Chapter 19
Combining Proximal and Penetrating Soil Electrical Conductivity Sensors for High-Resolution Digital Soil Mapping

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Abstract Proximal ground conductivity sensors produce high spatial resolution maps that integrate the bulk electrical conductivity (EC_a) of the soil profile. For meaningful interpretation, variability in conductivity maps must either be inverted to profile conductivity or be directly calibrated to profile properties. Penetrating apparent electrical conductivity ($EC_{a\text{–}P}$) sensors produce high depth resolution data at relatively fewer spatial locations. The objectives of this research were to (i) investigate the profile source of EC_a in claypan soils via a detailed examination of $EC_{a\text{–}P}$ profiles; (ii) examine the potential for feature detection with $EC_{a\text{–}P}$ in claypan soils; and (iii) determine if EC_a sensors can be calibrated to $EC_{a\text{–}P}$ features. Two study areas were chosen representing the claypan soils of north-east Missouri, USA. Profile conductivity was measured at high depth resolution on soil cores using a miniaturised Wenner conductivity probe and in the field using a conductivity penetrometer. Proximal ground conductivity was mapped with one direct contact sensor and two non-contact sensors, providing five distinct coil/electrode geometries. Increasing $EC_{a\text{–}P}$ was observed below the claypan, correlated with decreasing clay and water content and increasing bulk density. Depth to the claypan was successfully calibrated to derivative peaks on $EC_{a\text{–}P}$ profiles ($R^2 = 0.72$, $p < 0.001$). Relationships between EC_a and $EC_{a\text{–}P}$ features were poor ($R^2 \sim 0.21$) to good ($R^2 \sim 0.87$) on a field-specific basis. Results show that $EC_{a\text{–}P}$ can be used for calibration of EC_a to the depth to claypan.

Keywords Claypan soils · Soil bulk apparent electrical conductivity · Penetrometer · Wenner mini-probe

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19.1 Introduction

Proximal bulk apparent electrical conductivity (EC_a) sensors can be used to produce high spatial resolution maps that integrate soil profile EC_a variation by a depth–response function. For meaningful interpretation, the conductivity data must either be inverted to approximate profile conductivity or be directly calibrated to profile properties. Penetrating apparent electrical conductivity (EC_{a-P}) sensors measure EC_a from a small soil volume localised to their sensing electrode. Penetrating sensors measure at high depth resolution, but at sparse locations compared to proximal EC_a sensors. These two types of EC_a sensors have synergistic potential. We examined two avenues for their combined use with a case study in the claypan landscapes of north-east Missouri, USA. Firstly, we examined the potential for EC_{a-P} to identify soil morphological features. Next we examined the calibration of EC_{a-P} features to the spatially dense EC_a data. We focus here on resolving the profile source of conductivity integrated by proximal EC_a sensors.

Three specific pathways of electrical conductance occur in soils: free water in large soil pores, hygroscopic or tightly interacting particle–water interfaces, and direct soil particle contact (Corwin and Lesch, 2005). As outlined by Corwin and Lesch (working in western US soils formed in semi-arid to arid environments), the magnitude of EC_a is dependent mainly on soil salinity, Na^+ saturation percentage, water content, and bulk density (BD). The claypan soils of Missouri exist in a humid, temperate environment. They are leached of salts and free carbonates and have a small concentration of exchangeable Na^+ (<2 cmol kg^{-1}). These variables are unlikely to affect EC_a. The experiments described in this work allowed the examination of the remaining factors important for influencing proximal EC_a variation in claypan soils.

Previous studies in claypan soils discovered the relationship between EC_a and depth to claypan (DTC) (Dolittle et al., 1994; Sudduth and Kitchen, 2006). These investigations speculated that depth to argillic horizon layer silicates was the primary cause of proximal EC_a variation. Several properties of the smectite clay mineralogy were considered to be important. Smectite and similar clay minerals might provide greater physical contact due to their size and platy structure, substantial interlayer water (which is usually present), and very large concentration of exchangeable cations. Clay content decreases below the claypan and therefore, if clay mineralogy were largely responsible for EC_a variation, then less conductivity response would be expected from there. However, greater below-claypan EC_{a-P} was detected during some of our early investigations with EC_{a-P} data (Sudduth et al., 2000). Confirmation of these observations on isolated samples is needed to understand the proximal EC_a response.

From our experiences with proximal EC_a and EC_{a-P} data, we suspected that profile conductivity features could be identified by penetrometer more objectively, at better depth resolution, and more quantitatively than by coring or augering. Mapping subsoil EC_{a-P} features via their relationship to EC_a would be more efficient than grid survey. An EC_a-to-EC_{a-P} feature calibration should provide the spatial and depth resolution needed for high-resolution soil mapping. We hypothesised that a large gradient in the first derivative of the $EC_{a\text{–}P}$ profile could be used to identify a claypan or other lithologic discontinuity. We examined the relationship between $EC_{a\text{–}P}$ derivative peaks and observed depth to claypan in order to test this possibility. Further, we hypothesised that EC_a could predict the depth to $EC_{a\text{–}P}$ first-derivative peaks.

The specific objectives of this research were to

i. confirm the increase in EC_a below the claypan;
ii. determine if $EC_{a\text{–}P}$ data can be used to estimate depth to claypan; and
iii. determine if EC_a sensors can be calibrated to $EC_{a\text{–}P}$ features.

19.2 Materials and Methods

19.2.1 Soil Landscapes, Measurements, and Observations

Four agricultural fields in the claypan region of north-east Missouri were chosen for this study: three fields with a loess solum near Centralia, MO (fields A, B, and C) (39°13′43" N, 92°8′20" W), and a field with a loess-till solum near Novelty, MO (field D) (40°1′46.5" N, 92°11′19" W). Fields A, B, and C are located near the southern limit of the claypan region, while field D is at the northern limit, about 90 km away. Physical and chemical characterisation data by horizon were available from 44 profiles with claypan features. Field descriptions and horizon designations for these pedons were made by experienced soil morphologists. Observed depth to claypan was determined as depth to the Bt1 or the Bt2 horizon based on the field descriptions and lab data.

19.2.2 $EC_{a\text{–}P}$ Measurement

Penetrometer $EC_{a\text{–}P}$ (see Table 19.1 for EC_a abbreviations) and cone index (CI) were measured at the 44 claypan locations using a Veris[1] Profiler 3000 with an insulated shaft (Veris Technologies, Salina, KS, USA). Measurements of $EC_{a\text{–}P}$ and CI were made on all fields in the late spring of 2007 and occurred within a few days of proximal EC_a measurements on fields B and D. However, $EC_{a\text{–}P}$ and CI were measured on fields A and C approximately 18 months after the EC_a surveys. Gravimetric soil moisture (w) and BD determinations were made in 15-cm layers at the time of $EC_{a\text{–}P}$ measurement.

Cone index and $EC_{a\text{–}P}$ were measured to 92 cm, with five penetrations per site. Replicate $EC_{a\text{–}P}$ profiles were pooled and fitted with locally weighted regression

[1] Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture, University of Missouri, or University of Florida.

Table 19.1 Bulk apparent electrical conductivity (EC_a) is a generic terminology that can be applied to a variety of sensors which can have multiple measurement channels. We differentiate the various EC_a sensors used in this study by the following abbreviations

Sensor	Symbol	Channel	Effective depth[a]	Sensor type	Coil/electrode geometry
DUALEM-2S	$EC_{a\text{–}Dsh}$	Shallow	2.2 m	Induction	2 m PCP[b]
DUALEM-2S	$EC_{a\text{–}Ddp}$	Deep	10 m	Induction	2.1 m HCP[c]
Geonics EM-38	$EC_{a\text{–}EM}$	Deep	5 m	Induction	1 m HCP
Veris 3150 MSP	$EC_{a\text{–}Vsh}$	Shallow	0.3 m	Wenner contact	0.7 m
Veris 3150 MSP	$EC_{a\text{–}Vdp}$	Deep	1 m	Wenner contact	2.2 m
Veris Profiler	$EC_{a\text{–}P}$	Single	–	Dipole contact	Cone electrode
Wenner mini-probe	$EC_{a\text{–}M}$	Single	–	Wenner contact	5 mm

[a]Depth to 90% of total response (Sudduth and Kitchen, 2000)
[b]PCP, perpendicular coplanar
[c]HCP, horizontal coplanar

models. A Savitzky–Golay procedure was used to calculate the derivative of the fitted $EC_{a\text{–}P}$ profile. A large peak in the first derivative, referred to as the transition peak, corresponds to the transition between the E horizon and the upper boundary of the claypan. Depth to the transition peak was determined for all of the fitted profiles. Clay-maximum depth translation was applied to each fitted $EC_{a\text{–}P}$ profile independently in order to explore the landscape relationship in sub-claypan EC_a. Translated depth (D_t) indicates the depth at which a measurement occurs either above or below the claypan. Translated depth profiles were pooled into a single dataset and again fitted with a locally weighted regression.

19.2.3 $EC_{a\text{–}M}$ Measurement

We developed a miniaturised Wenner array on a handheld probe (mini-probe) to measure EC_a ($EC_{a\text{–}M}$) on ex situ soil cores to confirm $EC_{a\text{–}P}$ observations. Wenner mini-probe apparent electrical conductivity was measured every 1.25 cm. The mini-probe had 5 mm electrode spacing, 5 mm insertion depth, and was operated using the electronics from a Veris EC_a sensor. Veris supplied custom software accounting for the probe geometry. Measurements of $EC_{a\text{–}M}$ were made on soil cores compressed into a steel channel which formed the cores into triangular prisms. This procedure repaired breaks and extrusion cracks in soil cores, consolidated loose soil, and formed two flat surfaces providing consistent contact for the mini-probe. Gravimetric soil moisture (w) of these cores was measured at 2.54 cm intervals.

19.2.4 Proximal EC_a Measurement

Three conductivity sensors were used to measure proximal EC_a with DGPS position on 10 m transects at 4–6 m intervals. Sensors were the DUALEM-2S electromagnetic induction (EMI) sensor (Dualem, Inc., Milton, Ontario, Canada) in horizontal coplanar mode (EC_{a-Dsh}) and perpendicular planar mode (EC_{a-Ddp}) (2 m coil spacing); the Geonics EM-38 EMI sensor (Geonics Limited, Mississauga, Ontario, Canada) in horizontal coplanar mode (EC_{a-EM}), 1 m coil spacing; and the Veris 3150 rolling coulter Wenner array (Veris Technologies, Salina, KS, USA) with 0.7 m (EC_{a-Vsh}) and 2.2 m (EC_{a-Vdp}) electrode spacing. This combination of sensors provided five distinct coil/electrode geometries for EC_a measurement. Fields B and D had all EC_a surveys made within a relatively narrow window of 1 month in the spring of 2007. Surveys of fields A and C were made within 3 days in the fall of 2005.

The five proximal EC_a instrument geometries used for this study were unique (Table 19.1), but their depth–response functions were overlapping to one degree or another and their measurements were correlated (Sudduth and Kitchen, 2000). Partial least squares regression (PLSR) was used to model the EC_a relationship to EC_{a-P} features in order to mitigate correlation in the predictors and to capitalise on any orthogonality in their response to EC_{a-P}.

19.3 Results and Discussion

19.3.1 Soil Profile EC_a

The major morphological features found throughout the study fields were visible in the depth profile of EC_{a-P} or EC_{a-M} in a representative claypan site from field A (Fig. 19.1a). Firstly, the silty, granular, and low-density surface had very small EC_{a-P}. The remaining A horizons had greater EC_{a-P}, but still relatively smaller EC_{a-P} compared to the claypan and below. When an E horizon was present, it appeared as a zone of minimum conductivity. Conductivity abruptly increased in the transition to the Bt1 horizon, the claypan feature. Conductivity continued to increase below the claypan to 90 cm and beyond, even as clay content decreased.

Mean EC_{a-P} above and below the claypan for all 44 study locations was 20.9 and 47.4 mS m^{-1} with standard errors 0.31 and 0.26 mS m^{-1} respectively, and was significantly different ($p<0.001$). This difference and the landscape trend in EC_{a-P} distribution were emphasised in pooled D_t profiles of EC_{a-P} (Fig. 19.2). The depth translation procedure allowed comparison of profiles on a coherent depth scale. These results verified large and increasing sub-claypan EC_{a-P} and emphasised the similarity of these soils to the theoretical bilayered earth discussed in the geotechnical literature (McNeill, 1980; Callegary et al., 2007).

Measurements of EC_{a-M} were highly correlated with EC_{a-P} measurements ($r = 0.82$), but were greater by a factor of 3.3 (Fig. 19.3). These results confirmed the EC_{a-P} sensor measurement and further indicated that as clay content decreases, profile EC_{a-P} increases – counter to the clay-source hypothesis. The greater magnitude of EC_{a-M} data relative to EC_{a-P} warrants further investigation but is potentially due to increased particle contact caused by the core-pressing procedure used in the EC_{a-M} measurement.

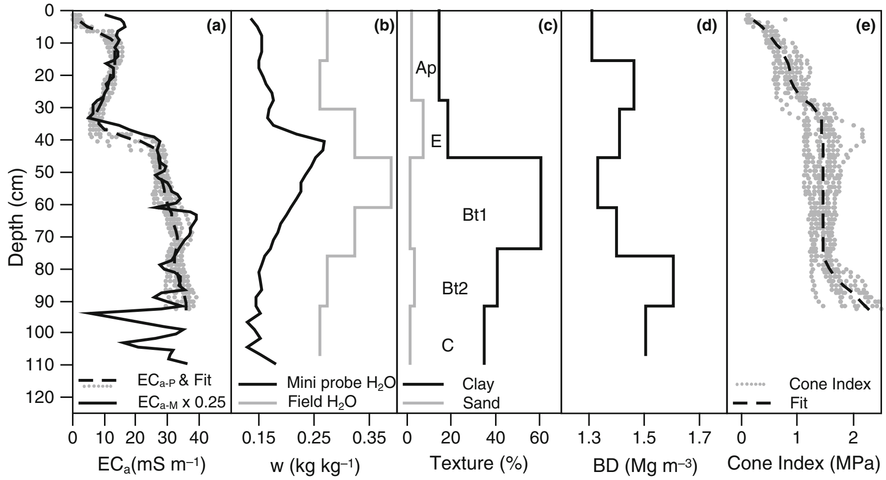

Fig. 19.1 Data from a representative claypan soil on field A. (**a**) Penetrometer electrical conductivity (EC_{a-P}) and scaled Wenner mini-probe conductivity ($EC_{a-M} \times 0.25$). (**b**) Field (taken with EC_{a-P}) and high-resolution (taken with EC_{a-M}) gravimetric soil moisture (w). (**c**) Percent clay and sand. (**d**) Bulk density (BD). (**e**) Cone index

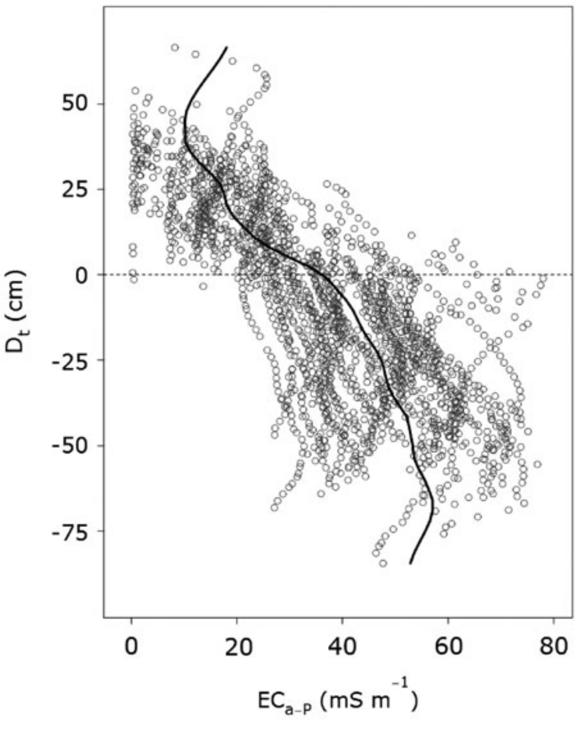

Fig. 19.2 Clay-maximum translated depth (D_t) profiles of EC_{a-P} from 44 locations in 4 claypan fields. The depth scale is translated such that the profile clay maximum for each location is at 0 cm (*dashed horizontal line*). Translated depth is positive above the claypan and negative below. Measurements of EC_a increase below the claypan (D_t<0) as emphasised by the locally weighted regression (*solid black line*)

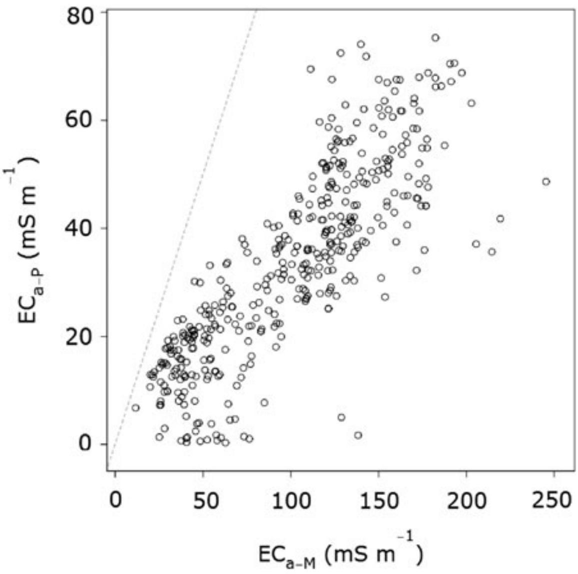

Fig. 19.3 Scatter plot showing the correlation between EC_a in claypan soil profiles measured in situ by penetrometer (EC_{a-P}) and ex situ by a Wenner mini-probe (EC_{a-M}). The Pearson correlation coefficient between these sensor measurements is 0.82 and EC_{a-M} is proportional to EC_{a-P} by a factor of 3.3

19.3.2 EC_{a-P} Predicted Depth to Claypan

A major objective of this research was to examine the potential for using EC_{a-P} to rapidly identify and map subsoil features. The claypan is a critical soil morphological feature because it impacts hydrology, plant-available water capacity, water quality, subsoil fertility, root distribution, and crop yield (see Chapter 31). The claypan transition peak was clear on first-derivative plots of EC_{a-P} (Fig. 19.4a).

Claypan transition peaks indicate the depth at which an experienced soil morphologist would describe the E–Bt boundary. The EC_{a-P} sensor allows an objective and quantitative determination of the claypan and provides a continuous representation. Depth to claypan was significantly related to EC_{a-P} transition peak depth ($R^2 = 0.71$, $n = 44$, $p < 0.001$) (Fig. 19.4b). This result includes data from all four study sites spanning opposite ends of the Missouri claypan region. Based on these results, EC_{a-P} might be used to predict claypan depth anywhere within this area or in a similar soil region. The penetrometer can rapidly capture short-range spatial variability with multiple penetrations and may be more consistent and quantitative than a soil morphologist could be. This type of relationship is very useful for densifying investigations along transects or within an area (Drummond et al., 2005). Quantified EC_{a-P} feature observations can be efficiently collected at smaller intervals, while more time-intensive coring or augering can be performed at larger intervals.

19.3.3 Calibrating EC_a to EC_{a-P} Features

Severe correlation between proximal EC_a measurements requires a non-traditional approach to modelling. Partial least squares regression of transition peak depth as

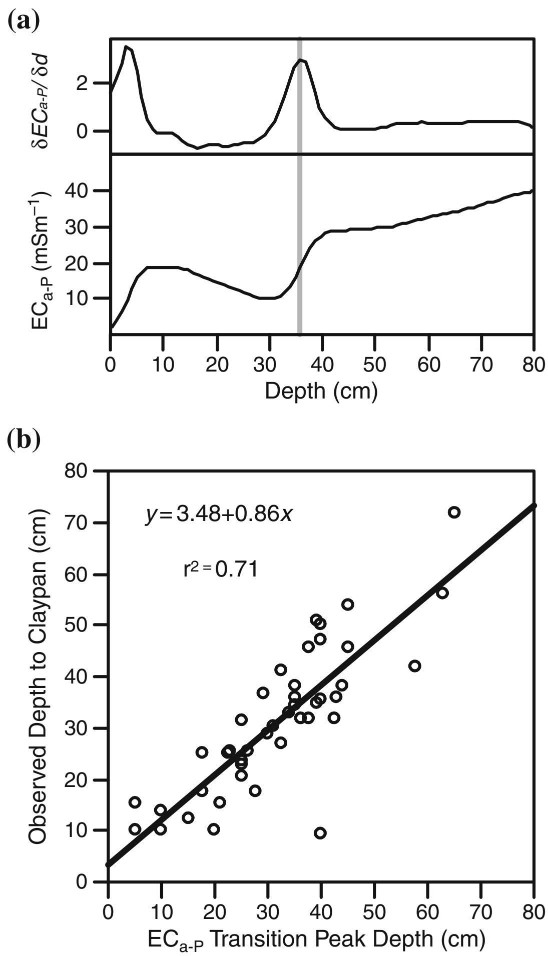

Fig. 19.4 Penetrometer electrical conductivity ($EC_{a\text{–}P}$) and first derivative ($\delta EC_{a\text{–}P}/\delta d$) of a representative claypan soil profile. $EC_{a\text{–}P}$ transition peak is identified by a vertical grey line. (**b**) Depth to $EC_{a\text{–}P}$ transition peak is analogous to depth to claypan (DTC) and is compared to observed DTC by linear regression

a function of $EC_{a\text{–}EM}$, $EC_{a\text{–}Dsh}$, $EC_{a\text{–}Ddp}$, $EC_{a\text{–}Vsh}$, and $EC_{a\text{–}Vdp}$ produced varying results, from no significant model for field A to a very good relationship for field C (Table 19.2). The profiles from these four field sites were chosen, based on previous research needs, to represent the landscape variability present within each field. However, the field datasets differed in their realisation of this goal. Fields C and D have greater relief and a wider range of landscape positions and thus a wider range of DTC than does field A. Field B had a relatively wider range in DTC than did A, but had a lower number of profile samples concentrated in a fairly narrow range of DTC, and transition peak depth was poorly related to EC_a. Pooled results showed a moderate relationship (Table 19.2). A better stratified sample of $EC_{a\text{–}P}$ profiles from within each field might produce better results. The potential for within-field mapping of $EC_{a\text{–}P}$ features with EC_a data is shown in the site C results (Table 19.2, Fig. 19.5).

Table 19.2 Fit statistics and number of components for partial least squares regression models of EC_{a-P} transition peak as a function of five EC_a sensor measurements

		Intercept	Comp. 1		Comp. 1–2		Comp. 1–3		Comp. 1–4	
Field	*N*	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
A	16	12.38	–	–	–	–	–	–	–	–
B	7	17.67	−0.01	15.20	0.21	13.45	–	–	–	–
C	9	13.67	0.80	5.40	0.76	5.90	0.87	4.45	–	–
D	11	16.00	0.64	8.75	–	–	–	–	–	–
Pooled	43	13.71	0.37	10.67	0.39	10.48	0.43	10.12	0.44	9.99

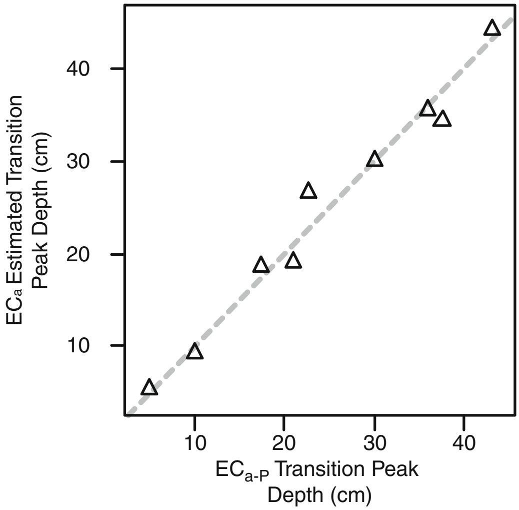

Fig. 19.5 Transition peak depth was modelled by five proximal EC_a measurements (see Table 19.2) using partial least squares regression. The resulting EC_a estimated transition peak depth is compared to measured transition peak depth from site C. Diagonal line is one-to-one

Multi-component PLSR models provided only minor gains in R^2 or root mean squared error for transition peak depth over single-component models. One or two components accounted for most of the variability within sites B, C, and D. This suggests that a single proximal EC_a instrument with dual-simultaneous investigation depths is sufficient for mapping transition peak depth. The pooled model included four components, potentially due to additional orthogonal variability in EC_a caused by temporal differences in temperature and soil moisture between EC_a surveys. This asynchrony in survey conditions is known to cause bias between surveys of the same field (Abdu et al., 2007).

19.3.4 Profile Sources of Proximal EC_a

According to Corwin and Lesch (2005), and discounting salinity and Na^+ saturation, the next most important factors determining profile conductivity are water content and BD. As mentioned previously, lower EC_{a-P} values in surface soils are probably due to granular structure and silty texture which cause reduced particle contact and proximity (Fig. 19.1a). Minimum conductivity in the strongly leached E horizons may have been due to the high felsic mineral (e.g. quartz, feldspar) content and reduced contact of the silt-sized particles. The particle-contact pathway of EC_a may be dominating response above the claypan.

The large positive EC_{a-P} gradient at the transition peak coincides with the largest increase in clay and water content (Fig. 19.1b, c). Conversely, elevated concentrations of expanded smectite clays in the claypan cause a reduction in BD (Fig. 19.1c, d). These relationships suggest that within the transition zone, EC_{a-P} is more sensitive to the clay-bound soil–solution conductivity pathway (perhaps enhanced by large cation saturation) than to the particle-contact pathway. This is in contrast to what happens below the claypan where BD and CI are greater.

We found that clay and water content decreased below the claypan, while BD and CI both increased. These relationships suggest that below the claypan, EC_{a-P} is more sensitive to the particle-contact pathway than to the soil–solution or solution–particle pathway. Processes of cementation may be enhancing this effect. Structural units also tend to be larger in size with depth. Profile distribution of clay, bulk density, structure, and water content are confounded by soil genesis. Integrated processes of soil formation, including loess deposition, eluviation, illuviation, and subsoil densification, vary systematically with landscape. This combination of effects is probably responsible for success in the calibration of proximal EC_a to DTC and transition peak depth.

19.4 Conclusions

The spatial resolution of EC_a sensors and the depth resolution of EC_{a-P} sensors offer the potential to synergistically improve high-resolution soil mapping. Claypan soils are successfully handled in this way because they are essentially bilayered with respect to EC_a. Direct calibration of EC_{a-P} depth profile features to soil profile features such as depth to claypan is effective, but global or regional calibration of proximal EC_a to EC_{a-P} features is complicated by field-to-field and temporal variability in proximal EC_a measurements. In general, the multiple EC_a sensor geometries of the common commercially available platforms studied here do provide at least two orthogonal components of EC_a information. Finally, profile conductivity actually increases somewhat below the claypan, probably due to increased particle contact in denser soil. Response of EC_a to EC_{a-P} transition peak and DTC is due to the confounded processes of soil and landscape genesis rather than just depth to argillic horizon clay minerals. It is a combined effect of lesser EC_a near the surface, a profile minimum EC_a in E horizons, greater EC_a in the claypan, and even greater EC_a in the dense soil material below the claypan.

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