JOURNAL OF ENVIRONMENTAL SCIENCES 45 (2016) 224–232

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JES JOURNAL OF ENVIRONMENTAL SCIENCES

www.jesc.ac.cn

Remediation of saline–sodic soil with flue gas desulfurization gypsum in a reclaimed tidal flat of southeast China

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ARTICLE INFO

Article history:
Received 9 November 2015
Revised 20 January 2016
Accepted 21 January 2016
Available online 13 February 2016

Keywords:
FGD-gypsum
Saline–sodic soil
Tidal flat
ESP
Composition of soluble salt

ABSTRACT

Salinization and sodicity are obstacles for vegetation reconstruction of coastal tidal flat soils. A study was conducted with flue gas desulfurization (FGD)-gypsum applied at rates of 0, 15, 30, 45 and 60 Mg/ha to remediate tidal flat soils of the Yangtze River estuary. Exchangeable sodium percentage (ESP), exchangeable sodium (Ex_{Na}), pH, soluble salt concentration, and composition of soluble salts were measured in 10 cm increments from the surface to 30 cm depth after 6 and 18 months. The results indicated that the effect of FGD-gypsum is greatest in the 0–10 cm mixing soil layer and 60 Mg/ha was the optimal rate that can reduce the ESP to below 6% and decrease soil pH to neutral (7.0). The improvement effect was reached after 6 months, and remained after 18 months. The composition of soluble salts was transformed from sodic salt ions mainly containing Na^+, HCO_3^- + CO_3^{2-} and Cl^- to neutral salt ions mainly containing Ca^{2+} and SO_4^{2-}. Non-halophyte plants were survived at 90%. The study demonstrates that the use of FGD-gypsum for remediating tidal flat soils is promising.

Introduction

Saline–sodic soils are an important land resource widely distributed on the earth. They occupy an area of 9.5×10^7 ha, accounting for almost 25% of total global area (Arunin, 1995). Unfavorable physical and chemical properties seriously impede plant growth and restrict their agricultural production (Malcolm and Sumner, 1998; Rengasamy, 2002). It is a challenge to improve saline–sodic soils for restoring vegetation, improving land ecosystems and developing agriculture. Many studies have focused on ameliorating saline–sodic soils by using techniques such as water conservancy measures, chemical measures, and physical measures (Barrett-Lennard, 2002; Yang and Wan, 2014). However, many of these methods need a long time to ameliorate soil. Furthermore, irrigation also requires abundant freshwater resources and easily washes away soil nutrients.

Mined gypsum is the most commonly used product to remediate sodic soils and for agricultural management of sodic soils in irrigated lands (Shainberg et al., 1989; Oster and Jayawardane, 1998). In recent years, flue gas desulfurization (FGD)-gypsum has become widely available and is also considered an effective ameliorant for saline–sodic soils because of its low cost and quick reaction compared with other reclamation practices (Yang and Wan, 2014). FGD-gypsum is a by-product produced during the process of removing sulfur from the flue gas of coal fired power plants (Laperche and Bigham, 2002). It has the same basic chemical composition as mined gypsum ($CaSO_4 \cdot 2H_2O$). Compared with mined gypsum, the purity of FGD-gypsum is higher

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http://dx.doi.org/10.1016/j.jes.2016.01.006

and its composition is more stable, its particle size is smaller and more uniform and its dissolution rate is much higher (USEPA, 2008; Amezketa et al., 2005). Many studies have shown that FGD-gypsum has great potential for saline–sodic soil remediation while it does not cause recontamination (Chen et al., 2014; Chun et al., 2001; Li et al., 2014; Wang et al., 2008; Watts and Dick, 2014). The principle is that gypsum is able to provide Ca^{2+} to replace exchangeable Na^+ on the colloid's cation exchange sites (Frenkel et al., 1989), which leads to improvements in soil chemical, physical and biological properties.

Most of the studies reported to date have focused on FGD-gypsum improving the soil of arid and semiarid areas (Amezketa et al., 2005; Lee et al., 2007; Li et al., 2012; Yu et al., 2014a, 2014b). However, only a limited amount of work has been done to evaluate the effects of FGD-gypsum in tidal flat soils. Compared with saline–sodic soils in dryland areas, coastal saline–sodic soils are characterized by higher soil salinity, groundwater salinity, and water table levels and lower natural desalinization rates because their formation is strongly affected by sea water and soil transpiration (Rengasamy, 2006). A relevant study has shown that FGD-gypsum could significantly change aggregation and hydraulic conductivity of tidal flat soil in the Yangtze River estuary (Cheng et al., 2014). So we hypothesize that amelioration with FGD-gypsum is an effective technology for remediation of saline–sodic soils in tidal flats.

Therefore, a field-scale demonstration study was conducted on a tidal flat soil in the Yangtze River estuary, China to evaluate the effects of different FGD-gypsum application rates on salinization and sodicity in tidal flat soil at different depths by measuring the changes in exchangeable Na^+, exchangeable sodium percentage (ESP), pH and the concentrations and composition of soluble salts, and to determine the optimal rate that could reduce the ESP to below 6%, decrease soil pH to neutral and transform the composition of soluble salts from sodic salt ions to neutral salt ions.

1. Materials and methods

1.1. Study site description

A field study was conducted on a reclaimed tidal flat soil (silt loam), located in Chongming Island (31°37′06″ N 121°33′12″E), near Shanghai, southeast China, where it lies against the north shore of the Yangtze River Delta. The region has a typical subtropical monsoon climate, and the annual average evaporation capacity (1346 mm) is higher than the annual average precipitation (1078 mm). In this area, Na^+ and Cl^- were the major ions in groundwater with average concentrations of 10.8 and 19.4 g/L, respectively (Han, 2013). The soil was characterized as saline–sodic soil (Richards, 1954), and the main soluble salt was NaCl followed by bicarbonate. Selected chemical properties of soil (0–30 cm) from the experimental site are presented in Table 1.

1.2. FGD-gypsum

FGD-gypsum was obtained from a coal-fired power plant in Shanghai with 74.7% $CaSO_4{\cdot}2H_2O$ and 25.3% moisture. Chemical components of FGD-gypsum were determined by the Center Testing International Corporation, Shanghai. Hg and As of FGD-gypsum were measured by atomic fluorescence spectrometry (AFS-830, Perkinelmer, USA) while other heavy metals were analyzed by inductively coupled plasma spectrum spectrometry (Optima8300, Perkinelmer, USA) after total acid digestion. The concentrations of major hazard pollution elements (As 5.1 mg/kg, Cr 0.47 mg/kg, Pb 14.7 mg/kg, Hg 0.20 mg/kg) were far below the secondary standard of environmental quality standard for soils (Administration, 1995) and control standards of pollutants in fly ash for agricultural use (Administration, 1987).

1.3. Experimental design and soil sampling

A field experiment was established in December 2011. The treatments included five FGD-gypsum rates: 0 (Control), 15, 30, 45 and 60 Mg/ha that were arranged in a randomized block design with four replicates. There were 20 plots in total, and each plot area was 10 × 10 m. FGD-gypsum was thoroughly mixed with the surface 10 cm depth of soil.

Six months and 18 months after FGD-gypsum application (Mid-July of 2012 and 2013), soil samples were collected from surface to 30 cm depth and sub-sampled at 10 cm intervals using an auger (5 cm inner diameter × 40 cm length) at each plot. Then soil samples were air-dried and crushed to pass through a 2-mm sieve. Soluble cations and anions were extracted at the rate of 1:5 (soil:water, W/W). Exchangeable cations were extracted with 1 mol/L NH_4OAc. The concentrations of soluble and exchangeable cations were measured using inductively coupled plasma atomic emission spectroscopy (IRIS Intrepid IIXSP, Thermofisher, USA). The concentrations of

Table 1 – Selected chemical properties of flue gas desulfurization gypsum (FGD)-gypsum and soil (0–30 cm) from experimental site at the initiation of experiment.

Sample	pH	ESP (%)	EC (ds/m)	Water-soluble anions (cmol/kg)			Water-soluble cations (cmol/kg)			
				SO_4^{2-}	$HCO_3^- + CO_3^{2-}$	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	K^+
Soil	8.62	32.8	4.03	0.07	0.86	1.42	0.41	0.49	2.87	0.23
FGD-gypsum	7.25	0.17	ND	25.5	0.11	0.39	46.6	3.29	0.31	0.04

ESP: exchangeable sodium percentage;
EC: electrical conductivity (soil:water, 1:1, W/W);
FGD: flue gas desulfurization;
ND: the value was not determined.