BIOSYSTEMS ENGINEERING XXX (2016) 1–10

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Predicting total dissolved salts and soluble ion concentrations in agricultural soils using portable visible near-infrared and mid-infrared spectrometers

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ARTICLE INFO

Article history:
Received 4 December 2015
Received in revised form
27 March 2016
Accepted 26 April 2016
Published online xxx

Keywords:
Arid region
Soil salinization
Visible-near infrared spectroscopy
Mid-infrared spectroscopy
Partial least-square regression
Support vector machine

Soil salinization is the primary obstacle to sustainable agricultural development in arid regions. Because total dissolved salts and soluble ion content are the primary indicators of the degree of soil salinization, their accurate estimation is essential to the determination of appropriate soil salinization remediation techniques, irrigation regimes, and the agricultural distribution layout. A total of 261 soil samples were collected from agricultural fields in the province of Xinjiang, China. A portable Fourier transform (FT) mid-infrared (MIR) spectrometer (4000–600 cm^{-1}) and a visible near-infrared (VNIR) field spectrometer (350–2500 nm) were used to obtain soil spectra. We subsequently used partial least-square regression (PLSR) and support vector machine (SVM) algorithms to establish models in VNIR, MIR, and VNIR–MIR regions. The main objectives of this study are (i) to investigate the possibility of using spectroscopic techniques to predict total dissolved salts and soluble ion content; (ii) to compare the prediction accuracy of these soil properties in the VNIR, MIR, and VNIR–MIR spectral regions; (3) to compare the prediction accuracy with linear and nonlinear algorithms. Our findings demonstrated that spectroscopic techniques are a promising way to predict total dissolved salts and soluble ion content. Good predictions were obtained for total dissolved salts content, HCO_3^-, SO_4^{2-} and Ca^{2+}, satisfactory for Mg^{2+}, Cl^-, and Na^+, but poor for K^+. This work demonstrates the potential of portable VNIR and MIR spectrometers as proximal soil sensors for more efficient soil analysis and acquisition of soil salinity information.

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http://dx.doi.org/10.1016/j.biosystemseng.2016.04.015

1. Introduction

Soil salinization is one of the main causes of soil degradation in arid and semiarid areas (Farifteh, Farshad, & George, 2006); it leads to declines in soil fertility and soil productivity, and intensifies soil desertification. Negative implications of this include decreased production and quality of agricultural products, and risks to the stability of the environmental balance of arid and semiarid regions (Ammari et al., 2013; Rozema & Flowers, 2008; Schoups et al., 2005; Zhang et al., 2015). On a global scale, areas experiencing soil salinization represent 23% of global agricultural soil (about 1.5×10^9 ha) and 10% of the global available land (Massoud, 1981). In some countries with relatively developed irrigation systems, the proportion of the areas experiencing soil salinization are very high; these countries include Iraq (50%), Egypt (30%), Pakistan (28%), India (27%), Australia (20%), China (15%), and Israel (13%) (Stockle, 2007). As the global population continues to rise rapidly, an increasing number of wastelands may be reclaimed or transferred into arable lands, which would require irrigation to improve productivity, which in turn intensifies soil salinization and increases the potential risks to productivity and fertility (Metternicht & Zink, 2003). Therefore, the development of methods for the effective monitoring of soil salinization is a very urgent task.

Soluble ion content and the characteristics of various base ions are the primary indicators of the level and type of soil salinization, respectively; these indexes are always used as references for the development of soil amelioration strategies, and economical irrigation regimes. Though traditional laboratory analysis of soil salt has many advantages, such as high precision and reliability, it is also time-consuming, labour-intensive, and environmentally damaging, especially for large soil samples (Forouzangohar et al., 2009). There is an urgent need to develop new methods and technologies that would be rapid, inexpensive, and efficient substitutes for traditional methods.

Electromagnetic induction (EMI) is generally considered an effective method for *in situ*, quantitative analysis of soil salinization. However, it is also time-consuming and labour-intensive, and it can only provide point-based measurements (Dehaan & Taylor, 2002; Li, Shi, Webster, & Triantafilis, 2013). Additionally, EMI can only obtain data on the soil's salt content, which can be used to evaluate the level of salinization, while soluble ion content cannot be obtained. Therefore, identification of the type of soil salinization, which is crucial to determine the rational distribution of crops and to guide soil amelioration strategies, cannot be made. Remote sensing might therefore be a more suitable method than EMI for monitoring soil salinization (Farifteh, Meer, Atzberger, & Carranza, 2007); this technology has already been applied for monitoring and mapping of soil salinization (Abbas, Khan, Hussain, Hanjra, & Akbar, 2013; Allbed, Kumar, & Aldakheel, 2014; Ben-Dor, Patkin, Banin, & Karnieli, 2002). Though remote sensing has the ability to predict serious salinization, it cannot be used to diagnose moderate and mild soil concentrations (Farifteh et al., 2006). Additionally, broadband images lose some important fine spectral characteristics as a result of limitations of the spatial and spectral resolutions and sampling bandwidths of satellites (Cloutis, 1996). Remote sensing technologies are restricted with respect to monitoring soil salinization, for example, (1) the boundary between different levels of soil salinization is not very clear; (2) soil salinization cannot easily be detected until it reaches a level at which it seriously affects productivity; (3) optical remote sensing cannot identify salinization below the soil surface, which is a problem because salinization can occur throughout the soil profile (Farifteh, Meer, Meijde, & Atzberger, 2008). Another obstacle to the measurement of soil salinization is that some trace salt ion elements are always fixed in the crystals, thus, it is difficult to discover pure soil salt (Hunt & Salisbury, 1970, 1971, Hunt, Salisbury, & Lenhoff, 1972).

Diffuse reflectance spectrometry is a promising tool for measuring land surface characteristics. It has high resolution and approximately continuous wavebands, and contains some subtle absorbance and reflectance features. It has attracted significant attention in recent years as a potential method to replace traditional laboratory methods for the analysis of soil properties. Over the last few decades, substantial efforts have been made in the exploration of new models for the prediction of soil properties with visible near-infrared (VNIR) and mid-infrared (MIR) spectroscopy (Viscarra Rossel & Behrens, 2010; Knox et al., 2015). These studies have provided reasonable evidence of the capacity of VNIR and MIR to rapidly, precisely, and non-destructively obtain soil property estimates. Early studies investigating hyperspectral reflectance spectroscopy for soil salinity mainly focused on qualitative evaluations (Shi, Huang, & Li, 2003, 2006), though Aldabaa, Weindorf, Chakraborty, Sharma, and Li (2015) quantitatively measured electrical conductivity (EC) of soil samples with a portable VNIR spectroradiometer. Limited work has been done to predict soil dissolved salt and soluble ion content with VNIR and/or MIR through different models or data mining methods, especially for agricultural areas with relatively low soil salt content.

The aims of this study are: (1) to identify the feasibility of spectroscopic technology to evaluate the soil dissolved salt and soluble ion content, and to investigate the types of soluble ion that can be estimated with this technology; (2) to compare the prediction accuracies of soil dissolved salt and soluble ion content through VNIR and/or MIR; (3) to compare the performance of the two models: the linear model (Partial Least Square Regression, PLSR) and the non-linear model (Support Vector Machine, SVM) with respect to their predictive abilities for soil dissolved salt and various soluble soil ions.

2. Materials and methods

2.1. *Site description*

The province of Xinjiang is located in the extreme northwest part of China and is divided into two geographic areas: northern and southern Xinjiang. Samples were collected from four regions in southern Xinjiang: Wensu, Awat and Toksu counties in the Aksu Prefecture, and Hotan County in Hotan Prefecture. Aksu (78°03′–84°07′E; 39°30′–42°41′N) is located in the centre of

Please cite this article in press as: Peng, J., et al., Predicting total dissolved salts and soluble ion concentrations in agricultural soils using portable visible near-infrared and mid-infrared spectrometers, *Biosystems Engineering* (2016), http://dx.doi.org/10.1016/j.biosystemseng.2016.04.015