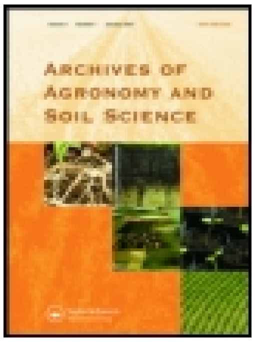

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Long-term effects of combining gypsuming with brackish ice irrigation on soil desalinization and crop growth in abandoned saline-sodic land

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ABSTRACT

Salinity-sodicity may be reduced by freezing and melting (FM) brackish ice irrigation combined with gypsum for the highly saline-sodic soils. A 5-year field study was carried out in the Songnen Plain, northeast China, to investigate the effects of FM brackish ice irrigation in combination with phosphogypsum on soil salinity-sodicity. The treatments consisted of no amendment, no irrigation (CK) and FM brackish ice irrigation using the local brackish water (SW), and required phosphogypsum application to fully reclaim the 0–10 cm, 0–20 cm, 0–30 cm and 0–40 cm soil layer, combined with SW (10GR + SW, 20GR + SW, 30GR + SW and 40GR + SW), respectively. The findings showed that five FM brackish ice irrigation significantly decreased soil salinity–sodicity, and the lowest value of electrical conductivity (EC) (0.49 dS m^{-1}) in the soil layer of 0–40 cm was observed in 30GR + SW treatment. Maximum sunflower and tomato yields (2670.28 kg ha^{-1} and 31,854.28 kg ha^{-1}) were observed in the 30GR + SW treatment. Results indicate that FM brackish ice irrigation in combination with the phosphogypsum required for reclaiming 30 cm depth of soil is a cost-effective scenario for the abandoned saline-sodic land.

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KEYWORDS
Soil; freezing and melting; saline-sodic soil; phosphogypsum; Songnen Plain

Introduction

The Songnen Plain is situated in the semi-arid region of northeastern China and is characterized by poor surface drainage, a high groundwater table and native vegetation degradation (Li et al. 2004). As a result of intensive grazing pressure and the large-scale conversion of grassland to cropland since the 1950s, the land cover in the native grassland has been reduced significantly, by 40.7%, compared to 1965, which, in turn, caused increased evaporation, runoff, and salt accumulation in the top soil (Li et al. 2004; Wang et al. 2009). The area of salt-affected soils, mainly located in the western part of the Songnen Plain, is 3.42 million ha, thus accounting for 20% of the total land area, and the rate of expansion of the salt-affected area is approximately 1.4% per year (Li et al. 2003). Not only does the intensification of soil salinization and sodification limit the development of agriculture but it also threatens the ecological environment (Qiu et al. 2003; Srivastava et al. 2016).

The saline-sodic soils in the Songnen Plain, northeast China, are dominated by montmorillonite clay minerals, sodium carbonate and sodium bicarbonate, with a pH ranging from 9.5 to 11 and high exchangeable sodium (ESP) ranging from 30% to 85% (Chi et al. 2011). High exchangeable sodium

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induces clay dispersion, resulting in plugged soil pores, reduced infiltration and hydraulic conductivity (Ayers and Westcot 1976). Each of these conditions makes it more difficult to desalinate (Warrence et al. 2002). To ameliorate sodic soils, two aspects are of importance; namely, the reduction or removal of exchangeable Na and the increase in the electrolyte concentration of the soil solution. The flocculating effects of increased soil electrolyte concentration can mitigate a reduction in infiltration and hydraulic conductivity. Thus, saline water irrigation is one alternative to increase electrolyte concentration of the soil solution and thereby improve soil structure (Agassi et al. 1981; Li et al. 2004; Ghafoor et al. 2012). The Songnen Plain is rich in brackish groundwater; however, maintenance of the structure of the severe saline-sodic soil by the brackish irrigation is limited because of its low electrolyte concentration (Xiao et al. 2014).

The processes of freezing and melting (FM) saline water can separate the saline and fresh parts of water. In winter, saline water is used for irrigation and is frozen to form saline ice, which melts in spring. The initial melting water has a higher salinity and the later melting water has a lower salinity (Li et al. 2008). The advantage of FM saline water ice irrigation for improving saline-sodic soil is that the high electrolyte water first increases the infiltration rate in the soil, and later, the low electrolyte or even freshwater helps to leach the salts out of the root zone. In addition, FM saline water can increase soil moisture through infiltration during ice forming and ice melting, thus reducing ground temperature variation and salt and sodium accumulation in the surface soil because of the ice cover in winter (Li et al. 2008; Guo et al. 2010). Previous studies on FM saline ice irrigation were mainly conducted to improve saline soil in central China (Guo et al. 2010; Cheng et al. 2011), in combination with other amelioration methods, such as plastic mulching (Xiao et al. 2011). For saline-sodic soil with high pH and ESP in the Songnen Plain, northeast Xiao et al. (2014), Xiao et al. (2017)) tested the effect of FM brackish ice irrigation in a short-term laboratory soil-column experiment, indicating that FM brackish ice combined with gypsum application played a significant role in decreasing the salinity-sodicity of the upper layer (0–20 cm) soil.

To obtain increased crop yields, soil salinity should be reduced; otherwise, it actually prohibits crop growth at EC_e above 2 or 3 dS m^{-1} (Tanji 1990). As a result, it is not possible to keep increasing EC to merely counter the dispersive effects of sodium in soil (Warrence et al. 2002). Soil sodicity can be lowered by chemical amendments, which replace the sodium adsorbed to the surface of soil particles with calcium (USDA 1954; Tanji 1990). Because of the lower cost, an industrial by-product, phosphogypsum, as a calcium source, has been widely used in sodic soil amelioration for decades without significant increases in the pollutant levels in soils (Al-Oudat et al. 1998; Abril et al. 2008). Thus, any ameliorative measure of FM saline ice irrigation and gypsum application for saline-sodic soil with higher pH and ESP must simultaneously consider the salinity-sodicity tolerance of crops, the effect of soil amelioration and economic feasibility. Gypsum application with brackish ice on soil chemical properties and maize growth has already been investigated for coastal saline soil in China (Tao et al. 2019). However, there is no information available on the appropriate combinations of FM brackish ice irrigation and gypsum in inland saline-sodic soil for crop lands.

We hypothesized that FM brackish ice irrigation may result in lower values of soil salinity-sodicity and increased crop yields if it is combined with gypsum for the highly saline-sodic soils in Songnen Plain, northeast China. The FM saline water ice irrigation with higher electrolyte concentration can inhibit clay dispersion, keep stable porosity and increases the infiltration, while phosphogypsum will provide extra Ca^{2+} to replace Na^{+} on exchange complex as an amendment in practice. In this field study, sunflower (*Helianthus annuus* Linn.) and tomato (*Lycopersicon esculentum* Mill.) were selected as salt-tolerant cash crops. The overall aim of this study was to investigate the ameliorating effect of FM saline ice irrigation with different combinations of phosphogypsum application in a long-term field experiment in the Songnen Plain, northeast China. The specific purposes of this study were: (1) to assess the desalinization of the root zone by the combination of FM saline ice irrigation and phosphogypsum; (2) to identify the effect of FM saline ice irrigation in combination with phosphogypsum on crop yields; and (3) to evaluate the economic feasibility of the amelioration practice.

Materials and methods

Study area

The five-year field experiment was carried out in the Da'an Sodic Land Experiment Station, Chinese Academy of Sciences, in the western part of the Songnen Plain, northeast China (N45°35′58″-45°36′28″, E123°50′27″-123°51′31″). The saline-sodic area is lacking in surface water but is rich in shallow groundwater resources. The shallow water table ranges from 1 to 3 m, and the EC ranges from 1.56 to 4.69 dS m^{-1}. Affected by the mid-temperate zone continental monsoon climate, the region is dry and windy in spring with strong evaporation, the maximum value of which is more than 6 times that of the precipitation. Precipitation in July-August accounts for 56% of the whole year and the amount of precipitation is small in both autumn and winter. The top soil is generally frozen from mid-November to mid-April. The frozen soil, going down to 180 cm (Deng et al. 2005), thoroughly melts in early June.

Experimental design and data collection

The experiment site had been uncultivated and without vegetation owing to the extremely high soil salinity-sodicity for the last two decades. The soil pH, $EC_{1:5}$ (EC in 1:5 soil-water extract) and the exchangeable sodium percentage of the 0–40 cm soil layer was 10.48, 2.65 dS m^{-1} and 77.16% ($SAR_{1:5}$ = 28.75), respectively, meaning that it was a typical saline-sodic soil. The soil bulk density is 1.61 g cm^{-3}. The predominant clay mineral is smectite with a soil texture of sandy-loam to medium-clay and low organic matter content (less than 3 g kg^{-1}). Six treatments were designed in this field experiment as follows:

(1) No amendment, no irrigation (CK)
(2) Brackish ice irrigation, using the brackish water with EC 1.62 dS m^{-1} from local shallow groundwater (SW)
(3) Required amount of phosphogypsum to fully reclaim the 0–10 cm soil layer (20.69 t ha^{-1}) combined with brackish ice irrigation (10GR + SW)
(4) Required amount of phosphogypsum to fully reclaim the 0–20 cm soil layer (41.28 t ha^{-1}) combined with brackish ice irrigation (20GR + SW)
(5) Required amount of phosphogypsum to fully reclaim the 0–30 cm soil layer (61.95 t ha^{-1}) combined with brackish ice irrigation (30GR + SW)
(6) Required amount of phosphogypsum to fully reclaim the 0–40 cm soil layer (82.57 t ha^{-1}) combined with brackish ice irrigation (40GR + SW)

In 2009, phosphogypsum was applied as a sodic soil amendment before the start of the field experiment, and the targeted depth of reclamation ranged from 0cm to 40 cm. The phosphogypsum was obtained from the Heishan Phosphate Fertilizer Plant, Liaoning, China. The gypsum ($CaSO_4 \cdot 2H_2O$) content in phosphogypsum was 60% and the water content was 25%. The amount of phosphogypsum applied in these four treatments was based on Mace et al.'s (1999) formula. Some doses of treatments are high because of the extremely high exchangeable sodium percentage in 0–100 cm soil layers, ranging from 71.5% to 79.7%. There were three replicates for each treatment in a randomized block design.

There were 18 experimental plots, each of which was 5 m long and 4 m wide. The plots were levelled before the start of the experiment. A ridge (1 m wide and 0.5 m high) was set between the adjacent plots to avoid lateral seepage and overflow. A drainage outlet was provided for each plot, by which the excess water would be discharged to the outside. Prior to the experiment, phosphogypsum was spread evenly on the soil surface of the experimental plot in the autumn of 2009, and then it was incorporated into the 20 cm soil layer through the use of a rotary cultivator.

The experiment ran from 2010 to 2014. The annual precipitation was 185.7 mm, 374.0 mm, 489.4 mm, 328.7 mm and 343.7 mm, respectively. When the air temperature was as low as −20 °C in winter, irrigation with brackish water was initiated for each experimental plot. An ice layer formed on the surface of the plot after irrigation. The brackish water of 1.14 pore volume (PV), equivalent to 180 mm, was applied for the ice irrigation each year, with the total water of 2.34 PV, 3.55 PV, 4.29 PV, 3.26 PV and 3.36 PV used for 2010, 2011, 2012, 2013 and 2014, respectively.

Soil sampling was carried out on each plot prior to cultivation on April 20–25, 2010–2014. Three sampling points were randomly taken from each plot. Soil samples were taken at the following soil layers: 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm. The total number of soil samples was 1620 (5 years × 6 treatments × 3 replicate plots × 3 within plot replicates × 6 depths). The Baikuza No. 6 sunflower variety, which has a high sodium tolerance, was planted in the experimental plots in 2010–2011 with a planting distance of 50 cm and a line spacing of 65 cm. Compound fertilizer (N 12%, P_2O_5 18%, K_2O 15%) was applied at 220 kg ha^{-1} prior to sowing each year as a base fertilizer in spring. Cherry tomatoes, which have a lower sodium tolerance than sunflowers (Tanji 1990), were transplanted in 2012–2014 with a planting distance of 30 cm and a line spacing of 65 cm. Diammonium phosphate was applied at 10 g to each hole prior to field planting as a base fertilizer. According to the USDA texture triangle, the soil texture was loam at 0–20 cm and 60–100 cm, while it was clay loam at 20–60 cm soil depth (Table 2). Soil bulk density at the upper 10 cm soil depth was 1.5 g cm^{-3}, which was the lowest in the soil profile. For the 10–100 cm depth, values were in the range of 1.62–1.65 g cm^{-3}. Infiltration rate of the pre-experiment soil was relatively low (0.20 mm h^{-1}) due to the high exchangeable sodium percentage (ESP) (Warrence et al. 2002). The soil wilting percentage (WP) was 18.6% and the field capacity was 32.5%. The minimum and maximum shallow groundwater table depth was 0.50 m and 2.98 m from 2010 to 2014, respectively. Experimental irrigation water comes from local shallow groundwater (30–40 m in depth) with pH and EC values of 7.94 and 1.62 dS m^{-1}, respectively. The shallow groundwater was alkaline in reaction. The dominant cation was Na^+, with a concentration 13.26 mmol$_c$ L^{-1}, and the dominant anion was HCO_3^- with a concentration of 15.36 mmol$_c$ L^{-1}. The shallow groundwater was brackish (Murtaza et al. 2010).

Soil and water analysis

The soil samples were air-dried, mixed thoroughly, and then passed through a 1 mm round-hole sieve. Soluble salt analyses were based on soil:water 1:5 (w w^{-1}) extracts. The electrical conductivity (EC) in dS m^{-1} was measured with a DDS-12DW Microprocessor conductivity Meter (A&E Laboratory Co. Ltd., Shanghai, China). Soluble Na^+ and K^+ were measured with a flame spectrophotometer, while soluble Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrometry (GBC-906AAS). The sodium adsorption ratio (SAR), reflecting the relative quantity of sodium ions and calcium and magnesium ions, was calculated according to the following formula (Mahmoodabadi et al. 2013):

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

where the concentration unit of ions is mmol$_c$ L^{-1} and the unit of SAR is (mmol$_c$ L^{-1})$^{1/2}$. Since it is difficult to accurately determine the soil cation's exchangeable capacity and exchangeable sodium to calculate soil ESP and because there is a correlation between ESP and SAR (Rengasamy et al. 1984), a SAR of 1:5 soil-water extract, which is easier to obtain, was used to assess the sodicity of soils in this study.

Crop measurements and harvest

The plant height, head diameter, and thousand-kernel weight (TWK) of sunflowers were measured in early October 2010–2011. All of the sunflowers were harvested from each plot and dried naturally to measure the yield of sunflower seeds. Ripe tomatoes were harvested in late July 2012–2014. The plant height, diameter and the weight of a single tomato were measured, and all tomatoes were harvested from each plot.

Statistical analysis

All data were subjected to Variance analysis using SPSS 11.5. Significance was tested using univariate analysis between treatments with subsequent mean separation determined through a least significant difference (LSD) test.

Results

Soil salinity-sodicity in the soil profile under different treatments

Soil EC

The treatments had different effects on soil EC in the soil profile (Figure 1). Over the five experimental years, there was little change in soil EC in the soil profile in CK treatment. In the SW and 10GR + SW treatments, soil EC showed a trend of low values at the 0–20 cm soil layers and high EC values at the 20–100 cm layers during the five experimental years. The three treatments, 20GR + SW, 30GR + SW

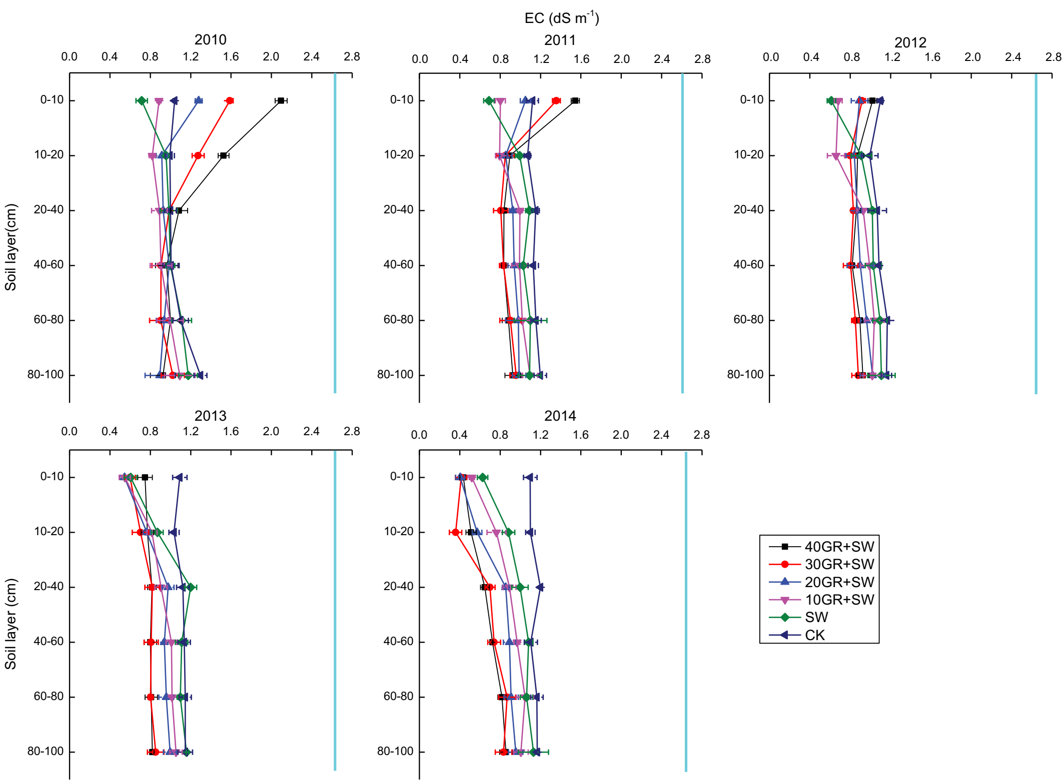

Figure 1. Electrical conductivity distribution in soil profile from 2010–2014. Error bars indicate standard error of the mean. The blue solid line is the pre-experiment soil EC.

and 40GR + SW, showed an opposite trend in the first 2 years, and the low EC at top 20 cm soil layer and high EC at deep layers in the last two years, with an almost uniform distribution of salts in the soil profile in 2012. Over the five experimental years ($p < 0.05$), as compared to CK, the SW and 10GR + SW treatments significantly decreased the soil EC in the 0–20 cm soil layers with an average of 0.28 dS m^{-1} and 0.34 dS m^{-1}, respectively. In the other three gypsum treatments, the soil EC values in 20GR + SW and 30GR + SW treatments were lower in 0–40 cm than those in CK and SW, while the lowest value of EC in the soil layer of 0–40 cm was observed in the treatment 30GR + SW after 3 years of the study. For the last two years, the EC values in these three gypsum treatments decreased significantly from 1.11 (CK) to 0.41 dS m^{-1} (40GR + SW), 0.46 dS m^{-1} (30GR + SW) and 0.38 dS m^{-1} (20GR + SW treatment), respectively (Table 1). The lowest value of EC 0.49 dS m^{-1} in the soil depth 0–40 cm was found in the 30GR + SW treatment. The results showed that the application of phosphogypsum at the starting years contributed to an EC increase in the 0–20 cm soil layer, and EC significantly decreased in the 0–40 cm soil layer after the addition of phosphogypsum over subsequent years.

Soil pH

Under six treatments, the soil pH varied with the depth in the soil profile (Figure 2). Over the five experimental years, there was little change in the pH values in the soil profile for CK treatment. For the other five treatments, the annual pattern of pH values in the soil profile showed a similar trend of low pH values at the top layers (0–20 cm) and high pH values at the deep layers (20–100 cm). The average soil pH values in the 0–40 cm layer were recorded in the order of 40GR + SW (8.55) < 30GR + SW (8.80) < 20GR + SW (9.38) < 10GR + SW (9.75) < SW (9.85) < CK (10.48) in the first two experimental years. For the last three years of the study, the maximum decreases in pH in 0–40 cm depth were recorded in the 40GR + SW (8.22) and 30GR + SW treatments (8.37) compared to the CK treatments (10.43), respectively.

Soil SAR

All treatments showed a similar trend of SAR in the soil profile, with low values in the top layers and higher values in the deep layers during the five experimental years (Figure 3). In the 0–40 cm depth, there were significant variations in the soil SAR in both treatments and experimental years. There was a significant decrease in the soil SAR at a soil depth of 0–40 cm with the application of phosphogypsum (Table 2). The values were recorded in the order of 40GR + SW < 30GR + SW <20GR + SW< 10GR + SW < SW < CK, and the minimum SAR (7.94) was recorded in 40GR + SW, while SAR 26.45 and 28.75 for CK and for pre-experiment were measured in the first experimental year. The maximum decreases of SAR in the 0–40 cm depth occurred in 40GR + SW and 30GR + SW treatments in the second year and the third year. In the subsequent 2 years, SAR in 0–40 cm depth of 40GR + SW, 30GR + SW and 20GR + SW treatments decreased to 6.47, 7.53 and 8.38 from 25.18 in CK, with no significant difference, respectively.

Crop growth and yield

Sunflower yields under different treatments

The vegetative parameters and yields of sunflowers showed significant differences among treatments (Table 3). Sunflowers could not survive in CK treatment in any year. In the first year (2010), both the maximum thousand kernel weight (TKW; 150.4 g) and maximum sunflower seed yield (2160 kg ha^{-1}) were observed in 30GR + SW, while the lowest TKW (40.1 g) and sunflower seed yield (428 kg ha^{-1}) were recorded in SW treatments. In 2011, the highest values in head diameter, TKW and yield were observed in the 40GR + SW treatments, followed by 30GR + SW and 20GR + SW, whereas the lowest values were obtained in the SW treatment.

When comparing 2010 and 2011, plant height in SW treatment in 2011 was significantly higher than in 2010. However, there was no significant change in plant height for the other treatments. The yield in SW and the four GR + SW treatments were higher in 2011 than those in 2010, and the rates of

Table 1. Multiple Comparisons of EC from 2010 to 2014 for soil layers and treatments.

		LSD														
	(I)	1					2				3			4		5
	(J)	2	3	4	5	6	3	4	5	6	4	5	6	5	6	6
SL	Mean Difference (I-J)	0.03	−0.05	−0.05	−0.09	−0.12*	−0.07	−0.08	−0.12*	−0.15*	−0.00	−0.05	−0.08	−0.04	−0.08	−0.03
TM	Mean Difference (I-J)	0.13*	0.21*	0.21*	0.25*	0.19*	0.08	0.09	0.12*	0.06	0.01	0.04	−0.02	0.03	−0.02	−0.06

Based on observed means.
* The mean difference is significant at 0.05 level.
SL: Soil Layer; SL1: 0–10 cm soil layer, SL2: 10–20 cm soil layer, SL3: 20–40 cm soil layer, SL4: 40–60 cm soil layer, SL5: 60–80 cm soil layer, SL6: 80–100 cm soil layer.
TM: Treatment; TM1: CK, TM2: SW, TM3: 10GR + SW, TM4: 20GR + SW, TM5: 30GR + SW, TM6: 40GR + SW.
I-J: Two treatment of pairwise comparisons.

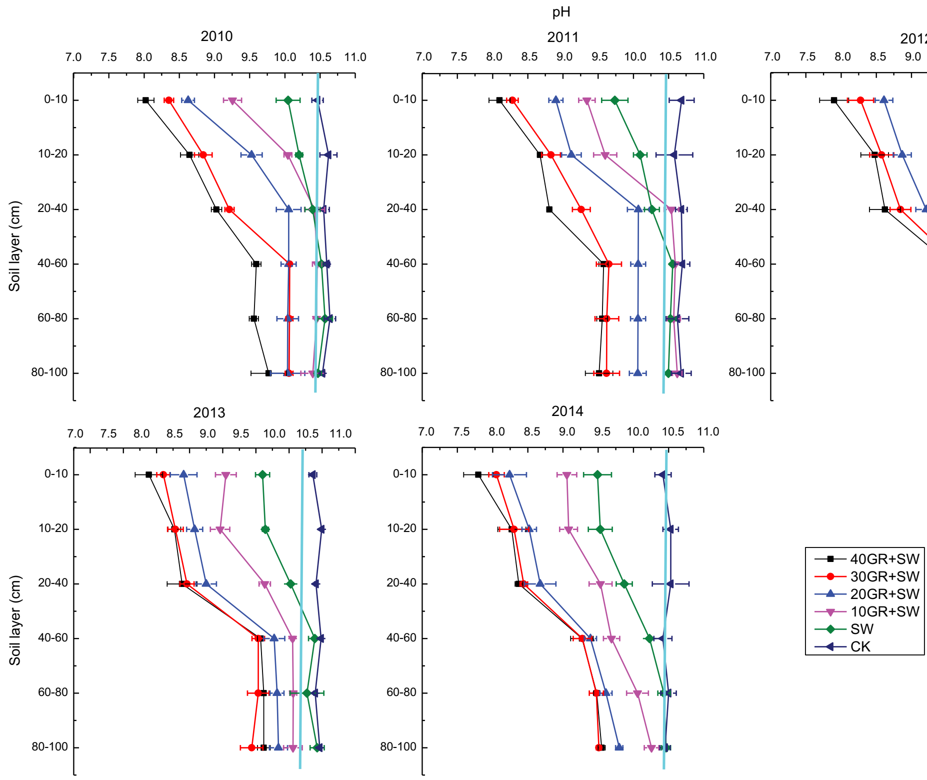

Figure 2. pH distribution in soil profile from 2010–2014. Error bars indicate standard error of the mean. The blue solid line is the pre-experiment soil pH.

increases were 42.5% (40GR + SW), 23.6% (30GR + SW), 37.0% (10GR + SW), 56.5% (40GR + SW) and 102.8% (SW), respectively.

Tomato growth and yield

Tomato seedlings were transplanted into the experimental plots for the third, the fourth and the fifth year of freezing irrigation (2012). The treatment responses for tomato were the same as those for sunflower (Table 4). Tomato could not survive in the CK treatment through the 3 years. The lowest parameters of tomato growth (plant height and diameter) were recorded in SW each year, and the highest were obtained in the 40GR + SW or 30GR + SW treatments.

The weights of the single tomato fruit (WST) and tomato yields for the 3 years (2012–2014) were consistent with those of the sunflower yields in 2011. The lowest values of these two parameters were recorded in the SW treatments. Phosphogypsum addition increased the values of these two parameters, with the increase by the rate of phosphogypsum application. The maximum values were observed in 40GR + SW and 30GR + SW treatments. The maximum tomato yield was 3–3.2 times that of SW, while the maximum WST was 1.1–1.4 times that of the SW.

Correlations among different crop growth/yield parameters and soil properties

Plant height, head diameter, TKW and yield of sunflower were negatively and significantly ($p < 0.05$) correlated with soil pH, Na^+, SAR. However, the yield attributes and growth parameters of the sunflower were not significantly correlated with soil EC. Tomato was different from sunflower,

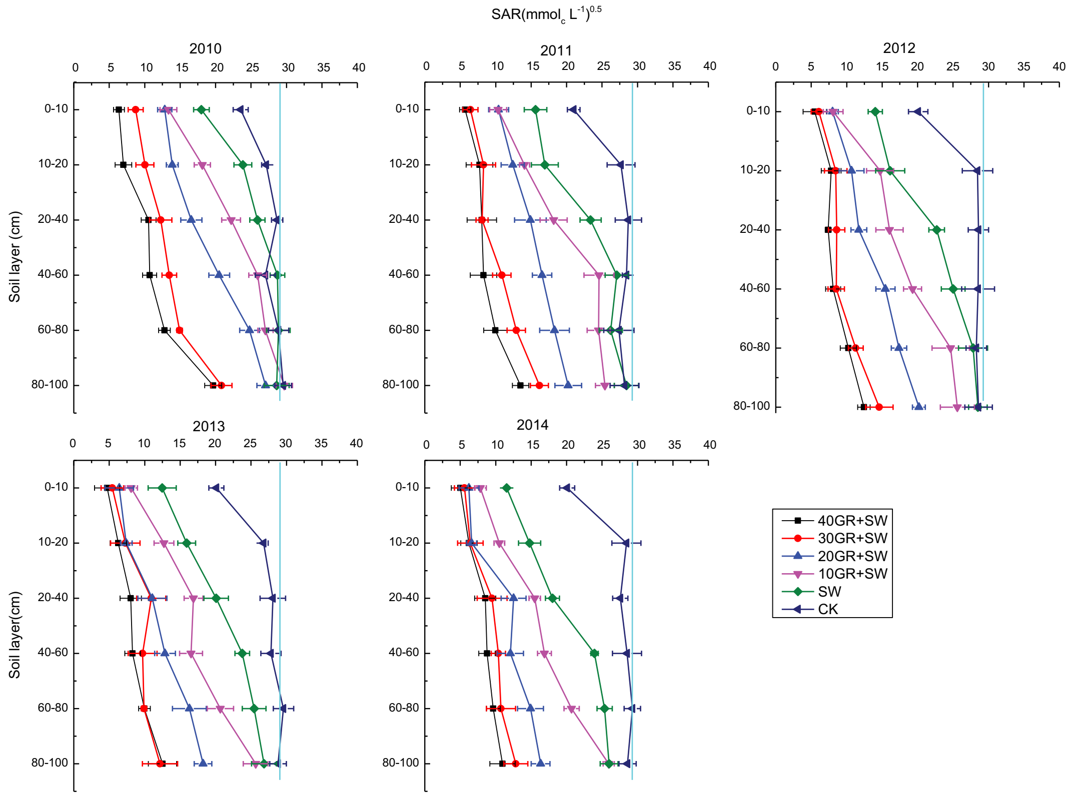

Figure 3. SAR distribution in soil profile from 2010–2014. Error bars indicate standard error of the mean. The blue solid line is the pre-experiment soil SAR value.

tomato plant height, diameter, WST and yield, which were negatively and significantly ($p < 0.05$) correlated with soil EC, pH and SAR (Table 5). Thus, soil alkalinity-sodicity (pH, SAR) influenced the crop growth and yield in the saline-sodic soils.

Cost-benefit analysis of the treatments

The test soil was unproductive before the experiment because of the high salinity-sodicity. Profit could not be expected without amendment application under the FM brackish ice irrigation. The costs were calculated from the expenditures of seeds (seedlings), fertilizers, ploughing, weeding and amendments, excluding the labor inputs. The incomes were estimated at the market price averages of the local sunflower seeds and fresh tomato fruit for the years of 2010–2011 and the years of 2012–2014, respectively.

For the sunflowers, the highest net benefits per hectare were received in 30GR + SW among the 6 treatments for both years, followed by 40GR + SW and 10GR + SW, while there was no economic return in SW and control in the first year, and a limited return in SW treatment for the second year (Table 6). For tomato cultivation, amendment with four levels of phosphogypsum application, the treatments 30GR + SW gave the highest net benefits per hectare for the years of 2012 and 2014, whereas it came second (after 40GR + SW) in 2013 among the 6 treatments. Limited net benefits were received for SW in 2013 and 2014; however, there was still zero economic return in the control treatment for the 5 years. In general, 30GR + SW treatment showed the best option of the cost-effective practice for reclaiming the saline-sodic soils and for cropping in the Songnen Plain, northeast China.

Table 2. Multiple Comparisons of SAR from 2010 to 2014 for soil layers and treatments.

		LSD														
	(I)	1					2				3			4		5
	(J)	2	3	4	5	6	3	4	5	6	4	5	6	5	6	6
SL	Mean Difference (I-J)	−3.17*	−5.72*	−7.30*	−9.04*	−11.15*	−2.55*	−4.13*	−5.89*	−7.98*	−1.58*	−3.32*	−5.43*	−1.74*	−3.85*	−2.11*
TM	Mean Difference (I-J)	4.75*	8.42*	12.65*	16.70*	18.06*	3.67*	7.91*	11.95*	13.31*	4.23*	8.28*	9.64*	4.05*	5.41*	1.36*

Based on observed means.
* The mean difference is significant at the 0.05 level.
SL: Soil Layer; SL1: 0–10 cm soil layer; SL2: 10–20 cm soil layer; SL3: 20–40 cm soil layer; SL4: 40–60 cm soil layer; SL5: 60–80 cm soil layer; SL6: 80–100 cm soil layer.
TM: Treatment; TM1: CK, TM2: SW, TM3: 10GR + SW, TM4: 20GR + SW, TM5: 30GR + SW, TM6: 40GR + SW.
I-J: Two treatment of pairwise comparisons.

Table 3. Parameters of sunflower growth characteristic/yield under different treatments.

Year	Treatment	Height (cm)	Head diameter (cm)	Thousand Kernel Weight (g)	Yield (kg ha^{-1})
2010	40GR+SW	198.41 ± 16.80a	15.57 ± 1.22a	124.58 ± 18.64a	1710.05 ± 102.41a
	30GR+SW	196.82 ± 12.21a	18.64 ± 0.82a	150.47 ± 12.42b	2160.35 ± 168.63b
	20GR+SW	185.24 ± 10.63a	15.02 ± 2.31ab	91.75 ± 15.83 c	1419.76 ± 200.21b
	10GR+SW	148.81 ± 21.70b	10.60 ± 1.44ab	74.17 ± 14.26 c	920.43 ± 254.82 c
	SW	74.67 ± 25.31 c	6.48 ± 2.51b	40.18 ± 12.72d	427.58 ± 176.29d
	CK	-	-	-	-
2011	40GR+SW	212.14 ± 14.13a	19.50 ± 2.12a	158.44 ± 21.83a	2435.64 ± 204.82a
	30GR+SW	208.52 ± 25.82a	20.64 ± 1.84a	156.78 ± 18.65a	2670.28 ± 189.43a
	20GR+SW	190.43 ± 16.42ab	16.39 ± 0.91b	132.61 ± 20.42b	1946.32 ± 103.47b
	10GR+SW	160.82 ± 15.71b	13.42 ± 1.17b	85.18 ± 15.65 c	1440.19 ± 220.68 c
	SW	120.72 ± 20.25 c-	9.53 ± 2.42d-	68.39 ± 13.78 c-	867.67 ± 256.41d-
	CK				

[1]sunflower not survived; Mean ± SE followed by common letter are not significantly different ($p < 0 \cdot 05$).

Table 4. Parameters of tomato growth characteristic/yield under different treatments.

Year	Treatment	Height (cm)	Diameter (cm)	Weight of single tomato (g)	Yield (kg ha^{-1})
2012	40GR+SW	120.18 ± 12.82a	1.70 ± 0.13a	24.52 ± 2.41a	26,122.54 ± 301.22a
	30GR+SW	116.44 ± 11.21a	1.78 ± 0.16ab	24.35 ± 1.58a	29,701.53 ± 198.44a
	20GR+SW	104.83 ± 8.39a	1.53 ± 0.14b	22.73 ± 0.81a	15,663.01 ± 256.30b
	10GR+SW	81.64 ± 6.93b	1.24 ± 0.22 c	20.20 ± 1.12b	11,784.02 ± 184.23bc
	SW	54.26 ± 10.35 c	1.18 ± 0.09 c	18.37 ± 0.55b	6390.04 ± 165.71 c
	CK	–[1]	-	-	-
2013	40GR+SW	119.84 ± 10.22a	1.75 ± 0.12a	28.44 ± 3.23a	28,985.68 ± 203.85a
	30GR+SW	120.43 ± 16.37a	1.86 ± 0.23a	30.82 ± 2.51ab	28,072.46 ± 231.81a
	20GR+SW	108.22 ± 10.61ab	1.62 ± 0.18ab	25.57 ± 1.76b	23,203.50 ± 89.42b
	10GR+SW	92.34 ± 14.76b	1.38 ± 0.07b	22.22 ± 2.04bc	15,130.48 ± 157.56 c
	SW	65.38 ± 18.11b	1.30 ± 0.14b	20.36 ± 1.37 c	10,287.04 ± 123.68d
	CK	-	-	-	-
2014	40GR+SW	118.74 ± 16.18a	1.82 ± 0.20a	32.44 ± 2.62a	30,962.76 ± 186.34a
	30GR+SW	120.09 ± 20.61a	1.78 ± 0.17a	30.62 ± 2.14a	31,854.28 ± 205.65ab
	20GR+SW	112.43 ± 14.66ab	1.65 ± 0.14ab	26.78 ± 1.80b	27,066.02 ± 124.48b
	10GR+SW	100.74 ± 21.82b	1.29 ± 0.21b	22.82 ± 0.94 c	15,402.03 ± 78.50b
	SW	63.47 ± 18.16b	1.28 ± 0.34b	20.56 ± 1.17 c	10,933.52 ± 204.31 c
	CK	-	-	-	-

[1]tomato not survived; Mean ± SE followed by common letter are not significantly different ($p < 0 \cdot 05$).

Table 5. Pearson's correlation coefficients between soil properties in 0–100 cm soil layer and crop growth/yield studied.

	Sunflower				Tomato			
Soil parameters	H	HD	TKW	Y	H	D	WS	Y
EC	−0.47[a]	−0.47[a]	−0.53[a]	−0.51[a]	−0.63**	−0.63**	−0.74**	−0.68**
pH	−0.96**	−0.96**	−0.97**	−0.96**	−0.96**	−0.92**	−0.95**	−0.98**
Na^+	−0.97**	−0.98**	−0.97**	−0.94**	−0.93**	−0.89**	−0.95**	−0.96**
SAR	−0.94**	−0.92**	−0.92**	−0.90**	−0.95**	−0.92**	−0.96**	−0.93**
W	0.13[a]	−0.00[a]	−0.04[a]	−0.08[a]	0.34[a]	0.44*	0.21[a]	0.10[a]

H, plant height; HD, head diameter; TKW, thousand kernel weight; D, diameter; WS, weight of single tomato; Y, yield; EC, electrical conductivity; SAR, sodium adsorption ratio; W, soil water content.
[a]Not significant; *$p < 0 \cdot 05$; **$p < 0 \cdot 01$.

FM brackish ice irrigation leads to other benefits. On one hand, the water table could be reduced by the saline water pumping from the shallow groundwater, which is favorable for salinization control. On the other hand, freezing saline water forms an ice layer on the soil surface in winter (ice

Table 6. Economics of different soil reclamation treatments with sunflower and tomato cropping 2010–2014 (US\$ ha^{-1}).

Year	Crop	Treatment	Cost	Gross income	Net income
2010	Sunflower	40GR+SW	746.27	1786.95	1040.68
		30GR+SW	671.64	2257.2	1585.56
		20GR+SW	597.01	1483.9	886.89
		10GR+SW	522.39	961.4	439.01
		SW	447.76	447.26	−0.50
		CK	393.35	0.00	−393.35
2011	Sunflower	40GR+SW	447.76	2545.62	2097.86
		30GR+SW	447.76	2790.15	2342.39
		20GR+SW	447.76	2033.57	1585.81
		10GR+SW	447.76	1504.8	1057.04
		SW	447.76	907.06	459.30
		CK	393.35	0.00	−393.35
2012	Tomato	40GR+SW	597.01	2339.27	1742.26
		30GR+SW	597.01	2659.77	2062.76
		20GR+SW	597.01	1402.62	805.61
		10GR+SW	597.01	1055.26	458.25
		SW	597.01	572.22	−24.79
		CK	542.60	0.00	−542.60
2013	Tomato	40GR+SW	597.01	2595.70	1998.69
		30GR+SW	597.01	2513.89	1916.88
		20GR+SW	597.01	2077.87	1480.86
		10GR+SW	597.01	1354.94	757.93
		SW	597.01	921.20	324.19
		CK	542.60	0.00	−542.60
2014	Tomato	40GR+SW	597.01	2772.74	2175.73
		30GR+SW	597.01	2852.53	2255.52
		20GR+SW	597.01	2423.76	1826.75
		10GR+SW	597.01	1379.25	782.24
		SW	597.01	979.09	382.08
		CK	542.60	0.00	−542.60

mulching) to keep higher moisture for the following dry spring. Utilizing the shallow water resources in the region could be developed as an innovation.

Discussion

Changes in soil salinity-sodicity

The increase in salt concentration by FM brackish ice irrigation could increase the infiltration rate, while phosphogypsum was found to further improve the hydraulic conductivity and decrease the water content of the top soil (Li et al. 2008). The FM brackish ice irrigation resulted in a reduction in dramatic salinity-sodicity parameters (pH and SAR) in the top soil (SAR at the 0–40 cm soil layer decreased by 30% and 37.5% compared to CK and the pre-experiment value, respectively). The addition of phosphogypsum further reduced soil salinity-sodicity with the calcium-sodium exchange, particularly in the later years of the study. In the final year 2014, soil bulk density average at 10–40 cm depth decreased to 1.43 g cm^{-3}, 1.44 g cm^{-3}, 1.51 g cm^{-3} and 1.53 g cm^{-3} in 40GR+SW, 30GR+SW, 20GR+SW, 10GR+SW treatments from 1.62 g cm^{-3} before the experiment, respectively. The reduction in bulk density could partly be attributed to the FM saline ice irrigation and gypsum application improving soil structure. The desalinized soil depth became deeper with the experimental years. However, phosphogypsum application at the beginning years contributed to the increase in EC in the top soil (0–20 cm). The top soil EC decreased with the addition of more phosphogypsum over the years. The maximum reduction in EC was recorded in the 30GR+SW treatment in 0–40 cm for the 5 years. These results were inconsistent with that of the saline soil in coastal areas and could be greatly improved by saline water freezing irrigation and a modifying agent (Cheng et al. 2011). This inconsistency might have been due to high levels of exchangeable sodium of the saline-sodic soils in the Songnen Plain, northeast China (Chi et al. 2011). Salinization occurred in the CK treatment, which was not covered by an ice layer in winter, and where soluble salts accumulated in the surface soil through a capillary rise in spring because of strong evaporation. Ultimately, this led to the highest salt content in the top soil. For saline water ice irrigation treatments, the soil surface was covered with an ice layer in winter, which influences the soil freeze-thawing process and inhibits salinization generated by freeze-thawing (Li et al. 2008). In addition, the elevated electrolyte concentration in the soil solution could facilitate particle flocculation instead of clay dispersion, resulting in increased infiltration. The ratio of divalent to total cations in the freezing saline irrigation water was 54.8%, which also contributed to the salt leaching (Reeve and Doering 1966) because the high salinity water in the micropores is more likely to flow into the larger macropores in the soil due to the osmotic potential difference between the bulk soil solution and the interior of the soil aggregates. As a result, fine particles bind together into aggregates and flocculation is enhanced because of the effects of high electrolytes, which also improve soil aeration and permeability (Warrence et al. 2002). The low-salinity water, which subsequently melts, leaches the salts out of the root zone, which decreases soil salinity in the top soil (Li et al. 2008).

High salinity in the soil solution has a positive effect on soil structure, but it also has a negative effect on plants (Warrence et al. 2002). Thus, it is necessary to consider the impact of increased salinity on plants, without continuously increasing salinity to maintain soil structure (Miller and Donahue 1995; USDA, Natural Resources Conservation Service 2002). The addition of an extra calcium source in the form of phosphogypsum was an effective means to improve sodic soil structure (Vyshpolsky et al. 2010). The contents of both Ca^{2+} and SO_4^{2-} were increased after the phosphogypsum dissolved in water at the beginning of the year in the combined brackish ice irrigation and phosphogypsum treatment, which resulted in the significant increase of EC in the top soil. The addition of higher amounts of phosphogypsum led to a higher EC in top soil (Xiao et al. 2014). However, the increase in soil salinity is temporary because phosphogypsum application and brackish ice irrigation could sustain a favorable soil solution electrolyte concentration, which could, in turn, increase the infiltration rate (Shainberg and Letey 1984), maintain high Ca:Na ratios in the soil solution, and thus alleviate soil dispersion (Murtaza et al. 2010). Increased input of brackish ice irrigation and higher salinity level enhanced the leaching of soluble salts, thereby lowering EC in the top soil layers in subsequent years. Similar effects were observed for the soil SAR and pH. This might have been due to the exchange complex acting as a sink for Ca^{2+}, which replaced the excess exchangeable Na^+ (Ahmad et al. 2016; Mace et al. 1999) with phosphogypsum, thereby enabling more efficient leaching because of the brackish melt water.

For the semi-arid region of the Songnen Plain, intensive salt and sodium accumulation in the top soil occurs under evaporation in winter and spring. Brackish ice provides mulching on the soil surface, which can inhibit evaporation and the subsequent upward movement of water and salt. The ice irrigation treatment also plays a critical role in seeding and drought control through increasing the moisture of the soil cultivation layer in dry spring.

Sunflower and tomato yields and economics of applied treatments

The increase in crop growth and yield with phosphogypsum application, combined with brackish ice irrigation, might be attributed to the favorable effects of this treatment on the physical and chemical properties of the soil, particularly the favorable Ca^{2+}:Na^+ ratios in the soil solution. The crop yield increased with increased phosphogypsum input; however, too much phosphogypsum could lead to high soil ion concentrations in the first year, eventually resulting in crop yield decline. The 30GR + SW treatment produced the maximum sunflower and tomato yields. Relatively low crop yields were observed with brackish ice irrigation, although yield increased over time, while crops completely failed because of high salinity-sodicity in the control treatment. The results showed that the highly saline-sodic soil could be greatly ameliorated by brackish ice irrigation combined with an appropriate dose of phosphogypsum. In terms of the salinity-sodicity of the top soil and crop yield, in agreement with previous findings, 30GR + SW was the best treatment option for improving the saline-sodic soils (Cheng et al. 2011). In this experiment, for this highly saline-sodic soil, 180 mm freezing irrigation and 25,800 kg ha^{-1} phosphogypsum were used. The optimal amount of phosphogypsum for the saline-sodic soil was much higher than that of the coastal saline soil, mainly because the saline-sodic soil in the northeast of China has high exchangeable Na^+ (Wang et al. 2003; Chi and Wang 2009) content. The sunflowers and tomatoes used in this study are moderately salt-tolerant plants, however, to achieve effective root development, they need deep soil reclamation. The optimal reclamation option is 30 cm in depth and a full dose of amendment. These results agreed with previous investigations by Vyshpolsky et al. (2010). The improvement of severe saline-sodic soil by brackish ice irrigation in combination with phosphogypsum can facilitate seed germination and the seedling growth of vegetation during dry springs in the region, and, on the other hand, reduce the water table by pumping. Phosphogypsum application could improve saline-sodic soil rapidly for a higher crop yield. Sunflower and tomato, as main local cash crops, showed higher returns (1586–2342 US$ ha^{-1}) than field crops (572–945 US$ ha^{-1}) in the best reclaiming practice for saline/sodicity soil (Vyshpolsky et al. 2010; Murtaza et al. 2010).

Conclusion

This study evaluated the effects of brackish ice irrigation, phosphogypsum and their combination on saline-sodic soil amelioration. The treatment 30GR+SW performed the best in terms of (1) improving soil quality of top soil (0–40 cm) through a reduction in soil soluble pH, SAR, (2) increasing sunflower and tomato yields (3) and offering the additional advantage of integrating brackish groundwater for soil reclamation and saving freshwater for producing high-value cash crops. Results suggest that brackish ice irrigation, coupled with a phosphogypsum requirement of 30 cm soil depth is the most effective technique for the saline-sodic soil reclamation in cold winter areas of the Songnen Plain, northeast China.

Disclosure statement

No potential conflict of interest was reported by the authors.

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