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

Mingming Wang,1,2,3 Fu Yang,1,2 Hongyuan Ma,1,2 Lixing Wei,2,3 Lihua Huang,1,2 Miao Liu,1,2 Haoyu Yang1,2, Jipeng Li1,2, Xiaowei Li3,4, Xiaolong Liu1,2, Chang-Jie Jiang4 and Zhengwei Liang1,2

1Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun, China; 2Da’an Sodic Land Experiment Station, Chinese Academy of Sciences, Da’an, China; 3Key Laboratory of Molisols Agroecology, Chinese Academy of Sciences, Harbin, China; 4Dongying Academy of Agricultural Sciences, Dongying, China; 5Ministry of Education Engineering Research Center of Bioreactor and Pharmaceutical Development, Jilin Agricultural University, Changchun, China; 6Disease Resistant Crop Research Unit, National Institute of Agrobiological Sciences, Tsukuba, Japan

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.

INTRODUCTION
Salt-affected soils are widespread in arid and semi-arid regions. It is estimated that about 955 × 10⁶ 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...
et al., 2007a, 2007b). As an effective practice 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, 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 × 10⁶ ha of salt-affected soils characterized mainly by NaHCO₃ and Na₂CO₃ 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 × 10⁶ 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 (pHₑ = 10.8, ECₑ = 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;
- SA: sand application;
Each plot was 87.5 m² (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 m³/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 Ca²⁺, Mg²⁺, K⁺, Na⁺, Cl⁻, CO₃⁻, HCO₃⁻, and SO₄²⁻ were 1.85, 1.30, .07, 5.63, 1.90, .00, 9.60, and .15 mmolc /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 P₂O₅/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⁺, Ca²⁺, and Mg²⁺ 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/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):

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

(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 $AB = 1/2 \times ($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
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).

**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 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 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$_{1:5}$=10.4; EC$_{1:5}$=14.3 mS/cm; SAR =83.3 (mmol/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 plains, India; Rice–wheat rotation | pH$_{1:5}$=9.8; EC$_{1:5}$=1.9 mS/cm; ESP=38.5%; Surface soil layer | 50% GR, following vertical leaching | 4.5 t/ha, 4.6 t/ha and 4.7 t/ha in three paddy seasons, respectively | Nayak et al., 2013 |
| Satghara, Pakistan; Rice–wheat rotation | pH$_{1:5}$=9.1; EC$_{1:5}$=9.4 mS/cm; SAR$_{1:5}$=58.7 (mmol/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$_{1:5}$=8.95–9.36; EC$_{1:5}$=9.05–12.07 mS/cm; SAR$_{1:5}$=95–134.2 (mmol/L)$^{1/2}$ 0–30 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/L)$^{1/2}$ 0–20 cm soil layer | 10 cm thick sand application | 4.87 t/ha | Liu et al., 2010 |
| Songnen plain, China; Single rice cropping | pH$_{1:5}$=10.8; EC$_{1:5}$=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 (pH1:5 = 10.20, EC1:5 = 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.

Funding

This study was supported by the Chinese Academy of Sciences [grant number KZCX2-XB2-13]; the National Natural Science Foundation of China [grant number 41101304], [grant number 31301233]; Key Laboratory of Molisols Agroecology, Chinese Academy of Sciences under Grant of the Open Research Fund; and the Natural Science Foundation of Jilin province [grant number 201201003]; the project grant from Chinese Academy of Sciences [grant number Y281001001]; Special Institute Project of Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences.

Acknowledgments

The authors thank the two anonymous reviewers for their kind and constructive advices.

References

Asch, F., & Wopereis, M. C. S. (2001). Responses of field-grown irrigated rice cultivars to varying levels of floodwater salinity in a semi-arid environment. Field Crops Research, 70, 127–137. http://dx.doi.org/10.1016/S0378-4290(01)00128-9.

Chen, Y. Q., Zhang, G. X., Xu, Y., & Huang, Z. G. (2013). Influence of irrigation water discharge frequency on soil salt removal and rice yield in a semi-arid and saline-sodic area. Water, 5, 578–592. http://dx.doi.org/10.3390/w50203578.

Chi, C. M., & Wang, Z. C. (2010). Characterizing Salt-affected soils of songnen plain using saturated paste and 1:5 soil-to-water extraction methods. Arid Land Research and Management, 24, 1–11. http://dx.doi.org/10.1080/15324980903439362.

Cho, J. Y., Son, J. G., Choi, J. K., Song, C. H., & Chung, B. Y. (2008). Surface and subsurface losses of N and P from salt-affected rice paddy fields of Saemangeum reclaimed land in South Korea. Paddy and Water Environment, 6, 211–219. http://dx.doi.org/10.1007/s10333-007-0082-x.

Dodd, K., Guppy, C. N., Lockwood, P. V., & Rochester, I. J. (2004, December). Comparison of applications of sand and polyacrylamide for separating the impact of the physical and chemical properties of sodic soils on the growth and nutrition of cotton (Gossypium hirsutum L.). Supersoil 2004: Proceedings of 3rd Australian New Zealand Soils Conference, Sydney.

Fageria, N. K. (2003). Plant tissue test for determination of optimum concentration and uptake of nitrogen at different growth stages in lowland rice. Communications in Soil Science and Plant Analysis, 34, 259–270. http://dx.doi.org/10.1081/CSS-120017430.

Fageria, N. K. (2007). Yield physiology of rice. Journal of Plant Nutrition, 30, 843–879. http://dx.doi.org/10.1080/15226510701374831.

Grattan, S. R., & Grieve, C. M. (1999). Salinity–mineral nutrient relations in horticultural crops. Scientia Horticulturae, 78, 127–157. http://dx.doi.org/10.1016/S0304-4238(98)00192-7.

Gregory, P. J., Ingram, J. S. I., Andersson, R., Betts, R. A., Brovkin, V., Chase, T. N., … Grace, P. R. (2002). Environmental consequences of alternative practices for intensifying crop production. Agriculture, Ecosystems & Environment, 88, 279–290. http://dx.doi.org/10.1016/S0167-8809(01)00263-8.

Haq, I. U., Habib, U. R., Niazi, B. H., & Saleem, M. (2001). Effect of horizontal flushing on the reclamation of sodic soils and yield of fodder crops after gypsum application. International Journal of Agricultural and Biological, 3, 323–325. Retrieved from http://www.ijab.org.

Kewat, M. L., Agrawal, S. B., Agrawal, K. K., & Sharma, R. S. (2002). Effect of divergent plant spacings and age of seedlings on yield and economics of hybrid rice (Oryza sativa). Indian Journal of Agronomy, 47, 367–371. Retrieved from www.indianjournals.com.

Li, Q. S., Liu, S. W., & Deng, W. (1999). 土壤水分和肥水对松嫩平原土壤盐碱化程度的研究. Indian Journal of Agronomy, 47, 367–371. Retrieved from www.indianjournals.com.

Liu, M., Liang, Z. W., Yang, F., Ma, H. Y., Huang, L. H., & Wang, M. M. (2010). Impacts of sand amendment on rice (oryza sativa L.) growth and yield in saline-sodic soils of North-East China. Journal of Food Agricultural and Environment, 8, 412–418. Retrieved from www.world-food.net.

Luan, Z. Q., Zhang, G. X., Deng, W., Hu, J. M., & Zhou, D. M. (2007). 50 years of changes in air temperature and precipitation for last 50 years in the songnen plain. Science Geographica Sinica, 18, 268–272. Retrieved from http://www.cnki.com.cn.

Liu, M., Liang, Z. W., Yang, F., Ma, H. Y., Huang, L. H., & Wang, M. M. (2010). Impacts of sand amendment on rice (oryza sativa L.) growth and yield in saline-sodic soils of North-East China. Journal of Food Agricultural and Environment, 8, 412–418. Retrieved from www.world-food.net.
Songnen Plain]. Chinese Journal of Agrometeorology, 28, 355–358. Retrieved from http://www.cnki.com.cn
Luo, J. Q., Wang, L. L., Li, Q. S., Zhang, Q. K., He, B. Y., Wang, Y., ... Qin, L.-P. (2015). Improvement of hard saline–sodic soils using polymeric aluminum ferric sulfate (PAFS). Soil and Tillage Research, 149, 12–20. http://dx.doi.org/10.1016/j.still.2014.12.014
Luo, J. Q., Wang, L. L., Li, Q. S., Zhang, Q. K., He, B. Y., Wang, Y., ... Qin, L.-P. (2015). Improvement of hard saline–sodic soils using polymeric aluminum ferric sulfate (PAFS). Soil and Tillage Research, 149, 12–20. http://dx.doi.org/10.1016/j.still.2014.12.014
Luo, J. Q., Wang, L. L., Li, Q. S., Zhang, Q. K., He, B. Y., Wang, Y., ... Qin, L.-P. (2015). Improvement of hard saline–sodic soils using polymeric aluminum ferric sulfate (PAFS). Soil and Tillage Research, 149, 12–20. http://dx.doi.org/10.1016/j.still.2014.12.014
Luo, J. Q., Wang, L. L., Li, Q. S., Zhang, Q. K., He, B. Y., Wang, Y., ... Qin, L.-P. (2015). Improvement of hard saline–sodic soils using polymeric aluminum ferric sulfate (PAFS). Soil and Tillage Research, 149, 12–20. http://dx.doi.org/10.1016/j.still.2014.12.014
Luo, J. Q., Wang, L. L., Li, Q. S., Zhang, Q. K., He, B. Y., Wang, Y., ... Qin, L.-P. (2015). Improvement of hard saline–sodic soils using polymeric aluminum ferric sulfate (PAFS). Soil and Tillage Research, 149, 12–20. http://dx.doi.org/10.1016/j.still.2014.12.014
Luo, J. Q., Wang, L. L., Li, Q. S., Zhang, Q. K., He, B. Y., Wang, Y., ... Qin, L.-P. (2015). Improvement of hard saline–sodic soils using polymeric aluminum ferric sulfate (PAFS). Soil and Tillage Research, 149, 12–20. http://dx.doi.org/10.1016/j.still.2014.12.014
Qadir, M., Schubert, S., Badia, D., Sharma, B. R., Qureshi, A. S., & Murtaza, G. (2007b). Amelioration and nutrient management strategies for sodic and alkali soils. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 21, 1–13. Retrieved from http://www.cababstractsplus.org/cabreviews
Qadir, M., Quillérou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R. J., ... Drechsel, P. (2014). Economics of salt-induced land degradation and restoration. Natural Resources Forum, 38, 282–295. Retrieved from http://inweh.unu.edu
Qiu, S. W., Zhang, B., & Wang, Z. C. (2003). 吉林省西部土地荒漠化现状、特征与治理途径研究 [Status features and management practices of land desertification in the west of Jilin province]. Science Geographica Sinica, 23, 188–192. Retrieved from http://www.cnki.com.cn
Rao, P. S., Mishra, B., Gupta, S. R., & Rathore, A. (2008). Reproductive stage tolerance to salinity and alkalinity stresses in rice genotypes. Plant Breeding, 127, 256–261. http://dx.doi.org/10.1111/j.1439-0523.2007.01455.x
Rengasamy, P., & Vadakattu, G. (2002, August). Rootzone soil constraints: an overview. 17th World Congress of Soil Science, Thailand.
Rengasamy, P., Chittleborough, D., & Helyar, K. (2003). Root-zone constraints and plant-based solutions for dryland salinity. Plant and Soil, 257, 249–260. Retrieved from http://www.springer.com
Shaaban, M., Abid, M., & Abou-Shanab, R. A. I. (2013). Amelioration of salt affected soils in rice paddy system by application of organic and inorganic amendments. Plant, Soil and Environment, 59, 227–233. Retrieved from http://www.agriculturejournals.cz
Shahi, H. N., Gill, P. S., Singh, N., Thind, I. S., & Maskina, M. S. (1977). Effect of seedling age at transplanting on rice in saline-sodic soils of NW India. Experimental Agriculture, 13, 169–175. Retrieved from http://journals.cambridge.org/
Shainberg, I., & Letey, J. (1984). Response of soils to sodic and saline conditions. Hilgardia, 52, 1–57. http://dx.doi.org/10.3733/hilg.v52n02p057
Sharma, S. K. (1986). Mechanism of tolerance in rice varieties differing in sodicity tolerance. Plant and Soil, 93, 141–145.
Siband, P., Wey, J., Oliver, R., Letourmy, P., & Manichon, H. (1999). Analysis of the yield of two groups of tropical maize cultivars. Varietal characteristics yield potentials, optimum densities. Agronomie, 19, 379–394. http://dx.doi.org/10.1051/agro:19990505
Song, C. C., Deng, W., Li, Q. S., Wang, Z. C., & Zhang, G. X. (2002). 松嫩平原西部土壤次生盐渍化防治技术研究 [Techniques of controlling secondary soil salinization in the west of songnen plain]. Science Geographica Sinica, 22, 610–614. Retrieved from http://www.cnki.com.cn
Sui, B., Feng, X. M., Tian, G. L., Hu, X. Y., Shen, Q. R., & Guo, S. W. (2013). Optimizing nitrogen supply increases rice yield and nitrogen use efficiency by regulating yield formation factors. Field Crops Research, 150, 99–107. http://dx.doi.org/10.1016/j.fcr.2013.06.012
Sumner, M. E. (1993). Sodic soils – New perspectives. Australian Journal of Soil Research, 31, 683–750. http://dx.doi.org/10.1071/SR9930683
United Nations. (2009). World population prospects: The 2008 revision population database. New York, NY: Earthscan.
Wang, M. M., Liang, Z. W., Yang, F., Ma, H. Y., Huang, L. H., & Liu, M. (2010a). Effect of sand application and flushing during the
sensitive stages on rice biomass allocation and yield in a saline sodic soil. *Journal of Food, Agriculture and Environment, 8*, 692–697. Retrieved from www.world-food.net

Wang, M. M., Liang, Z. W., Yang, F., Ma, H. Y., Huang, L. H., & Liu, M. (2010b). Effects of number of seedlings per hill on rice biomass partitioning and yield in a saline-sodic soil. *Journal of Food, Agriculture and Environment, 8*, 628–633. Retrieved from www.world-food.net

Wang, Z. C., Li, Q. S., Li, X. J., Song, C. C., & Zhang, G. J. (2003). Sustainable agriculture development in saline-alkali soil area of Songnen Plain, Northeast China. *Chinese Geographical Science, 13*, 171–174. http://dx.doi.org/10.1007/s11769-003-0012-9

Wong, V. N. L., Greene, R. S. B., Dalal, R. C., & Murphy, B. W. (2010). Soil carbon dynamics in saline and sodic soils: A review. *Soil Use and Management, 26*, 2–11. http://dx.doi.org/10.1111/j.1475-2743.2009.00251.x

Yamaguchi, J., & Tanaka, A. (1990). Quantitative observation on the root system of various crops growing in the field. *Soil Science and Plant Nutrition, 36*, 483–493. http://dx.doi.org/10.1080/00380768.1990.10416917

Zeng, L., & Shannon, M. C. (2000). Salinity effects on seedling growth and yield components of rice. *Crop Science, 40*, 996–1003. http://dx.doi.org/10.2135/cropsci2000.404996x

Wang, Z. C., Li, Q. S., Li, X. J., Song, C. C., & Zhang, G. J. (2003). Sustainable agriculture development in saline-alkali soil area of Songnen Plain, Northeast China. *Chinese Geographical Science, 13*, 171–174. http://dx.doi.org/10.1007/s11769-003-0012-9

Yu, J., Wang, Z., Meixner, F., Yang, F., Wu, H., & Chen, X. (2010). Biogeochemical characterizations and reclamation strategies of saline sodic soil in Northeastern China. *Clean - Soil, Air, Water, 38*, 1010–1016. http://dx.doi.org/10.1002/clen.201000276

Wong, V. N. L., Greene, R. S. B., Dalal, R. C., & Murphy, B. W. (2010). Soil carbon dynamics in saline and sodic soils: A review. *Soil Use and Management, 26*, 2–11. http://dx.doi.org/10.1111/j.1475-2743.2009.00251.x