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Salt characteristics and soluble cations redistribution in an impermeable calcareous saline-sodic soil reclaimed with an improved drip irrigation

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ABSTRACT

Saline-sodic and sodic soils are characterized by the occurrence of excessive Na^+ that adversely affect soil properties. Takyric solonetz, a saline-sodic soil with a poor structure, a low permeability (saturated hydraulic conductivity <0.1 mm d^{-1}) and a considerable $CaCO_3$, widely distributes in arid regions, Northwest China. A 3-year field experiment was conducted to reclaim this impermeable saline-sodic wasteland with an improved drip irrigation, where a sand-filled niche beneath drip emitter was adopted for ridge cultivation of *Lycium barbarum* L. Through the extensive sampling in soil transects, the salt characteristics and redistributions of soluble cations were evaluated. Results indicated that the soil properties that hindered takyric solonetz from being reclaimed orderly were, soil salinity, structure, alkalinity, and the concentrations of other ions (e.g. K^+). Salt leaching through the water regulation had the highest priority in reclaiming takyric solonetz, and followed by improving soil structure through changing ions composition and reducing soil sodicity. After reclamation, soil Na^+ concentrations decreased in root zone, but increased in top layers of ridge slope and furrow, while the increases of K^+ were only found beneath drip line, behaving little mobility with water flow. Considerable increases of divalent cations (Ca^{2+} and Mg^{2+}) occurred beneath drip line, but no obvious changes occurred in other regions of soil transect. It was concluded that irrigation water and dissolution of intrinsic $CaCO_3$ provided sufficient Ca^{2+} to replace the excessive Na^+, and the replaced Na^+ was leached out of root zone, resulting in a decrease of soil sodicity and improvement of soil structure. The reclamation measures were expected to have good sustainability, which was supported theoretically by the priorities of actions derived from salt characteristics. Thus, this improved drip irrigation provided a potential substitute for the costly amendments to ameliorate impermeable saline-sodic soils, especially with considerable amount of $CaCO_3$.

1. Introduction

Reclamation of salt-affected soils is a global issue, especially for the arid and semiarid regions (Mahmoodabadi et al., 2013). Among the categories of salt-affected soils, the saline-sodic and sodic soils are characterized by presence of excessive Na^+ in soil solution and in the exchange phase up to the levels, which can adversely affect the soil properties (Qadir et al., 2001; Tejada et al., 2006). It is widely considered more difficult for the saline-sodic and sodic soils to be ameliorated, than the saline soils (Oster and Shainberg, 2001; Qadir et al., 2001), because various obstacles should be coped with when reclaiming a saline-sodic or sodic soil, e.g., high alkalinity, poor soil structure, low permeability, as well as the high salinity, among which only the last probably occurred in saline soils.

Takyric solonetz (IUSS Working Group WRB, 2007) is a saline-sodic soil widely spread in arid regions, Northwest China. Generally, it does not have very high salinity except for the surface layer, but is always characterized by the high alkalinity (pH > 9.5), high sodicity (exchangeable sodium percentage (ESP) >60), extremely poor soil structure, and compacted soil layers (bulk density > 1.6 g cm^{-3}) with the crusting-prone surface. All these soil properties result in a low soil hydraulic conductivity of takyric solonetz, saturated hydraulic conductivity (K_s) is usually less than 0.1 mm d^{-1} (Wang et al., 1993; Chi et al., 2012; Zhang et al., 2013). Considerable

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CaCO3 generally exists in the form of calcite in the native profile. No vegetation was supported in this soil, except some blue-green algae, such as microcoleus, growing in patches during the monsoon season (Comprehensive Exploration Team, 1963; Yin, 1985; Wang et al., 1993). Therefore, the successful reclamation of this highly saline-sodic wasteland is of great importance both for environmental improvement and for agricultural productivity. In the recent decades, many methods have been reported to be effective to reclaim saline-sodic soils (Mace et al., 1999; Oster et al., 1999; Qadir et al., 2001; Clark et al., 2007; Yazdanpanah et al., 2013). However, many conventional methods (e.g. deep ploughing, application of organic fertilizer, phytoremediation) were not effective for takyric solonetz primarily due to the extremely low K_s (Yin, 1985; Wang et al., 1993). And application of the chemical amendments (gypsum) was too costly and provided only marginal economic interest for the local farmer (Wang et al., 2016).

Since 2009, a field study had been conducted to test the possibility of reclaiming takyric solonetz with drip irrigation but without chemical amendments. The vegetation planted was wolfberry (*Lycium barbarum* L.), a renowned medicinal fruit crop in Northwest China (Zhang et al., 2013; Zhang et al., 2017). The results showed that a considerable reclamation of this impermeable saline-sodic wasteland could be achieved in three years (Zhang et al., 2013). The drip irrigation used in this study was improved through adoption of the sand-filled niches beneath drip emitters, which facilitated the soil infiltration, and finally made the reclamation possible. Then, the changes of soil water and salt distribution (Zhang et al., 2013), nutrients status (Zhang et al., 2017) and soil enzymes activities (Zhang et al., 2014) were studied. An integrated agronomic measure was proposed for reclamation of takyric solonetz, mainly including ridge cultivation, sand-filled niches beneath drip emitters, mulched drip irrigation triggered by soil matric potential. However, some further studies are still needed for the amelioration mechanism and sustainability evaluation of the agronomic measure.

Quantitative study of soil salt characteristics is the basis for salt-affected soil management. However, the specific salt characteristics, dominative and restrictive factors of reclamation, and priorities of various actions in reclamation process, are still unknown for takyric solonetz. Meanwhile, the complexity and large spatial variability of soil salt compositions increased the difficulty of such quantitative study. This problem might be partly solved by extensive sampling and appropriate factor analysis. Additionally, a widely used amelioration method for sodicity-induced degraded soil is addition of chemical amendment (gypsum) to promote the replacement of exchangeable Na^+ by Ca^{2+}, and the replaced Na^+ is removed either below root zone or out of soil profile with leaching water (Oster et al., 1999; Qadir et al., 2001; Mahmoodabadi et al., 2013). However, in our study, takyric solonetz was reclaimed through exclusive drip irrigation without any chemical amendments containing Ca^{2+}. In this case, some questions may be raised: what were the Ca^{2+} resources and whether they were sufficient, and how about the leaching efficiency of excessive Na^+ out of the root zone, and even what were the migration and redistribution of soluble cations concurrent with the complex ions exchange adsorption and desorption. The answers to these questions would help us to understand the amelioration mechanism and to evaluate the sustainability of agronomic measures.

In this study, it was hypothesized that the theoretical possibility of our reclamation measures could be proved by the salt characteristics and restrictive factors emerged in takyric solonetz, and that the solution of native calcite ($CaCO_3$) under cropped conditions can supply sufficient Ca^{2+} to reclaim this saline-sodic soil. The objectives of this study were: (1) to analyze salt characteristics and dominative factors of takyric solonetz to prioritize the relevant actions during the reclamation; and (2) to evaluate the migrations and redistributions of soluble cations in soil transects in three continuous planting years. The results will not only provide an alternative soil amelioration technique for impermeable saline-sodic soils, but also help complete the methodology of salt-affected soil amelioration.

2. Materials and methods

2.1. Experimental site

The experimental site is located in Xidatan area (38°47′–38°57′N, 106°20′–106°30′E, 1095 m), in Pingluo County, Ningxia Hui Autonomous Region, Northwest China. The station has a typical arid continental climate, with a mean annual temperature of 9.4 °C, and a mean annual precipitation of 178 mm. The mean annual potential evaporation is >2000 mm. The studied soil is classified as takyric solonetz (IUSS Working Group WRB, 2007). Xidatan, where is the low-lying area (a natural collecting area) of piedmont alluvial plain of Helan Mountain, is the typical distribution area of takyric solonetz in China (Wang et al., 1993). Without any vegetation, local soil environment is extremely infertile. The local water table is about 2.5 m and the mineral concentration of groundwater is generally <3 g L^{-1}. Little inter-annual variation existed in water table and salinity of ground water, indicating that groundwater did not participate in modern soil formation, probably due to the impermeability of takyric solonetz (Wang et al., 1993).

The typical arid climate and geographical conditions result in the high salinity and sodicity in the surface of takyric solonetz. For the 0–30 cm soil layer, the average electrical conductivity of saturated paste extract (EC_e), pH of saturated paste (pH_s) and sodium adsorption ratio of saturated paste extract (SAR) were 12.3 dS m^{-1}, 9.4 and 44.1 $(mmol_c\ L^{-1})^{0.5}$, respectively (Table 1). Besides the high pH and

Table 1
Main physicochemical properties in uncultivated soil and irrigation water.

Soil depth (cm)	Soil texture components (%)			Soil texture [a]	Bulk density ($g\ cm^{-3}$)	$CaCO_3$ (%)	EC_e ($dS\ m^{-1}$)	pH_s	SAR $(mmol_c\ L^{-1})^{0.5}$	Cation concentration ($mmol_c\ L^{-1}$) [b]			
	<2 µm	2–50 µm	>50 µm							Na^+	K^+	Ca^{2+}	Mg^{2+}
0–10	1.35	90.59	8.07	Silt	1.44	10.62	18.54	8.90	35.7	123.5	0.39	5.5	6.5
10–20	0.99	95.93	3.08	Silt	1.53	14.53	11.66	9.58	54.0	108.0	0.34	2.0	2.0
20–30	0.85	95.75	3.40	Silt	1.59	12.40	6.69	9.52	38.6	77.2	0.2	2.0	2.0
30–40	1.02	92.32	6.66	Silt	1.64	18.61	4.16	9.51	23.2	46.4	0.2	2.0	2.0
40–80	0.65	82.38	16.97	Silt loam	1.62	11.14	2.17	9.47	11.6	23.2	0.27	2.0	2.0
80–120	0.48	77.45	22.07	Silt loam	1.58	6.19	1.59	9.21	6.9	15.4	0.65	2.5	2.5
Irrigation water [c]							2.14	8.87	6.0	11.9	0.34	1.32	6.46

[a] According to American soil classification standards.
[b] Cation concentration in saturated paste extract.
[c] The salinity values of irrigation water were the three-year averages measured once every year during the experiment. EC_e, electrical conductivity of saturated paste extract; pH_s, pH of saturated paste; SAR, sodium adsorption ratio of saturated paste extract.

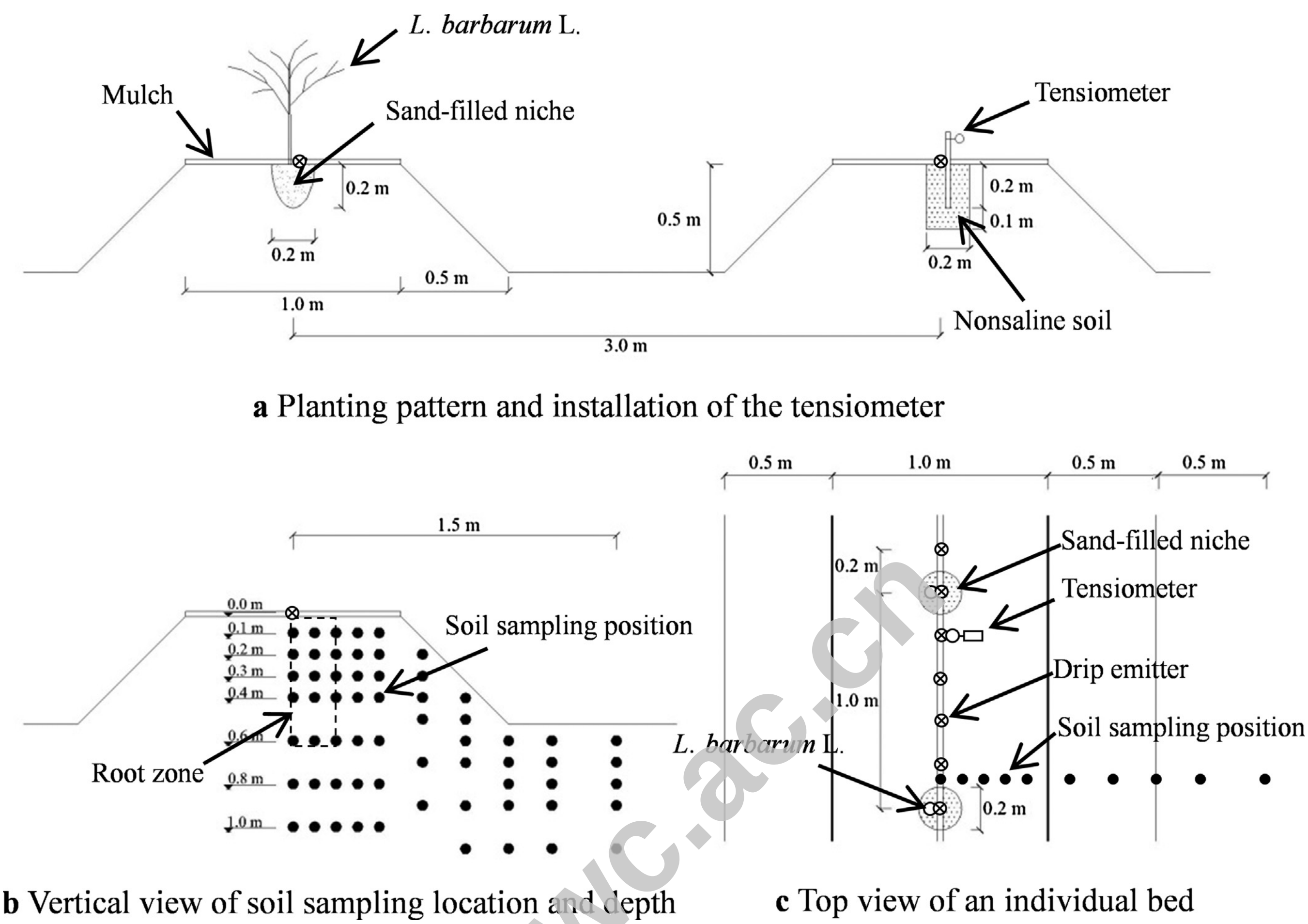

Fig 1. Planting pattern and soil sampling positions in field experiment of wolfberry (*L. barbarum* L.) with drip irrigation for reclamation of takyric solonetz in Ningxia, China.

SAR, takyric solonetz usually had a high bulk density of around 1.6 g cm^{-3}, a low K_s of <0.1 mm d^{-1}, and a considerable $CaCO_3$ in subsoil (Table 1).

2.2. Agronomic practices

In April 2009, this highly saline-sodic wasteland was reclaimed for growing wolfberry with ridge cultivation and drip irrigation. The ridge had a height of 0.5 m, a width of 1 m, and an inter-ridge distance of 3 m between bed centers (Fig. 1a). Drip irrigation tapes (emitter space of 0.2 m, flow rate of 0.76 L h^{-1} at an operating pressure of 0.03 MPa) were placed in the center of each raised bed. After constructing the beds, semiellipsoid pits (volume of about 4.2 L with a ground surface diameter of 0.2 m, and a depth of 0.2 m) were dug beneath the emitters, where wolfberry seedlings were planted (Fig. 1a) and filled with sands. The purposes of sand-filled niches could be summarized as following (Zhang et al., 2013): (1) to expand the soil-water contact area and thereby increase the area over which infiltration of applied water occurs, which will reduce the water application rates to levels that more closely match the hydraulic conductivity of the native soil; (2) to provide a reservoir to hold the applied water before it infiltrates into the soil; and (3) to alleviate the negative effects caused by the stirring action of applied water on surface soil.

Seedlings of wolfberry (cultivar of 'Ningqi No. 1′) were transplanted into the center of the beds at an interval of 1 m and the ridges were mulched with white polyethylene film (Fig. 1). During the growing seasons, drip irrigation was triggered by controlling the soil matric potential higher than −15 kPa, which was measured at a depth of 0.2 m beneath drip emitter (Zhang et al., 2013). The irrigation ratio was 5 mm during the growing season. And a 10–20 mm irrigation was applied at the beginning of each growing season to leach the salts brought to soil surface in winter because of the lack of irrigation and upward water movement caused by the freeze/thaw cycle and direct soil evaporation. Irrigation water with EC of 2.1 dS m^{-1} and SAR of 6.0 $(mmol_c\ L^{-1})^{0.5}$ (Table 1) was obtained from a reservoir pumped from the Yellow River. Urea, phosphoric acid and potassium nitrate were dissolved and applied with the irrigation water in each irrigation event during the growing seasons. The fertilization rates were about half of the corresponding level in local farmland (Table 2).

A drainage ditch (width of 0.5 m and depth of 0.5 m) was dug around the field to minimize temporary waterlogging and associated soil saturation in the experimental plots. Similar to local high-yield wolfberry fields, field management mainly included regular pruning, trimming, weeding, and application of pesticides to control insects.

2.3. Soil sampling and analysis

Soil samples were obtained with an auger (a diameter of 4.0 cm and length of 20 cm) at selected locations as shown in Fig. 1b and c at the end of three growing seasons (i.e. 28 October in 2009, 18 October in 2010, and 16 October in 2011), which were denoted as reclaimed for 1, 2 and 3 years, respectively. The location of sampling soil transect was as close as possible to the sand-filled niche, but must avoid sampling the foreign sand in the niches (Fig. 1c). A total of 62 soil samples were obtained in each transect (Fig. 1b) and

Table 2
Rainfall, evaporation, irrigation and fertilization during the growing seasons of *Lycium barbarum* L.

Years	Rainfall (mm)	Evaporation[a] (mm)	Irrigation amount (mm)	Fertilization rate (kg ha^{-1})		
				N	P_2O_5	K_2O
2009	153.5	1309.2	130	160	100	75
2010	150.3	1475.1	150	300	150	100
2011	120.8	1490.8	280	500	240	50

[a] Evaporation refers to cumulative pan evaporation of a standard evaporimeter with 20 cm diameter.

three replicate transects were sampled in each year. After carefully removing surface organic materials and fine roots, gravimetrical soil water content was determined for field moist subsamples. The remaining soil subsamples were air-dried and passed through a 1-mm sieve. Then the three replicates of soil samples were mixed for chemical analysis.

Saturated soil paste was prepared for chemical analysis. The pH_s was measured with a pH meter (PHS-3C, Shanghai Precision & Scientific Instrument Co., LTD., Shanghai, China). Then clear extracts of saturated soil pastes were obtained by centrifugation (4000 rpm, 30 min) and analyzed for EC_e and ions concentrations. The values of EC_e were measured with a conductivity meter (DDS-11A, Shanghai Precision & Scientific Instrument Co., LTD., Shanghai, China). Concentrations of $CO_3{}^{2-}$ and $HCO_3{}^{-}$ were measured by double indicator titration method, Cl^- by silver nitrate titration method, $SO_4{}^{2-}$ by EDTA complexiometric titration method, Ca^{2+} and Mg^{2+} by EDTA titration method, and Na^+ and K^+ by flame photometry. The detailed methods of ions concentration measurement were done as described by Bao (2005). The total soluble salt content (TSS, the sum of the eight ions concentrations) and soluble sodium percentage (SSP) were calculated by mass concentration, and SAR was calculated by molar concentration using the following formula:

$$SAR = \frac{Na^+}{[(Ca^{2+}+Mg^{2+})/2]^{0.5}} \quad (1)$$

where a chemical element symbol indicates a concentration in $mmol_c\,L^{-1}$.

2.4. Data analysis

The root zone was defined as 20 cm horizontal distance from the drip line and 60 cm in depth (Fig. 1b). Average values of soil properties in root zone were calculated as the spatially weighted mean of all samples within this zone. The Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test of Sphericity were used to test whether the samples were suitable for factor analysis. Results showed that the KMO value was 0.635 and the concomitant probability of Sphericity Test was 0.000 (<0.05), which indicated that these samples were suitable for factor analysis (Hao et al., 2003). Then, principal component analysis (PCA) was performed. The principle components were selected when the cumulated contribution rate of total variance accounted for >85%. Then the factors were extracted and rotated by Varimas, and finally, the eigenvalues of the selected eigenvectors and the factor loading were calculated.

SPSS 11.5 statistical software (SPSS Inc., Chicago, IL, USA) was used to analyze the data, and the figures were created using Surfer 8.0 (Golden Software Inc., CO, USA) and SigmaPlot 10.0 (Systat Software Inc., CA, USA).

3. Results

3.1. Establishment of soil salt eigenfactor

The molar concentration of $CO_3{}^{2-}$ was found very low during the analysis, partly due to the non-timely assay of some occasional samples, so only $HCO_3{}^{-}$ concentrations were used in this study for the analysis to represent soil alkalinity ($CO_3{}^{2-}$ + $HCO_3{}^{-}$) (Hao and Chang, 2003).

The sum of eigenvalues of the first four principle components were 10.461, while the corresponding cumulated contribution rate of variance reached up to 87.18% (Table 3). This result illuminated that the first four principle components included the most variance of the initial 12 factors, while the loss information was only 12.82%.

The factor loading was the correlation coefficient between principle component and original variable factor. The factors loadings exhibited a "clustering distribution" phenomenon obviously in the spaces defined by two components (Fig. 2). For principle component 1 (PC1), the four factors with biggest positive loadings were Na^+, EC_e, TSS and Cl^- (i.e., 0.952, 0.942, 0.929 and 0.91, respectively), followed by SAR and $SO_4{}^{2-}$ concentrations. This indicated that PC1 could represent the soil salinity of takyric solonetz and substitute six variables (Na^+, EC_e, TSS, Cl^-, SAR and $SO_4{}^{2-}$) among the original total 12 variables.

Divalent cations (Mg^{2+} and Ca^{2+}) had the highest positive loadings in PC2 (0.902 and 0.869, respectively) (Fig. 2a). Considering the positive effects of divalent cations on soil physical properties, it could be concluded that PC2 represented the soil structural status. Meanwhile, among the original factors in PC2, SSP had higher negative loadings, which was because the decreases of SSP indicated the increased ratios of Mg^{2+} and Ca^{2+} in total cations. Therefore, PC2 could substitute three variables (Mg^{2+}, Ca^{2+} and SSP) among the original 12 variables.

The PC3 was characterized with higher positive loadings for soil pH_s and $HCO_3{}^{-}$ concentration (Fig. 2b). The reduction in soil pH_s not only indicated the mitigation of soil alkalinity ($CO_3{}^{2-}$ + $HCO_3{}^{-}$), but also helped dissolution of Mg and Ca compounds in native soil. Thus, PC3 represented the soil alkalinity and could substitute 2 variables (pH_s and $HCO_3{}^{-}$) among the original 12 variables.

The high positive loading of K^+ (0.958) was apparent in PC4, as shown in Fig. 2c. Since the ratio of $(Na^+ + K^+)/(Mg^{2+} + Ca^{2+})$ is an important indicator of soil structure (Smith et al., 2015), not only the cations composition, PC4 represented the other cation (K^+) concentration in saline-sodic soils besides the crucial cations (Na^+,

Table 3
Rotation sums of squared loadings in the principle component analysis of soil salt characteristics.

Principle components	Eigenvalues[a]	Contribution rate of variance (%)	Cumulated contribution rate of variance (%)
1	5.032	41.936	41.936
2	2.936	24.470	66.406
3	1.430	11.920	78.327
4	1.063	8.856	87.183

[a] Based on the rotation method of Varimax with Kaiser Normalization.

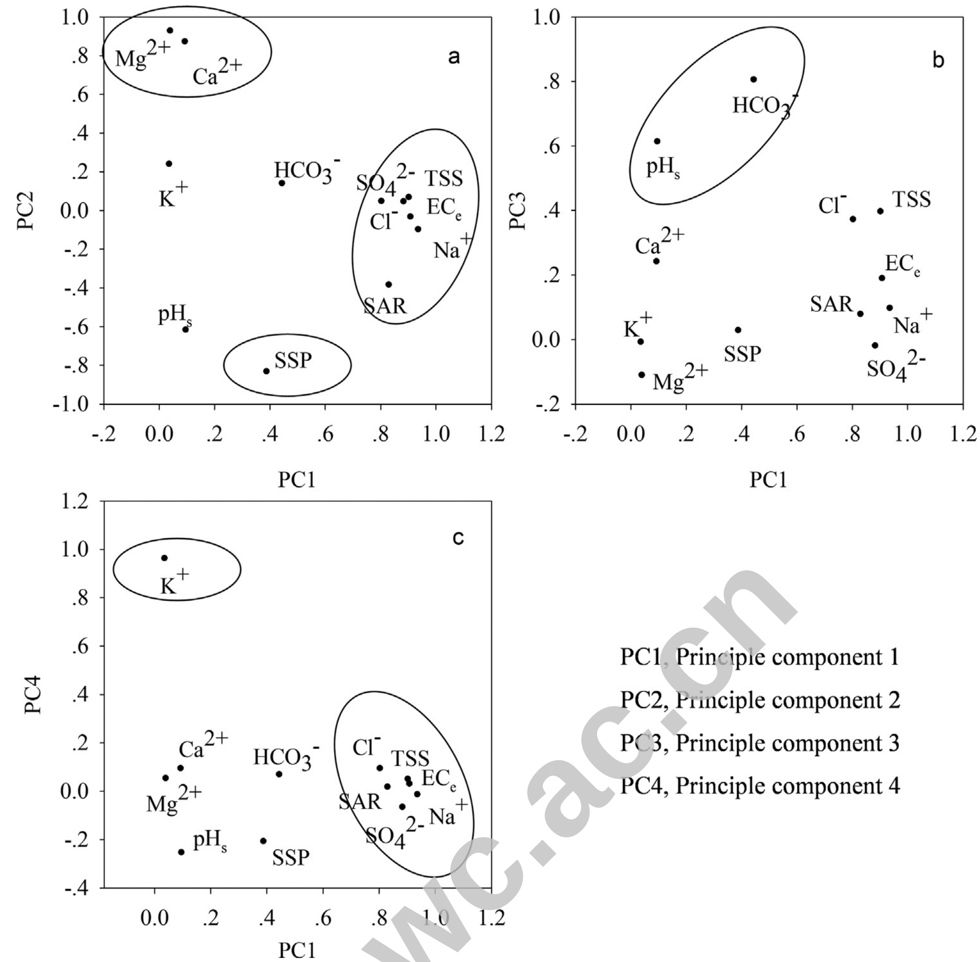

Fig. 2. Factor loadings of soil salt variables in the space defined by two components. An ionic formula indicates a concentration in $mmol_c\ L^{-1}$; TSS, total soluble salt in mass concentrations ($g\ kg^{-1}$); SSP, soluble sodium percentage in mass concentrations (%); EC_e, electrical conductivity of saturated paste extract ($dS\ m^{-1}$); pH_s, pH value of saturated paste; SAR, sodium adsorption ratio of saturated paste extract with unit of $(mmol_c\ L^{-1})^{0.5}$.

Table 4
Pearson correlations coefficients among concentrations of different soil ions.

	HCO_3^-	Cl^-	SO_4^{2-}	Mg^{2+}	Ca^{2+}	K^+	Na^+
Cl^-	0.688**						
SO_4^{2-}	0.478**	0.788**					
Mg^{2+}	−0.036	−0.031	0.065				
Ca^{2+}	0.178**	0.114*	0.136*	0.711**			
K^+	0.078	0.132*	0.148*	0.405**	0.476**		
Na^+	0.595**	0.902**	0.846**	−0.060	0.047	0.083	

**, significant at $P < 0.01$ (Two-tailed test); *, significant at $P < 0.05$ (Two-tailed test). An ionic formula indicates a concentration in $mmol_c\ L^{-1}$.

Mg^{2+} and Ca^{2+}), and was the supplement component to PC1 (soil salinity) and PC2 (soil structure).

3.2. Soluble cations redistribution after reclamation

The correlation analysis between soil ions concentrations could help reveal the synergistc effects of some ions migrations to a certain extent. Correlation analysis show that as the dominating cation, Na^+ had the biggest correlation coefficient with Cl^-, (0.902, $p < 0.01$), followed by SO_4^{2-} (0.846, $p < 0.01$) and HCO_3^- (0.595, $p < 0.01$) (Table 4). The correlations between Na^+ and other cations (Mg^{2+}, Ca^{2+} and K^+) were completely non-significant. The correlation coefficient of Ca^{2+} and Mg^{2+} was up to 0.711, which was the biggest among the mutual of four cations. K^+ always gave a relative smaller coefficent with others (Table 4), probably due to the low concentration of K^+ in soil solution.

Excessive Na^+ is the most prominent characteristic of takyric solonetz. Undoubtedly, Na^+ was the dominant cation among all soluble cations and accounted for over 70% of total cations concentrations in the uncultivated soil. The Na^+ concentrations in saturated paste extract were even more than 100 $mmol_c\ L^{-1}$ in the top layers of 0–20 cm, and decreased gradually to 15.4 $mmol_c\ L^{-1}$ at depth of 80–120 cm (Table 1). After reclamation, the Na^+ concentrations beneath drip line decreased remarkably with the increasing planting years. More Na^+ moved to the top layers of ridge slope and furrow, which indicated the greater mobility of Na^+ with water flow. These spatial redistributions of Na^+ were similar to the changes of soil EC_e after reclamation (Zhang et al., 2013), indicating again the dominative contribution of Na^+ to soil total salt.

In uncultivated soil, soluble K^+ concentration was the smallest among the four cations, always less than 1 $mmol_c\ L^{-1}$ in saturated paste extract. After reclamation, soil K^+ concentrations beneath drip line increased remarkably, while no obvious change was observed in other regions. The addition of potassium nitrate should be the main reason for the increased K^+ content beneath drip line.

The bivalent cations (Ca^{2+} and Mg^{2+}) exhibited the same distribution in soil transect whether cultivated or not. In uncultivated soil, the concentrations of Ca^{2+} and Mg^{2+} showed a homogeneous distribution throughout the soil profile at a level of 2 $mmol_c\ L^{-1}$, however, with an exception of top layer (0–10 cm), where their concentrations were higher, 5.5 $mmol_c\ L^{-1}$ and 6.5 $mmol_c\ L^{-1}$ for

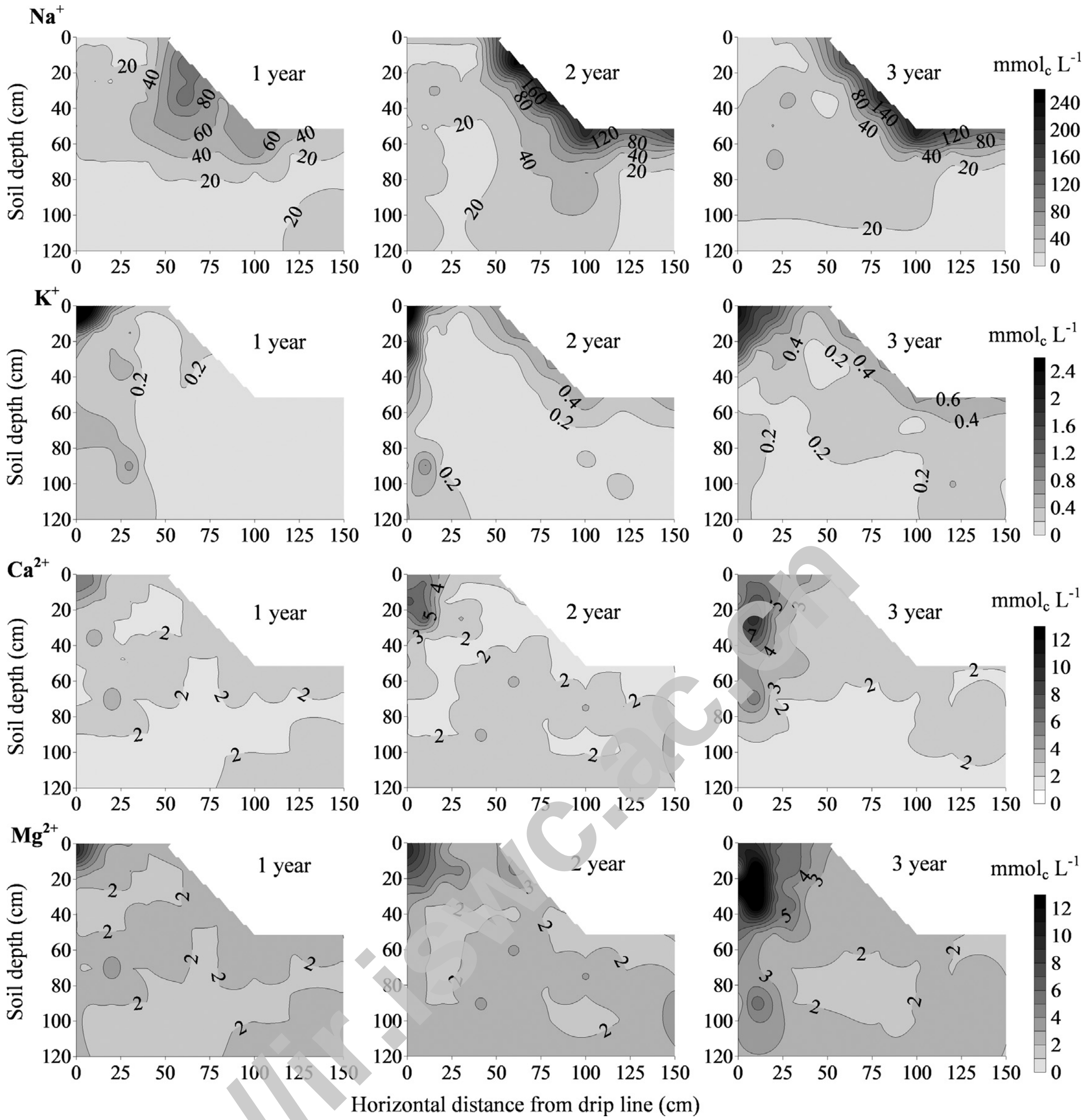

Fig. 3. Spatial distributions of main cations in the soil transects of takyric solonetz reclaimed for different years.

Ca^{2+} and Mg^{2+} respectively. After cultivation, the increases of bivalent cations concentrations only occurred in small regions beneath drip line with the increasing planting years (Fig. 3). After 3 years, the Ca^{2+} and Mg^{2+} concentrations increased moren than 10 $mmol_c\ L^{-1}$ in the depth of 0–40 cm beneath drip line, but remained still around 2 $mmol_c\ L^{-1}$ in other regions of soil transect, no different from the uncultivated soil. This result indicated litter mobility of Ca^{2+} and Mg^{2+} with water flow.

4. Discussion

4.1. The changing salt characteristics of takyric solonetz during reclamation

Reclaiming and managing a saline-sodic or sodic soil requires an understanding of the adverse impacts of salinity and sodicity on soil properties. The studied soil is characterized distingushingly by the excessive Na^+. Ayers and Westcot (1985) have stated that a relatively high Na^+ content (the ratio of Na^+:Ca^{2+} > 3:1) often results in a severe water infiltration problem due to soil clay dispersion and swelling and sealing of the surface pores. The ratio of Na^+:Ca^{2+} in takyric solonetz was up to 50:1 in top layers (Table 1). Researches conducted since 1954 have also documented many instances in which the tencency for swelling, aggregate failure, and dispersion increases as soil salnity (EC_e) decreases even if the ESP is less than 3, that is, a soil with low salinity can behave like a sodic soil (Oster and Jayawardane, 1998). Swelling reduces the radii of soil pores while dispersion after breakdown or slaking and subsequent clay movement lead to the blockage of soil pores. It can be said that both swelling and dispersion reduce the saturated and unsaturated hydraulic conductivity of the soil (Oster and Jayawardane, 1998). This adverse effect of Na^+ on soil physical properties would be magnified when irrigated with non-saline water (Quirk and Schofield 1955; Tedeschi and Dell'Aquila 2005; Basile et al., 2012). These facts combinatively result in the extremely poor hydraulic properties ($K_s < 0.1\ mm\ d^{-1}$) in the undisturbed soil of takyric solonetz.

The high coefficient between Na^+ and Cl^- (Table 4) indicated that a synergistic effect existed between Na^+ and Cl^- migrations. Previous studies also showed that chloride was usually the most active in the soil salt movements, sulfate the second, and carbonate (bicarbonate) relatively static (Jiao et al., 2008). Mg^{2+} had the biggest correlation coefficient with Ca^{2+}, which endorsed the fact that these two cations have, for practical purposes, generally been grouped together as similar ions in maintaining soil structure when quantifying sodicity of soils and irrigation waters (U.S. Salinity Lab. Staff, 1954).

Salt-affected soils in the arid area of Northwest China are generally rich in potassium (K), since the main soil parent material is mica (illite), which has high K content (Bao, 2005). However, it does not mean that there is sufficient K for plant growth, because most K exists as the insoluble mineral compounds in soil, and the available K (soluble and exchangeable K^+) only account for 1% of total K (Bao, 2005). This low K^+ concentration in soil solution (Table 1) might result in the poor correlation of K^+ with other ions (Table 4). As for the increased K^+ after reclamation, besides the addition of potassium nitrate, it should also be noted that with the addition of phosphoric acid and decreased soil pH_s (Zhang et al., 2013), more H^+ and complex aluminum hydroxide ions (e.g., $Al(OH)_2{}^+$) were generated, and less negative charges were available in the soils. As a result, more K^+ were displaced from the soils through the cation exchange (Zhang et al., 2007). The accumulation of K^+ beneath drip line in soil transects indicated the less mobility of K^+ with water flow, which was different from Na^+. This finding was consistent with the results of Hao and Chang (2003), who also observed low K^+ mobility in soil with manure application, but inconsistent with that of Mahmoodabadi et al. (2013), who suggested that Na^+ and K^+ had the same much higher mobility than Ca^{2+} and Mg^{2+}.

It is widely accepted that divalent cations (Ca^{2+} and Mg^{2+}) can replace adsorbed Na^+ in soil colloids, cause flocculation of colloids, and improve soil structure (Zhang and Norton, 2002; Jalali, 2008). This is the fundamental of the successful amelioration of sodic soil whether for the native calcareous soil or the additional calcium sources. There were two sources of Ca^{2+} in this study: irrigation water and dissolution of calcite ($CaCO_3$) present in the native soil. The $CaCO_3$ contents were around 14% in native soil (Table 1), and its dissolution was even enhanced by the decrease of soil pH and the increase of partial pressures of carbon dioxide caused by the microbial and root respiration under cropped condition, and decomposition of organic matter in the soil (Qadir et al., 2002; Qadir and Oster, 2002). The higher concentration of Mg^{2+} in irrigation water (Table 1) should be mainly responsible for the increased Mg^{2+} to a great extent. And the accumulation of Ca^{2+} and Mg^{2+} beneath drip line indicated the lower mobility of bivalent cations with water flow, which was consistent with the previous findings (Mahmoodabadi et al., 2013).

Additionally, in a soil-water system, there is an equilibrium between monovalent and divalent cations on the soil's exchange site and solution. The equilibrium condition will be altered if water is added to the system. This dilution of the soil solution favors the adsorption of divalent caitons like Ca^{2+} at cost of monovalent cations, such as Na^+ (Chi et al., 2012). This is the "valence dilution" mechanism as reported by Reeve and Bower (1960), which should also be responsible for the removal of Na^+ and decreased soil sodicity.

4.2. Priorities of actions in ameliorating takyric solonetz

Because of large spatial variation, it is difficult to quantify the spatial distribution of soil salt and ions in soil transects during the amelioration process. PCA was used in this study to explore the salt characteristics. Then the dominant restrictive factors (soil chemical properties) of takyric solonetz were proposed. The clustering distribution of soil salt variables in PC factors loadings (Fig. 2) obviously illustrated the restrictive factors that hindered the reclamation of takyric solonetz, which orderly were soil salinity, structure, alkalinity and the concentrations of other ions (e.g. K^+). So during the reclamation of takyric solonetz, the first consideration should be to reduce the soil salinity through water regulation, and then to improve soil structure through changing ions composition in soil solution and reducing soil alkalinity and sodicity (soil pH, SAR et al.). This new finding might provide a guide for the amelioration and agricultural utilization of takyric solonetz. The adoption of sand-filled niches beneath drip emitters in our study was just the actual measure aimed for the first consideration. This improved water regulation method of drip irrigation could facilitate soil water infiltration, ensure salt leaching, and finally make the reclamation possible without any chemical amendment.

Our previous study also stated that once the problem of soil infiltration problem at soil surface caused by bad combination of EC and SAR is solved by the improved drip irrigation, the salt ions compositions will change and the hydraulic conductivity of soil below the surface will not be a limiting factor (Zhang et al., 2013). Additionally, after soil salinity reduction, addition of phosphoric acid with irrigation water could be helpful in reducing soil sodicity (SAR), since the native soil had considerable amount of $CaCO_3$ (Table 1), and also supply the phosphorus nutrition for plant growth at the same time. This strategy can be used for saline sodic and sodic soils in the regions with considerable amount of $CaCO_3$ (Qadir et al., 2001).

4.3. Different effects of cations in maintaining soil structure

A literature review dating back to the 1930s supported a general conclusion that the relative order of deleterious effects of the four common cations on soil hydraulic properties is $Na^+ > K^+ > Mg^{2+} > Ca^{2+}$ (Smith et al., 2015). Previous studies also confirmed that Ca^{2+} could improve soil structure through cationic bridging with clay particles and soil organic matter (David and Dimitrios, 2002; Qadir et al., 2003). In addition, Ca^{2+} could inhibit clay dispersion and associated disruption of aggregates by replacing Na^+ and Mg^{2+} in clay and aggregates, thereby increased aggregate stability (Chan, 1995; Zhang and Norton, 2002). Mace and Amerhein (2001) observed a successful leaching reclamation of a sodic soil without amendments. But it was also stated that the reclamation under such conditions could only take place when soil provided a good drainage along its profile when leaching water was adequate and when a source of Ca^{2+} (e.g., $CaCO_3$) was present (Keren, 1996). As for this study, the two sources of Ca^{2+} discussed above were available, but drainage was not good enough. Drip irrigation improved soil infiltration considerably after the adoption of sand-filled niches beneath drip emitters. Although soil salt could not be directly leached down to deep layer for drainage by the relatively low irrigation amount, the setting of 50-cm-height ridges provided room for leached salt to flow to the top layers of ridge slope and furrow, which was supported by soil EC_e redistribution reported in our previous studies (Zhang et al., 2013; Zhang et al., 2017).

Mg^{2+} has long been considered to have effects similar to Ca^{2+} on soil physical properties, leading the U.S. Salinity Lab. Staff (1954) to group these two bivalent cations together as promoting and maintaining good soil structure. However, it was also reported that the effects of Ca^{2+} and Mg^{2+} as complementary cations for Na^+ on soil stability could be very different (Zhang and Norton, 2002). For example, some previous studies showed that Mg^{2+} could be a deleterious ion when its concentration was higher than Ca^{2+} (Yuan et al., 2007), or that adsorbed Mg^{2+} had adverse effects on infiltration rate for montmorillonitic non-calcareous and calcareous soils (Keren, 1996). The ratio of Ca^{2+}/Mg^{2+} in the soil-water system was used to predict a potential Ca^{2+} deficiency in soil (Ayers and Westcot, 1985). In an Mg-dominated soil (soil-water molar ratio of Ca^{2+}/Mg^{2+} less than 1), the potential effect of Na^+ may slightly increase (Smith et al., 2015). In this study, the molar ratio of Ca^{2+}/Mg^{2+} of studied soil was less than 1 in top layers (Table 1 and Fig. 3). This might aggravate the adverse effect of Na^+ on soil structure (Quirk and Schofield, 1955), and partly helped resulting in the extremely poor

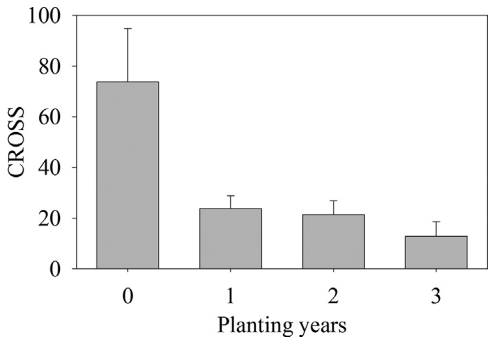

Fig. 4. Cation ratio of structural stability (CROSS) of takyric solonetz reclaimed for different years. CROSS is an improved soil quality parameter considering different effects of different cations on soil structure, calculated from the concentrations of Na^+, K^+ Ca^{2+} and Mg^{2+} in mmol$_c$ L^{-1}: CROSS = $(Na^+ + 0.335\,K^+)/[(Ca^{2+} + 0.0758Mg^{2+})/2]^{0.5}$.

hydraulic properties (K_s < 0.1 mm d^{-1}), in the case of the fact that soil salinity (EC_e) and sodicity (SAR) were not unacceptably high (Table 1). As for the reasons, it was reported that high exchangeable Mg^{2+} was sometimes associated with conditions of low soil conductivity and crusting (Yuan et al., 2007). Oster and Jayawardane (1998) stated that the surface soil was more unstable than the underlying at low soil salinity and exchangeable Na^+ and Mg^{2+} levels, because the mechanical impact and the stirring action of the applied water on the soil surface destroyed soil aggregates and rearranged soil particles into a densely packed, thin soil layer (seal) on the surface. The surface impermeable crust (seal) was exactly the distinctive characteristic of takyric solonetz, and the negative mechanical impact of applied water was partly eliminated by the sand-filled niches beneath drip emitters and film mulching in this study.

In order to take into account of the different effects of different cations on soil structure, the cation ratio of structural stability (CROSS), an improved irrigation water and soil quality parameter, was proposed by Smith et al. (2015) to replace SAR. The study which was based on optimizing CROSS with threshold electrolyte concentration data for a Sodosol in Australia, showed that the deleterious effect of K^+ was estimated to be about one-third of that of Na^+, while the concentration of Mg^{2+} needed to be about 13 times larger than Ca^{2+} to have the same beneficial effect. The optimized CROSS was calculated as following in the concentration of mmol$_c$ L^{-1} (Smith et al., 2015):

$$\mathrm{CROSS} = \frac{Na^{+} + 0.335K^{+}}{[(Ca^{2+} + 0.0758Mg^{2+})/2]^{0.5}} \quad (2)$$

According to this method, we obtained the changes of CROSS in root zone during reclaiming takyric solonetz (Fig. 4). The CROSS for uncultivated soil was around 70, and a large decrease in CROSS occurred after reclamation for one year (down ot about 20), but little in the following two years, this trend was similar to the changes of SAR, but larger than the latter in changing amplitude (Zia et al., 2006; Zhang et al., 2013). This proposed CROSS is expected to be used more widely on various soils, to provide more alternative and accurate parameters to evaluate the potential deleterious or beneficial effects of cations on soil structure.

5. Conclusions

During the reclamation of takyric solonetz, salt leaching through water regulation still had the highest priority, followed by improvement of soil structure through changing ions composition in soil solution and reducing soil sodicity (SAR). Irrigation water and dissolution of calcite ($CaCO_3$) present in native soil provided sufficient Ca^{2+} to replace the excessive Na^+. The ridge cultivation made leached salt move to top layers of ridge slope and furrow. Then, more Na^+ would be leached out of root zone, which resulted in a decrease in soil sodicity and improvement of soil structure in root zone. The reduced soil pH_s and the increasingly growing roots could enhance the beneficial effect of Ca^{2+} on soil physical properties.

The agronomic practices in this study exactly followed the priorities of reclamation actions derived from salt characteristics, indicating the sustainability of this reclamation measure was proved theoretically. Thus, this intergrated reclamation measure, mainly including ridge cultivation, sand-filled niches beneath drip emitters, mulched drip irrigation triggered by soil matric potential, was expected to have a good sustainability in takyric solonetz, and could be adopted more widely for ameliorating the impermeable saline-sodic soils, especially with considerable amount of CaCO3.

However, the cations (Na^+, Ca^{2+} et al.) uptaken by plants were not measured in this study, which was a shortcoming of this study. Because it was reported that the leaf cations content of *Lycium barbarum* L. increased under salt stress (Wei et al., 2006), indicating that the plant has the phytoremediation potential for salt-affected soils through biological salt removal (Zhao et al., 2004). Another shortcoming of this study was the unconsideration of exchangeable cations concentrations due to the possible errors involved in the direct measurement of ESP (Bower and Hatcher, 1962). Although soil ESP is often approximated from the traditional generalized SAR-ESP equation (U.S. Salinity Lab. Staff, 1954), this relationship varies with soil types and clay mineralogy under certain conditions (Kopittke et al., 2006). Additionally, the mathematical hydrosalinity models (e.g. HYDRUS 2D/3D) need to be developed and used in the future, so as to evaluate the long-term reclamation effect and environmental impacts in saline-sodic soils.

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