Mapping conductivity-depth relationships by combining proximal and penetrating EC_a sensors

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Abstract

Apparent soil electrical conductivity (EC_a), a widely used proximal soil sensing technology, could be made more useful through better calibration to subsurface variations in soil properties. In this research we develop methods to improve calibrations through combining by-depth measurements from an EC_a penetrometer with data from mobile proximal EC_a sensors. Penetrating EC_a data facilitated visualization and parameterization of a more accurate soil-layer model and provided an efficient way to obtain model calibration data for topsoil depth determination in strongly-layered claypan soils. Further research is required to validate this approach for other profile properties and soils.

Keywords: electrical conductivity, model inversion, penetrometer, claypan, topsoil depth

Introduction

Apparent soil electrical conductivity (EC_a) has become widely used to map within-field soil variability. The dominant soil parameters affecting EC_a vary from place to place, and therefore maps made with proximal EC_a sensors have been locally calibrated to variations in soil parameters such as salinity, texture or moisture. Combining multiple EC_a datasets through mathematical inversion of a multi-layer soil model, it is possible to infer by-depth variations in soil properties (Hendrickx et al., 2002; Saey et al., 2008; Sudduth et al., 2010). However, inversion solutions are often of limited practicality due to multicolinearity of EC_a datasets, which may lead to inaccurate results. The goal of this research is to overcome this limitation by combining point measurements of layer conductivity obtained using EC_a-equipped penetrometers with mapped EC_a data from multiple proximal sensors.

Materials and methods

The study site was a set of thirty research plots, each 18 x 189 m, established in 1991 near Centralia in north-central Missouri, USA (39º13'N, 92º07'W). The distinguishing factor of the claypan soils at the site is the namesake "claypan" argillic horizon which has an abrupt upper boundary with at least 100% more clay than in the horizon above. This horizon commonly contains as much as 50 to 60% smectitic clay and strongly affects water infiltration and soil water holding capacity. In past research (Kitchen et al., 1999) variation in topsoil depth above the claypan was often correlated to within-field yield variation.
Cropping systems (CS) on the plots included four rotational grain CS and three perennial grass CS. Two of the three grass CS were established in 2001 by splitting the original grass CS plots; thus each grass CS plot was 6 x 189 m. Each plot encompassed three landscape positions (LP): summit, backslope and footslope. Additional information about soils, CS, and plots is given in Jung et al. (2010).
Soil sampling and EC_a data collection were completed in November 2010. Proximal EC_a data were obtained with a mobilized DUALEM-2S sensor (Dualem, Inc., Milton, ON) on an approximate 4.5 m transect spacing. This instrument provided two EC_a readings, designated herein as $EC_{a\text{-}Ddp}$ and $EC_{a\text{-}Dsh}$, with effective sensing depths of 3.0 m and 1.2 m, respectively.

Proximal EC_a data (EC_{a-V}) were also obtained on the same transects with a Veris 2000XA sensor (Veris Technologies, Salina, KS) having an effective sensing depth of approximately 0.3 m, similar to the shallow measurement from the Veris 3100 sensor.

Profile EC_a measurements and soil samples were obtained at predefined locations within each plot centered on each of the three LP. At each location, three sampling points were established in a triangular arrangement within a 3-m radius to average short-scale variability. One soil core and two profile EC_a measurements were obtained at each point and averaged to represent the LP. Topsoil depth (TD) above the claypan horizon was determined from the soil core. Profile EC_a data were obtained with a Veris Profiler 3000 penetrometer (Sudduth et al., 2004) to approximately 0.9 m deep on a 1.27-cm interval.

Profile and proximal datasets were merged by selecting the proximal EC_a measurements that were within 3 m of each profile measurement point. This procedure selected a minimum of 5, and an average of 10 proximal EC_a measurements at each LP location. A total of 108 observations were obtained (36 plots – including grass subplots – and 3 LP). Two-thirds of these observations were used as a calibration set and one-third for validation.

In a preliminary analysis, observations with large residuals from the calibration were generally in locations of short-range spatial variation in proximal EC_a. Thus, prior to additional analysis these high-variation observations were removed from the dataset based on the standard deviation of the proximal EC_a data points that were averaged for that location. Standard deviation cutoff values of 3.0 mS/m were used for $1/EC_{a-Dsh}$ and $1/EC_{a-Ddp}$, and 4.5 mS/m for EC_{a-V}, removing approximately 40% of the observations.

The first analysis step was inversion of a two-layer model using only proximal data. This model was based on EC_a sensor response curves that assumed the boundary between two homogeneous EC-layers was at TD. Models based both on a single EC_a variable and multiple variables were applied using procedures described in Sudduth et al. (2010). Incorporation of penetrating EC_a data entailed examination of Profiler EC_a data, revising the soil model to fit these data, and obtaining model estimates.

Results and discussion

Inversion results for the two-layer model are shown in Table 1. Both fit statistics and layer EC_a values were similar to those obtained in previous research (Sudduth et al., 2010). Furthermore, estimated layer EC_a values were similar in magnitude to profile EC_a values measured over four claypan-soil fields by Myers et al. (2010).

Penetrating EC_a data obtained with the Profiler 3000 (Figure 1a) clearly revealed that the two-homogeneous-layer assumption was not valid for this site. Neglecting near-surface effects, a more reasonable model would include constant EC_a above TD, linearly increasing EC_a below TD for some distance, and then another layer of constant EC_a. Thus, a three-layer model was revealed by data from the penetrating EC_a sensor (Figure 1b). This model included four parameters – TD, EC_a of the topsoil (EC_{a-T}), rate of increase of EC_a below TD (ΔEC_a), and EC_a of the subsoil layer (EC_{a-S}). Solution of the model then proceeded as for the two-layer model: the appropriate cumulative response function was inverted and solved for TD, with the three unknown constants (EC_{a-T}, ΔEC_a, and EC_{a-S}) determined iteratively to minimize TD RMSE in the calibration dataset.

Best results for the three-layer model (Table 1) were similar to those obtained with the two-layer model in terms of the RMSE in TD estimation; however the three-layer model was clearly a better match to depthwise variations in EC_a measured by the Profiler sensor (Figure 1c). As a further refinement of the process, we used penetrating EC_a data to define TD at the calibration sites. A simple searching algorithm operating on mean Profiler EC_a traces from each calibration site was able to reproduce TD measured from soil cores (TD_s) very accurately (R^2 = 0.92, RMSE = 4.8 cm). Using this Profiler-estimated TD (TD_p) in model calibration provided results very similar to those from TD_s (Table 1, Figure 1c), with a significantly more efficient approach to calibration. Further gains in efficiency could be obtained if fewer calibration points could be used. We found that TD_p model results with only 11 points were nearly as accurate as those with the full 44-point calibration set.

Figure 2 maps TD variation over the study area. Estimated TD ranged from near zero to over 1 m. Some effect of CS is apparent as discontinuities in the spatial patterns, especially for the grass CS plots, which can be identified by three calibration points at each LP. Further examination of CS effects is warranted. One goal of this research was to model and map other subsoil EC_a parameters in addition to TD, such as $EC_{a\text{-}T}$ and ΔEC_a. However, these parameters were not significantly correlated to any of the proximal EC_a datasets obtained in this study. Further research will be needed to determine the possibility of mapping profile EC_a parameters other than TD on claypan soils.

Table 1. Calibration and validation statistics for estimation of claypan soil topsoil depth by inversion of two- and three-layer models using proximal EC_a data. Three-layer models also use penetrating EC_a data in model definition and, in TD_p models, for calibration data.

Model and EC_a source	Calibration set					Validation set	
	EC_{aT} (mS/m)	ΔEC_a (mS/m^2)	EC_{aS} (mS/m)	RMSE (cm)	Bias (cm)	RMSE (cm)	Bias (cm)
2 layer - $EC_{a\text{-}Dsh,\ Ddp}$	12	--	66	9.0	-0.2	9.3	3.5
2 layer - $EC_{a\text{-}Dsh}$	12	--	63	8.2	0.0	7.6	3.8
3 layer - $EC_{a\text{-}Dsh,\ Ddp}$	7	45	72	11.6	-0.6	12.7	2.9
3 layer - $EC_{a\text{-}Dsh}$	14	46	56	7.8	-0.4	7.7	3.6
3 layer, TD_P - $EC_{a\text{-}Dsh,\ Ddp}$	6	51	72	11.8	0.3	13.2	0.8
3 layer, TD_P - $EC_{a\text{-}Dsh}$	14	51	55	8.2	-0.9	7.0	0.5

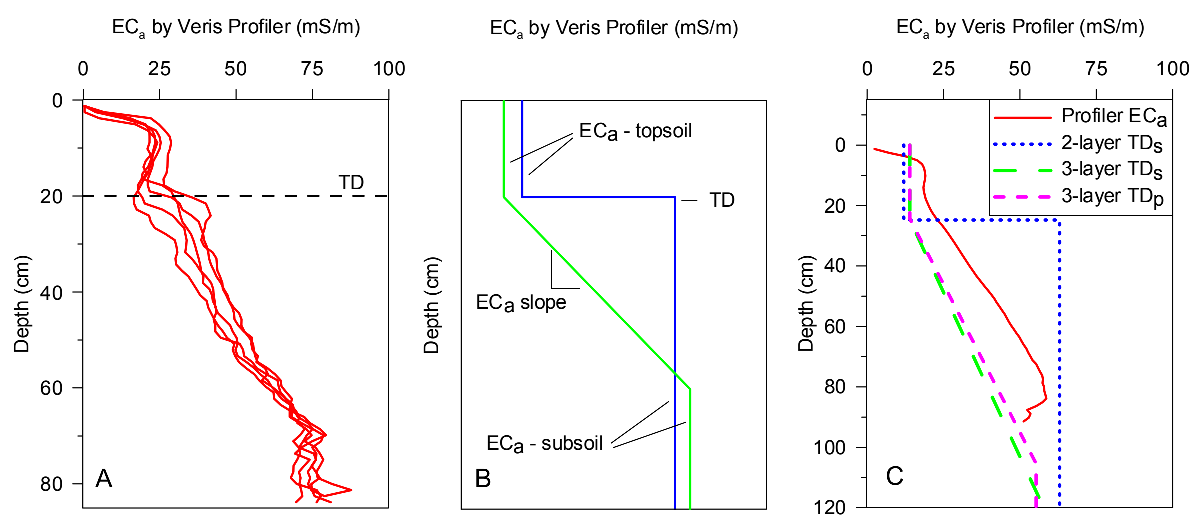

Figure 1. Penetrating EC_a datasets and their use: (A) typical EC_a-depth relationship at a location, (B) conceptual 2-layer and 3-layer soil models, and (C) comparison of model results to mean EC_a profile from study area. Calibration topsoil depths (TD) for models in panel C were by examination of soil cores (TD_S) or calculated from Profiler data (TD_P).

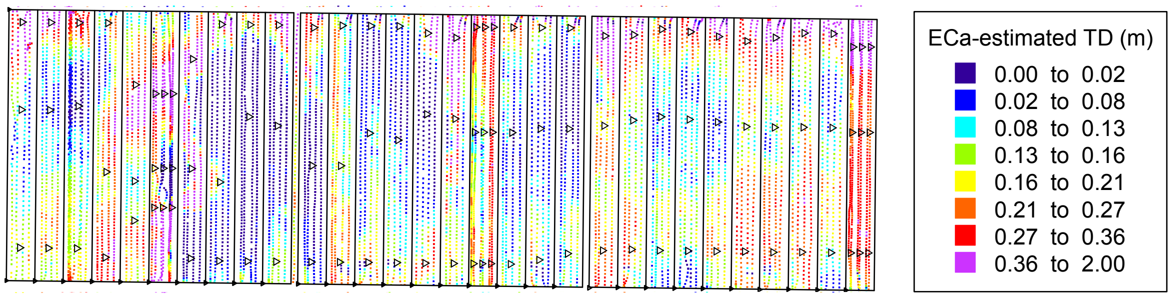

Figure 2. Map of topsoil depth (TD) estimated over the study area using three-layer model inversion of $EC_{a\text{-}Dsh}$ data. Triangles identify calibration sampling locations.

Conclusions

Methods of combining proximal and penetrating EC_a sensors for improved soil profile characterization were investigated. A key use of penetrating sensor data was in visualizing and parameterizing the soil-layer model. Penetrating sensor data also provided efficient and accurate estimation of claypan-soil TD when using data from as few as 11 points for model calibration. A key to accurate model calibration was selection of calibration points from areas of spatially-homogeneous proximal EC_a.

Disclaimer

Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation by the US Department of Agriculture.

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