Ecological Engineering 82 (2015) 566–570

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Flue gas desulfurization gypsum application for enhancing the desalination of reclaimed tidal lands

Xiaoping Li*, Yumei Mao, Xiaochen Liu

State Key Lab of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China

ARTICLE INFO

Article history:
Received 8 November 2014
Received in revised form 7 February 2015
Accepted 5 April 2015
Available online 15 June 2015

Keywords:
Flue gas desulfurization (FGD) gypsum
Sodic soils
Soil desalination

ABSTRACT

Soil desalination of estuary wetlands by the natural processes of rainfall leaching and plant community succession requires several decades for complete remediation. We hypothesize that flue gas desulfurization (FGD) gypsum can be used as a soil amendment to accelerate the desalination process via calcium ions (Ca^{2+}) replacing exchangeable sodium (Na^{+}) ions. Field experiments in reclaimed tidal lands in the Yangtze River delta were conducted with FGD gypsum applied at concentrations of 0, 15, 30, 45, and 60 Mg ha^{-1} during the period of 2011–2013. The total salt content of the topsoil (0–30 cm) was approximately 10 g/kg and the average rainfall at this site during the experimental period was 1000 mm. The dominant halophytes were *Phragmites australis* and *Spartina alterniflora*. After one year of FGD gypsum treatment, salt content of the topsoil represented as exchangeable sodium percentage (ESP) was reduced by up to 50%. Species richness and the coverage of herbaceous plants, other than *P. australis* and *S. alterniflora*, increased with increasing rates of FGD gypsum ($P < 0.05$). Halophytic herbs such as *Suaeda glauca*, *Herba taraxaci*, and *Artemisia lavandulaefolia* as well as the non-halophytic species *Medicago sativa* and *Alternanthera philoxeroides* were observed in the gypsum treated areas. In the plots treated with 45 and 60 Mg ha^{-1} of FGD gypsum, survival rates of woody plants were significantly higher than in the plots with lower treatment levels ($P < 0.05$). FGD gypsum increased the amount of Ca on the soil cation exchange sites which resulted in enhanced salt leaching efficiency, plant diversity, and succession. FGD gypsum is readily available and can be applied on a large scale to promote the rapid and effective remediation of the saline soil in reclaimed tidal lands.

1. Introduction

The urban areas of China are primarily located along the coast and in main delta areas such as the Yangtze River and Pearl River (McKinsey Global Institute, 2009). It has been estimated that the Yangtze delta plain advances into the East China Sea by approximately two kilometers per century due to sedimentary deposition of the Yangtze River (Van Slyke, 1988). Shanghai, the largest megacity at the mouth of the Yangtze River, reclaimed 520 km^2 of river delta land from the 1950s to 1990. Between 1990 and 2015, this reclamation activity has increased by a factor of six or seven. These tidal lands require desalination before complete restoration is accomplished.

Soil desalination of estuary wetlands by the natural processes of rainfall leaching and plant community succession requires several decades. Even for areas with plentiful rainfall like reclaimed tidal lands in the Yangtze delta, the desalination process takes at least 10 years (Yao and Ye, 1996). Therefore, efforts are being made to quicken the desalination process. Technologies such as irrigation leaching, phyto-desalination (Sakai et al., 2012), and subsurface pipe drainage systems (Li et al., 2012) have been developed and applied. However, the effectiveness of these technologies is often limited due to poorly draining soils. Reclamation success requires huge amounts of water to leach salt from the soil profile.

Gypsum has been used in agriculture for centuries to provide plant nutrients, improve soil physical and chemical properties, and increase crop productivity (Watts and Dick, 2014). Recently flue gas desulfurization (FGD) gypsum (calcium sulfate dihydrate, $CaSO_4 \cdot 2H_2O$) has become widely available. In 2010, approximately 52.3 million tons of FGD gypsum were produced. Only 69% of this total was used, and 80 million tons of stock have been generated by China in the last decade (http://www.cpnn.com.cn, March 5, 2010). FGD gypsum is produced as a byproduct of forced-oxidation wet scrubbers that are used to reduce sulfur emissions from coal-fired power plants. FGD gypsum has been widely used in building materials (such as wallboard, plaster coatings, and concrete), as an

* Corresponding author. Tel.: +86 21 62238913; fax: +86 21 62238913.
E-mail addresses: lixp_2008@hotmail.com, lixp@sklec.ecnu.edu.cn (X. Li).

http://dx.doi.org/10.1016/j.ecoleng.2015.04.010
0925-8574/

agricultural soil amendment, and in mining reclamation (Wolfe et al., 2009; Chen et al., 2009). FGD gypsum is currently being widely recycled because it is often purer than mined gypsum and recycled FGD gypsum has agricultural and environmental benefits (Watts and Dick, 2014; Mishra et al., 2012; Greenway et al., 2011).

Gypsum is 23% calcium and 19% sulfur in its pure form. After 2.5 cm of rainfall, gypsum reacts with rainwater and dissolves at a rate of 530 kg/ha (USDA, 2006). Thus, gypsum can provide a direct source of calcium ions (Ca^{2+}) to replace exchangeable sodium adsorbed on the soil complex. Applying FGD gypsum as a sodic soil amendment to improve crop yields has shown excellent results in some inland areas with low precipitation (Xu et al., 2011). We hypothesize that FGD gypsum can quicken the reclamation of saline delta soils in coastal areas where there is plentiful rainfall.

The purposes of this study are to evaluate the use of FGD gypsum for (1) reclamation of tidal lands with high salt content and (2) the improvement of herbaceous and woody plant growth on these reclaimed lands. The study also aims at (3) determining the rate and extent of remediation caused by an acceleration of the desalination process due to calcium ions (Ca^{2+}) replacing exchangeable sodium (Na^{+}). If FGD gypsum can be used for the rapid and effective remediation of saline soil in reclaimed tidal lands it will encourage more scrubbers and thereby provide air quality improvement.

2. Materials and methods

2.1. Description of site and materials

Chongming Island (31°37′06″N, 121°33′12″E) is located on the northern shore of the Yangtze River. The island was formed from alluvial silt material carried by the river to the delta. The study site is located at the east end of the island on 1 ha of reclaimed tidal land. The experimental period spans from October 2011 to the end of 2013. The annual average precipitation is 1000 mm, with approximately 950 mm in 2011 and 1005 mm in 2012. Rainfall in the first eight months of 2013 was only 457 mm. In August, there was a heat wave with a maximum of 40 °C and few rainfall events.

Soil samples at the experimental site were collected each month from the top 30 cm of soil. Selected soil physicochemical properties are shown in Table 1. The soil at the site can be characterized as sodic. The total salt content in the top 30 cm of soil had a mean concentration of 10 g/kg. The dominate halophytes were *Phragmites australis* and *Spartina alterniflora*.

An industrial source of FGD gypsum (as powder) was obtained from a coal-fired power plant located in Shanghai. Relevant properties of this material are shown in Table 1.

Table 1
Characteristics of the sodic soil and the FGD gypsum used in this study.

Parameter	Sodic soil	FGD gypsum
pH	9.1	ND[a]
Salt content (g/kg)	10.2	ND
Organic matter (%)	1.52	ND
Total N (mg/kg)	0.10	ND
Total P (mg/kg)	322	
Exchangeable cations (mg/kg)		
Ca	8.62	93400
Mg	5.92	0.04
K	ND	11.3
Na	912	70.2
Soluble anions (mg/kg)		
CO_3^{2-}	0	0
HCO_3^{-}	526	0.007
SO_4^{2-}	36. 4	125
Cl^{2-}	504	0.01
Trace elements (mg/kg)		
Ag	0.47[b]	0.47[b]
As	13.1	5.1
Cd	0.07	ND
Cu	37.8	11.5
Cr	86.3	0.47
Hg	0.08	0.20
Ni	50.4	15.0
Pb	22.1	14.7
Se	5[b]	5[b]

Soil quality standards for China (GB15618-1995) class II at pH > 7.5 are ≤20 for Ag, ≤0.6 for Cd, ≤250 for Cr, ≤100 for Cu, ≤1.0 for Hg, ≤60 for Ni and ≤350 for Pb.
[a] ND: not determined or not detected.
[b] The lower detection limit was 0.47 mg/kg for Ag and 5.0 mg/kg for Se.

2.2. Experimental design and measurement

The 1 ha research plot was established on the reclaimed tidal land in 2011, with 10 subplots separated by ditches that were 0.5 m deep. In the winter of 2011, five treatment levels of FGD gypsum (0, 15, 30, 45, and 60 Mg ha^{-1}) were applied along with composted plant litter (30 Mg ha^{-1}) to duplicate 1 × 1 m quadrats within each subplot. Woody and shrubby plants including *Ginkgo biloba*, *Taxodium ascendens*, *Sapium sebiferum*, and *Salix maizhokung garensi* (bamboo willow) were planted in each subplot in the spring of 2012 with a density of 1 individual per 2 m^2. Planting took place approximately six months after the application of the FGD gypsum treatments. A drainage system driven by a windmill was set up to pump out leached water from ditches after each rainfall event (Fig. 1).

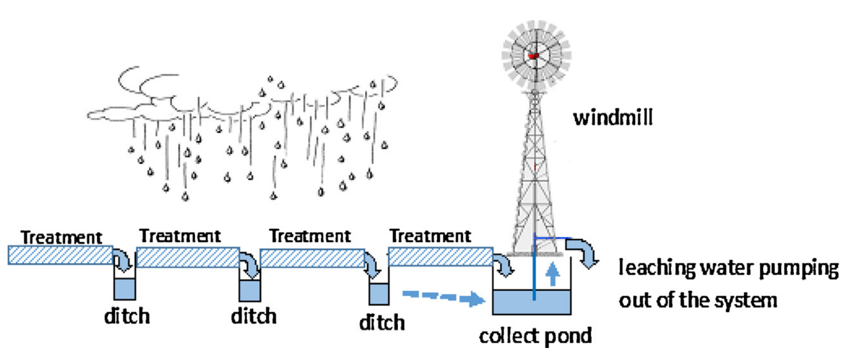

Fig. 1. Schematic diagram of experimental plot design. Each subplot is separated by a 0.5 m-depth ditch. Salty water, leached from the treatment plots after rainfall events, is collected via the drainage system driven by a windmill and pumped out of the experimental site.