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High-resolution prediction of soil available water content within the crop root zone

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SUMMARY

A detailed understanding of soil hydraulic properties, particularly soil available water content (AWC) within the effective root zone, is needed to optimally schedule irrigation in fields with substantial spatial heterogeneity. However, it is difficult and time consuming to directly measure soil hydraulic properties. Therefore, easily collected and measured soil properties, such as soil texture and/or bulk density, that are well correlated with hydraulic properties are used as proxies to develop pedotransfer functions (PTF). In this study, multiple modeling scenarios were developed and evaluated to indirectly predict high resolution AWC maps within the effective root zone. The modeling techniques included kriging, co-kriging, regression kriging, artificial neural networks (NN) and geographically weighted regression (GWR). The efficiency of soil apparent electrical conductivity (EC_a) as proximal data in the modeling process was assessed. There was a good agreement (root mean square error (RMSE) = 0.052 $cm^3\ cm^{-3}$ and $r = 0.88$) between observed and point prediction of water contents using pseudo continuous PTFs. We found that both GWR (mean RMSE = 0.062 $cm^3\ cm^{-3}$) and regression kriging (mean RMSE = 0.063 $cm^3\ cm^{-3}$) produced the best water content maps with these accuracies improved up to 19% when EC_a was used as an ancillary soil attribute in the interpolation process. The maps indicated fourfold differences in AWC between coarse- and fine-textured soils across the study site. This provided a template for future investigations for evaluating the efficiency of variable rate irrigation management scenarios in accounting for the spatial heterogeneity of soil hydraulic attributes.

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1. Introduction

Across the globe, water has become the most valuable input for agriculture. The growing demand for food and fiber production along with uncertainties in rainfall patterns has resulted in increased attention on irrigation practices. If field-level spatial soil variation is substantial, variable rate irrigation becomes a desirable method to apply an optimum amount of water to each soil type in order to maximize yield. Duncan (2012) conducted a two-year cotton irrigation study and showed that the optimum supplemental irrigation strategy was different among plots with high, moderate and low water holding capacity (WHC). He emphasized that in the long term it is not possible to maximize yield with a uniform supplemental irrigation strategy in fields with a significant degree of heterogeneity in soil available water content (AWC).

Soil hydraulic information is required for the majority of agro-hydrological studies and irrigation management including providing essential inputs for irrigation, drainage, and hydrological models. The main goal of these endeavors is to account for the spatial heterogeneity of these hydraulic properties by mapping their spatial distribution at high resolution. However, obtaining information on soil hydraulic properties such as soil water retention and hydraulic conductivity is challenging due to the time-consuming and labor-intensive nature of *in situ* and laboratory methods. The traditional solution to this problem was to develop proxies of soil hydraulic properties by collecting easily measured soil characteristics such as texture, bulk density, and organic matter content that are well correlated with soil hydraulic properties

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to produce pedotransfer functions (PTFs, Bouma, 1989). Another easily collected soil attribute is apparent electrical conductivity (EC_a), which is a function of the electrical conductivity of porous media solution, the soil porosity, and the cementation exponent, i.e., Archie's law (Archie, 1942). When soil salinity is not a major factor, EC_a may be a useful proxy of soil physical and hydraulic attributes (Sudduth et al., 2005) including depth to sand layer (Duncan, 2012), clay percentage under non-saline conditions (Saey et al., 2009), and soil texture and WHC (Abdu et al., 2008). Abdu et al. (2008) predicted WHC in the subsurface soil of a small watershed using EC_a data. Their PTFs for clay percentage ($r = 0.86$) and WHC ($r = 0.75$) showed good performance, but they emphasized the need for additional studies to appropriately relate EC_a to other soil hydraulic attributes, a goal of this particular study (Abdu et al., 2008).

PTFs were initially derived using multiple regression techniques, but machine-learning algorithms are now predominantly used to derive PTFs (Vereecken et al., 2010). A combination of PTFs and interpolation techniques is usually required to generate a map of soil hydraulic properties. For example, Ferrer Julià et al. (2004) used kriging to interpolate the PTF of saturated hydraulic conductivity to produce a 1-km^2 resolution saturated hydraulic conductivity map of Spain. They reported that soil texture was the most important input predictor to the PTF, while organic matter content showed a low influence on saturated soils (Ferrer Julià et al., 2004). In recent years, alternative interpolation techniques have been introduced and evaluated to map the spatial variability of environmental attributes such as regression kriging, geographically weighted regression (GWR), and machine learning-based spatial models (Eldeiry and Garcia, 2010; Li et al., 2011; Sharma et al., 2011). Herbst et al. (2006) compared the use of different interpolation techniques in conjunction with terrain attributes such as slope to predict soil hydraulic properties in a micro-scale catchment. They found that regression kriging had the smallest average prediction error and thus was the most appropriate method to use. Additionally, they found up to 15% improvement in spatial predictions of hydraulic properties when using terrain attributes as co-variables in comparison with ordinary kriging without co-variables.

Traditionally, two modeling approaches, the CI and the IC, have been implemented to produce maps of predicted soil physical and hydraulic properties. One can first run PTFs at individual points or locations of input variables throughout the area of interest and then interpolate the point predictions to generate maps, i.e. using a 'calculate first, interpolate later' (CI) approach. Alternatively, one can interpolate the soil attribute, such as bulk density, texture or organic matter content across the study area and then convert the soil attribute maps to soil hydraulic properties maps by PTFs, i.e.; an 'interpolate first, calculate later' (IC) approach. Many researchers have compared different IC procedures against CI techniques (e.g. Sinowski et al., 1997; Heuvelink and Pebesma, 1999; Bechini et al., 2003), yet the reported results are different and do not indicate the supremacy of either procedure. However, procedures to predict the spatial distribution of soil hydraulic properties may be improved with the additional use of on-the-go sensing (e.g. Hedley and Yule, 2009a, 2009b; Hedley et al., 2013) and remote sensing (e.g. Jana and Mohanty, 2011) technologies.

Consequently, the objectives of this study are to

(i) Develop PTFs from soil physical properties within the effective crop root zone.
(ii) Determine the best interpolation method for generating AWC maps at the field spatial scale.
(iii) Investigate the use of EC_a to improve spatial prediction of AWC.

2. Materials and methods

2.1. Study area & collection of soil physical/hydraulic data

The 73 ha field of study is located in west Tennessee close to the Mississippi River (Fig. 1). The field contained two center pivot irrigation systems that were used for supplemental irrigation of no-till cotton during each cropping season. Field soil sampling was conducted from March 20 to 22, 2014 after rainfall events when soil was assumed to be close to field capacity. A truck mounted hydraulic probe was used on March 21 and 22, 2014 to sample 100 undisturbed sites at 0–100 cm depth (Fig. 1). Fig. 1 shows the sampling scheme where each soil sample was divided into four segments. Hereafter, the word "layer" is used to distinguish among subsamples rather than real soil horizons. The default depth of subsamples was 25-cm, though adjustments were made that accounted for soil horizon transitions. Soil texture, bulk density (BD), and gravimetric water content were measured in the lab. Prior to this, on March 20, 2014, EC_a was measured at 4700 points at shallow (0–30-cm) and deep (0–90-cm) depths across the study area using a Veris 3100 (Veris Technologies, Salina, KS).

The Veris 3100 uses the principle of electrical resistivity to measure EC_a. A small electrical current is introduced by a pair of coulter-electrodes (rotating disks) into the soil and the drop in voltage at two different depths [i.e., shallow (approximately 0–30 cm) and deep (approximately 0–90 cm)] are measured (Sudduth et al., 2005). The current flowing through three different conductance pathways (i.e. liquid, soil-liquid and solid) affects the measure of EC_a (Corwin and Lesch, 2005; Sudduth et al., 2005). In this study, the shallow EC_a readings exhibited a normal distribution, but the deep EC_a readings were skewed and thus needed to be log transformed.

2.2. Pedotransfer function development

To predict soil water retention curves (WRCs), i.e., the relationship between water content and soil matric potential, for the

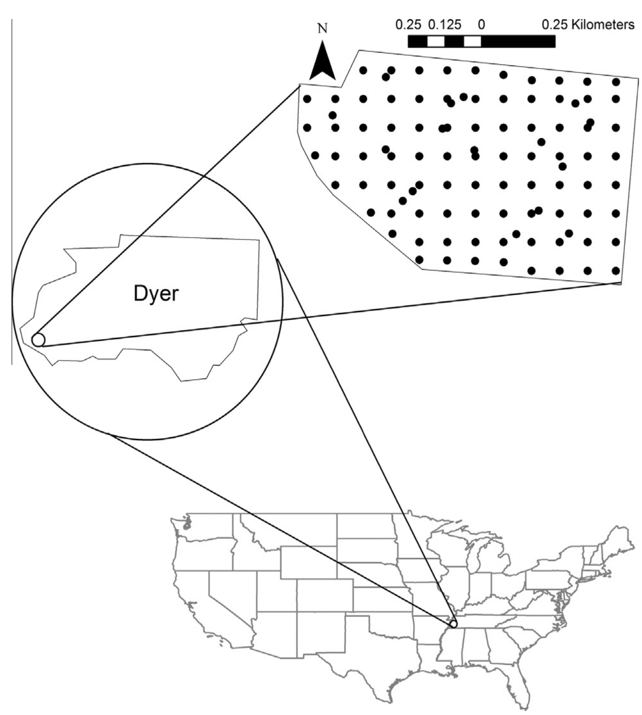

Fig. 1. The soil sampling scheme of soil physical properties that was used within a 73-ha study field of cotton that is located in Dyer County, Tennessee.

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