Pol. J. Environ. Stud. Vol. 23, No. 5 (2014), 1763-1772

Original Research

The Dynamics of Soil Moisture and Salinity after Using Saline Water Freezing-Melting Combined with Flue Gas Desulfurization Gypsum

Ye Xiao[1,2], Zhi-Gang Huang[3], Fan Yang[1]*, Xian-Guo Lu[1]

[1]Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun, 130102, China
[2]Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[3]Nanyang Normal University, Nanyang 473061, China

Received: 3 January 2014
Accepted: 21 March 2014

Abstract

A laboratory experiment was conducted in soil columns to study the moisture and salt redistribution through soil profile after the application of saline ice melt-water (SIMW) and flue gas desulfurization gypsum (FGDG) in a saline-sodic soil. The study consisted of SIMW (3200 ml frozen saline groundwater) and four SIMW+FGDG treatments which were SIMW+25%GR (7.9 mg·cm^{-2}, gypsum require (GR) in the surface of soil column), SIMW+50%GR (15.9 mg·cm^{-2}), SIMW+70%GR (23.8 mg·cm^{-2}), and SIMW+100%GR (31.8 mg·cm^{-2}). The results showed that Na^+ content, EC, SAR, and pH were reduced near the surface layers in all treatments, but the trend was reversed in deeper soil layers. Comparing the SIMW treatments, treatments containing FGDG showed higher desalting rate, leaching depth, and soil moisture at the end of the experiment. The SIMW+50%GR treatment resulted in the highest leaching rate of Na^+ and lowest EC and SAR in 0-40 cm soil layer. With the increase of the applied FGDG, there was no significant difference in reclamation effect. Therefore, when the small amount of gypsum was added in conjunction with saline ice meltwater, better leached effect of sodium was achieved.

Keywords: saline ice meltwater, flue gas desulfurization gypsum (FGDG), reclamation, saline-sodic soil

Introduction

Agriculture irrigation has become a major problem in many saline soil areas of the world, especially in arid and semi-arid areas. Estimates show that salt-affected soils in these regions occupy at least 20 percent of the irrigated land with an annual global income loss of about US$ 12 billion [1]. Because of severe saline-alkali soil, freshwater resources are very scarce. The long-term low-quality saline water irrigation has not only caused production losses, but also damaged the environment and ecosystems and seriously threatened the socio-economic development of the world [2, 3].

Natural freeze desalting of saline water in winter offers many advantages for separation of salts over conventional treatment methods, such as low energy consumption, few corrosion and scaling problems, and little requirement for complex pretreatment. Freeze separation has been applied to desalt for sea water and brackish water since the 1960s [4, 5]. It relies on the principle that under freezing conditions ice crystals grow from pure water molecules, rejecting impurities ahead of the growing crystal front [6]. Because of discharge of impurities from the ice in the initial melt water, the purity of the remaining ice is enhanced [7, 8].

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*e-mail: yangfan@neigae.ac.cn

Desalting by freeze has been proven effective in production of freshwater from seawater and a variety of high ionic concentration liquid wastes [9, 10]. Danish physician Thomas Bartholinus (1616-80) was the first man to report that freshwater can be obtained by melting ice formed in seawater [11]. Nicholas used the source waters frozen at an ambient temperature of -15ºC and with 3,000 mg·L^{-1} (NaCl) or less, and found that 80% removal of salts was possible after melting 9% of the produced ice [12]. Bohai sea ice salinity can be decreased to 0.2-2‰ from 3-8‰ through natural freezing in winter and thawing in spring [13]. Acting as a good prospect, the freeze desalination has been used in industry for food processing [14, 15] and contaminants separation of wastewater [6, 16, 17]. Nowadays, the use of "new water" through desalination of seawater or brackish water for crop irrigation also has been receiving great attention in water-starved areas of China.

Irrigation with saline groundwater that contains much dissolved divalent cations such as Ca^{2+} is one way to leach soil salinity to a lower level [18]. One critical problem of this method is an insufficient amount of divalent cations in saline water, particularly Ca^{2+}, to exchange the higher level Na^+, which is the main influencing factor in saline-alkali soil. When sodium ions are absorbed by soil particles as exchangeable cations, soil becomes stiffness and the soil structure is degraded by means of clay swelling and dispersion. Exchangeable potassium can also cause similar effects, but it has been neglected because of very low content in salt-affected soils. Therefore, it not only needs excessive freshwater to leach the desorbed Na^+ from soil, but also requires more Ca^{2+} replacing the Na^+. It usually requires the application of soil amendment. Gypsum is generally added as a calcium source; the increased Ca^{2+} can improve soil structure through cationic bridging with clay particles and enhanced aggregate stability [19, 20]. Several studies have indicated that gypsum is an economic and efficient soil amendment both in the field [21, 22] and in the laboratory [23]. However, few studies have been conducted to assess the combined effects of different amounts of gypsum with saline ice during remediation processes.

Therefore, our soil column experiment was conducted to study the change of the soil moisture content and solution cations by adding diffirent amounts of flue gas desulfurization gypsum (FGDG) under infiltration of saline ice water, and to elucidate the possible mechanisms of soil desalination, and to determine the optimum usage amounts of gypsum by freezing saline water irrigation.

Materials and Methods

Study Area Description and Sampling

Soil used in the laboratory experiment was obtained from 0 to 100 cm depth of a saline-sodic soil and water sample was obtained from the local shallow groundwater in Da'an Sodic Land Experimental Station of China (45º35′58″-45º36′28″N, 123º50′27″-123º51′31″E), located at Da'an City of Songnen Plain. The Songnen Plain has salt-affected land area of more than 3.2×10^6 ha and is one of the three largest soda saline-alkali soil areas in the world [24]. The average annual rainfall of the region is about 370-410 mm, 70-80% of which occurs in July and August. The potential evaporation is about 1,000-2,500 mm [25]. Mean maximum of 23.4ºC in July and minimum -18.1ºC in January and the frost-free period is 137 days [24]. Affected by the climate monsoon, soil salt and moisture migration of study area presents seasonal changes. Spring is considered to be the salinization period because of high evaporation and less rainfall; summer is the desalination period due to high rainfall; autumn is the re-accumulation period for drought and wind; and winter is the latent period for low temperature and high evaporation. Long low-quality saline water irrigation has deteriorated soil properties. In the soil profile from the top layer to 60 cm soil layer, the main constituents of the soil are montmorillonite clay and sodium bicarbonate, with pH larger than 9.5 and $EC_{1:5}$ more than 4.15 ms·cm^{-1} [26]. It is a typical alkali spot land.

Soil Columns Setup

The soil columns experiment was conducted in the laboratory. Fifteen transparent polymethyl methacrylate (PMMA) cylinders (inner diameter: 20 cm; height: 120 cm) were used to prepare the soil columns. The tops of the vertically positioned columns were open to the atmosphere and the bottom of each column with a porous base which was padded with a 5-cm thick filter layer to facilitate leaching. The soil sample was air-dried (with water content of 3.1%), crushed, and closely mixed to pass through a 2-mm sieve. To obtain a homogeneous soil bulk density (1.4 g·cm^{-3}), the sieved soil (≤2.0 mm) was poured into cylinders in 10 cm sections and stirred with the soil surface of previously packed layer before filling each increment to prevent layering. Soil columns were packed to a height of 100 cm.

Flue gas desulfurization gypsum (FGDG) containing 981.2 g·kg^{-1} $CaSO_4·2H_2O$ and 11.4 g·kg^{-1} $CaSO_4·H_2O$ with particle size<0.5 mm was used in this study. Experiments consisted of five treatments, four of which added different amounts of FGDG and the gypsum requirement (GR) as follows: saline ice melt-water (SIMW), SIMW+25%GR, SIMW+50%GR, SIMW+75%GR, and SIMW+100% GR. The 25% GR, 50% GR, 75% GR, and 100% GR were 7.9, 15.9. 23.8, and 31.8 mg·cm^{-2} FGDG in soil columns, corresponding to field gypsum applications of 790, 1,590, 2,380, and 3,180 kg·ha^{-1}, respectively. The amount of FGDG used to achieve the fraction GR was calculated by the following formula [27, 28]:

$$GR=1.25\times(\text{mmol}_c\ Na^+ \text{ removed to reduce ESP to 5}) = \\ = \text{mmol}_c\ SO_4^{2-} \text{ of amendment added}$$

...where GR is gypsum requirement weight (mg·cm^{-2}) and ESP is exchangeable sodium percentage of the soils.

The 3,200 ml of shallow underground water was prepared for each treatment in soil column, corresponding to field irrigation rate of 160 mm. It was frozen at -14ºC in a refrigerator for 24 h in advance. At the beginning of the infiltration experiment, FGDG evenly was scattered on the surface layer of each prepared soil column at first and then the ice was put on it at 16ºC. The infiltration depth of the saline ice melt-water was observed. When the melt-water infiltration was over, soil samples were collected from each soil column at an interval of 5 cm in 0-20 cm soil layer and at an interval of 10 cm from 20 cm to the position where infiltration was ended. The soil samples were analyzed to determine soil moisture, pH, salt content, monovalent (i.e., Na^+ and K^+) and bivalent (i.e., Ca^{2+} and Mg^{2+}), as well as final EC and SAR. Three repetitions were performed.

Analysis of Soil and Water Samples Chemical Properties

Some physical and chemical properties of original soil and water samples were initially measured before the infiltration experiments (Table 1). Soil moisture was determined by the oven-drying method. Soil water-soluble salts were extracted using a 1:5 soil:water suspension. The pH and EC were determined by glass electrode (Shanghai Precision Scientific Instrument Co., Ltd) after extraction (1:5 w/v soil:deionized water). The concentrations of Na^+ and K^+ were determined by atomic absorption spectrometry (GBC-906AAS) and Ca^{2+} and Mg^{2+} were analyzed by EDTA titration method [29]. The concentrations of CO_3^{2-} and HCO_3^- were determined by neutral titration method. The concentrations of Cl^- were determined by silver nitrate titration method, and the concentrations of SO_4^{2-} were determined by barium sulfate turbidimetric method. The total salt content was calculated as the sum of cations and anions.

The percentage of leached cation (i.e. Na^+ or K^+) and salinity from soil columns after the infiltration experiment was calculated from Eq.:

$$C_M(\%) = \frac{(C_0 - C_1)}{C_0} \times 100$$

...where C_M (%) value is the leaching rate of cation or desalting rate. C_0 ($mg \cdot kg^{-1}$) is the content of cation or salt before infiltration experiments, C_1 ($mg \cdot kg^{-1}$) is the corresponding content of cation or salt after infiltration experiments.

Sodium adsorption ratio (SAR) was calculated by the following equation, where the concentrations of soluble cations are expressed in $mmol_c \cdot L^{-1}$ [30].

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

Statistical Evaluation

The experiment design of this study is a complete randomized design. The experiment consists of five treatments and each treatment has three replications. Statistical analyses were performed using the SPSS 18.0 software for Windows. The differences in reclamation effect among treatments were evaluated using one-way ANOVA followed by a Tukey test at $p<0.05$. Excel 2003 was used to generate graphs.

Table 1. Some chemical properties of the initial soil and water samples were determination before the infiltration experiment.

Soil and water sample property	Unit	Air-dry soil	Saline water
Clay (<0.002 mm)	%	38.78	-
Silt (0.002-0.02 mm)	%	37.30	-
Sand (0.02-2 mm)	%	23.92	-
PH	-	10.45	7.94
EC	$dS \cdot m^{-1}$	12.73	3.19
K^+	$mg \cdot kg^{-1}$	3.53	1.62
Na^+	$mg \cdot kg^{-1}$	3,707.90	705.64
Ca^{2+}	$mg \cdot kg^{-1}$	28.00	87.61
Mg^{2+}	$mg \cdot kg^{-1}$	2.44	259.32
Cl^-	$mg \cdot kg^{-1}$	2,485.00	1,109.40
HCO_3^-	$mg \cdot kg^{-1}$	3,515	1867
CO_3^{2-}	$mg \cdot kg^{-1}$	1,800	1.81
SO_4^{2-}	$mg \cdot kg^{-1}$	307.20	74.70
SAR	$[mmol_c \cdot L^{-1}]^{0.5}$	80.52	3.81
Total salt content	%	1.19	0.41

Results and Discussion

Initial Properties of Soil and Water Samples

Table 1 shows initial physical and chemical properties of the soil. The salinity and sodicity of original soil were in high levels (EC=12.73 $dS \cdot m^{-1}$, SAR=80.52 $[mmol_c \cdot L^{-1}]^{0.5}$, total salt content=1.19%). Among soluble cations, Na^+ was the dominant cation and accounted for 99.1% of water-soluble cations, whereas the concentration of Mg^{2+} was the lowest (2.44 $mg \cdot kg^{-1}$). The shallow underground water has pH of 7.94, sodium absorption ratio (SAR) of 3.81, and total salt content of 0.41% (Table 1). So the shallow underground water belongs to saline water with saline content in the range of 0.3-1.0% [31].

The Change of Soil Moisture Content in Soil Profile

The soil moisture content and infiltration depth increased in added FGDG treatments at the end of the experiment (Fig. 1). In 0-5 cm soil layer, soil moisture content was 40.0% in the SIMW treatment and 25.7-29.0% in the SIMW+FGDG treatments. But in the subsequent infiltration, soil moisture content was higher in the

SIMW+FGDG treatments than in the SIMW treatment. In 60-70 cm soil layer, soil moisture content in the four SIMW+FGDG treatments ranged from 11.4% to 23.1%, but it was still at the initial value (3.12%) in SIMW treatment. However, the average soil moisture content in the SIMW treatment and the SIMW+FGDG treatments was 24.9% and 26.3-28.3% in 0-40 cm, respectively, but there was no significant difference among the SIMW+FGDG treatments. These results showed that those treatments with FGDG increased soil moisture content and leaching depth compared with the SIMW treatment. The reason is probably that saline water during freeze-thawing caused the separation of water and salt. Earlier melted saline water contains more dissolved divalent ions (e.g., Ca^{2+}), which exchanged Na^+ of soil columns and late melted ice water produced a large amount of freshwater to leach soil salt; therefore, soil physical properties might be improved [32]. Furthermore, increased Ca^{2+} was provided by the addition of gypsum, perhaps further flocculating the dispersed clay and improving soil permeability. Thus, the application of gypsum potentially increased water infiltration rate [33].

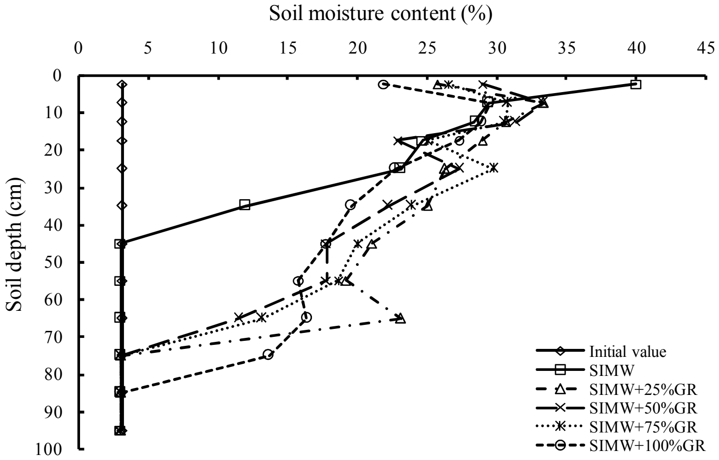

Fig. 1. The change of soil moisture after infiltration experiment.

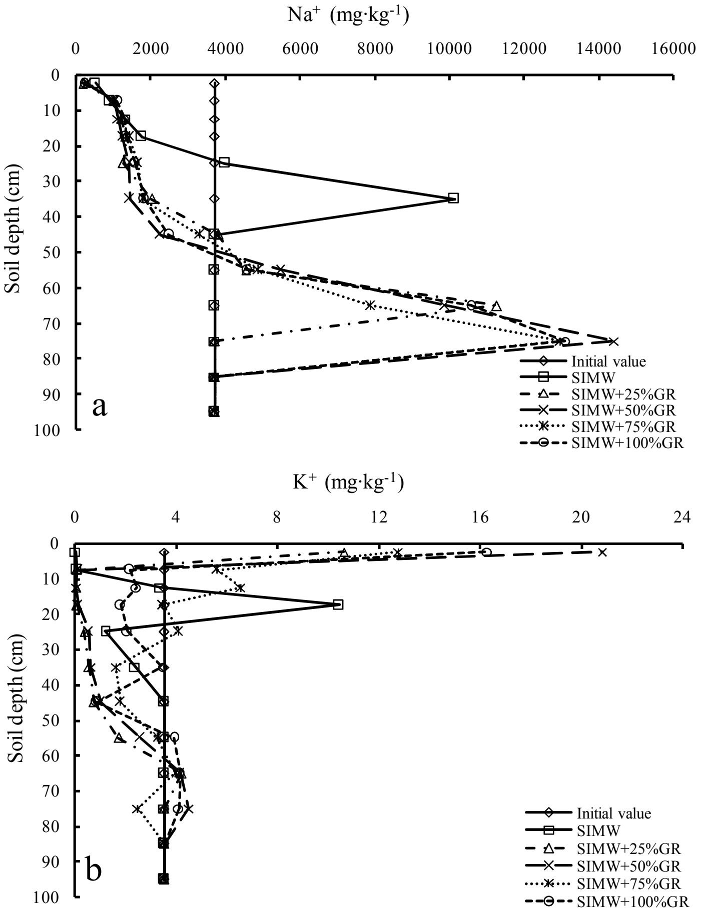

Fig. 2. The change of monovalent cations (Na^+ and K^+) concentration in leaching experiment.

Table 2. Leaching rate of soluble Na^+ and K^+ along the soil profile after infiltration.

Treatments	Leaching rate (%)					
	Na^+			K^+		
	0-20 cm	20-40 cm	0-40 cm	0-20 cm	20-40 cm	0-40 cm
SIMW	69.6±4.6 b	-90.3±16.2 c	16.3±4.9 c	1.6±0.5 e	49.5±9.4 b	17.6±3.9 e
SIMW+25%GR	74.7±7.5 a	55.5±6.8 b	68.3±9.2 a	23.5±2.8 d	87.2±7.7 c	44.7±6.3 d
SIMW+50%GR	75.1±6.7 a	61.4±7.7 a	70.5±7.3 a	-49.4±6.8 c	83.6±12.7 c	-5.1±1.2 c
SIMW+75%GR	73.1±7.7 a	53.9±4.8 b	66.7±6.4 a	-101.7±14.1 a	18.6 ±5.9a	-61.6±11.5 a
SIMW+100%GR	73.2±8.4 a	53.8±6.9 b	66.8±8.7 a	-60.7±9.5 b	21.9 ±5.4a	-33.2±5.8 b

Mean values followed by different letters in a column differ significantly at $P < 0.05$; "-" indicated accumulation ratio of Na^+ or K^+.

Leaching of Monovalent Cations

Fig. 2 shows the changes of soluble monovalent cation (i.e. Na^+ and K^+) concentrations in the soil profile after infiltration. For all the treatments, concentration of soluble Na^+ increased with infiltration depth (Fig. 2a). For the SIMW treatment, the average Na^+ concentration was 1,127.67 mg·kg^{-1} in 0-20 cm soil layer, lower than initial value (3,707.90 mg·kg^{-1}), suggesting the ability in decreasing soluble Na^+. But Na^+ accumulation appeared below 20 cm. For the SIMW+FGDG treatments, with an average range of 923.81-997.09 mg·kg^{-1} in 0-20 cm and exceeding initial value until below 50 cm depth, they showed more effect in decreasing soluble Na^+ compared to the SIMW treatment (Fig. 2a). The change curves of soluble K^+ were irregular along the soil profile for all treatments (Fig. 2b). The SIMW+FGDG treatments increased soil K^+ content comparison with initial value in 0-5 cm soil layer, but it decreased rapidly with depth. While soluble K^+ in the SIMW treatment was smaller than initial value near the soil surface, it increased along the soil profile.

There were some differences in the leaching rate of monovalent cations (i.e. Na^+ and K^+) in all treatments due to the application of the different amount of FGDG (Table 2). For the SIMW treatment, the leaching rate of Na^+ was 69.6% in 0-20 cm, but it caused 90.3% accumualtion rate in 20-40 cm. By contrast, the SIMW+FGDG treatments showed 73.1-74.7% and 53.8-61.4% of Na^+ leaching rate in 0-20 cm and 20-40 cm, respectively: a greater amount of sodium was leached. In short, the SIMW+FGDG treatments showed more than 66.7% of soluble Na^+ leaching rate, and these leaching effects were significantly higher than the SIMW treatment (16.3%) in 0-40 cm ($p<0.05$). Especially the SIMW+50%GR treatment, with leaching rate of 70.5%, showed the best leaching effect. On the contrary, it might cause plenty of soluble K^+ accumulation in the SIMW+FGDG treatments (except for SIMW+25%GR) near the soil surface, but most of them kept lower K^+ concent than initial value in deeper soil layer. In 0-20 cm, leaching rate of soluble K^+ in SIMW and SIMW+25%GR was 1.6% and 23.5%, respectively, significantly higher than in the other three treatments, which acculuated 49.4-101.7% soluble K^+ ($p<0.05$) (Table 2). In 20-40 cm, more K^+ was removed to deeper layers in all treatments and it showed a significant difference among these treatments ($p<0.05$). However, SIMW and SIMW+25%GR decreased 17.6% and 44.7% soluble K^+, respectively, while the other three treatments showed different K^+ accumulation ratios in 0-40 cm. In fact, increased potassium as one of the macronutrients is a benefit to plant growth.

In the combined application of FGDG with saline ice meltwater, gypsum had the ability to release appreciable amounts of additional Ca^{2+}. Adsorbed Na^+ in soil solution can be replaced by Ca^{2+}, then removed either below the root zone or out of the profile by later meltwater [34]. Therefore, the treatments with the addition of FGDG, resulted in lower values of soluble Na^+ than SIMW and initial value. Although the Ca^{2+} replaced Na^+ and K^+ through percolating water in soluble soil, which improved soil aggregation, meanwhile, activity on the exchange sites probably led to some increase in soluble Na^+ and K^+ [20, 30]. However, the smallest soluble Na^+ concentration near the soil surface observed in all treatments could be partly explained by the leaching of freshwater, which produced in the process of saline water freezing, separation, and thawing of crystals [35, 36].

Leaching of Bivalent Cations

Bivalent cations (i.e. $Ca^{2+}+Mg^{2+}$) exhibited a different redistribution relative to the dominant monovalent cations along the soil profile (Fig. 3). Similar to the change of soluble K^+, there was higher concentration of $Ca^{2+}+Mg^{2+}$ near the surface soil and rapidly reduced with increasing depth. The contents of $Ca^{2+}+Mg^{2+}$ were 592.72-903.84 mg·kg^{-1} in the SIMW+FGDG treatments, significantly higher than in the initial soil (30.44 mg·kg^{-1}) and the SIMW treatment (22.44 mg·kg^{-1}) in 0-5 cm ($p<0.05$). This result was consistent with that of Mahmoodabadi et al. [30], who observed that the application of gypsum amplified soluble Ca^{2+} and Mg^{2+} concentrations. It was irregular curve change trends for all treatments at deeper soil layers. But the change of $Ca^{2+}+Mg^{2+}$ was much smaller than Na^+ and K^+ in the soil profile, as can be observed from the comparison (Fig. 2). The average content of soluble $Ca^{2+}+Mg^{2+}$ was 18.46-26.29 mg·kg^{-1} in the four SIMW+FGDG treatments, and lower than that in the SIMW treatment (33.23 mg·kg^{-1}) and the

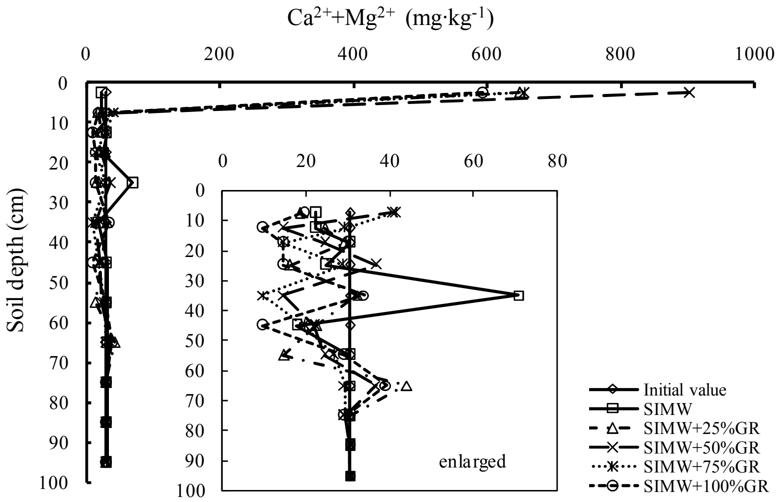

Fig. 3. Bivalent cation (Ca^{2+}+Mg^{2+}) concentrations in leaching experiment.

initial value in 10-40 cm (enlarged part in Fig. 3). The results indicated that addition of gypsum reduced concentration of soluble Ca^{2+}+Mg^{2+} in the deep soil layer. This could be attributed to the high SO_4^{2-} concentration existing in FGDG, which limited the dissolution of soil $CaCO_3$ and $MgCO_3$. In addition, Ca^{2+} can inhibit clay dispersion and the associated disruption of aggregates by replacing Na^+ in clay and aggregates to increase aggregate stability [19], therefore, soil permeability is increased. So more soluble Ca^{2+} and Mg^{2+} were removed out of the soil column.

Changes in Soil EC and SAR

Since the levels of electrical conductivity (EC) and sodium adsorption radio (SAR) have been proven to be harmful to soil structure [37], one of the important purposes in ameliorating of saline-sodic soil is to reduce EC and SAR in soil solution by depleting deleterious ions (i.e. Na^+, Mg^{2+}). After infiltration experiments, final soil EC and SAR were strongly influenced by the application of SIMW and SIMW+FGDG.

Significant reductions in soil EC were found in soil columns for the SIMW+FGDG treatments compared with the SIMW treatment along the soil profile ($p<0.05$) (Fig. 4a). The SIMW+FGDG treatments exhibited an average EC range of 2.04-2.75 $dS \cdot m^{-1}$ in 0-70 cm and there was no significant difference among them. Nevertheless, these values were significantly lower than the initial soil EC (12.7 $dS \cdot m^{-1}$) ($p<0.05$). While the SIMW treatment had an average EC of 6.0 $dS \cdot m^{-1}$ in 0-20 cm, significantly higher than the SIMW+FGDG treatments ($p<0.05$). Furthermore, EC value of the SIMW treatment was higher than initial EC below 20 cm. Obviously, the SIMW+FGDG treatments had a better ability in reducing soil EC. Lower soil EC values for all treatments were near the soil surface. The observed increase of EC was probably due to the ions' rise in the solution, which resulted in complex ion exchange and downward leaching of salts by ice melt-water (Fig. 4a). Tejada and Gonzalez [38] demonstrated that an increase in electrical conductivity has adverse effects on soil structural stability, bulk density, and permeability. Thus, in our study the application of SIMW was effective in decreasing soil EC value, but adding of FGDG was more conducive to reduce EC and enhance the stability of soil structure.

SAR level is more important for the stability of soil structure. The experimental results of Lentz et al. [39] demonstrated that irrigation water with EC of 0.5 $dS \cdot m^{-1}$ and SAR of 12.0 $(mmol_c \cdot L^{-1})^{0.5}$ resulted in a greater amount of soil loss than that with EC of 2.0 $dS \cdot m^{-1}$ and SAR of 0.7 $(mmol_c \cdot L^{-1})^{0.5}$. Therefore, SAR can better reflect the improvement effect of saline-alkali soil. The variation of soil SAR in soil profile is shown in Fig. 4b. Compared with the monovalent cations (Fig. 2a), it shows that SAR and Na^+ had the similar change trends in soil profile. The average SAR value in the SIMW treatment was 32.0 $(mmol_c \cdot L^{-1})^{0.5}$ in 0-30 cm, but it caused higher soil SAR than initial value of 80.5 $(mmol_c \cdot L^{-1})^{0.5}$ below 30 cm. While an average SAR range in the SIMW+FGDG treatments was 21.6-28.9 $(mmol_c \cdot L^{-1})^{0.5}$ in 0-40 cm, it was higher than initial soil SAR at 50 cm depth. These results suggested that the application of FGDG combination with SIMW was more efficient in decreasing soil SAR than the SIMW treatment in 0-50 cm. The SIMW+50%GR treatment showed the smallest SAR value 21.6 $(mmol_c \cdot L^{-1})^{0.5}$ in 0-40 cm. The observed reduction in SAR may be attributed to the removal of Na^+ from the soil solution by the application of FGDG as presented in Table 2. This research result was consistent with that of Qadir et al., [40] and Muraoka and Dos Santos [41], who concluded that gypsum application led to a significant decrease in the SAR of soil solution.

Fig. 4 showed that the SIMW+FGDG treatments caused lower EC and SAR values in soil columns than the SIMW treatment at the end of the leaching experiment. Many researches have proven that high gypsum application rates not only remove the excess Na^+ from the soil profile but also cause a great reduction of soil EC and SAR [21, 42]. However, our study concluded that the SIMW+50%GR treatment exhibited the smallest mean of EC (1.19 $dS \cdot m^{-1}$)

and SAR (21.6 (mmol$_c$·L^{-1})$^{0.5}$ in 0-40 cm. Therefore, the SIMW+50%GR treatment could achieve the optimum reclamation effect without waste of excessive gypsum.

Soil Salt Content and Desalting Rate

The difference in infiltration rate and depth for all treatments led to redistribution of salts in the soil columns. Soil salt content gradually increased in the vertical soil profile in all treatments (Fig. 5). However, the SIMW and SIMW+FGDG treatments showed lower salt concentration than initial soil salt content in 0-20 cm and 0-50 cm, respectively; moreover, the smallest salt content for these treatments was near the soil surface.

There were no significant differences in the desalting rate in 0-20 cm among all treatments ranging from 61.2% to 63.0% (Table 3). With increasing depth, the desalting rate was reduced. The SIMW+FGDG treatments showed the desalting rate ranged from 46.5% to 52.8%, while the SIMW treatment accumulated salt in 20-40 cm. There were significant differences between the SIMW+FGDG treatments and the SIMW treatment (p<0.05) in 20-40 cm. Overall, the average desalting rate was 56.7-58.8% in the SIMW+FGDG treatments, significantly higher than the SIMW treatment (10.8%) in 0-40 cm (p<0.05). Compared with the SIMW treatment, more salt was leached to deep soil layer in the SIMW+FGDG treatments. This probably is

Table 3. Desalting rate along the soil profile after infiltration.

Treatments	Desalting rate (%)		
	0-20 cm	20-40 cm	0-40 cm
SIMW	61.4±6.1 a	-90.4±13.1 c	10.8±2.3 c
SIMW+25%GR	61.8±8.9 a	46.5±7.5 b	56.7±7.6 a
SIMW+50%GR	61.2±6.5 a	52.8±6.9 a	58.4±11.2a
SIMW+75%GR	63.0±8.3 a	50.4±4.7 a	58.8±9.1a
SIMW+100%GR	62.9±6.9 a	48.4±8.2 b	58.0±6.6a

Mean values followed by different letters in a column differ significantly at P < 0.05; "-" indicated rate of salt accumulation.

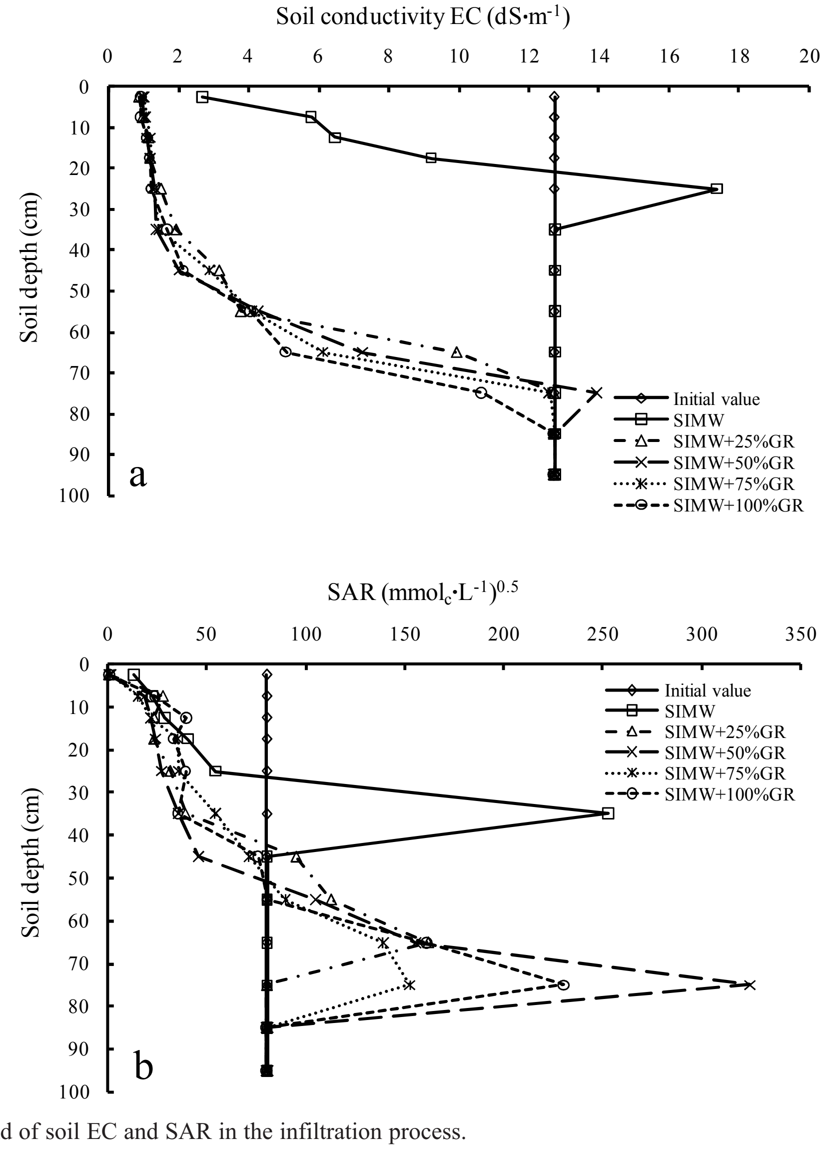

Fig. 4. The change trend of soil EC and SAR in the infiltration process.

Table 4. The change of soil pH after infiltration experiment.

Soil depth (cm)	Treatments				
	SIMW	SIMW+25%GR	SIMW+50%GR	SIMW+75%GR	SIMW+100%GR
0-5	10.26±0.16 a	7.96±0.09 c	7.88±0.08 c	8.38±0.10 b	8.68±0.09 b
5-10	10.43±0.08 a	10.34±0.05 a	10.25±0.06 a	10.19±0.08 a	10.28±0.06 a
10-15	10.60±0.12 a	10.35±0.05 a	10.35±0.07 a	10.28±0.06 a	10.31±0.03 a
15-20	10.78±0.13 a	10.39±0.08 a	10.38±0.05 a	10.39±0.08 a	10.35±0.05 a
20-30	10.80±0.09 a	10.42±0.07 a	10.40±0.07 a	10.39±0.06 a	10.42±0.07 a
30-40	10.88±0.08 a	10.44±0.04 a	10.43±0.08 a	10.42±0.05 a	10.44±0.06 a
0-40	10.63±0.10 a	9.98±0.06 b	9.93±0.07 b	10.01±0.07 a	10.08±0.06 a

Mean values followed by different letters in a column differ significantly at $P < 0.05$; "-" indicated rate of salt accumulation.

due to the fact that the high Ca^{2+} concentration supplied by FGDG and high ionic strength in soil solution can result in compression of the electrical double layer, which in turn decreases the repulsive force between soil particles [43]. Hence, salts were leached downward with irrigation. Experimental results had proved that the melted ice water from a single freezing, without a wash step, has three to six times less salt content than the feed water [44]. Li et al. also demonstrated that the desalting rate increased with the increasing volume of saline ice meltwater [45]. Gypsum application in saline-alkali soil can increase soil permeability by increasing electrolyte concentration and by cation-exchange effects during the infiltration process [46, 34], so a higher amount of soluble salt was removed out of the soil column in the SIMW+FGDG treatments.

Change of Soil pH Value

Soil pH is an important indicator reflecting the level of soil salinity. The changes of soil pH in all treatments are given in Table 4. Soil pH was 10.26 in the SIMW treatment and ranged from 7.96 to 8.68 in the SIMW+FGDG treatments at 0-5 cm. These values were lower than soil pH values of deeper layers and initial pH value (10.45). It was found that the SIMW+ FGDG treatments were more effective at reducing soil pH value at the 0-5 cm soil layer, especially the SIMW+50%GR treatment with the lowest soil pH value (7.88). For all treatments, soil pH values increased with increasing depths. In 0-40 cm depth, the average soil pH value was 10.63 in the SIMW treatment and ranged from 9.93 to 10.08 in the SIMW+FGDG treatments, respectively. However, all treatments had lower soil pH value near the soil surface and the SIMW+50%GR treatment had better ability in decreasing soil pH value. This might be attributed to exchangeable Na^+ replaced by Ca^{2+} from gypsum and the leaching of saline ice water, which greatly decreased the concentration of soil solution. In addition, adding gypsum also leads to proton generation and further reductions in pH [47].

Conclusion

In the reclamation of saline-sodic soil, soil moisture content, the concentration of monovalent anions (Na^+ and K^+), and bivalent anions (Ca^{2+}+Mg^{2+}), as well as, EC, SAR,

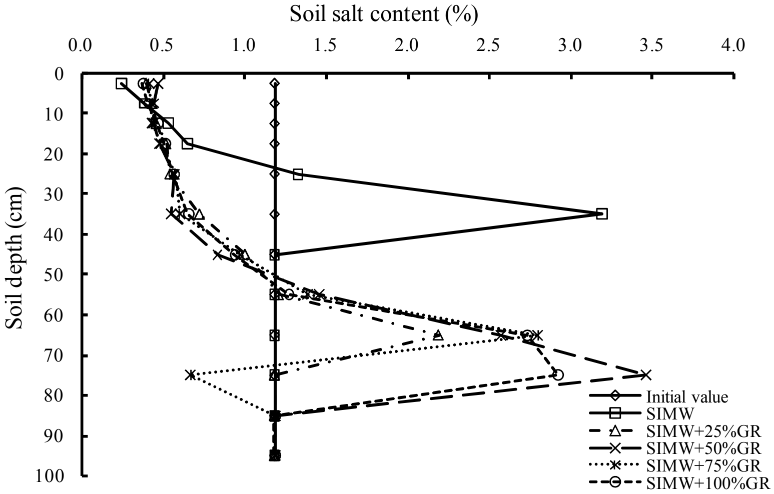

Fig. 5. The various soil salt contents in soil profile at the end of infiltration.

salt content, and PH were affected significantly by the application of FGDG under infiltration of saline ice meltwater. At the end of the experiments, soil moisture content and infiltration depth increased under the interactions between salinity ice water and FGDG. Moreover, soil Na^+ and salt content as well as soil EC, SAR, and pH were lower near the top layer in the SIMW+FGDG treatments than in the SIMW treatment, but these parameters increased in all treatments along the soil profile. However, the application of FGDG has a negligible effect for increasing K^+ and Ca^{2+}+Mg^{2+} near the surface layers. In soil solution, Na^+ and K^+ showed greater mobility than Ca^{2+} and Mg^{2+}. Infiltration of FGDG combination with saline ice meltwater might enhance some synergistic effects on reducing soil parameters. Compared with the SIMW treatment, the SIMW+FGDG treatments had significantly lower Na^+ concentration and higher desalting rate, suggesting the ability in 0-40 cm soil layers. The final EC and SAR also strongly decreased with the addition of FGDG. Especially, the SIMW+50%GR treatment showed the best reclamation effect.

Our results indicated that infiltration of saline ice meltwater along with an optimum amount of FGDG application was beneficial for reclamation of saline soil. Therefore, saline ice water irrigation is economical and feasible strategy for solving lack of water in spring in saline-alkali areas. In particular, if the proper amount of gypsum is added, it can achieve a better desalting effect.

Acknowledgements

This research was supported by the Chinese Academy of Sciences action-plan for West Development (KZCX3-XB3-16), Project of the Special Fund for Public Welfare Industrial (Agriculture) Research of China (200903001), and the National Natural Science Foundation of China (41071022). We also wish to acknowledge the support of Da'an Sodic Land Experimental Station.

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