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Hierarchical Bayesian models for predicting soil salinity and sodicity characteristics in a coastal reclamation region

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ABSTRACT

Knowledge of soil saline-alkaline distributions and salt migration mechanism is important when developing strategies that reduce soil salinity, improve soil fertility, and enhance soil management in coastal reclamation regions. Soil saline-alkaline characteristics are indicated by the soil salt content (SSC) and sodium adsorption ratio (SAR). However, direct measurements of these parameters are typically expensive, labor intensive and time consuming. Data that is more easily obtained for a property and that may already exist, such as soil organic matter (SOM), may be used to predict SSC and SAR if SOM contents are closely related to soil sodicity and salinity. Data collected in a coastal reclamation area in Rudong County, Jiangsu Province, China, was used to generate regression equations for the relationships between SSC and SOM and between SAR and SOM based on hierarchical Bayesian methods. Results showed that SSC and SAR both decreased with increases in SOM. The deviance information criterion (DIC) indicated that a modified power function model and a log-quadratic model could best describe the two relationships, respectively. Therefore, predicting SSC could be achieved from the relationship between ln[SSC] and a quadratic function of ln[SOM], while SAR used the relationship between ln[SAR] and a quadratic function of SOM. This further suggests that increasing SOM may enhance reductions in soil salinity and sodicity, which would improve soil structure and fertility in the study region and probably at other coastal reclamation sites.

1. Introduction

Exploiting tidal flat resources has an important role in land management that is intended to reduce the gap between land resource supply and demand, thereby helping to ensure food security and to achieve sustainable development. However, coastal reclamation naturally involves the use of soil forming parent materials that have been exposed to highly saline sea water. Thus, high levels of soil salinity are inherited from the parent material even as soil formation begins. Consequently, the soils initially formed in the reclamation area are typically sullage-puddle soils with high salt levels and poor structures that are readily compacted under wet conditions (Agarwala et al., 1978; Marlet et al., 1998; He et al., 2015). The permeability coefficient and leaching efficiency of the compact soils is low, which increases runoff and leads to severe erosion of soils that are inherently highly erodible (She et al., 2014; Li et al., 2015). The high levels of salinity and alkalinity restrict the development and utilization of tideland resources. Construction of a system of drainage and irrigation channels has encountered maintenance problems due to the erosion of the channels, and especially of the steep banks (She et al., 2014; Liu et al., 2015). In order to more effectively address these practical problems, sufficient and accurate information about soil saline-alkaline distributions and salt migration mechanisms is crucial. Furthermore, this information would increase the understanding of soil quality and improvement in coastal reclamation areas.

Soil salt content (SSC), which affects soil structure and water quality properties as well as their various interactive processes and mechanisms, can be used as a representative index of soil salinity; e.g., Fang et al. (2005) used SSC distributions to suggest appropriate land management practices of saline soils. The sodium adsorption ratio (SAR) of the soil solution that, in association with the exchangeable sodium percentage of the soil cation exchange complex, also affects soil structure by determining the degree of clay dispersion as well as other physicochemical properties and is another indicator of soil salinity and alkalization (Suarez, 1981).

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Therefore, SSC and SAR are often used to evaluate saline-alkaline characteristics, and obtaining sufficient and accurate SSC and SAR data is important (Grattan and Grieve, 1999; Li et al., 2007; Jesus et al., 2015). The SSC can be defined by Eq. (1) and the sodium adsorption ratio (SAR) is defined by Eq. (2) (US Salinity Laboratory Staff, 1954):

$$SSC = C_{Ca} + C_{Mg} + C_{Na} + C_{K} + C_{HCO_3} + C_{CO_3} + C_{SO_4} + C_{Cl} \quad (1)$$

$$SAR = C_{Na}/[(C_{Ca} + C_{Mg})/2]^{0.5} \quad (2)$$

where C indicates the concentrations of the ions calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), hydrogen carbonate (HCO_3), carbonate (CO_3), sulfate (SO_4), and chloride (Cl), which are identified by the respective subscripts ($mmol_c L^{-1}$).

The parameters in Eqs. (1) and (2) imply that it is necessary to measure the various ionic contents in order to obtain values of SSC and SAR. Due to high degrees of spatial variation, measuring all of the ionic contents for a sufficient number of sites is a labor intensive and time consuming method. This suggests the need to use a simpler index or one that typically already exists by which to obtain SSC and SAR values indirectly. Some studies have suggested various ways for making these estimations. Li et al. (2007) used an artificial neural network model and a back propagation algorithm to predict SSC in the Inner Mongolian Hetao irrigated area under freeze-thaw conditions and considered ten influencing parameters. Suarez (1981) discussed the quantitative relationship between soil pH and SAR, and successfully predicted dynamic changes of SAR by taking in account the various environmental conditions to which the solutions were exposed. Hasheminejhad et al. (2013) used irrigation water quality to predict the resulting SAR of groundwater in seepage experiments. These and other studies, including our own preliminary studies, indicated that the main factors that determine SSC include the rainfall amount, mineralization in underground water, and temperature while the main factors that affect soil SAR are soil pH, groundwater quality and level, irrigation water quality and various soil hydraulic properties (Robbins, 1984; Suarez et al., 2008; Nuerbiya et al., 2012; Asadollahfardi et al., 2013).

Even so, these studies did not consider a simpler link involving an indicator property that could readily predict SSC and SAR. Rough estimates of the degree of soil salinity can be indicated by certain plant species (Lin and Bañuelos, 2015), but such indicator species are likely to be tolerant of a wide range of salinity levels and are not suitable as model inputs. A property that might be more suitable is the content of soil organic matter (SOM).

While the effects of soil salinity and sodicity on organic matter dynamics are relatively well known, less is known about how SOM influences soil salinity and sodicity. Mavi et al. (2012) has suggested that there was an intimate interaction between them. Soil structure can be improved by increasing SOM, which can enhance salt leaching thereby reducing salinity over time (Tzanakakis et al., 2011). Microbial activity can produce organic acids from SOM and these can ameliorate soil salinization and alkalization. In addition, the capacity of SOM to adsorb ions can enable it to act as a buffer and affect the proportions of salts in solution; dissolved organic matter (DOM) contains inorganic ions such as K^+, Ca^+, Na^+ and Mg^+ that influence the migration of soil metal ions by the processes of ion exchange, adsorption, complexation, and precipitation (Lin et al., 1993; Mavi et al., 2012). Hence, due to the interaction between SOM and SSC or salinity, as the reclamation time increases in a coastal reclamation area, the amount of salt removed by leaching increases, soil development improves and SOM gradually increases. Thus, desalinization and changes in SOM tend to have complicated causality.

Consequently, SOM can be used as a simpler index and/or as an index where data already exists by which to determine SSC and SAR. Chen et al., (1986) used a simple linear regression equation ($SSC = 0.418 - 0.148 \times SOM$; $R^2 = 0.79$) to estimate the SSC of a moderately saline soil in a coastal area from SOM data. In contrast, Xie and Li (1993) used a significant ($P < 0.05$) logarithm-linear relationship ($Ln(SSC) = -1.8 \times SOM7 + 0.103$; $F = 90.3$) to predict the SSC in the 0–20 cm soil layer from SOM data. Sumner and Naidu (1998) also presented a non-linear regression relationship between SOM and the SAR in the upper 0.05 m layer of a Red Brown Earth from South Australia. Hence it should be reasonable to use SOM to predict SSC and SAR.

Traditional multiple regression approaches have been applied to describe the variability of soil characteristics at many sites. Although these classical methods provide estimates of variables, they have some limitations (Majumdar et al., 2008). Often these techniques have been applied in situations where soil sampling was sparse, which presents difficulties when considering the randomness, which is an assumption of the regression analysis, and the high spatial heterogeneity of the data, thus resulting in greater uncertainty of the predicted values. The Bayesian statistical method, which was developed in the 1990s, has some advantages over regression. It retains the flexibility of handling dependencies of the spatial data and can directly reflect the uncertainty of models and parameters. It provides a reasonable framework structure for analyzing and forecasting complex and high-dimensional data. Using Bayes' theorem, posterior probability estimation can be obtained by the combination of data from collected samples and revised prior knowledge of posterior probability. This enables the involvement of aggregate and individual-level specification of parameters, which results in a more accurate prediction (Eisen-Hecht et al., 2004).

Although several studies have shown quantitative relationships between SOM and SSC or SAR, there appear to have been no studies that quantify their relationships in coastal reclamation areas. In these areas, widespread destruction of natural wetland vegetation has been caused by long-term human reclamation activities. In addition, frequent alternating soil desalination and re-salinization processes occur. Consequently, revegetation systems in coastal reclamation areas have often been established in a patchwork or mosaic pattern of land use established at different times (She et al., 2014). Hence, the distribution characteristics and dynamics of soil salinity and sodicity at a large scale (e.g., the coastal reclamation region scale) under diverse land uses become more complex, thereby giving rise to scale-dependent non-stationary patterns in soil salinity and sodicity. In this situation, the study of SSC and SAR along a temporal coastal reclamation transect can be important, especially when applied to soil desalination and melioration management practices during the reclamation of a coastal region. Therefore, the objective of this present study was to predict soil saline-alkaline characteristics in a coastal reclamation area. This was achieved by considering SOM as the input variable of a model that could estimate SSC and SAR based on a multilevel Bayesian statistical analysis. In addition, the deviance information criterion (DIC) was used to select the most reasonable model. The model was then used to investigate how SSC and SAR have changed with changes in SOM in the reclamation area. This study should provide a new approach to reducing soil salinity and sodicity, which would reduce soil erosion and improve the soil management in the region. The results of this study were also used to formulate a plan by which to construct similar Bayesian models for other site-specific locations.

2. Materials and methods

2.1. Study site description

The experiment was conducted in a coastal reclamation area in Rudong County, Jiangsu Province, China (32°12′–32°36′N latitude,