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Special Issue: Proximal Soil Sensing

Research Paper

Soil physical property estimation from soil strength and apparent electrical conductivity sensor data

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Proximal soil sensing is an attractive approach for quantifying soil properties, but many currently available sensors do not respond to a single soil property. For example, soil strength and apparent electrical conductivity (EC_a) sensor measurements are significantly affected by soil texture, bulk density (BD), and water content (WC). The objective of this study was to explore the potential for estimating soil texture, BD, and WC using combinations of sensor-based soil strength and EC_a data obtained from sites with varying soil physical properties. Data collected from three research sites in Missouri included on-the-go horizontal soil strength at five depths up to 0.5 m on a 0.1-m interval, cone index measurements at the same depths, EC_a measured by a Veris 3100, and depth-dependent, laboratory-determined soil properties. An EC_a model inversion approach was used to generate layer EC values corresponding to the depth increments of the other variables. Fits of models using EC to estimate WC were variable ($R^2 = 0.31–0.79$). Best fitting BD estimation models ($R^2 = 0.11–0.55$) generally included EC, but soil strength was included in fewer than half of the models. BD model fits were improved considerably by adding lab-measured WC to the model ($R^2 = 0.30–0.86$), suggesting the need for a WC sensor. Soil clay texture fraction models based on EC and WC fit well ($R^2 = 0.80–0.93$). This study showed the potential of combining data from multiple mobile proximal sensors to estimate important soil physical properties.

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1. Introduction

Precision agriculture, or site-specific management (SSM), where information about within-field variability is used to match inputs to crop needs, has been studied and increasingly adopted in many countries throughout the world. Soil properties provide some of the most important information sources for successful SSM. Soil physical and chemical properties govern the transport of plant-available nutrients and water (Barber, 1984). Soil provides physical support for roots, but soils that are too compacted may exhibit high mechanical resistance impairing seedling emergence or root growth, thereby affecting plant growth (Letey, 1985).

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Accurate quantification of soil properties is needed in development and assessment of SSM strategies. Historically, most soil properties have been determined by laboratory testing of collected samples. Some of these include bulk density, water content, texture, porosity, pH, cation exchange capacity (CEC), nutrient status, and organic matter (Tan, 2005). Although laboratory tests may provide useful information for whole-field management, the number of measurements required for SSM makes laboratory tests time-, cost-, and labour-consuming. A sensor-based approach may be one way to alleviate the problems associated with soil sampling and laboratory testing.

Soil strength, an indicator of soil compaction, is affected by various soil physical (e.g., bulk density) and chemical (e.g., organic matter content) properties and provides surrogate information on these properties. Although compaction can be quantified by laboratory determination of related soil properties (e.g., dry bulk density), the common field procedure is to measure soil strength. The main tool used to quantify soil strength by depth and thereby provide information related to soil compaction is the cone penetrometer (Mulqueen, Stafford, & Tanner, 1977). The index of soil strength measured by a cone penetrometer, cone index (CI, in MPa), is defined as the force per unit base area required to push the penetrometer through a specified small increment of soil (ASABE, 2011). Soil strength measured as CI is affected by soil properties such as soil water content, bulk density, and texture (Elbanna & Witney, 1987; Guerif, 1994; Perumpral, 1987). Operating depth also affects soil strength due to differences in soil conditions and soil failure mechanisms within the soil profile. Ayers and Perumpral (1982) developed an equation for CI as a function of soil water content and bulk density for five different soil types. They concluded that the specific water content for maximum soil strength depended on the soil type and increased as the percentage of clay increased. Sojka, Busscher, and Lehrsch (2001) related CI to water content and bulk density of a silt loam soil. The relationship was poor when derived from full-profile data sets but improved when data were segregated by depth.

Because it is difficult to collect enough penetrometer data to adequately describe within-field compaction variations, several on-the-go, horizontally-operating soil strength sensors have been developed, as reviewed by Hemmat and Adamchuk (2008). In previous research, our team developed the Soil Strength Profile Sensor (SSPS), which measured soil strength to a 0.5-m depth on 0.1-m increments (Chung, Sudduth, & Hummel, 2006). Cutting forces of five prismatic tips that extended in front of a main blade were measured by load cells as the tractor-mounted device moved through the soil. Analogous to the CI of a cone penetrometer, the variable quantified by the SPSS was force divided by the base area of the sensing tip, termed prismatic soil strength index (PSSI, MPa). Field research (Chung, Sudduth, Plouffe, & Kitchen, 2008) showed that PSSI was affected by WC, BD, and texture. Best results were obtained when depth of operation was included in the model relating soil strength to soil properties (R^2 = 0.61–0.66), or when analysis was conducted within a single depth. If the analysis was conducted across all depths, results were not as good, with R^2 of 0.46 and 0.51 for the two field sites. Andrade-Sanchez, Upadhyaya, and Jenkins (2007) developed a soil cutting-force profile sensor that could measure down to a 0.6 m depth in increments of 0.075 m. In field tests in three different soil types, soil cutting force divided by BD was well-estimated as a function of WC and sensing depth. (R^2 = 0.85).

Another sensor-based measurement that can provide an indirect indicator of important soil physical properties is EC_a of the soil profile (Sudduth, Kitchen, Myers, & Drummond, 2010). Soil salinity, clay content, cation exchange capacity (CEC), clay mineralogy, soil pore size and distribution, and soil water content are some of the factors affecting EC_a (McNeill, 1992). In non-saline soils, EC_a variation is primarily a function of soil texture, water content, bulk density, and CEC (Corwin & Lesch, 2005). One EC_a sensor widely used in North America is the Veris 3100/3150 (Veris Technologies, Salina, KS) that uses six rolling coulters for electrodes and provides two simultaneous EC_a measurements (Lund, Christy, & Drummond, 1999). For the shallower of the two measurements, 90% of the response comes from soil depths of 0–0.3 m, while for the deeper measurement, 90% of the response comes from soil depths of 0–1.0 m (Sudduth et al., 2010). Several approaches have been developed to calculate EC values of discrete soil layers of interest from the integrated EC_a measurement, with varying degrees of success. Recently, a spatially-constrained one-dimensional inversion model has shown promise in estimating the true vertical distribution of soil conductivity (Monteiro Santos, Triantafilis, & Bruzgulis, 2011; Triantafilis & Monteiro Santos, 2013).

As described above, soil sensor measurements, including soil strength and EC_a, respond to a number of different soil properties. Therefore, it is often difficult to quantify individual soil properties with data from a single sensor. For improved results, a fusion approach (Adamchuk, Viscarra Rossel, Sudduth, & Schulze Lammers, 2011) could be used to combine multiple sensors. For example, multifunction penetrometers have been developed to measure additional soil variables important for interpreting CI, including soil water content (e.g., Hummel, Ahmad, Newman, Sudduth, & Drummond, 2004; Sun, Ma, Schulze Lammers, Schmittmann, & Rose, 2006) and apparent electrical conductivity (EC_a) as a surrogate indicator for soil texture (e.g., Sudduth, Hummel, & Drummond, 2004). Sun, Schulze Lammers, Daokun, Jianhui, and Qingmeng (2008) developed a multi-sensor penetrometer for measuring soil WC, mechanical strength and electrical conductivity. Sun, Cheng, Lin, Schellberg, and Schulze Lammers (2013) used a similar device to investigate the relationship of the measured soil sensor data (water content and CI by penetrometer and EC_a determined by Geonics EM38) to crop yield. They reported that yield was significantly related to all three sensor readings. Multifunction penetrometers have been commercialised, including the Veris P3000 and P4000 (Veris Technologies, Salina, KS, USA), and their uses in soil investigations have been described (Sudduth, Myers, Kitchen, & Drummond, 2013; Wetterlind, Piikki, Stenberg, & Söderström, 2015).

Other sensor fusion projects incorporated horizontal soil strength sensors. Mouazen and Ramon (2009) and Quraishi and Mouazen (2013) tested an on-line sensor for the prediction of BD. The sensor consisted of a load cell to measure draft, a visible and near infrared (vis-NIR) reflectance sensor to