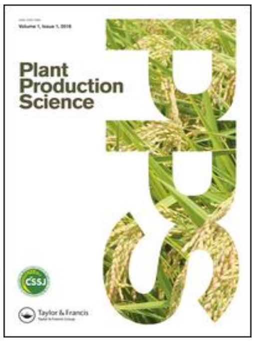

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REGULAR PAPER

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Cooperative effects of sand application and flushing during the sensitive stages of rice on its yield in a hard saline–sodic soil

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ABSTRACT

Application of sand can ameliorate rice paddy fields converted from saline–sodic land. However, the requirement of huge amount of sand has been limiting its practical application. In this study, flushing during saline sodic-sensitive stages of rice plant growth was incorporated into the ameliorating system to reduce the sand usage. A split-plot design was adopted with sand application (SA) with two levels as main plots and flushing during the sensitive stages (FL) with two levels as subplots in a hard saline–sodic soil, Northeast China. Four treatments included CK (no-sand, no-flush flooding), NF (non-sand, flush flooding), SN (sand, no-flush flooding), and SF (sand, flush flooding). The results showed that both SA and FL significantly affected all the investigated yield parameters. The combined effect of SA and FL on the grain yield was additive in the first year in respect of the effect on panicle density and seed weight per panicle; while it showed synergistic effect on the seed weight per panicle and grain yield in the second year. The rice yield in different treatments was in the order of SF > SN > NF > CK in both years, with the highest yield (4.37 t ha^{-1}) obtained by SF treatment in the second year. Our results demonstrate that half the traditional amount of sand in combination with water-flushing during the saline–sodic-sensitive growth stages of rice is sufficiently effective in ameliorating saline–sodic soil and thereby enhancing rice grain yield in saline–sodic paddy fields.

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Introduction

Salt-affected soils are widespread in arid and semiarid regions. It is estimated that about 955 × 10^6 ha land is suffering from salinity and sodicity globally (Pandey et al., 2011; Wong et al., 2010). Approximately, 60% of the salt affected soils in the world (Qadir et al., 2007a) are sodic/saline–sodic soils, causing structural problems created by certain physical processes (slaking, swelling, and dispersion of clay) and specific conditions (surface crusting and hardsetting) (Qadir & Schubert, 2002; Shainberg & Letey, 1984; Sumner, 1993), and affecting water and air movement, plant-available water holding capacity, root penetration, and tillage operations (Oster & Jayawardane, 1998). In addition, there also exist osmotic and ion-specific effects together with imbalances in plant nutrition (Grattan & Grieve, 1999; Naidu & Rengasamy, 1993). In such cases, negative physical and chemical impacts are imposed on the activity of plant roots (Rengasamy & Vadakattu, 2002; Shaaban et al., 2013) as well as on soil microbes (Wong et al., 2010), and ultimately on crop growth and yield (Qadir et al., 2007a; Rengasamy et al., 2003; Shaaban et al., 2013).

It is estimated that about 20% of future increases in crop production will still come from land extensification (Gregory et al., 2002). In such a context, development and effective utilization of the saline–sodic land resource is essential for agricultural expansion to sustain the food needs of the ever-increasing human population that is expected to reach 9.1 billion by 2050 (Qadir et al., 2014; United Nations, 2009). Currently, it is imperative to find ways to improve such land productivity of salt-affected soils (Qadir et al., 2007a). Several measures involving chemical amendments (inorganic and organic amendments), water-related approaches, crop-assisted interventions, soil-profile modification (such as sanding, deep plowing), and electrical currents have been developed to ameliorate–sodic and saline–sodic soils (Qadir

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et al., 2007a, 2007b). As an effective practices to make surface soil more permeable in the salt-affected soils, especially in sodic soil or saline–sodic soil, physically sanding can result in leaching of soluble Na^+ out of the root zone and decrease soil pH to some extent, and consequently improve soil physical and chemical properties (Qadir et al., 2007b; Yu et al., 2010). Traditionally, the depth of sanding should be at least 10 cm for better amelioration results, but the practical application at the field scale is limited due to the requirement of huge amount of sand (Qadir et al., 2001). Therefore, the amount of sand application needs to be reduced in order to ease and expedite practical application at the field scale.

As one of the five largest salt-affected soil regions in China (Chi & Wang, 2010; Yu & Cheng, 1991), Songnen plain encompasses 3.42×10^6 ha of salt-affected soils characterized mainly by $NaHCO_3$ and Na_2CO_3 salts (Chi & Wang, 2010; Wang et al., 2003), and most of such salt-affected soils are hard saline–sodic (Li et al., 1998). Currently, the ever largest land reclamation project with supportive irrigation and drainage facilities in the Songnen plain in China, has been constructed to focally convert 9.6×10^4 ha area of several concentrated contiguous salt-affected lands into the rice paddy fields, since rice culture has been regarded as an effective amelioration approach in such salt-affected soils in the region (Song et al., 2002; Zhao et al., 2012). The sandy soil resources within the research region are accessible to obtain and transport from the surrounding sandy soil dunes since about 15.39% area of western Jilin Province is also sandy soil distribution area (Qiu et al., 2003; Yu et al., 2010). Ideally, it is a win–win strategy to ameliorate the saline–sodic soil in this region by properly utilizing the local unexploited sand resources. Several reports have shown that the sand application practices in this region (Liu et al., 2010; Yu et al., 2010) have been successively adopted to ameliorate such saline–sodic soil and improve the rice yield. However, sanding is usually conducted as one of the physically driven approaches in such saline–sodic soils during the land preparation stage (Qadir et al., 2006), further supplementary practices may be still needed to strengthen the continuous driving effects of a starter dose of sand amendment on rice yield improvement in sand-ameliorated environments, especially during the rice growth stages, while considering the necessity of lowering the amount of sand application.

Rice yield components are sequentially and successively formed in the order of the vegetative stage, reproductive growth stage, and spikelet filling growth stage; at any stage of which biotic or abiotic stresses can significantly reduce the rice yield (Fageria, 2007). In other words, the formation of each rice yield component has its own sensitive growth stage, and rice yield can be improved by an effective supplementary practice that can mitigate the stresses such as soil salinity and sodicity. It has been reported that flushing during the rice growth stages evacuated salts from the fields with the less permeable soils (Nayak et al., 2008; Qadir et al., 1998). Chen et al. (2013) further revealed that soil salt reduction increased with the increasing frequency of flushing. However, few studies report on flushing at the sensitive stages of yield component formation during the rice growth stages in the field.

We previously reported that a combined treatment of sand application with a half traditional application amount and flushing during the sensitive stages has significant effects on the rice biomass partitioning between shoot and root, grain yield, and its components (Wang et al., 2010a). However, the interactive effect of the sand application with flushing during the sensitive stages on rice yield and yield components still remains unexplored. The present study was aimed to further explore the effects of half traditional amount of sand application and flushing during the sensitive stages of rice, either alone or in combination, on rice yield, and yield components in a hard saline–sodic soil in the Songnen plain, northeast China.

Materials and methods

Study site

The field trial was conducted at the Da'an Sodic Land Experiment Station (45°36′N, 123°53′E, and 132.1 m a.s.l.) of Chinese Academy of Sciences, in Da'an city, in the Songnen plain of northeast China in 2009 and 2010, respectively. Annual mean precipitation in Da'an city is 413.7 mm, with 88.3% occurring from May to September. Annual mean evaporation is 1696.9 mm and annual mean temperature is 4.70 °C. Annual reference evapotranspiration from May to September is 683.3 mm. The salt-affected soil in this study site is similar with such a highly dispersed hard saline–sodic soil ($pH_e = 10.8$, $EC_e = 16.42$) reported by Luo et al. (2015) who conducted their study near our study site. The main soil characteristics are presented in Table 1. There were more details about the study site in Wang et al. (2010a).

Experimental design

A split-plot design was adopted for the experiment with sand application (SA) as the main plots and flushing during the sensitive stages (FL) as the subplots. The SA had two levels, with non-SA level and SA level. The FL had two levels, with non-FL level and FL level. Then the four treatments were:

CK: no-sand, no-flush flooding;
NF: non-sand, flush flooding;
SN: sand, no-flush flooding;

Table 1. Soil analysis before trial (0–20 cm) and soil properties of added sandy soil.

Item	$pH_{1:5}$	$EC_{1:5}$ (mS/cm)	Organic C (mg kg^{-1})	Ion content (mg kg^{-1})								Available (mg kg^{-1})			Soil texture (%)		
				Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	CO_3^{2-}	HCO_3^-	SO_4^{2-}	N	P	K	Sand	Silt	Clay
Before Trial	10.20	1.29	64.0	1679.60	95.20	124.89	2486.10	887.50	799.20	8374.08	9.86	26.21	21.91	285.16	41.81	33.91	24.28
Added Sand	6.22	.06	90.0	109.35	10.38	14.33	107.20	-	-	-	-	58.8	4.08	34.74	84.08	11.32	4.61

Notes. 1:5 means 1 part soil with 5 parts water.

SF: sand, flush flooding.

Each plot was 87.5 m^2 (25 m length and 3.5 m width) with three replicates. The sandy soil was obtained from the surrounding sandy soil dunes. The amount of sand application was lowered to half of traditional application amount (10 cm depth layer) (Qadir et al., 2001), meaning that the application standard was 5 cm depth layer (500 m^3/ha) in this study. In SN and SF treatments, the 5 cm sand layer was mixed with the upper 20 cm soil during the land preparation period. FL means that the extra irrigation water (2 cm depth) for each flushing was first applied, and then flushed out of the field after it was kept for 24 h and normal irrigation started. The sensitive growth stages of rice include vegetative, reproductive, and spikelet filling growth stage (Fageria, 2007). And every sensitive stage of rice has two flushings. During the land preparation stage (about a week), about total 15 cm depth water was applied to leach the soil salts in all the experimental plots, then the ponded water was flushed out of the field. During the growth stages of rice, each normal irrigation with about 5-cm depth water was applied when the standing water disappeared. The irrigation water from the 80-meter depth well was sampled and measured with an electrical conductivity of 1.05 mS/cm and pH of 7.52 at 25 °C. And its chemical composition of Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, CO_3^{2-}, HCO_3^-, and SO_4^{2-} were 1.85, 1.30, .07, 5.63, 1.90, .00, 9.60, and .15 $mmol_c$/L, respectively.

A local inbred rice cultivar (Changxuan 10) was used in the study. Rice was transplanted into the experimental plots with a fixed planting spacing of 30 cm × 16.7 cm with 3–5 seedlings per hill. The 40 days old seedlings were used because a bit bold seedlings can alleviate the salinity and sodicity stresses compared with the younger ones (Kewat et al., 2002; Shahi et al., 1977). They were transplanted on 4 June 2009 and 2 June 2010. Herbicide (1.2% powder mixture of 20% butachlor and 1.15% prometryne) was applied before transplanting. A basal fertilization of 63 kg N/ha, 49 kg P_2O_5/ha and 49 kg K/ha was applied during the land preparation. A second dose of 22.5 kg N/ha was applied at the re-greening stage, and a third dose of 11.3 kg N/ha was applied at the maximum tillering stage. The other details of fertilizer and herbicide application were shown in Wang et al. (2010b).

Analysis of soil chemical properties

Soil samples from each plot were taken in 10-cm increments to a depth of 40 cm after rice harvest in the second year (2010). Then these soil samples were air dried, passed through the 2-mm sieve, and analyzed for pH, EC, soluble Na^+, Ca^{2+}, and Mg^{2+} using 1:5 soil to water extracts. The 1:5 soil to water extracts were prepared by adding 20-mL distilled water to 4 g soil in a 100-mL bottle. The bottle was sealed with a stopper, agitated for 15 min on a mechanical shaker (100 rpm), allowed to stand for one hour then agitated again for 5 min, before a sample was obtained by filtration. The EC of 1:5 soil to water extracts ($EC_{1:5}$) was determined by DDS-307 conductivity meter (Shanghai Precision Scientific Instrument Co., Ltd), the concentrations in $mmol_c/L$ of Na^+, Ca^{2+}, and Mg^{2+} were determined using inductively couple-plasma spectroscopy (GBC-906AAS, Australia). Sodium adsorption ratio (SAR) was calculated by the following Equation (1):

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

Measurements of plant growth

The leaf area index (LAI), which is the amount of leaf area per unit land area, was measured by LAI-2000 Plant Canopy Analyzer (Li-COR, Lincoln, USA) during the re-greening stage (about 15 days after transplanting), tillering stage (about 38 days after transplanting), jointing-booting stage (about 60 days after transplanting), flowering stage (about 73 days after transplanting), and grain-filling stage (about 102 days after transplanting) at each plot in 2009 and 2010.

Measurements of rice yield and yield components

Rice was harvested at the end of September in both 2009 and 2010. Seven sample quadrats of 1 m^2 were randomly selected in undisturbed area of each plot to measure grain yield. For each quadrant, the total number of panicles from all hills was counted, and then divided with the total hill number to obtain the average panicles per hill. The hills with panicles similar to the average number were selected to determine the following yield components: panicles per hill, kernel weight, and filled and unfilled spikelets per panicle. Main stems were not distinguished from tillers. Kernel weight was adjusted to .14 g g^{-1} water content on a dry weight basis. The yield parameters included rice yield (YD), panicle density (PD), seed weight per panicle (SWP), spikelets per panicle (SP), percentage of filled spikelets (PFS), and kernel weight (KW).

Data analysis

The significance of all experimental factors in the split plot design was calculated by deriving the mean squares in the analysis of variance using the GLM procedure of SPSS (IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY, USA). The treatments of SA were assigned as main plot factor and FL and year factor was assigned as sub-plot and sub–sub plot factors, respectively. All factors were considered as fixed effects. The analysis of variance technique was adopted, and the least significant difference (LSD) test was also applied to differentiate the treatments effects when more than two treatments were compared.

The interactive effects of SA and FL on the rice yield components were calculated by the following formula (2).

The interaction effect AB = 1/2 × (the simple effect of A at the high level of B – the simple effect of A at the low level of B) (2)

In the formula (2), simple effect of A at high level of B is the difference between the high level of A and the low level of A when B is fixed at high level. Simple effect of A at low level of B is the difference between the high level of A and the low level of A when B is fixed at low level. And the interaction of A and B is the same as the interaction of B and A. Where A stands for SA, B stands for FL.

Results

Soil salinity and sodicity

As shown in Figure 1, irrespective of treatments, soil $EC_{1:5,}$ pH and $SAR_{1:5}$ all increased with increase in soil depths. For the upper soil layers, the value of every investigated soil index, soil $EC_{1:5}$, pH and $SAR_{1:5}$ in the 0–10 cm soil layer significantly decreased in the order of CK > NF > SN > SF. For the 10–20 cm soil layer, SF was minimum in soil $EC_{1:5}$, pH and $SAR_{1:5}$, significantly lower than that of CK and NF, respectively. For two lower soil layers, 20–30 cm soil layer and 30–40 cm soil layer, there were no significant differences between different treatments.

Leaf area index

LAI increased in all plots until the booting-jointing stage, kept constant and then gradually decreased thereafter (Figure 2). The differences between the three treatments were small before the booting-jointing stage. However, the gaps became larger from the booting-jointing stage to the grain filling stage. The maximum LAI was still observed at the SF treatment.

Interactive effects of SA, FL, and year factor

The variances of rice yield parameters were analyzed and the results are summarized in Table 2. The overall effects of SA, FL, and year factor were highly significant ($p < .001$) for all investigated parameters except for the year effect on seed weight per panicle. Additionally, the mean squares of the investigated yield parameters were all higher in SA compared with that of FL. The interactions between SA and FL were not significant ($p > .05$) for any parameters but panicle density. The interaction between SA and year was not significant ($p > .05$) for any yield parameters but panicle density and spikelets per panicle. It was similar for

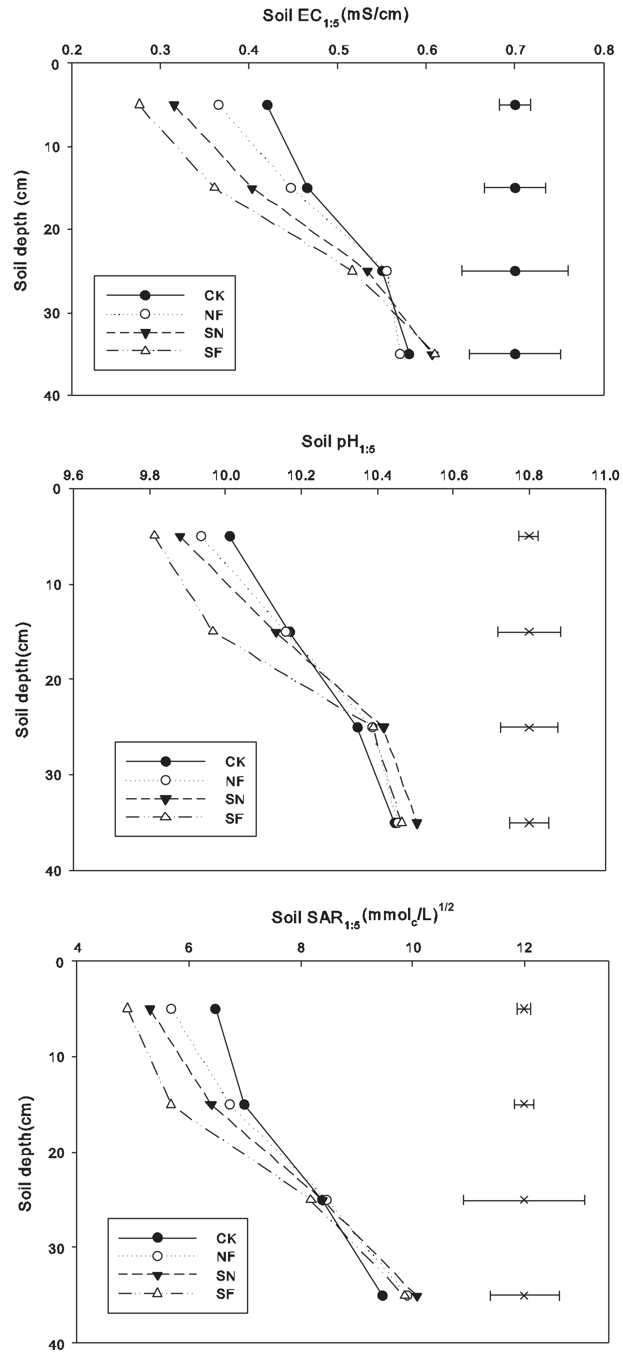

Figure 1. Soil $EC_{1:5,}$ $pH_{1:5}$ and $SAR_{1:5}$ in soil profiles of different treatments after rice harvest in the second year. Horizontal bars indicate LSD (.05).

the interactions between FL and year factors. However, there were no significant ($p > .05$) interactions of SA, FL, and year factor on any investigated parameters.

Inter-annually, the overall effects of SA and FL were highly significant ($p < .001$) for all parameters investigated in both the first and second years (Table 3). In addition, no significant interactions between SA and FL were found for all the investigated yield parameters in the first year. However, the interactions between SA and FL in the second year were significant ($p < .05$) for rice yield, panicle density, and seed weight per panicle. And the mean squares of SA were all found higher for investigated yield parameters than that of FL (Tables 2 and 3). Furthermore, the interactive effect of SA and FL on grain yield was positive across the two years (Table 4). By contrast, it showed different effect on the different yield parameters, negative on panicle density, and positive on seed weight per panicle (Table 4).

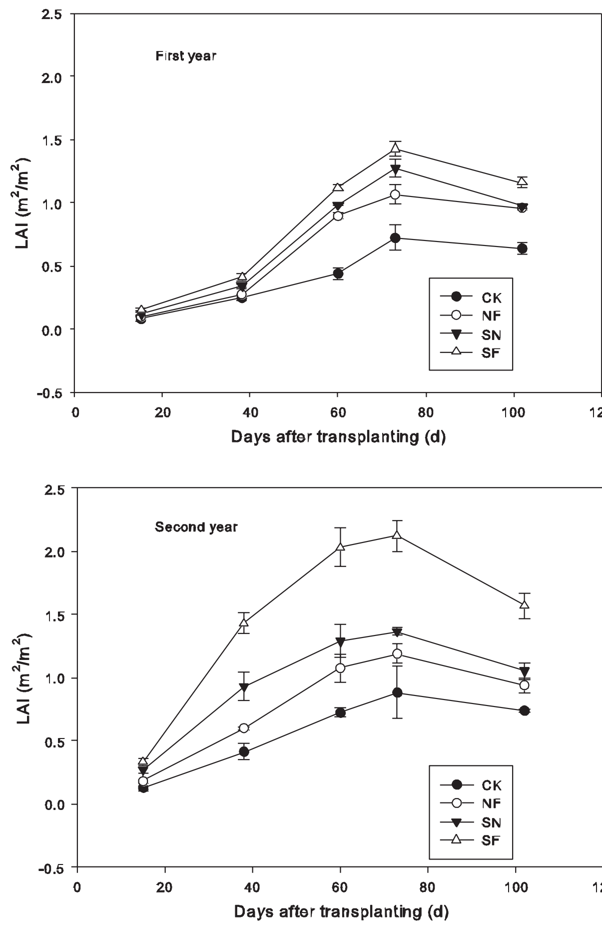

Figure 2. Changes in LAI in different treatments with increasing days after transplanting in the first and second year. Vertical bars represent standard error.

Effects of CK, NF, SN, and SF on rice yield parameter

The means of rice yield parameters were also separated at different SA levels, FL levels and years (Table 5). As shown in Table 5, increasing trends for all investigated yield parameters in the order of CK < NF < SN < SF were both found in the first and second year. For the part of inter-annual yield parameters, all treatments of CK, NF, SN, and SF in the second year were significantly higher ($p < .05$) in the investigated yield parameters except for the seed weight per panicle, spikelets per panicle and kernel weight than those of CK, NF, SN, and SF in the first

Table 2. Analysis of variance for yield parameters in each different treatment.

Resources	df	YD	PD	SWP	SP	KW	PFS
SA	1	147.3**	139931.2**	14.6**	6973.5**	919.6**	2.9**
FL	1	32.8**	41432.8**	4.2**	2219.4**	285.3**	1.2**
Year	1	16.2**	81147.2**	.3	1013.9**	69.4**	2.5**
SA × FL	1	2.3	12144.7**	.2	30.3	.0	.0
SA × Year	1	.7	63213.3**	.5	1579.5**	26.3	.0
FL × Year	1	1.3	7051.8*	.2	376.1**	.1	.0
SA × FL × Year	1	1.4	3426.0	.1	262.2	19.5	.0

Notes. YD, rice yield; PD, panicle density; SWP, seed weight per panicle; SP, spikelets per panicle; PFS, percentage of filled spikelets; KW, kernel weight.
*Significant at .05 significance level in *F*-tests; **Significant at .01 significance level in *F*-tests.

Table 3. The variance analysis of yield parameters over the two years.

Year	Resources	df	YD	PD	SWP	SP	KW	PFS
First year	SA	1	67.7**	8805.2*	10.9**	5745.9**	678.0**	19499.5**
	FL	1	11.3**	8369.1*	1.5**	1673.0**	147.3**	5160.6**
	SA × FL	1	.1	1562.7	.0	178.2	10.3	1.5
Second year	SA	1	65.1**	158245.3**	4.6**	952.3**	222.8**	7087.0**
	FL	1	19.6**	27654.6**	2.8**	800.5**	113.1**	6128.9**
	SA × FL	1	3.6*	7212.7*	.3*	301.4	12.2	8.2

Notes. YD, rice yield; PD, panicle density; SWP, seed weight per panicle; SP, spikelets per panicle; PFS, percentage of filled spikelets; KW, kernel weight.
*Significant at .05 significance level in *F*-tests; **Significant at .01 significance level in *F*-tests.

Table 4. Quantification of interactive effects of SA and FL factors on rice yield and its components in the two years.

Year	YD (t ha^{-1})	PD (No. m^{-2})	SWP (g panicle^{-1})	SP (No. panicle^{-1})	KW (mg)	PFS (%)
First year	.11	−20.25	.02	.65	−.75	−.11
Second Year	.48	−22.01	.14	2.29	.76	−.02

Notes. YD, rice yield; PD, panicle density; SWP, seed weight per panicle; SP, spikelets per panicle; PFS, percentage of filled spikelets; KW, kernel weight.

Table 5. Effects of different treatments on rice yield and its components over the two years.

		Treatment			
Item	Year	CK	NF	SN	SF
YD (t ha^{-1})	First year	.43d	1.14c	2.21b	3.13a
	Second year	.97d	1.67c	2.72b	4.37a
		*	*	*	*
PD(no. m^{-2})	First year	144.22c	210.80b	218.84b	244.92a
	Second year	180.00c	245.11b	305.11a	326.20a
		*	*	*	*
SWP(g panicle^{-1})	First year	.22b	.49b	.97a	1.27a
	Second year	.42c	.70b	.82b	1.37a
		*	NS	NS	NS
SP (no. panicle^{-1})	First year	64.43b	64.46b	78.29a	79.62a
	Second year	54.37c	58.02bc	61.46b	69.69a
		NS	NS	*	*
KW (mg)	First year	17.05c	20.61b	23.84a	25.91a
	Second year	17.20c	19.38b	20.73b	24.43a
		NS	NS	*	*
PFS (%)	First year	18.01d	34.73c	50.32b	66.82a
	Second year	46.39c	66.36b	71.73b	91.67a
		*	*	*	*

Notes. Means in the same row and followed by different letters are significantly different at $p = .05$. For one fixed item, such as YD,
*indicates that means in the same column (the first year and second year) are significantly different at $p = .05$, and NS indicates means in the same column are not significantly different at $p = .05$.
YD, rice yield; PD, panicle density; SWP, seed weight per panicle; SP, spikelets per panicle; PFS, percentage of filled spikelets; KW, kernel weight.

year. For example, there was a marked increase ($p < .05$) of rice yield in the second year for CK by 125.58% to .97 t ha^{-1}, NF by 46.49% to 1.67 t ha^{-1}, SN by 23.08% to 2.72 t ha^{-1} and SF by 39.62% to 4.37 t ha^{-1} when compared with the first year.

Discussion

Soil salinity and sodicity after harvest

The soil salinity, pH and SAR in all the four treatments after harvest were decreased in the upper soil layers of 0–20 cm, especially in the 0–10 cm soil layer, in comparison with the lower soil layers (Figure 1). In addition, the decrease extent in soil $EC_{1:5}$ in the 0–20 cm in all the four treatments (65.7–75.4%) was larger than that in pH (1.1–3.0%) and $SAR_{1:5}$ (5.6–25.8%), indicating that the transaction trends from the saline–sodic soil to sodic soil in the surface soil layer. This is due probably to amelioration practices without direct chemical agents, such as Ca^{2+}, can be effective in decreasing salinity but may be limited in decreasing sodicity (Haq et al., 2001; Niazi et al., 2001; Qadir et al., 1998). The resulting circumstance of 0–20 cm soil conditions may be important for rice growth since the rice plant has characteristics that root system distributes mainly in the top 20 cm of soil (Yamaguchi & Tanaka, 1990) and of tolerance to high sodicity (Sharma, 1986).

Main effects of SA and FL

The results of present study show that overall effects of SA, FL were highly significant ($p < .001$) for all investigated parameters (Tables 2 and 3), indicating that the sand application and flushing during the sensitive stages are effective in improving the rice yield and yield components. These results are consistent with previous reports that sand application and flushing improved crop productivity in saline–sodic soils and sodic soils (Asch & Wopereis, 2001; Liu et al., 2010; Niazi et al., 2001; Nayak et al., 2008; Qadir et al., 1998, 2007b; Yu et al., 2010).

The mean squares of SA were all higher for investigated yield parameters than that of FL (Tables 1 and 2), suggesting that main effects of SA on rice yield and yield components is superior to that of FL, as partly evidenced by SN treatment with lower EC, pH, and SAR in the surface soil compared with NF in Figure 1. In a way, sand application can be a better choice of amelioration for such as saline–sodic soil with high sodicity and pH and low infiltration rate when compared with only flushing during the sensitive stages. This finding has important implications for selecting appropriate practices to improve rice production and economic performance in salt-affected fields.

Interactive effects of SA and FL

The interaction between SA and FL on panicle density was negative (Table 3), implying a significant antagonistic interaction between them on panicle density. This may be explained by several reasons: (1) When combining SA and FL, there exists a trade-off between increase and reduction in panicle density, resulting from the reductions in soil salinity and sodicity (Liu et al., 2010; Niazi et al., 2001; Qadir et al., 1998) and soil nutrient loss (Chen et al., 2013; Cho et al., 2008; Dodd et al., 2004), respectively. (2) Nutrients, such as N, are mainly absorbed at early middle growth stages of rice (Fageria, 2003; Yang et al., 2004), and in these stages rice tiller appearance and/or abortion can be affected by environmental conditions, such as N deficiency (Fageria, 2003, 2007). In our study, fertilizer application was mostly conducted during the early middle growth stages, mainly the vegetative growth stage, so it is possible that there were some nutrient losses from the rice root zones in its early middle growth stages. (3) SN treatment and NF treatment in the second year increased panicle density significantly compared with CK (Table 5), indicating that the net positive impact from sand application and flushing during the sensitive stages on panicle density. Since panicle density was determined during the vegetative growth stage, in which environmental conditions affect the final number of fertile rice panicles (Fageria, 2007), we may infer that net negative interaction between sand application and flushing during the sensitive stages on panicle density was probably partially owing to nutrient loss out of rice root zone, such as N. In other words, a probable disadvantage of combination of sand application practice and flushing during the sensitive stages practice is nutrient loss. Relatively, the interaction between SA and FL on panicle density in the first year was insignificant and negative (Tables 3 and 4). It seems possible that nutrient uptake of rice during panicle density formation stage in the first year was probably lower than that of the second year during the vegetative growth stage, which might be reflected by indirect evidence that panicle density (144.22 no. m^{-2}) in CK in the first year was significantly lower ($p < .05$) than that (180.00 no. m^{-2}) in CK in the second year (Table 5).

On the other hand, the interaction between SA and FL on seed weight per panicle in the second year was positive (Table 4), indicating a synergistic interaction between the two factors on seed weight per panicle. There could be several reasons for this result. (1) Since the interaction between SA and FL on panicle density was significantly negative, the rice plants may act to compensate and enhance the seed weight per panicle on their own (Siband et al., 1999; Zeng & Shannon, 2000). (2) Salinity and sodicity (alkalinity) stresses during the seed weight per panicle formation stage were probably lower than that of the panicle density formation stage (Asch & Wopereis, 2001; Chen et al., 2013; Yu et al., 2010). As rice is more sensitive to saline-alkaline stresses in its reproductive stages than that in vegetative stages (Rao et al., 2008; Zeng et al., 2001), it is also possible that direct saline-alkaline stresses rather than nutrients loss were the dominant constraints during the rice reproductive stage, and seed weight per panicle could be increased by the synergistic interactions of sand application and flushing during the reproductive stages, especially spikelets per panicle and kernel weight formation stages (Table 4), in relatively lower salinity and sodicity (alkalinity) stresses compared with that during the panicle density formation stage. Similarly in the second year, the interaction between SA and FL on seed weight per panicle in the first year was also positive but insignificant, indicating that SA and FL additively interacted during the seed weight per panicle formation stage.

Consequently, the interaction between SA and FL in the first year was found additive on rice yield on the basis of additive effects on panicle density and seed weight per panicle. In addition, their coupled interaction in the second year were synergistic on rice yield, probably resulting from their synergistic effect on seed weight per panicle rather than their antagonistic effect on panicle density. These results may imply that combined practices of sand application and flushing during the sensitive stages could be considered to cooperatively improve rice yield of paddy fields, such as newly converted from hard saline–sodic land. What's more, when selecting sand application and flushing during the sensitive stages in future to ameliorate such salt-affected soils as the hard saline–sodic soil in Songnen plain, nutrient loss should be also concerned in addition to salinity and sodicity (alkalinity) reduction in order to optimize the amelioration effectiveness and sustain the improvements. In addition, irrigation water use efficiency should be also incorporated and monitored (Chen et al., 2013) considering the projected increase of temperature and decrease of precipitation in the Songnen plain (Luan et al., 2007).

Effects of CK, NF, SN, and SF on rice yield parameter

This study provides an estimate of SA and FL on rice yield and yield components under the hard saline–sodic soil with initial soil $pH_{1:5} > 9.5$, $EC_{1:5} > 1$ mS/cm. Rice yield was found significantly increased in the order of CK < NF < SN < SF in both the first and second year (Table 5). Maximum yield was found in SF in a hard saline–sodic soil ($pH_{1:5} = 10.20$, $EC_{1:5} = 1.29$ mS/cm) in the second year with a level of 4.37 t/ha, which is probably reflected by lower salinity and sodicity (alkalinity) (Figure 1) and bigger LAI during the growth stages (Figure 2). More importantly, the rice yield was comparable to that of extensively applied amelioration methods (Table 6). These results demonstrate the potential for effectively matching combined SA and FL practices to significantly enhance the rice yields in such the hard saline–sodic soil while decreasing the sand usage by half.

Rice yield of each treatment in the second year was found remarkably higher than that of the first year (Table 5), which is in accordance with the study by Nayak et al. (2013). Further analysis showed that panicle density of all four treatments in the second year was significantly higher than that in the first year. The panicle density as the first forming yield component, it was increased in the second year even in CK, which was probably related to soil amelioration with time (Qadir & Sharma, 2005). Compared with panicle density, seed weight per panicle in CK in the second year was also significantly increased, being different from the three other treatments. For CK, it may be in line with the conclusion that when rice grain yield is low, this trade-off between panicle density and seed weight per panicle is not prominent, and it cannot stop the yield from increasing (Sui et al., 2013). When panicle density is further increased, the negative compensations between panicle density and seed weight per panicle (Zeng & Shannon, 2000) could take effect with soil amelioration during the crop growth stages in the second year, probably causing seed weight per panicle in three other treatments invariable (Sui et al., 2013). Consequently, the reason why rice yield of each treatment in the second year

Table 6. Reported rice yield in salt affected land ameliorated by different practices related to typical water management and amendments.

Region and planting regimes	Important saline-alkali properties of surface soil	Typical treatments	Reported rice yield during the experiment	Authors
Central Indo Gangetic plains,India; Rice–wheat rotation	pH_e:10.4; EC_e:14.3 mS/cm; SAR_e:83.3 $(mmol_c/L)^{1/2}$ 0–30 cm soil layer	50% GR after second flushing, and 50% GR after third flushing	About 4 t/ha in the first and second paddy season, respectively	Nayak et al., 2008
Central Indo-Gangetic plain，India；Rice–wheat rotation	pH_e:9.8; EC_e:1.9mS/cm; ESP:38.5%; Surface soil layer	50% GR, following vertical leaching	4.5 t/ha, 4.6t/ha and 4.7 t/ha in three paddy seasons, respectively	Nayak et al., 2013
Satghara, Pakistan; Rice–wheat rotation	pH_e:9.1; EC_e:9.4 mS/cm; SAR_e:58.7 $(mmol_c/L)^{1/2}$; 0–20 cm soil layer	100% GR in between the two flushings	2.65 t/ha in the first paddy season	Qadir et al., 1998
Haveli Karimdad, Pakistan; Rice–wheat rotation	pH_e: 8.95–9.36; EC_e:9.05–12.07 mS/cm; SAR_e:95–134.5 $(mmol_c/L)^{1/2}$;0–15 cm soil layer	100% GR,following horizontal flushing	1.62 t/ha, 4.02 t/ha in the first and second season, respectively	Zaka et al., 2008;
Songnen plain, China; Single rice cropping	$pH_{1:5}$:9.0; Salt content:4.5 g/kg; Surface soil layer	Only flushing using large amounts of freshwater	No output in the initial two years; 4.25 t/ha in the fourth year	Luo & Sun, 2004
Songnen plain, China; Single rice cropping	$pH_{1:5}$:9.1;Salt content:6.3 g/kg; 0–20 cm soil layer	7.5 cm thick sand application	5.25 t/ha in the third year	Yu et al., 2010;
Songnen plain, China; Single rice cropping	$pH_{1:5}$:10.44; $EC_{1:5}$:.47 mS/cm; $SAR_{1:5}$: 11.86 $(mmol_c/L)^{1/2}$; 0–20 cm soil layer	10 cm thick sand application	4.87 t/ha in the second year	Liu et al., 2010
Songnen plain, China; Single rice cropping	pH_e:10.8; EC_e:16.42 mS/cm; ESP:92.49%;Surface soil layer	Inorganic polymer soil amendment	4.66 t/ha in the first year	Luo et al., 2015

Notes. GR means gypsum requirement.

was found remarkably higher than that of the first year was due mainly to significant increases in panicle density as well as insignificant change or significant increase in seed weight per panicle compared with that of the first year percentage of filled spikelets as one of seed weight per panicle component also significantly increased in the second year (Table 5). Further studies should be focused on the whole optimization of the rice yield component formation and maximization of the multiplication of rice yield components by regulating flushing during the sensitive stages more precisely on the basis of sand application considering it is difficult to increase rice yield potential by improving a single morphological trait (Sui et al., 2013). Moreover, since the conclusions in this study were based on only 2 years of data-sets, further studies are needed to monitor the amelioration effectiveness and interactive effects of sand application and flushing during the sensitive stages with time.

Conclusion

Our results showed that SA and FL both significantly affected all investigated yield parameters across the two years or in a single year. What's more, the main effects of SA were all higher for the investigated yield parameters than that of FL. SA and FL cooperatively affected the yield due mainly to their positive interaction on seed weight per panicle. This study also showed that rice yield was significantly increased in the order of CK < NF < SN < SF in both years of experiments. Maximum rice yield was found in SF in a saline–sodic soil ($pH_{1:5}$ = 10.20, $EC_{1:5}$ = 1.29 mS/cm) in the second year with a level of 4.37 t/ha, increased 350.5% compared with the yield in CK. Furthermore, rice yield of each treatment in the second year was found remarkably higher than that of the first year, owing to significant increases in panicle density as well as insignificant change or significant increase in seed weight per panicle.

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