Identifying Subsoil Variation Associated with Gilgai Using Electromagnetic Induction

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Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. EAR 0911317.

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Abstract

Proximal sensing, such as electromagnetic induction, has been used to map the spatial distribution of soil properties; however, the response of these instruments to short-interval variability associated with Vertisols has not been studied. Meter-scale circular landscape features called gilgai, which are associated with surface and subsurface variability, make sampling these soils difficult, especially if the surface has been plowed. The EM38 is an electromagnetic induction tool with a relatively small spatial footprint (1 m^2), which may be fine enough to identify subsoil variability associated with gilgai. In 2011, an EM38 survey was conducted for a 40 by 50 m field with intact circular gilgai in the Texas Blackland Prairies. Soil properties including gravimetric water content, bulk density, inorganic C content, and electrical conductivity of the soil solution were measured. In 2012, half of the field was plowed, and another EM38 survey was conducted. The EM38 was able to locate subsurface variability in soil properties between microhighs and microlows under both intact and plowed conditions. Semi-variance of soil properties increased with increasing distance and reached maximum variance at 3 meters, corresponding to the average diameter of gilgai features. The overall variability across the study site decreased after plowing. Water content and inorganic C content were the primary soil properties that forced the response of the EM38 in these landscapes, and the partial correlation coefficient suggests the effects of water content and inorganic C content on EM38 response are independent. In calcareous Vertisols, the EM38 can be used to identify subsurface variability and may be useful in developing sampling schemes for Vertisol classification, soil sampling, and fine-scale digital soil mapping.

Keywords: apparent electrical conductivity, Vertisol, gilgai, proximal sensing, EM38

Highlights

- EC_a can identify meter-scale variability of soil properties in calcareous Vertisols
- Plowing decreases the overall variance observed in EC_a
- Spatial variance in EC_a corresponded with average gilgai diameter
- Water content and inorganic C content were primary drivers of EC_a variability

1. Introduction

Quick, non-invasive proximal sensing of the spatial distribution of soil properties has applications in designing sampling strategies and soil mapping. These maps can then be used in precision agriculture, hydrology models, land surface models, and any other applications which require fine-scale soil variability maps. Vertisols have fine-scale (<10 m) soil variability caused by the shrinking and swelling of these soils with changes in water content. This pedoturbation causes both surface features called gilgai (Paton, 1974) and meter-scale variability in soil properties such as clay, organic C and inorganic C content (Wilding and Tessier, 1988; Wilding et al., 1989). Sampling of Vertisols with gilgai features needs to account for these variations for accurate characterization of soil properties, but when fields are plowed for production agriculture, the visual indication of subsurface features from surface topography is lost. Using proximal sensors to identify soil variation associated with gilgai, even under plowed conditions, would allow for improved accuracy in characterization of soil properties and spatial variability in these landscapes.

Soil maps at the landscape scale, including soil survey maps created by the National Resource Conservation Service (NRCS), customarily delineate soil types along landscape positions and based on soil forming factors (Jenny, 1946; Schelling, 1970), and assign a set of soil properties to a polygon. However, soil properties may vary on finer scales than landscapes (Cambardella et al., 1994). In the case of Vertisols, pedoturbation causes microtopography features, and in the case of circular gilgai, can be decomposed into microhighs (mounds) and microlows (depressions). These features are typically less than 10 m in diameter and have less than 1 m in elevation changes (Wilding and Tessier, 1988). However, the pedoturbation and water retention in microlows results in differences in soil weathering and often produce higher

clay and organic C contents and lower salinity and inorganic C content in the microlows than in the microhighs (Fig. 1) (Wilding et al., 1989; Brevik and Fenton, 2002; Nordt et al., 2004). If Vertisol descriptions are based on a limited number of samples, the presence of gilgai complicates soil sampling and influences estimates of soil properties at the field scale (Miller et al., 2010). As a consequence of subsoil features (deeper than 20 cm), Vertisols with gilgai often require sampling methods based on the surface features for correct classification (Coulombe et al., 1996; Nordt et al., 2004).

To create fine-scale soil maps, one solution is taking many direct measurements of soil physical and chemical properties; however, this is expensive and time-consuming. Apparent bulk electrical conductivity (EC_a), as measured by electromagnetic induction, has been used extensively in mapping subsoil variation and in precision agriculture (Brevik et al., 2006; Corwin and Lesch, 2005; Doolittle et al., 1994). Geo-referenced EC_a data can be collected at much higher densities than direct methods such as soil cores (McBride et al., 1990; Johnson et al., 2001; Akbar et al., 2004; Brevik et al., 2006; McBratney et al., 2005). This tool has been used to map soil salinity, clay content, soil water content (Rhoades et al., 1976; McBride et al., 1990; Corwin and Lesch, 2005; Brevik et al., 2006), soil inorganic C content (Neely et al., 2016), and soil temperature (Robinson et al., 2009). Because of the interdependence of water movement and soil formation, many of the soil properties correlated with EC_a response are also correlated with landscape position at the field scale (Clay et al., 2001; Weller et al., 2007; Harvey and Morgan, 2009). What is not known is if meter-scale variability associated with microtopography can be mapped using EC_a techniques.

We investigated the ability of EC_a measurement techniques to map differences in subsoil variability (deeper than 20 cm) associated with circular gilgai on a Texas Vertisol under both

intact and plowed conditions. The objectives of this study are to: 1) determine the response of EC_a measurements on an undisturbed Vertisol with circular gilgai at the meter scale, 2) identify the soil properties contributing to EC_a measurements, and 3) evaluate the effect of plowing on measurements of EC_a .

2. Material and Methods

2.1. Site Selection

The study site was located on the USDA-ARS Grassland, Soil and Water Research Laboratory watershed network near Riesel, TX, on a Houston Black clay (fine, smectitic, thermic, Udic Haplustert). The site is on the Wolfe Creek Formation in the Texas Blackland Prairies ecoregion with a mean annual precipitation of 700 to 1000 mm. The dominate parent materials are calcareous chalks and marls. The soil had intact soil microtopography with no known tillage events in the past 30 years and is under improved pasture and cattle production (Fig. 2). The gilgai are deep enough to retain water during the winter months. The dimensions of the study site were 40 by 50 m.

A typical Houston Black clay soil profile has a mollic epipedon with slickensides at approximately 60 cm. Pressure faces occur throughout the soil profile, including the soil surface. As the name suggests, these soils are very dark in color (10 YR 3/1) (USDA-NRCS, 2016). A microhigh profile typically has a shallower depth to the calcareous parent material, less organic C at the surface, and lower clay content when compared to the soil profile of the microlow position (Fig. 1). These soils are very fertile and are considered prime farmland. Typical agriculture production in the area (McLennan county) includes corn, winter wheat, oats, and pasture for cattle (USDA-NASS, 2016) under dryland agriculture.

2.2. Electrical Conductivity Mapping

The EM38 (Geonics EM38-M2K, Geomatrix Earth Science Ltd., Bedfordshire, UK) was used to measure EC_a for our field site, and has the benefit of being a relatively inexpensive, non-invasive proximal sensing instrument built for agricultural purposes (Rhoades et al., 1981; Sheets and Hendrickx, 1995). The EM38 has an effective spatial sensing area of approximately 1 m^2 (Clay et al., 2001), which may be fine enough to independently sense differences in soil properties among microlows and microhighs. However, due to the integrated response of the EM38 to several soil properties, field maps created based on EC_a must always be corroborated with soil data (Carroll and Oliver, 2005).

To evaluate the impact of plowing on EC_a response, two surveys were conducted. A survey of intact surface microtopography was conducted on 11 March 2011. The following year, half of the field was disked ten times at a depth of approximately 15 cm and another survey was taken two weeks following plowing on 12 April 2012. Proximal sensing surveys using the EM38 sensor were conducted in the vertical dipole mode. We chose to use only the vertical dipole mode due to the soil profiles being relatively homogeneous and a lack of detectable differences in the resulting maps. In this mode, the EM38 can sense approximately 1.5 m deep with a sampling radius of 1 m^2 . The instrument was walked on parallel, one-meter survey transects, traveling approximately 1.1 m s^{-1} . The EM38 was held at a constant height above the soil surface of approximately 10 cm. Instrument drift was observed by having one location marked and measuring that location before and after surveys, and soil temperature was recorded 5 cm below the soil surface before and after surveys. No drift was observed during either survey. Before data analysis, the collected EC_a data were standardized to a soil temperature of 25°C using the equation by Sheets and Hendricx (1995);

$$EC_{25} = EC_T * [0.4470 + 1.4034 * e^{(-T/26.815)}], \quad [1]$$

where EC_T is the EC_a collected, T is soil temperature ($^{\circ}C$). All temperature corrected EC_a will be referred to as EC_{25} .

A digital elevation model (DEM) was made using a Trimble GPS Surveying System (Trimble Navigation Limited, Sunnyvale, CA) capable of capturing spatial information in x, y, and z dimensions at the time of the EM38 surveys. In addition to the DEM, gilgai locations were recorded with the GPS by walking the edges of the microlows with a GPS and digitizing the resulting locations into polygons.

2.3. Soil Sample Collection and Analysis

Sampling sites were selected by stratifying microtopography locations and EC_{25} in an attempt to capture all combinations of EC_{25} and gilgai position; EC_{25} was stratified into high and low values and microtopography into microhighs and microlows. We wanted to capture microlows with both relatively high and low EC_{25} measurements, and also microhighs with high and low EC_{25} measurements. Seven locations were from microhighs and eight from microlows. At each sampling site, two soil cores were collected to a depth of 2 m, or until the parent material stopped the hydraulic sampling probe (Hydraulic Soil Sampling and Coring and Drilling Machine, Giddings Machine Company, Inc., Windsor, CO), and cut into 10-cm sections. One core was weighed and dried at $105^{\circ}C$ for gravimetric water content and bulk density, and the other was air-dried for analysis. Depth to parent material was recorded for each sampling location.

Soil core sections were air-dried, ground and passed through a 2-mm sieve. Soil analysis included particle size distribution, inorganic C content, organic C content of the surface soil layers (0 to 20, 20 to 40 cm), and electrical conductivity of the soil solution ($EC_{2:1}$). Soil particle size classification was determined using the pipette method (Kilmer and Alexander, 1949).

Electrical conductivity of the soil solution was performed using conductivity multicell probe (545, Amber Science Inc., Eugene, OR) with 2:1 water to soil extract (Sonneveld and van den Ende, 1971; Rhoades, 1982). We chose to use 2:1 extract for soil salinity instead of saturated paste due to the expected low salinity levels in these soils and low impact on the overall electrical conductivity as measured by the EM38. Inorganic C content was determined through the modified pressure calcimeter method (Sherrod et al., 2002). To determine organic C content, first total C content was measured by total combustion analysis (Vario Max-CNS, Elementar Analysensysteme GmbH, Hanau, Germany), and organic C content was calculated as the difference between total C and inorganic C contents.

2.5. Statistical Analysis

For direct comparison of soil properties with EC₂₅ surveys, soil properties were depth-weight averaged for each sampling location based on the theoretical response of the EM38 with depth (McNeil, 1980) so a single value can be reported for each sampling location:

$$R_v(z) = \frac{1}{(4z^2 + 1)^{1/2}}$$

where R_v is the relative influence of current flow and z is depth. This function gives the theoretical sensitivity of the EM38 with depth. For each measurement depth of physically measured soil samples, we can assign a weight based on how deep that property was measured in the soil. This was done instead of a simple average because the contribution of soil properties to the response of the EM38 is not equal with depth, and correlations between EC₂₅ measurements and soil properties are generally improved by weighted-averages of soil properties with depth when compared to simple averages (Harvey and Morgan, 2009).

All statistics were performed in R (R Development Core Team, 2014). The relationship between soil properties and microtopography position was tested using linear regression and Pearson's correlation. The spatial structure of the EC₂₅ data was evaluated using semivariograms and Moran's I. Semivariograms are a useful tool to identify the scale of variability over space. In this study, we are interested if the subsoil variability from gilgai can be identified. Semivariograms for both years, under plowed and unplowed conditions, were fit with exponential models. Spatial autocorrelation of elevation and EC₂₅ was investigated using Moran's I with an increase number of neighbors using the R "spdep" package. By increasing the number of neighbors used, we could visualize how the autocorrelation changed as the physical space increased in size. For each calculation of Moran's I, the number of neighbors was increased by 1 until 50 neighbors were considered, and the queen neighborhood structure was used. In addition, partial correlation coefficients test the correlation of two variables while controlling for a third and was performed using the R "ppcor" package. Often in soil science, and other natural systems, several variables will be co-correlated with each other. We chose to use partial correlation to test if two variables would still be correlated without the presence of a third, and therefore strengthen our conclusions about the true relationship between variables.

3. Results and Discussion

The elevation across the study site ranged from 147 to 149 m above sea level, with circular gilgai present throughout (Fig. 3). Interpolation of elevation data was done using a tension spline in ArcGIS v.10.0 (ESRI, Redland, CA). The mean depth of microlows below the elevation of the microhighs was approximately 20 cm, with a mean diameter of 3.2 m as calculated from the digitized gilgai maps. Both EC₂₅ surveys (March 2011 and April 2012) followed the visual trend of the gilgai, with higher EC₂₅ observed in the microlows and lower

EC₂₅ observed in the microhighs, although this trend appeared to be less strong after plowing (Fig. 4).

Measured soil properties for microhighs and microlows to a depth of 100 cm, and depth to parent material, are listed in Table 1. We analyzed soil properties down to 100 cm because that was the depth where we had complete soil property information for every soil core. The chemical and physical properties varied between microhighs and microlows, and followed the same trends observed by Wilding et al. (1989). Microlows tended to have deeper solums and more clay-sized particles, while microhighs contained greater inorganic C content. Electrical conductivity of the soil solution (EC_{2:1}) was statistically different between microhighs and microlows, but was overall very low. In this field, it did not appear that electrical conductivity was a driver of spatial differences observed in EC₂₅ as the majority of the correlation came from a single data point. Once this point was removed, the correlation disappeared (data not shown). Mean surface organic C content (0 to 20 cm) was not statistically different between gilgai positions, but microlows did contain more organic C at 20 to 40 cm. Even though soil properties followed the expected trends in microtopography, only clay content, organic C content at 20 to 40 cm, and EC_{2:1} were significantly correlated with microtopography (p-value < 0.1). One reason for this might be the low number of samples taken.

3.1. Unplowed Analysis, 2011

To evaluate the spatial variability of EC₂₅ measurements over the study site, semivariograms were calculated for both the north and south portions of the field. The semivariogram of EC₂₅ in 2011, before the southern portion of the field was plowed, showed a sill at 2 to 3 m (Fig. 5), which corresponds with the mean diameter of microlows in our study area, and the semivariograms for the north and south portions of the field were not different from

each other ($p > 0.01$). Results of Moran's I with an increase in the number of neighbors are shown in Figure 6. In 2011, spatial autocorrelation of elevation and EC_{25} decreased with an increasing number of neighbors, suggesting an association of EC_{25} with elevation at close distances. This relationship was also observed by Clay et al. (2001) at the landscape scale, with higher EC_a found at the footslope and lower EC_a on the summit positions. However, because subsurface soil properties such as clay content and inorganic C content are known to vary with surface elevation changes, this autocorrelation is likely due to subsoil properties associated with micro-elevation changes (microlows and microhighs), and not the elevation of the study site itself.

Correlation coefficients of measured soil properties, including gravimetric water content and bulk density, and EC_{25} , were used to investigate which properties were contributing to the response of the EM38. To improve normality of the distribution, EC_{25} was transformed using the natural log before correlations were calculated. Gravimetric water content across the study site ranged from 0.25 to 0.34 $kg\ kg^{-1}$, and was slightly lower at the microhighs (p -value < 0.05). Bulk density of dry soil ranged from 0.93 to 1.34 $Mg\ m^{-3}$ with higher bulk densities at the microhighs; however, the trend was not statistically significant. In unplowed conditions, gravimetric water content, inorganic C and surface organic C contents were all significantly correlated with EC_{25} (Table 2). There was also a significant correlation between water content and bulk density. The correlation of EC_{25} with surface organic C content is likely a function of landscape position and not an effect of the surface organic C content itself, as organic C content tends to be higher in the microlows, as does EC_{25} .

Variations in inorganic C and gravimetric water contents are also both associated with gilgai features, with lower inorganic C content found in microlows along with higher water

content. Clay et al. (2001) also observed a relationship between landscape position and increased EC_a in the lower landscape positions which correlated with both higher water and clay contents. To test the effect of inorganic C content on EC_a , and if it was an independent factor or just co-correlated with gravimetric water content, the partial correlation coefficient between EC_{25} and inorganic C content was calculated. The co-correlation coefficient of inorganic C content and EC_{25} while controlling for water content was -0.65 (p-value = 0.001), which did not differ from the correlation coefficient between EC_{25} and inorganic C content of -0.63. This is evidence that the correlation of EC_{25} and inorganic C content is not due to co-correlation of inorganic C content with other soil properties. This relationship may be due to a decrease in the surface conductivity of the soil particles (Rhoades et al., 1976; Neely et al., 2016).

3.2. Plowed Conditions, 2012

Two weeks after the south half of the field was plowed, the entire field was mapped with the EM38 (Fig. 4), and gravimetric water content and bulk density samples were taken at the same locations as in March 2011. We plowed only half the field (southern half) and left the northern half intact as a control treatment. A disc plow was pulled through the field 10 times at a depth of approximately 15 cm until all indication of surface features were removed. The mean water contents for the microhighs and microlows in the unplowed field were 0.28 and 0.33 kg kg⁻¹ respectively, and the mean water contents for the former microhighs and microlows of the plowed field were 0.28 and 0.34 kg kg⁻¹, respectively. Due to the small number of cores for each group, these means were not tested for statistical significance. Although it does appear that even after plowing removed surface features of the microlows, the microlow positions still had more water than microhighs. It is possible that there was not enough time between plowing and the EM38 survey for soil water content to come to equilibrium across the study area. However, due

the spatial differences in soil morphology between microhighs and microlows, it is also possible that the observed spatial pattern of EC₂₅ would remain intact over time.

The semivariogram of EC₂₅ for the north half of the field, which was not plowed, is similar to the semivariogram of the 2011 survey (Fig. 5). However, the semivariogram of EC₂₅ for the south field had much lower variance. When calculating Moran's I for an increasing number of neighbors, the spatial autocorrelation did not decrease as quickly for increasing neighbors for the plowed field (south) when compared to the unplowed field (north) (Fig. 6). By plowing the soil, the spatial pattern of EC₂₅ is smoothed out and the variability at close distances is decreased. Although the visual pattern of EC₂₅ associated with gilgai location remained mostly intact, the decrease in variance suggests a decrease in the overall variability of EC₂₅ across the field. Additionally, the increase in Moran's I shows stronger spatial autocorrelation over greater distances when compared to the unplowed field.

Correlation tables for the plowed (south) and unplowed (north) fields show a significant relationship between log-transformed EC₂₅ and inorganic C content for both fields (Table 3). In addition, gravimetric water content was significantly correlated to EC₂₅ for the plowed field. No other soil properties were significantly correlated with EC₂₅. These results are consistent with the 2011 survey and show that the major drivers of differences in observed EC₂₅ in a non-saline, calcareous Vertisol are gravimetric water content and inorganic C content under both intact (unplowed) and plowed conditions. This is useful because these properties are associated with subsurface variation tied to the presence of gilgai, even when the surface indication of gilgai has been removed by plowing.

4. Conclusions

The EM38 was able to pick up differences between the subsoil properties between microhighs and microlows under both intact (unplowed) and plowed conditions. Plowing tended to smooth the response of the EM38 leading to less variance across the field and an increase in spatial autocorrelation of EC_{25} and elevation at greater distances. The EM38 was able to respond to subsoil properties associated with gilgai even under plowed conditions, but the pattern was less apparent than in the undisturbed landscape. The effect of inorganic C content on decreasing EC_a may be independent of co-correlation with other soil properties, and in Vertisols not developed from calcareous parent materials, it may be more difficult to observe subsoil spatial variability in plowed fields, unless a different soil property varies that can be detected by EC_a .

When conducting EM38 surveys of areas suspected of having gilgai but has been plowed, areas of isolated, increased conductivity are likely to be microlows. To sample these fields, short-interval (meter-scale) variability could be stratified and sample sites selected based on observed EC_a . Organic C content appeared to vary on these landscapes with gilgai position; therefore, capturing the spatial variability is useful for locating and planning organic C content measurements and monitoring. Due to its response to differences in subsoil properties such as inorganic C content, the EM38 has shown potential in mapping subsurface variability in a non-saline, calcareous Vertisol.

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Figure 1. Cross-sectional profile of gilgai morphology (adapted from Spotts, 1974).

Figure 2. Images of the inactive gilgai at the research location under wet, winter conditions (left), dry, summer conditions (middle), and dry, summer conditions after plowing (right).

Figure 3. Elevation of study site with sampling site locations. Relative elevation is from lowest point in field (147.1 m above sea level). Gilgai are outlined, and the southern half of the field was plowed after elevation was surveyed.

Figure 4. Maps of temperature-corrected apparent electrical conductivity (EC_{25}) for March 2011 and April 2012. Surveys were conducted in the vertical dipole mode. Gilgai are outlined.

Figure 5. Semivariograms for temperature-corrected apparent electrical conductivity (EC_{25}) for 2011 and 2012. The south portion of the field was plowed for the 2012 survey.

Figure 6. Spatial autocorrelation of temperature-corrected apparent electrical conductivity (EC_{25}) and elevation as tested by Moran's I for an increasing number of neighbors. The south portion of the field was plowed for the 2012 survey.

Table 1. Summary of profiled-averaged soil properties for microhighs and microlows in the study area (n=15, 7 from microhighs and 8 from microlows).

Soil Property	Microhighs			Microlows		
	mean	min	max	mean	min	max
EC _{2:1} (mS m ⁻¹) *	0.17	0.13	0.28	0.18	0.13	0.31
Inorganic C (g kg ⁻¹)	31.8	18.2	50.9	25.2	13.5	37.5
Organic C (0-20 cm) (g kg ⁻¹)	16.9	9.2	21.3	16.2	9.2	29.9
Organic C (20-40 cm) (g kg ⁻¹)*	7.3	4.1	10.9	11.9	4.5	29.1
Depth to Parent Material (cm)	108	80	130	119	100	145
Clay (g kg ⁻¹)*	490	450	520	530	510	560

* Student's t-test statistically different at $\alpha = 0.1$.

Table 2. Correlation (Pearson's correlation coefficient, r) between soil properties in unplowed conditions (2011). Significance is reported at the 0.1, 0.01, and 0.001 p-value for correlation coefficients with *, **, and ***, respectively (n=15).

	$\ln(\text{EC}_a)$	Water Content (kg kg^{-1})	Inorganic C (g kg^{-1})	Bulk Density (Mg m^{-3})	Depth to Parent Material (cm)	Organic C (0-20 cm, g kg^{-1})	Organic C (20-40 cm, g kg^{-1})
$\ln(\text{EC}_a)$	1						
Water Content (kg kg^{-1})	0.60**	1					
Inorganic C (g kg^{-1})	-0.63**	-0.22	1				
Bulk Density (Mg m^{-3})	-0.25	-0.60**	-0.02	1			
Depth to Parent Material (cm)	0.01	0.11	-0.19	0.12	1		
Organic C (0-20 cm, g kg^{-1})	-0.43*	-0.01	0.26	0.18	0.38	1	
Organic C (20-40 cm, g kg^{-1})	0.19	0.46*	-0.02	-0.12	0.06	0.22	1

* EC_a is bulk apparent electrical conductivity corrected to 25°C

Table 3. Correlation (Pearson's correlation coefficient, r) between soil properties for 2012. Significance is reported at the 0.1, 0.01, and 0.001 p-value for correlation coefficients with *, **, and ***, respectively.

	$\ln(\text{EC}_a)$	Water Content (kg kg^{-1})	Inorganic C (g kg^{-1})	Bulk Density (Mg m^{-3})	Depth to Parent Material (cm)	Organic C (0-20 cm, g kg^{-1})	Organic C (20-40 cm, g kg^{-1})
<i>North (Unplowed)</i>							
$\ln(\text{EC}_a)$	1						
Water Content (kg kg^{-1})	0.57	1					
Inorganic C (g kg^{-1})	-0.70*	-0.51	1				
Bulk Density (Mg m^{-3})	-0.24	-0.05	-0.09	1			
Depth to Parent Material (cm)	0.41	0.11	-0.35	0.03	1		
Organic C (0-20 cm, g kg^{-1})	-0.38	0.11	0.03	0.66*	0.28	1	
Organic C (20-40 cm, g kg^{-1})	-0.10	0.54	-0.24	0.12	0.21	0.60*	1
<i>South (Plowed)</i>							
$\ln(\text{EC}_a)$	1						
Water Content (kg kg^{-1})	0.69*	1					
Inorganic C (g kg^{-1})	-0.67*	-0.74*	1				
Bulk Density (Mg m^{-3})	-0.18	-0.71*	0.51	1			
Depth to Parent Material (cm)	-0.15	0.07	-0.11	-0.48	1		
Organic C (0-20 cm, g kg^{-1})	-0.33	0.06	0.23	-0.25	0.67*	1	
Organic C (20-40 cm, g kg^{-1})	-0.32	0.31	-0.15	-0.68*	-0.04	0.00	1