed that there were no significant differences for *ECe* in the top 0-40 cm soil but significant difference

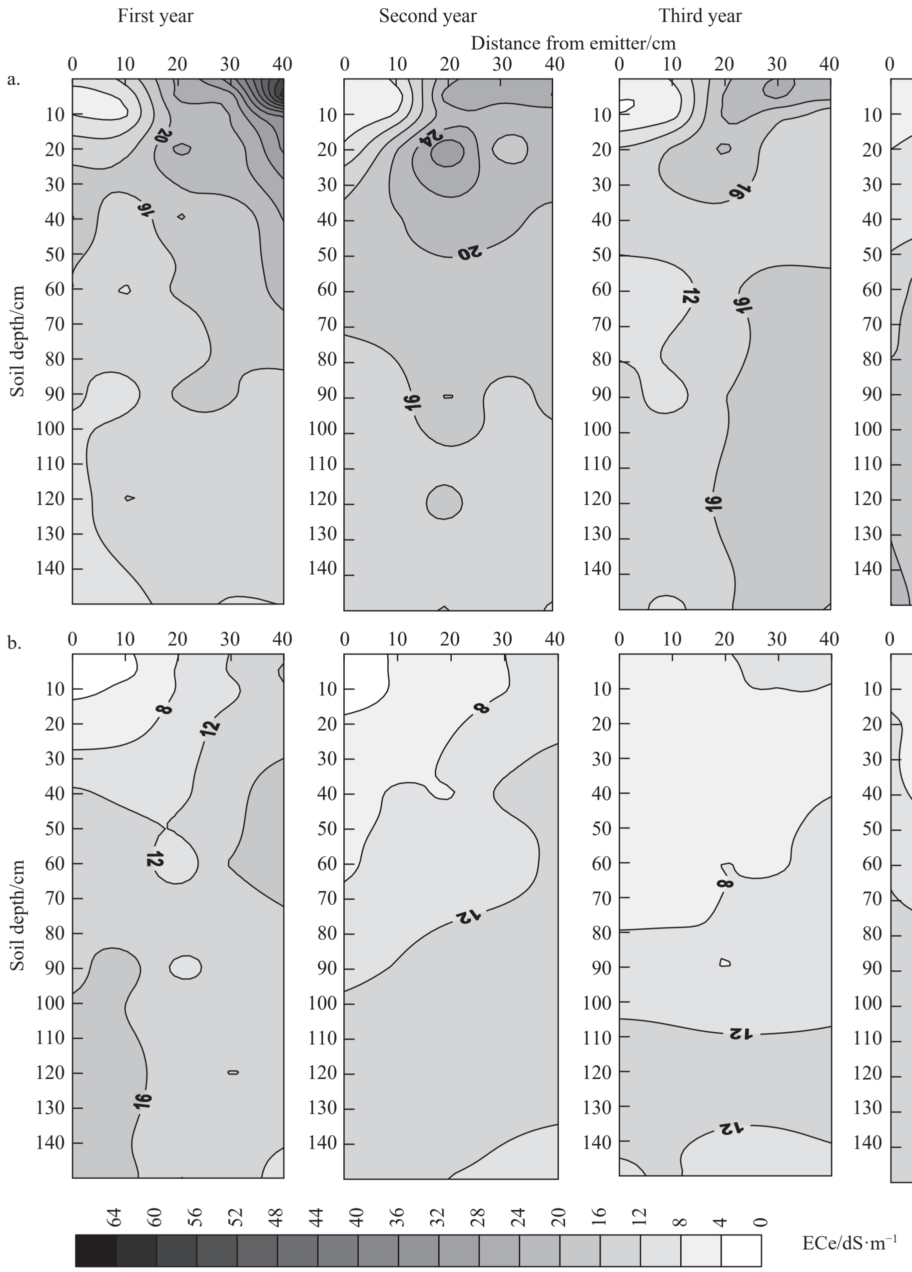


Figure 7 Spatial distribution of *ECe* (electrical conductivity of soil saturated paste extract) along the vertical transect perpendicular to drip tapes after initial irrigation (a) and at the end of the experiment (b) for different reclaimed year treatments in 2007

($p<0.05$) in the 40-150 cm soil layer among planting years treatments after the first irrigation event. The *ECe* of the 1st year in the 40-60 cm soil layer was significantly higher than those of others treatment and the highest *ECe* was achieved in the 60-150 cm soil layer for the 4th year. There was an extremely significant difference for *ECe* among the distances to the dripper in the top 0-20 cm soil, *ECe* at the distance of 40 cm to dripper far exceeding those at 0-30 cm to the dripper.

Table 6 The two-way ANOVA of *ECe* of planting years and distance to the dripper in the profile of 0-150 cm

Determined time	Factors	0-20 cm	20-40 cm	40-60 cm	60-150 cm
After the first irrigation event	Planting years	NS	NS	p=0.0360	p=0.0249
	Distance to the dripper	p<0.0001	NS	p=0.0145	NS
At the end of experiment	Planting years	NS	NS	NS	NS
	Distance to the dripper	p<0.0001	NS	NS	NS

3.3.3 At the end of experiment

Figure 7b illustrates the spatial distribution of salinity in the vertical transect perpendicular to the drip tapes at the end of experiment. A low salinity zone existed (with an average *ECe* of 8 dS/m) near the emitter for all reclaimed years. However, the range of the low salinity zone was expanded compared to after the first irrigation and was positively correlated with the number of reclaimed years. For instance, the horizontal and vertical radiuses of the ellipsoidal zone were 20 cm and 25 cm respectively for the 1st year, 30 cm and 65 cm for the 2nd year, and 40 cm and 80 cm for the 3rd year. As for the 4th year, the corresponding values were less than those of the 3rd year.

At the end of the experiment, average *ECe* of 0-150 cm soil profile decreased by 13.83%, 9.65%, 14.78% and 15.0% for the 1st, the 2nd, the 3rd and the 4th year after a crop season, respectively. Especially remarkable reductions occurred at 0-40 cm depth with salinity reduced correspondingly by 42.9%, 24.7%, 44% and 30.5%. The *ECe* of the assumed 40 by 40 cm root zone at the end of the experiment decreased linearly from 8.87 to 5.59 dS/m as a function of increased duration of reclamation.

The ANOVA (Table 6) showed there was no significant difference for *ECe* among planting years in the 0-150 cm soil profile and very significant difference among distances to the dripper in the top 0-20 cm soil at the end of experiment.

3.4 Ion composition

Table 7 presents changes in major anions in the 0-40 cm and 40-150 cm soil layers in different reclaimed years before sowing and at the end of experiment. Before sowing, Cl^- concentration in 0-40 cm soil depth was significantly less in the fields that had been reclaimed compared with non-reclaimed wasteland soil. However, there was no significant difference among reclaimed treatments. In the deeper, 40-150 cm soil layer, Cl^- concentrations were higher in reclaimed soils, regardless of duration of reclamation. We found that Cl^- concentrations in the 0-40 cm soil layer were more than in the 40-150 cm soil layer in non-reclaimed soil and 1st reclaimed year while they were close for the 2nd, 3rd and 4th years.

Table 7 Changes in Cl^- and SO_4^{2-} concentrations and the ratios of Cl^-/SO_4^{2-} in 0-40 cm and 40-150 cm soil over planting years before sowing and at the end of experiment

Soil layer/cm	Treatments	Before sowing			At the end of experiment			Seasonal change rate/%		
		Cl^-/mmol·L^{-1}	SO_4^{2-}/mmol·L^{-1}	Cl^-/SO_4^{2-}	Cl^-/mmol·L^{-1}	SO_4^{2-}/mmol·L^{-1}	Cl^-/SO_4^{2-}	Cl^-	SO_4^{2-}	Cl^-/SO_4^{2-}
0-40	non-reclaimed	37.32a	8.06ab	4.63a	40.40a	9.56a	4.23a	8.25	18.61	-8.73
	1st year	42.80a	8.23ab	5.20a	14.79b	6.79b	2.18b	-65.44	-17.50	-58.12
	2nd year	14.25b	7.53b	1.89b	7.71c	6.11b	1.26c	-45.89	-18.86	-33.32
	3rd year	15.20b	8.65a	1.76b	5.54c	6.61b	0.84c	-63.55	-23.58	-52.30
	4th year	13.41b	8.87a	1.51b	8.18c	7.19b	1.14c	-39.00	-18.94	-24.75
40-150	non-reclaimed	7.19a	7.12a	1.01a	13.93b	7.84a	1.78b	93.74	10.11	75.95
	1st year	9.56a	7.39a	1.29a	20.71a	7.65ab	2.71a	116.63	3.52	109.27
	2nd year	14.83a	8.76a	1.69a	16.76ab	6.49b	2.58ab	13.01	-25.91	52.54
	3rd year	10.13a	9.09a	1.11a	13.16b	6.36b	2.07ab	29.91	-30.03	85.67
	4th year	12.44a	8.80a	1.41a	15.56b	7.58ab	2.05ab	25.08	-13.86	45.21

Means (*n*=3) followed by the same letters in columns in the same soil layer are not significantly different at $p< 0.05$.

After a crop season, concentrations of Cl^- and SO_4^{2-} and Cl^-/SO_4^{2-} ratios decreased sharply at 0-40 cm soil depth for the reclaimed treatments with the maximum reductions in Cl^- and Cl^-/SO_4^{2-} ratio occurring in the 1st year treatment.

Table 8 shows the changes of concentrations of Ca^{2+}, Mg^{2+}, Na^+ and SAR at 0-40 cm and 40-150 cm soil layers as a function of duration of reclamation before sowing and at the end of the experiment. Before sowing, Na^+ concentrations at 0-40cm soil depth for treatments reclaimed for 1 year were significant less than those of non-reclaimed soil and decreased sharply after a crop season. Concentrations of Ca^{2+} and Mg^{2+} increased in all reclaimed treatments but were much lower than those of the non-reclaimed soil after the crop season.

We found SAR at 0-40 cm soil depth decreased gradually with the increase of reclaimed years before sowing and was reduced by over 50% after a cropping season. In the 40-150 cm soil layer, $Ca^{2+}+Mg^{2+}$ concentration increased at some extent after the cropping season, with exception of the 4th year.

Table 8 The changes in $Ca^{2+}+Mg^{2+}$ and Na^+ concentration and sodium adsorption ration (SAR) in the 0-40 cm and 40-150 cm soil layer over reclaimed years before sowing and at the end of experiment

Soil layer/cm	Treatments	Before sowing			At the end of experiment			Seasonal change rate/%		
		$Ca^{2+}+Mg^{2+}$/mmol·L^{-1}	Na^+/mmol·L^{-1}	SAR/(mmol·L^{-1})$^{0.5}$	$Ca^{2+}+Mg^{2+}$/mmol·L^{-1}	Na^+/mmol·L^{-1}	SAR/(mmol·L^{-1})$^{0.5}$	$Ca^{2+}+Mg^{2+}$	Na^+	SAR
0-40	non-reclaimed	8.74 a	49.49 a	16.74 a	13.52 a	53.6 a	14.58 a	54.7	8.3	-12.9
	1st year	6.75 a	45.37 a	17.46a	7.84 b	23.95 b	8.55b	16.1	-47.2	-51.0
	2nd year	5.32 a	25.88 b	11.22 ab	8.39 b	11.37 c	3.93 c	57.7	-56.1	-65.0
	3rd year	6.97 a	28.68 b	10.86 ab	8.12 b	7.63 c	2.68 c	16.5	-73.4	-75.3
	4th year	7.49 a	23.89 b	8.73 b	8.37 b	11.97 c	4.14c	11.7	-49.9	-52.6
40-150	non-reclaimed	7.88 b	17.95 a	6.39a	11.16 a	22.01 ab	6.59 a	41.6	22.6	3.1
	1st year	8.18 ab	32.38 a	11.32 a	11.02 a	27.47 a	8.27 a	34.7	-15.2	-26.9
	2nd year	9.18 b	26.70 a	8.81a	11.05 a	19.54 ab	5.88 a	20.4	-26.8	-33.3
	3rd year	8.64 b	24.05 a	8.18 a	8.71 a	16.39 b	5.55 a	0.8	-31.9	-32.2
	4th year	12.37 a	28.57 a	8.12a	10.54 a	19.54 ab	6.02a	-14.8	-31.6	-25.9

Means (*n*=3) followed by the same letters in columns in the same soil layer are not significantly different at $p< 0.05$.

3.5 pH

Figure 8 shows spatial distribution of pH in the vertical transect perpendicular to the drip tapes for each treatment under field condition. There was heterogeneity in pH near the emitter at the upper soil layer in all cases but, the depth of the heterogeneous region of pH increased with treatment from 0-40 cm for the 1st year to 0-60 cm for the 2nd year to the 4th year. Radially from the emitters, pH values increased as a function of distance. Average pH value in the 0-40 cm soil layer decreased from 8.8 to 8.3 as a function of duration of reclamation.

Table 9 illustrates the two-way ANOVA results of planting years and distance to the dripper at the end of experiment. There existed significant difference (p<0.05) for pH among planting years as well as among the distances to the dripper in the 0-20 cm soil layer.

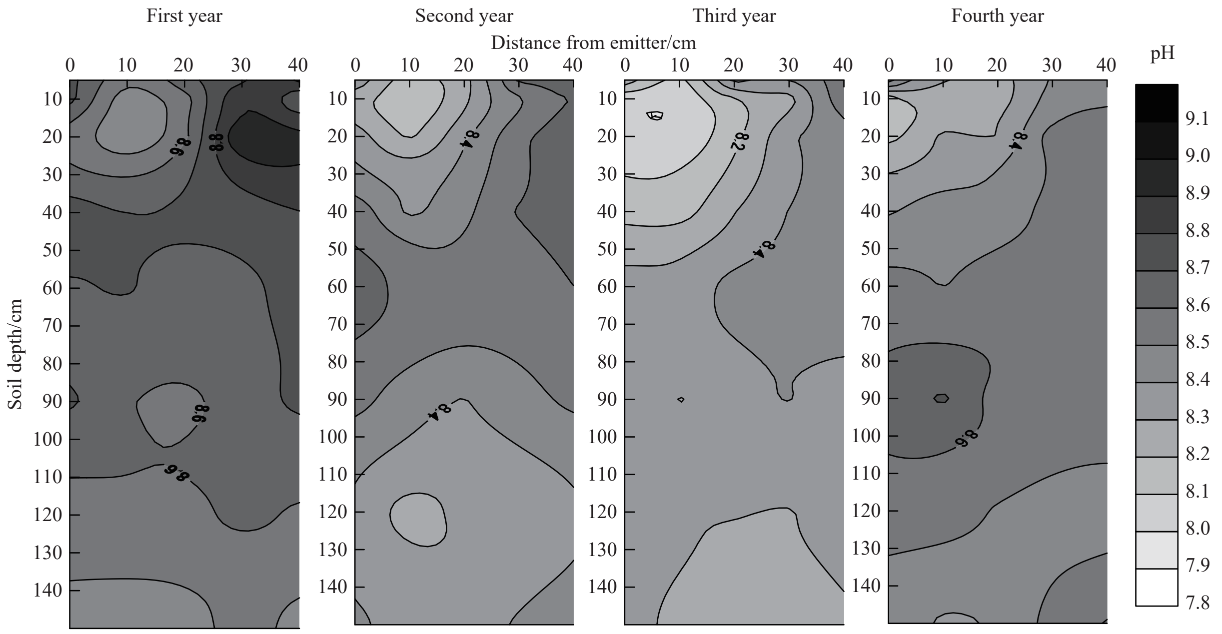


Figure 8 The spatial distribution of $pH_{1:5}$ in the 0-150cm soil profile along the vertical transect perpendicular to drip tapes at the end of experiment, 2007

Table 9 The two-way ANOVA of pH of planting years and distance to the dripper in the profile of 0-150cm at the end of experiment

factors	0-20 cm	20-40 cm	40-60 cm	60-150 cm
Planting years	p=0.0309	NS	NS	NS
Distance to the dripper	p=0.0314	NS	NS	p=0.0196

3.6 Waxy corn yield

Fresh ear yield, grain yield and above ground biomass were all similarly increased as a function of duration of reclamation (Figure 9a). The fresh ear yield of the 4th year with 13 520 kg/hm^2 was close to that expected in local non-saline affected soil. Despite linear increases, differences between individual years in fresh ear yield and above ground biomass after the first year were not significant. However, the grain yield in the 4th year was significantly higher than those in less than 4 years (p = 0.01).The number of growth days from sowing to harvesting decreased logarithmically with the increase of reclaimed years (Figure 9b). Lengths of growth period for the 1st year to the 4th year were 128 d, 108 d, 108 d and 97 d, respectively.

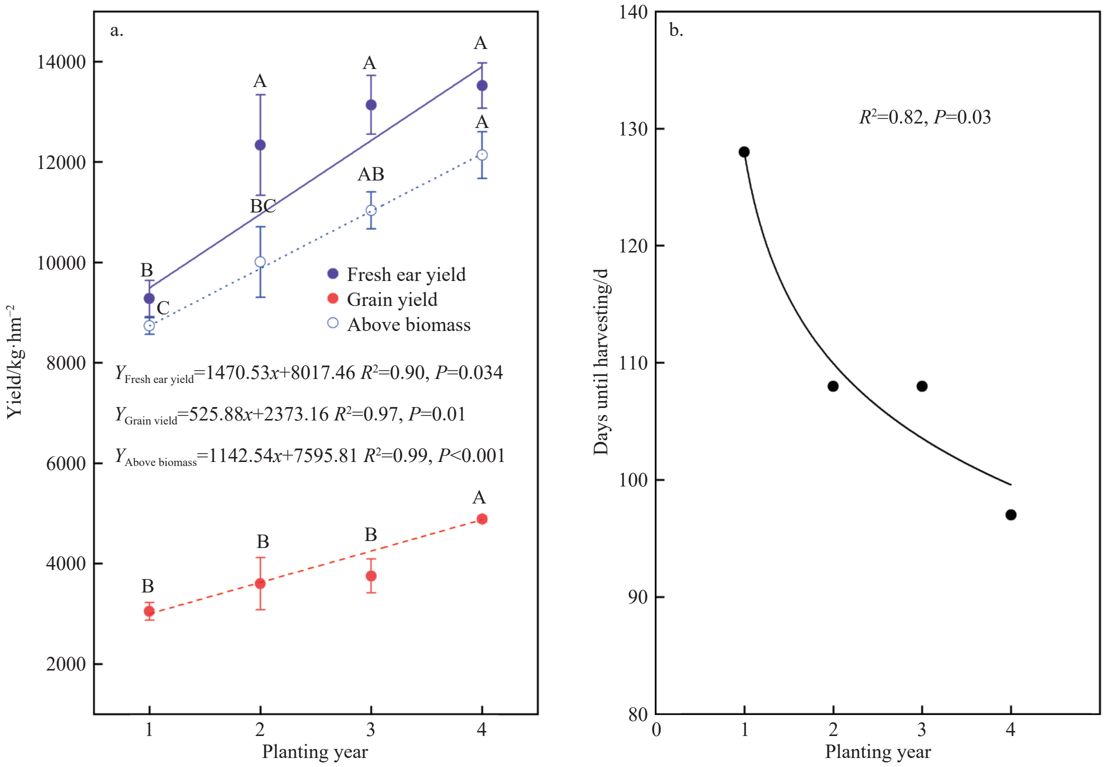


Figure 9 Relationship between yields and planting years (a) and relationship between length of growth period and planting years (b) in 2007

To estimate the effect of soil salinity on waxy corn yield, a simulated function between relative fresh ear yield (Y_r) and seasonal average ECe ($\overline{ECe}$) in the root zone was developed (Figure 10), expressed in the following equation:

$$Y_r = -8.12\overline{ECe} + 173.60(R^2 = 0.744) \tag{4}$$

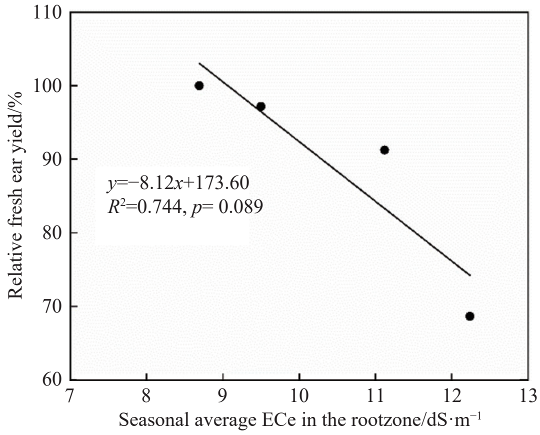


Figure 10 Relative fresh ear yield response to seasonal average *ECe* (electrical conductivity of saturated paste extract) in the root zone

4 Discussion

4.1 Leaching with drip irrigation

The SMP-based irrigation schedule is increasingly applied in drip irrigation. To compensate for decreased root zone osmotic potential induced by soil or irrigation water salinity, the optimum targeted SMPs for crop growth in saline soils are higher than in non-saline soils. While optimized SMP values for irrigation scheduling are certainly variable and dependent on the initial salinity of soil, crop tolerance to salinity and climate conditions, maintaining higher SMP in the root zone is clearly a key factor in leaching salt out of the root zone in saline soils under drip irrigation. In the current study, clear patterns of enduring low salinity were evident after 2 years of reclamation. In a previous study, Wan et al.[9] found that water moved downward to 35-50 cm depth when waxy corn was irrigated according to a -5 kPa set point treatment during waxy corn growth period. Wang et al.[24] observed that seasonal deep percolation was significantly linear with SMP threshold from -5 kPa to -25 kPa. Thus, to gain pronounced effectiveness of leaching salt, a higher SMP in the root zone in saline soils must be maintained and a threshold SMP of −10 kPa seems to often be optimal.

In this study, reduction in soil salinity occurred not only in the 0-40 cm depth but also to some extent in the complete 0-150 cm soil profile when targeted SMP was −10 kPa (Figures 5a and 5b). Similar results were obtained by Wan et al.[9,25] and Wang et al.[10]. The salts leaving the reclaimed profile were likely mainly transported into the adjacent drainage ditch, but could also have been moved to and accumulated in the dry wasteland surrounding the field[26,27]. Previous research has reported a low salinity zone close to emitters when drip irrigation was practiced in saline soils[9,25,28] or with brackish water[18]. Wan et al.[9] found that the extent of the zone of low salinity increased with the promotion of SMP. We additionally found that the extent of leached soil area positively related with the duration of reclamation in this study (Figure 5b) with the exception a smaller leached zone in the 4th year compared to that in the 3rd year. This exception might be due to the shorter growing period and earlier cessation of irrigation in the 4th year treatment. Less total irrigation meant suspension of the leaching process. In addition, the initial 40 mm technical irrigation also played an important role in leaching and redistributing salt from the 0-20 cm soil layer (Figure 5a) and to create a favorable low salinity environment for corn germination and establishment.

However, increased salinization under drip irrigation has been witnessed in many arid and semi-arid areas[28-31]. Reasons for the disparity, with drip irrigation sometimes beneficial and sometimes aggravating to soil salinity, are likely due to irrigation water quality[32] and drip irrigation regime[33]. Wang et al.[33] stated that drip irrigation regime determined the direction of soil salt accumulation or salt leaching. They found that soil was leached when 847 mm was irrigated for cotton in Xinjiang region under drip irrigation, while salt accumulated when only 270 mm was applied. Wang et al.[10] reported that when a SMP of –10 kPa was used to trigger irrigation with 460-541 mm for cotton in a saline-sodic soil for three years, significant reduction in soil salinity (*ECe*) of 0-120 cm depth occurred. The similar results from our current research suggest the potential for SMP driven drip irrigation as a reliable and effective method to reclaim salt-affected soils, when SMP is measured directly under a dripper and a high enough value is used to trigger irrigation events. Target SMP values will be relatively high under conditions of high soil salinity like the initial conditions in the present study and can then be adjusted to lower SMP as soil salinity declines with the progress of reclamation. Wan et al.[9] observed that the response of waxy corn growth and yield characteristics to SMP became less pronounced with prolonged cultivation.

4.2 Effects on crop response

The response function of relative fresh ear yield to seasonal average *ECe* in the root zone in this study (Figure 10) was developed the following linear equation: Y_r = -8.12$\overline{ECe}$ +173.60. The linear relationship illustrates that yield decreased by 8.12% for per unit of $\overline{ECe}$ increase in the root zone. This slope is on the high side of the wide-ranging salinity response functions found in the literature for maize. A threshold of 1.7 dS/m and a slope 12%[34] and 14% over 3.7 dS/m[35] for grain yield were reported. However, a slope of 3.9% for fresh ear yield of waxy corn[9] in Ningxia and an average of 5.5% reduction per unit increase in *ECe* for fresh ear yield of waxy corn in a 3-year field experiment[36]. Maas et al.[37] reported that fresh ear yield of sweet corn declined by 7.7% per unit increase in ECsw. Possible reasons for discrepancies between the response function in the present study and those from the literature are many and might be explained by the high *ECe* of even the lowest treatment in the present study, corn varietal differences, inaccuracies in acquisition of the actual mean root zone *ECe*, and that fresh ear yield rather than dry grain yield was taken into account in this experiment. Two additional explanations are possible. First, non-uniform distribution of root zone salinity may have allowed compensated uptake and less stress than expected when calculating average root zone salinity. Dong et al.[38] noticed that when only half of the root system was exposed to low-salinity, the inhibition effect of high salinity on growth and yield was significantly reduced. The second explanation could be that the literature based crop response assumes dominance of Na^+ and Cl^- ions, which, true for the initial soil, was reduced as the chemical composition of soil salinity changed during the years of reclamation.

In addition, the length of growth period of waxy corn decreased as the duration of reclamation was prolonged. Relative to the 1st year, nearly 30 d was curtailed for the 4th year (Figure 9b), nearing the expected days of growth in non-saline soils in Ningxia region. This is in agreement with results for oleic sunflower obtained at the same experimental site[25], where a shortened growth period as a function of extent of reclamation was found. This was due to reduction of soil salinity stress and increasingly favorable soil environment for crop growth as a function of the duration of reclamation and extent of leaching[11,13,39,40]. On the other hand, due to the high initial soil salt content in the first year, root growth was inhibited and maize growth was slow; while in the middle and later stages with soil salt leaching, the soil water and salt environment was favorable for maize growth, showing a rhythm of maize growth that was slow at early stage and then fast[41].

4.3 Effects on soil ion make-up

Soil ionic composition during reclamation of salt-affected soils, especially when calcareous and/or gypsiferous, is subject to complicated processes including ion exchange and diffusion, hydrolysis and ion precipitation, and plant uptake. Being more deleterious than other salt ions, Na^+ and Cl^- are the two most prevalent ions in salt affected soil in inland regions. The same situation occurs in the non-reclaimed soil in this study, Cl^- and Na^+ concentrations being far greater than SO_4^{2-} and (Ca^{2+}+Mg^{2+}), respectively in 0-40 cm depth (Tables 6 and 7).

The ratio of Cl^- to SO_4^{2-} in soil suspension extract is related to the chemical composition of soil salts and reflects the change of anionic composition. Before sowing, Cl^-/SO_4^{2-} ratios of non-reclaimed and the 1st year treated soils, with 4.63 and 5.20, respectively, were significantly greater than those of reclaimed fields with values below 2 at 0-40 cm soil depth (Table 6). There was no significant difference among the 2nd, 3rd and 4th reclaimed years. This indicates that Cl^- was predominant compared to SO_4^{2-} in the initial soil and the chemical composition changed remarkably after reclamation with drip irrigation and cropping. After a crop season, concentrations of Cl^- and SO_4^{2-} decreased with differential extent, higher declining rate for Cl^- than for SO_4^{2-}, at 0-40 cm soil depth for the reclaimed treatments as a result ratios of Cl^-/SO_4^{2-} even less than 1 for the 2nd year through the 4th year treatments. This indicates a change in anionic composition from Cl^- dominant to equal importance of Cl^- and SO_4^{2-}. Yet in the non-reclaimed soil, concentrations of Cl^- and SO_4^{2-} increased by 8.3% and 18.6% respectively and Cl^-/SO_4^{2-} ratio changed little. Wang et al.[33] also found the concentration of Cl^- decreased with duration of drip irrigation in Xinjiang region. At 40-150 cm soil depth, Cl^- concentration and Cl^-/SO_4^{2-} ratio increased with a variety of extent for all treatments including the non-reclaimed wasteland. This can be credited to leaching, either by drip irrigation or relatively strong rainfall events, of Cl^- from the upper soil layer.

Concentration of Na^+ decreased significantly after a crop season, but those of (Ca^{2+}+Mg^{2+}) increased in the root zone, maybe induced by the reduction of pH (Figure 6) owing to the respiration and exudation of roots. This very effect will facilitate to dissolve calcite in soil and enhance the level of Ca^{2+} in soil solution, especially in calcareous soils[42,43]. David and Dimitrious[44] pointed out that during the leaching of heavy textured saline and sodic soil, Na^+ diffusion rate was more rapid than that of Ca^{2+}, which may contribute to the reduction of solidity as leaching occurs. As a result, SAR in the root zone decreased sharply, which their values for the 3rd year representing less than one fifth of the corresponding values for non-reclaimed soils at the end of experiment. The result was consistent with result from Wang et al.[10] in Xinjiang region. With the decreases in Na^+ and SAR in soils, soil hydraulic and physical properties will be improved[32].

The mechanisms of reclamation of severely saline and calcareous and gypsiferous soil with drip irrigation and cropping could be summarized in three ways, as shown in Figure 11. The first way is to maintain the higher matric potential to create excess water through the rootzone to leach salt. And then, due to the speed of Na^+ is faster than Ca^{2+} and Mg^{2+} during the process of salt leaching resulting in more Ca^{2+} and Mg^{2+} in soil solution. The third way is that the decrease in soil pH and increase of CO_2 in rootzone lead to more $CaCO_3$ and $CaSO_4$ being dissolved and Na^+ being desorbed from soil colloid.

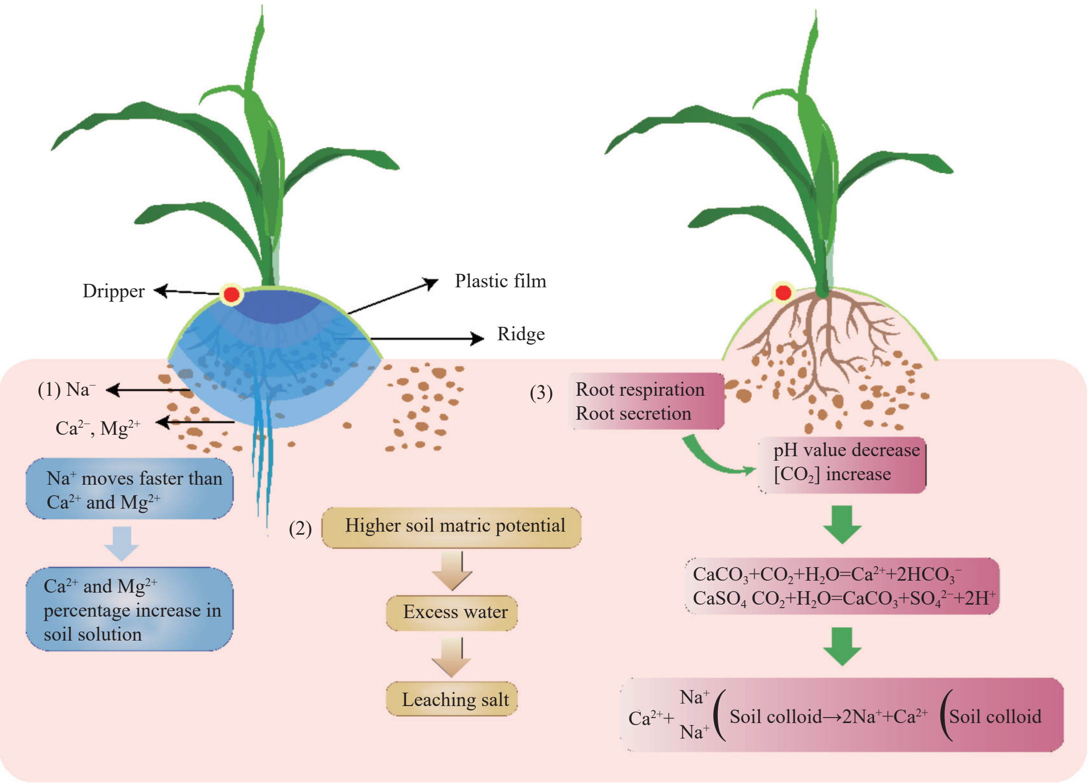


Figure 11 Mechanism diagram of reclamation of saline and calcareous and gypsiferous soil with drip irrigation and cropping

This study used a novel experimental method in which reclamation-irrigation regimes were followed for four consecutive years, with a new plot (treatment) added each year. This allowed analysis of the dynamics of the treatment over time and comparison and evaluation of the effect of time of the processes during the final year. The yearly addition of treatments was in plots immediately adjacent to one another, but replicates were taken from sections within each plot. We realize that this lack of block design could have led to statistical inaccuracies and also, that the different histories (more years of reclamation) may have introduced differential long-term effects influencing crop production in the final, comparison, year, beyond the reported effects of salt mobilization and leaching. In spite of these, we believe that the data are strong enough to allow our analyses, presentation and discussion. The conclusions in this study were based on 4 years of data, culminating with and focusing on a single season in which treatments of one to four years of reclamation were compared. To assess the sustainability of the method and evaluate its relevance for other places and conditions further research regarding drip irrigation for reclaiming saline soils should be carried out.

5 Conclusions

The drip irrigation regime created a region of low salinity proximal to the emitters conducive to seed germination and seedling establishment and growth after application of about 40 mm water in an initial irrigation event. When soil matric potential at 0.2 m immediately under emitters was maintain higher than –10 kPa, the areas leached of salts enlarged as the duration of drip irrigated time reclamation increased. Reduction of *ECe* of the entire 0-150 cm soil profile in irrigated treatments after a waxy corn season was variable. Dramatic decreases occurred at 0-40 cm soil depth. Together with the reduced salinity, the chemical composition of salts in the root zone soil changed as a function of duration of reclamation. Deleterious ions for crop growth such as Na^+ and Cl^- were reduced while Ca^{2+} and Mg^{2+} concentration increased. After only a single season of drip irrigated waxy corn production, both Cl^-/SO_4^{2-} ratios and SAR decreased sharply. At the same time, yield of waxy corn increased and days of growth to maturity decreased as a function of time and reclamation management using drip irrigation in an originally saline soil. The improvement in crop performance can be largely credited to the reduction of soil salinity and changes in salt composition under the drip-irrigated reclamation protocols.

Acknowledgements

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