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Extensive reclamation of saline-sodic soils with flue gas desulfurization gypsum on the Songnen Plain, Northeast China

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ABSTRACT

Previous studies have reported that flue gas desulfurization (FGD) gypsum can be used as an amendment for saline-alkali soils. However, little information is available regarding the effects of FGD gypsum on soil quality and crop production at large scales. Thus, we evaluated the changes in the soil salinity, sodicity, soluble ion levels, paddy rice (*Oryza sativa* L.) yield and heavy metal levels in soil and rice after reclamation with FGD gypsum and paddy planting over three years. Data (90 samples) were also collected from three neighbouring saline-sodic fields (1780 ha). As expected, soil salinity and sodicity decreased significantly after two years of reclamation. The levels of electrical conductivity (EC) and the sodium absorption ratio (SAR) decreased rapidly in the first year, and the pH and exchangeable sodium percentage (ESP) decreased substantially in the second year. Averaged across the experimental sites, the mean EC, pH, ESP and SAR levels of the soils two years after reclamation decreased by 38.6%, 14.6%, 61.2% and 87.8%, respectively, compared to those of the initial soils. In addition, the concentrations of water-soluble Na^+ and $CO_3^{2-} + HCO_3^-$ were 97.5% and 96.8% lower, respectively, two years after reclamation than the concentrations before reclamation. The paddy rice yield increased over time with reclamation; the mean level in the second year was 7.4 $t\,ha^{-1}$ or 80% of the yield harvested from the managed fields of neighbouring farmers. Moreover, the heavy metal (Cd, Cr, Hg, Pb and As) contents of both soils and rice were lower than the established standards and below detectable limits after FGD gypsum application. These results confirm that FGD gypsum is a safe and effective way to reclaim saline-sodic soils and worthy of widespread application on the Songnen Plain in Northeast China and in similar ecological areas.

!1. Introduction

As one of the three largest sodic saline-alkali soil distribution regions in the world, the Songnen Plain of Northeast China contains > 3.73 million ha of land estimated to be affected by sodicity (Wang et al., 2009). The parent materials, topographical features, climatic conditions and anthropogenic factors there contribute to the formation and evolution of the salinization of the soil (Liu et al., 2009; Wang et al., 2009). Furthermore, many salt lakes (e.g., Chagan Lake and Dabusu Lake) and wetlands are broadly distributed in this area (Liang et al., 2009), resulting in a low groundwater depth (1–3 m) and high levels of minerals in the water (i.e., concentrations of approximately 5 $g\,L^{-1}$), with $NaHCO_3$ being the main mineral compound (Shang et al., 2003). These factors have seriously restricted soil amelioration and utilization. In this area, approximately 20 thousand ha of land are newly salinized each year, and most of this land has been abandoned and cannot be used (Kang et al., 2013). As important reserve land resources for food production, saline-alkali lands should play a major role in ensuring national food security in the context of a global food crisis (Yang et al., 2010).

Due to substantial salinization and alkalization, the physical and chemical properties of the soil on the Songnen Plain have deteriorated. The typical characteristics of saline-sodic soil include the accumulation of excess Na^+, CO_3^{2-} and HCO_3^-, as well as a high pH, high sodium

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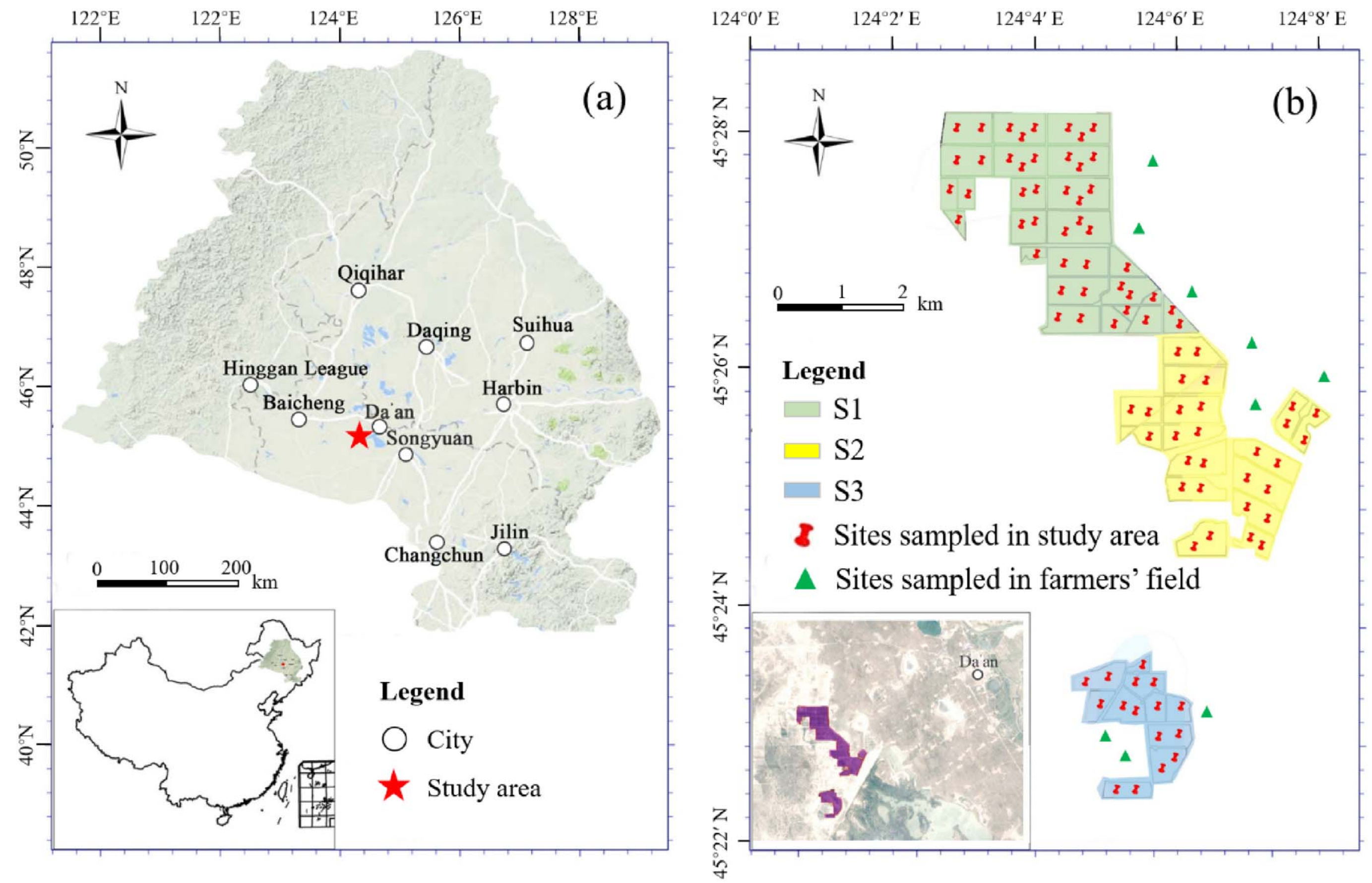

Fig. 1. Location of the Songnen Plain and the experimental area (a) and an illustration of the three experimental sites and the distribution of soil samples (b). S1: Xingye; S2: Jianshe; and S3: Dayushu.

absorption ratio (SAR) and high exchangeable sodium percentage (ESP) at the soil surface (Li et al., 2006; Qadir and Schubert, 2002). These factors cause destabilization of the soil structure, deterioration of soil hydraulic properties and imbalances in plant-available nutrients, resulting in poor vegetation coverage. Additionally, poor soil structure can lead to low water permeability (Chi and Wang, 2010; Wang et al., 2004). To resolve the salinity and sodicity problems that affect crop production, many techniques, including flood and drip irrigation, manure application, sand and gypsum amendments, and the planting of salt-tolerant crops, have been applied in this area (Li et al., 2003; Guo et al., 1998; Kang et al., 2013; Tang et al., 2012). However, only a few practices (e.g., gypsum application) are effective and still in use today.

The use of gypsum in agriculture was reported as early as the beginning of the 20th century (Hilgard, 1906; Kelley and Arany, 1928). The application of gypsum to saline-sodic soil causes an increase in exchangeable Ca^{2+} and a decrease in exchangeable Na^{+}, thereby improving the physical condition of the soil and increasing water infiltration (Poonia and Bhumbla, 1973). Furthermore, gypsum, as a source of Ca and Mg, improves plant growth (Clark et al., 2001). However, natural gypsum has rarely been used because of the high cost of exploitation, transportation, and crushing (Wang et al., 2017). Fortunately, a huge amount of flue gas desulfurization (FGD) gypsum is produced from the combustion of coal for electrical energy production. In China, for example, the production of FGD gypsum was 75.5 Mt in 2013 according to the China Electricity Council (Pan et al., 2015). FGD gypsum has the same main component ($CaSO_4 \cdot 2H_2O \geq 93\%$) as natural gypsum and a low heavy metal content (Chen et al., 2015; Mao et al., 2016); thus, it can be used as a substitute for natural gypsum to reclaim saline-alkali soils.

Presently, FGD gypsum is widely used as an amendment for saline-alkali soils throughout the world. To calculate the application rate of FGD gypsum, Chen et al. (2011) constructed a formula based on the molar amounts of Na_2CO_3, $NaHCO_3$, $Mg(HCO_3)_2$, and the exchangeable Na^{+} and Mg^{2+} per kilogram in saline-alkali soil. To facilitate the calculation of the application rate, Xiao et al. (2010) proposed a formula based on the cation exchange capacity (CEC), the ESP, the total alkalinity, the bulk density and the soil depth, as well as the use efficiency and the $CaSO_4$ content of FGD gypsum. In addition, Xiao et al. (2009, 2010) reported that FGD gypsum should be applied in the autumn to a depth of 60 cm for medlar (*Lycium barbarum* L.) production and should be combined with ploughing and rotary tillage. Nevertheless, to improve the effects of FGD gypsum application, some researchers combined it with other materials, such as humic acid, furfural residues, organic fertilizer and microbial agents (Shao et al., 2009; Wang et al., 2015; Nan et al., 2016).

The beneficial effects of FGD gypsum in improving the physical properties of sodic and non-sodic soils and in ameliorating subsoil acidity have been well documented (Chen et al., 2001; Sakai et al., 2012; Wang et al., 2017). However, most of the results are based on simulations or small trial experiments, and there is a lack of information regarding the application of FGD gypsum to large-scale fields. The treatment of barren saline-sodic soils with FGD gypsum would be of considerable benefit to both agricultural development and the improvement of local ecosystems. Based on the considerable potential of applying FGD gypsum to improve saline-sodic soils, a 3-year field study was performed on the Songnen Plain, Northeast China. The objective of this study was to evaluate the sustained effects of the application of FGD gypsum on the soil salinity, sodicity, soluble ions and paddy rice yield in a large-scale saline-sodic area.