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Sensor data fusion for soil health assessment

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ABSTRACT

Assessment of soil health involves determining how well a soil is performing its biological, chemical, and physical functions relative to its inherent potential. Due to high cost, labor requirements, and soil disturbance, traditional laboratory analyses cannot provide high resolution soil health data. Therefore, sensor-based approaches are important to facilitate cost-effective, site-specific management for soil health. In the Central Claypan Region of Missouri, USA, visible and near-infrared (VNIR) diffuse reflectance spectroscopy has successfully been used to estimate biological components of soil health as well as Soil Management Assessment Framework (SMAF) scores. In contrast, estimation models for important chemical and physical aspects of soil health have been less successful with VNIR spectroscopy. The primary objective of this study was to apply a sensor fusion approach to estimate soil health indicators and SMAF scores using VNIR spectroscopy in conjunction with soil apparent electrical conductivity (EC_a), and penetration resistance measured by cone penetrometer (i.e., cone index, CI). Soil samples were collected from two depths (0–5 and 5–15 cm) at 108 locations within a 10-ha research site encompassing different cropping systems and landscape positions. Soil health measurements and VNIR spectral data were obtained in the laboratory, while CI and EC_a data were obtained in situ. Calibration models were developed with partial least squares (PLS) regression and model performance was evaluated using coefficient of determination (R^2) and root mean square error (RMSE). Models integrating EC_a and CI with VNIR reflectance data improved estimates of the overall SMAF score (R^2 = 0.78, RMSE = 7.21%) relative to VNIR alone (R^2 = 0.69, RMSE = 8.41%), reducing RMSE by 14%. Improved models were also achieved for estimates of the individual chemical, biological, and physical soil health scores, demonstrating reductions in RMSE of 2.8, 5.4, and 10.0%, respectively. The results of this study illustrate the potential for rapid quantification of soil health by fusing VNIR sensor data with auxiliary data obtained from complementary sensors.

1. Introduction

Soil health represents the nexus of multiple ecosystem services provided by soil. A modern and widely accepted definition of soil health is “the capacity of soil to function as a living system, with ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots; recycle essential plant nutrients; improve soil structure with positive repercussions for soil water and nutrient holding capacity, and ultimately improve crop production” (FAO, 2008). In an effort to capture the broad categories of soil function, assessment and quantification of soil health requires measurement of multiple chemical, physical, and biological soil properties, referred to as soil health indicators (Karlen et al., 1997; Moebius-Clune et al., 2016). Measurement of these indicators often involves costly and labor-intensive laboratory analyses, which prohibits the production of spatially dense, field-scale information. In contrast, on-the-go sensor technology has the potential to provide high-resolution spatial data quickly at low cost (Hummel et al., 1996). Soil sensors have been widely used to estimate individual soil properties, and sensor fusion, as described by Adamchuk et al. (2011), has been applied to improve estimates of multiple soil attributes (e.g., Wetterlind et al., 2015). Although the ability to reliably estimate soil health indicators in the field has clear benefits for sustainable agricultural management and

Abbreviations: EC_a, apparent electrical conductivity; CI, cone index; VNIR, visible, near-infrared; SMAF, Soil Management Assessment Framework

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environmental protection, no single sensor has demonstrated the ability to estimate across the wide range of soil properties represented by soil health. Therefore, soil health assessment represents an ideal opportunity for the application of sensor fusion technology.

Visible, near-infrared diffuse reflectance (VNIR) spectroscopy has been used to successfully estimate several biological soil health indicators, including soil organic C, total N, β-glucosidase activity, active C, microbial biomass-C, and soil respiration (Chaudhary et al., 2012; Kinoshita et al., 2012; Sudduth and Hummel, 1991; Sudduth et al., 2012). Estimation of physical and chemical soil health indicators using VNIR spectra has been less consistent, although studies have demonstrated success with soil texture, aggregate stability, pH, and nutrients (Bogrekci and Lee, 2005; Chang et al., 2001; Hu, 2013; Vågen et al., 2006). To augment VNIR spectra for improved estimation of the physical and chemical components of soil health, simple laboratory measurements have been combined with VNIR spectra (e.g., Veum et al., 2015b). However, in-field sensors may be able to substitute for expensive and time-consuming laboratory analyses. For example, in-field soil strength (Hemmat and Adamchuk, 2008), electrical conductivity (Corwin and Lesch, 2005; Sudduth et al., 2013), or pH (Staggenborg et al., 2007) sensors could be used to supplement VNIR sensors for this purpose. Soil strength as cone index (CI) is commonly measured by cone penetrometer (ASAE, 2005). The CI is defined as the force per unit base area required to push the penetrometer through a specified increment of soil and reflects soil compaction, soil bulk density, texture, and moisture (ASAE, 2005; Chung et al., 2006). In addition, apparent electrical conductivity (EC_a) reflects numerous soil physical and chemical attributes such as texture, mineralogy, CEC, and moisture (McNeill, 1992; Sudduth et al., 2013).

Multiple soil attributes contribute to soil function, and a soil health index provides a way to monitor changes as a result of land management over time. The Soil Management Assessment Framework (SMAF) was developed to integrate multiple soil health indicators into a comprehensive, continuous (i.e., non-categorical) index to assess the impact of soil management practices on soil functions, such as ecosystem services, crop production, and environmental protection. The SMAF has been applied to soil health assessments in many countries, including the United States, India, China, Spain, and Ethiopia, (e.g., Cherubin et al., 2016; Gelaw et al., 2015; Ozgoz et al., 2013) and at multiple scales, including regional (Andrews et al., 2004), watershed (Karlen et al., 2008; Stott et al., 2011), and field (Stott et al., 2013; Veum et al., 2014). Currently, the SMAF integrates up to 13 indicators representing soil biological, physical, and chemical functions (Andrews et al., 2004; Stott et al., 2010). Biological soil health indicators in the SMAF include soil organic C, potentially mineralizable N, and β-glucosidase activity. Soil organic C is a keystone soil health indicator that mediates multiple soil functions (Doran and Parkin, 1996). Mineralizable N represents the fraction of N easily mineralized by soil microorganisms to support early vegetative growth (Drinkwater et al., 1996) and β-glucosidase activity reflects the ability of soil microorganisms to break down plant residues and recycle nutrients (Stott et al., 2010). Physical indicators, such as bulk density and macroaggregate stability, reflect multiple soil functions such as infiltration capacity and resistance to erosion (Angers, 1992; Franzluebbers, 1999; Logsdon and Karlen, 2004). Important chemical attributes associated with soil fertility and nutrient availability include soil pH, electrical conductivity, and extractable P and K (Smith and Doran, 1996; Wienhold et al., 2009).

Few studies have attempted the simultaneous estimation of a broad range of biological, physical, and chemical soil properties using VNIR for the purpose of soil health assessment. Vågen et al. (2006) estimated a three-category soil fertility index based on 10 indicators in Madagascar, Cohen et al. (2006) classified three levels of ecological soil degradation using 17 indicators in Georgia, USA, and Kinoshita et al. (2012) estimated a three-category soil quality index in Western Kenya. In addition, Veum et al. (2015b) estimated SMAF soil health indicators and scores using VNIR spectra and auxiliary laboratory data. They found that VNIR worked well for estimation of the biological components of the SMAF and performed poorly for estimation of chemical or physical SMAF scores. However, augmenting VNIR data with auxiliary laboratory data, including measured pH and bulk density, improved SMAF estimation models. This suggested that data from complementary sensors may overcome the limitations of VNIR spectra in soil health assessment by improving estimation of the physical and chemical components of soil health that are not captured well by VNIR spectra alone.

Fig. 1. Location of the Salt River Basin in Missouri, USA.

The Salt River Basin in northeastern Missouri, USA (Fig. 1) is a watershed that drains 6417 km^2 and includes Mark Twain Lake, a drinking water supply reservoir serving 42,000 people. The basin is part of the Central Mississippi River Basin (CMRB) Long-Term Agroecosystem Research (LTAR) network operated by USDA-ARS, and is located in the heart of the Central Claypan Region, designated as Major Land Resource Area 113 (USDA-NRCS, 2006). In this region, subsurface soil horizons with 45 to 65% clay (Bray, 1935) reduce water infiltration (Jung et al., 2007) and impede root growth (Myers et al., 2007). Due to the sensitivity of this ecosystem, monitoring and assessment of soil health is critical both at the field and sub-field level, and development of rapid, low-cost methods using in-field sensors to facilitate soil health assessment is a USDA priority. Therefore, the objectives of this study were to evaluate a sensor data fusion approach on claypan soils using VNIR spectra in conjunction with EC_a and CI sensor data to estimate (1) multiple biological, physical, and chemical soil health indicators, and (2) SMAF soil health scores.

2. Materials and methods

2.1. Study site

The study was conducted on a 10-ha site near Centralia, Missouri, USA (39°13 N, 92°07 W). The experimental design was a randomized complete block with three blocks (i.e., replications) where management was the main plot and landscape position was the split plot (Fig. 3). Twelve management systems are represented at the site. Annual cropping systems include varying crop rotations, cover crops, rotation phase, and tillage. Perennial systems include permanent cool- and warm-season grasses and legumes under Conservation Reserve Program (CRP) management and a hay production system (Table 1). Each plot