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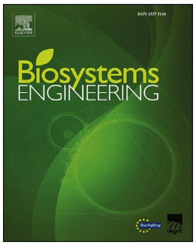

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Research Paper

Can subsurface soil salinity be predicted from surface spectral information? – From the perspective of structural equation modelling

Ya Liu [a], *Xianzhang Pan* [a,*], *Changkun Wang* [a], *Yanli Li* [a,b], *Rongjie Shi* [a,b]

[a] *State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, PR China*

[b] *University of Chinese Academy of Sciences, Beijing 100049, PR China*

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An efficient and reliable method for detecting soil salinity in deep saline soils using remote sensing is required to better manage soil salinization. In this study, a laboratory evaporation experiment was conducted to determine how subsurface soil salinity can be determined using soil surface spectra. Ten soil columns were observed, and measurements were taken at specific time intervals to monitor the variations in soil salinity and moisture content at depths of 5 cm and 15 cm relative to soil surface spectra during the evaporation process. The structural equation modelling (SEM) method was used to analyse the relationships between the spectral reflectance data and the salt content in the subsurface soil (15 cm). The results showed significant correlations (standard path coefficient = −0.37, t = −6.00) between the spectral reflectance of the soil surface and the subsurface soil salinity and between different types of multispectral data, such as the Landsat Thematic Mapper (TM) data, and the subsurface soil salinity. Overall, the results implied that surface soil spectral information can be used to capture some subsurface soil properties and that remote sensing images could provide an alternative method for monitoring changes in deeper soils.

1. Introduction

Remote sensing technology has been used widely for detecting soil salinity in recent years due to its wide spatial coverage, ability to update quickly, and low cost (Farifteh, Farshad, & George, 2006; Metternicht & Zinck, 2003; Shoshany, Goldshleger, & Chudnovsky, 2013). Several methods have been used to predict soil salinity with different degrees of success. These main methods are summarized as follows: 1) using soil salinity indices derived from single bands, band

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* *Corresponding author*. No. 71 East Beijing Road, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, PR China. Tel.: +86 25 86881271; fax: +86 25 86881000.

E-mail address: panxz@issas.ac.cn (X. Pan).

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ratios and other combinations (Allbed, Kumar, & Aldakheel, 2014; Bannari et al., 2007; Fernández-Buces, Siebe, Cram, & Palacio, 2006; Shoshany et al., 2013; Zhang et al., 2011); 2) using indirect indicators associated with plant reflectance (Fernández-Buces et al., 2006; Guerschman et al., 2009; Zhang et al., 2011); and 3) establishing soil salinity estimation models using the values of all bands and multivariate regression methods (Farifteh, Van der Meer, Atzberger, & Carranza, 2007; Liu, Pan, Wang, Li, & Shi, 2015; Nawar, Buddenbaum, Hill, & Kozak, 2014).

Most of these methods are only valid for the topsoil; however, because salinization results from the mobilization and accumulation of salts stored in deeper layers, acquiring soil salinity data from deeper soil layers is more important for agricultural management. Approaches for predicting subsurface soil salinity can be divided into the following three groups.

The first group contains proximal soil sensing methods, such as ground-penetrating radar (GPR) and frequency domain electromagnetic induction (FDEM), which are methods used for detecting subsoil salinity that were proposed within the last two decades (Goldshleger, Ben-Dor, Lugassi, & Eshel, 2010). Because the vertical and horizontal penetration depths of EM38 reach up to 0.75 and 1.5 m, respectively (Corwin & Lesch, 2003), the subsoil salinity was mapped using the apparent electrical conductivity (EC_a) measured by EM38 (Li, Shi, Webster, & Triantafilis, 2013; Li, Yang, Liu, Liu, & Yu, 2012; Sudduth, Myers, Kitchen, & Drummond, 2013). Recently, some researchers have applied EM inversion algorithms to map subsoil salinity (Guo, Huang, Shi, & Li, 2015; Huang, Mokhtari, Cohen, Monteiro Santos, & Triantafilis, 2015; Huang, Taghizadeh-Mehrjardi, Minasny, & Triantafilis, 2015; Zare, Huang, Santos, & Triantafilis, 2015). Ben-Dor et al. (2008) combined GPR and FDEM data from the ground with reflectance spectroscopy data to generate soil-salinity profile maps of saline-affected plots. However, these methods are limited with respect to their ability to obtain measurements from large areas, which can be solved by using remote sensing. Thus, the possibility of using remote sensing to monitor regional subsurface soil salinity should be considered.

The second type of method includes remote sensing methods, which use indicators that link surface spectral properties and subsurface soil salinity. Several important subsurface and subsoil properties have been successfully mapped using remote sensing data. Lagacherie et al. (2013) mapped soil properties at four depth intervals (15–30 cm, 30–60 cm, 60–100 cm and 30–100 cm) by combining modern remote sensing techniques with historic soil databases. Shi, Aspandiar, and Oldmeadow (2014) characterized acid sulphate soil (0–100 cm depth) using hyperspectral data, and Liu et al. (2013) used remote sensing data and spectral indices to estimate and simulate the three-dimensional (0–100 cm depth) spatial distribution of soil salinity. Taghizadeh-Mehrjardi, Minasny, Sarmadian, and Malone (2014) combined regression tree analysis and equal-area smoothing splines to predict subsurface soil salinity at three depth intervals (0–15, 15–30 and 30–60 cm). Many studies only established quantitative models between surface spectra and subsurface soil salinity; however, some studies have explored why a quantitative relationship exists between surface spectral reflectance and soil salinity in subsurface layers because soil spectra was not able to penetrate the deeper soil. Thus, it is unclear why surface soil spectra can be used to predict soil salinity in the subsurface. The following difficulties are encountered when using surface soil spectra to predict subsurface soil salinity: first, it is difficult to determine representative bands or indices, and second, normal multivariate analytical methods cannot be used to analyse the large number of dependent variables that simultaneously affect the dynamics of salt and water interactions. Therefore, we introduce a new method for analysing these sophisticated relationships.

When analysing visible and near-infrared spectral reflectance data (vis–NIR) and two of the most important soil properties (i.e., the salt and moisture content at different depths), multivariate statistical tools such as multivariate regression analysis are usually limited by the number of dependent variables (one, in normal). To overcome this limitation, structural equation modelling (SEM) was used for data analysis because it is a powerful tool that can be used to consider many dependent and independent variables simultaneously.

To explore the relationships between surface spectral data and subsurface soil salinity, we used SEM to analyse vis–NIR hyperspectral data and investigated the potential use of multispectral data, such as Landsat Thematic Mapper (TM) data, for mapping subsurface soil properties. The three objectives of this study, in which SEM was applied to data collected from soil columns in the laboratory, are as follows: (i) verify whether subsurface soil salinity can be predicted from spectral surface reflectance; (ii) determine the reasons why subsurface soil salinity can be predicted using surface spectra; and (iii) generalize the wide application of subsurface soil salinity predictions at a large scale by using resampling spectra according to Landsat TM bands.

2. Materials and methods

2.1. Laboratory experiment design

Many soil properties (e.g., pH) may affect soil spectra. However, because it is difficult to control multiple variables at once, we considered the soil moisture and salinity as the two most important variables in a dynamic soil and water system. Consequently, we designed a controlled laboratory experiment to remove the effects of the variations of other soil properties.

A controlled indoor laboratory experiment was set up to study the relationships between salt content at various soil depths and the spectral reflectance of the surface soil under simulated evaporation conditions. To test the robustness of our method, two base soils were collected from a typical coastal plain in Dafeng County, Jiangsu Province, China. Both soils were classified as Aquents with silt loam texture according to U.S. Soil Taxonomy (USDA). The soils originated from similar parent materials but had slightly different soil characteristics. The properties of the two base soils are shown in Table 1.

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