Apparent Electrical Conductivity Response to Spatially Variable Vertisol Properties

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Abstract

Though much has been done to understand proximally-sensed bulk apparent electrical conductivity (EC_a) in agricultural soils, many of the soil properties identified to be mappable using these techniques, such as salinity and clay content, are not expected to drive EC_a response in a non-saline Vertisol. In Vertisols, agrillipedoturbation creates meter-scale variability in soil moisture and chemical properties associated with gilgai features, and if developed from calcareous parent material, can exhibit meter and landscape scale variability in inorganic C content. The ability to map inorganic C may be especially useful in a Vertisol due to its strong correlation with shrink-swell potential. The overall goal of this project was to investigate the potential for mapping inorganic C using EC_a surveys in a calcareous Vertisol, with the future goal of mapping shrink-swell potential on these landscapes. On a 40- by 50-m field with intact circular gilgai, EC_a was mapped under both moist and dry soil conditions. Soil samples were taken for water content, clay content, inorganic C content, salinity, and depth to parent material. Under moist soil conditions, the strongest correlation to EC_a was inorganic C content ($r = -0.63$), followed by water content ($r = 0.49$); however, under dry conditions, only inorganic C content was significant ($r = -0.60$). In addition, EC_a surveys and inorganic C samples were taken for two larger watersheds of 10 and 14 ha. Again, inorganic C content was significantly and reliably correlated to EC_a for both fields, and the resulting regression slopes and intercepts were not significantly different between watersheds, though the surveys were conducted at different times. Results suggest that EC_a can be used to map inorganic C in Vertisols weathered from calcareous parent materials, allowing for spatial inference of shrink-swell potential which may be useful in distributed hydrology modeling.

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1. Introduction

Bulk apparent electrical conductivity of the soil (EC_a), as measured by electromagnetic induction, is a useful measurement that is commonly used to map the spatial variability of soil salinity, water content, and clay content, especially as they relate to agriculture and land management (Rhoades et al., 1976; McBride et al., 1990; Corwin and Lesch, 2005; Brevik et al., 2006). In moderately-fine to coarse-textured agricultural soils, the EM38 (Geonics Limited, Mississauga, Ontario, Canada), a popular electromagnetic induction instrument, has been used to map zones of soil variability for precision agriculture (Lund et al., 1999; Johnson et al., 2001; Corwin and Lesch, 2005), predict clay content (Carroll and Oliver, 2005; Weller et al., 2007; Harvey and Morgan, 2009) and soil depth (Doolittle et al., 1994; Akbar et al., 2004; Serrano et al., 2010), as well as map soil water content (Kachanoski et al., 1990; Zhu et al., 2010a; Zhu et al., 2010b). However, variability of EC_a has been observed in non-saline Vertisol landscapes when none of these properties vary under saturated soil moisture conditions (Rivera, 2011). In the calcareous Vertisols of the Texas Blackland Prairie, response of EC_a might be driven by changes in inorganic C content, as was observed in a calcareous sand (Kuhn et al., 2009). Knowledge of the soil properties that influence electromagnetic induction response on Vertisol landscapes would help assess the usability of these proximal sensors in otherwise relatively uniform, high-clay soil.

Soil properties can have a direct or indirect influence on the conductivity of the soil. Direct influence requires a soil property to alter the conductivity of either the liquid or solid phase of the soil (Rhoades et al., 1976). Soil properties such as salinity and clay content directly influence the EC_a due to increasing the conductivity of the liquid and solid phase respectively. An example of indirect influence would be soil organic matter, because while it influences the

water holding capacity and the number of cations in soil solution, EC_a does not respond directly to changes in organic matter content but rather the changes in the solid and liquid phase conductivity altered by the organic matter. We propose inorganic C will have a direct influence on EC_a because increasing the amount of inorganic C will decrease the overall solid phase conductivity through a decrease in specific surface area (Holford and Mattingly, 1975) and displacing charged clay particles (Rhoades et al., 1976).

In Vertisols formed from calcareous parent materials, inorganic C concentrations are largely driven by the extent of weathering of the parent material and translocation of inorganic C. Variability in weathering, and therefore inorganic C content, is influenced by landscape position and can occur at the 10-m scale. In addition, Wilding et al. (1989) observed variability in inorganic C on the meter-scale due to surface microtopography features called gilgai. Gilgai are surface features consisting of small depressions (microlows) separated by ridges (microhighs), and often coincide with surface topography. Within these features, increased clay content and organic C is found in the bowls/microlows and increased inorganic C in the chimneys/microhighs, relative to the opposite position. Inorganic C also has a strong relationship with the shrink-swell potential of the soil (Dinka et al., 2013), making it a potentially useful soil property for mapping shrink-swell potential.

The overall objective of this project was to investigate the potential for mapping inorganic C using EC_a surveys in a calcareous Vertisol, with the future goal of increased accuracy in mapping shrink-swell potential on these landscapes. In addition, it is useful to link EC_a with soil properties using correlations and empirical models, as in McBratney et al. (2005). The specific objectives of this study were to 1) describe the response of EC_a to measured soil properties on calcareous Vertisols through a small-scale, detailed study, 2) investigate the

response of the EM38 to inorganic C at the field scale under two land-uses, and 3) build an empirical model to predict inorganic C content across non-saline Vertic landscapes using proximally-sensed EC_a .

2. Materials and methods

This study was conducted in the Blackland Prairie of Texas, U.S.A., an ecoregion of around 50,000 km² that includes the large population centers of Dallas and Austin (Griffith et al., 2007). A detailed, small-field study and a large field study were conducted to evaluate the response of the EM38 to soil properties. The detailed field study measured multiple soil properties to determine the effect of soil moisture, clay content, salinity, depth of the soil to the parent material, and inorganic C on proximally sensed EC_a across a 0.2-ha area with circular gilgai. The large field study was conducted in two, adjacent watersheds of 10 and 14 ha each. One field was cropped annually and the other was under improved pasture conditions. The large field study was only sampled for inorganic C. All study sites were located on the USDA-ARS Grassland, Soil and Water Research Laboratory watershed network near Riesel, TX (Fig. 1).

2.1. Detailed field study

A 40- by 50-m area of a Houston Black clay (fine, smectitic, thermic Udic Haplusterts) was investigated for the detailed study. The study site had not been plowed for over 30 years and contained circular gilgai microtopography. One electromagnetic induction survey and soil sampling was conducted on 11 March 2011, when the field was close to field capacity, and an additional survey was conducted on 11 September 2011, under dry soil conditions. An EM38 sensor in the vertical dipole mode only was used to measure EC_a in combination with an AgGPS for geo-referencing (Trimble Navigation Limited, Sunnyvale, CA). In the vertical dipole mode, the EM38 senses from 1.5 to 2 m deep, with a sampling area of approximately 1 m² (McNeil,

1980). Both surveys were walked (1.1 m s^{-1}) on 1-m, parallel transects while logging EC_a measurements and GPS location automatically every second. Instrument drift was assessed using one location marked for measurements before and after surveys, and soil temperature was recorded 5 cm below the soil surface before and after surveys. All EC_a measurements were standardized to 25°C using the Sheets and Hendrickx (1995) correction,

$$\text{EC}_{25} = \text{EC}_T * \left(0.4470 + 1.4034e^{-T/26.815}\right), \quad [1]$$

where EC_T is the EC_a data collected, and T is the measured soil temperature ($^\circ\text{C}$). For simplicity, temperature corrected EC_a (EC_{25}) will still be referred to as EC_a .

Geo-referenced soil samples were collected for soil water content at the time of each survey, plus soil properties including clay content, soil depth, inorganic C content, and electrical conductivity of the soil solution were measured in the laboratory. Sampling locations across the field were stratified based on EC_a and landscape position to capture the range of measured EC_a measurements. A total of 16 sampling sites were selected for the March survey. At each sampling location, two 5 cm diameter cores were taken within 0.5 m distance. One core was taken for volumetric water content and cut at 10-cm intervals, and the other was cut into 20-cm sections and air-dried at 60°C for analysis of soil properties. During the September survey, 8 of the 16 original sampling locations were selected and soil cores for soil water content only were collected. Soil cores were taken to a depth of 2 m or to the weathered marl parent material.

Volumetric water content was calculated by multiplying by bulk density of the 10-cm core sections by their gravimetrically-determined water content. For gravimetric water content measurements, core sections were oven dried for over 48 hours at 105°C . The separate set of 20-

cm soil core sections were ground and passed through a 2-mm sieve for inorganic C content, electrical conductivity, and clay content characterization. Soil analysis methods included modified pressure calcimeter for inorganic C content (Sherrod et al., 2002). Electrical conductivity of the soil solution was performed using a multicell conductivity probe (545, Amber Science Inc., Eugene, OR) with 2:1 water to soil extract (Rhoades, 1982). Soil particle size distribution was measured using the pipette method (Kilmer and Alexander, 1949). Correlations of EC_a measured with soil properties at depth and across the field and as well as all regressions were calculated in R (R Development Core Team, 2012).

2.2. Large field study

To test EC_a response to inorganic C at a larger spatial scale, two additional surveys using the EM38 in the vertical dipole model were conducted when the soil water content was near field capacity (approximately $35 \text{ m}^3 \text{ m}^{-3}$). The goal of this study was to evaluate the response of the EM38 specifically to inorganic C and additional soil properties, including soil water content, were not measured. Surveys were conducted in January 2007 (Field 1) and March 2006 (Field 2) using 10-m transect spacing. Soils present in the field are mapped as Houston Black and Heiden clays (fine, smectitic, thermic Udic Haplusterts). The EM38 was pulled on a sled with an all-terrain vehicle at an approximate speed of 3 m s^{-1} , and both surveys were temperature corrected using Eq. [1] (Sheets and Hendrickx, 1995). Field 1 is a 14-ha field that has been terraced and cropped annually in a corn and wheat rotation. Immediately to the north is Field 2, a 10-ha field which is in perennial, grazed pastureland. Thirty-nine soil cores were collected and analyzed for inorganic C, 24 from Field 1, and 15 from Field 2. The coring sites were selected by stratifying the EC_a values across each field.

3. Results and discussion

3.1. Detailed field study

Bulk apparent electrical conductivity values were higher and greater in range in March (65 to 145 mS m⁻¹) when the soil was moist compared with September (17 to 55 mS m⁻¹) when the soil was dry. The spatial pattern of proximally-sensed EC_a visually correlated with gilgai position and surface shape across the study site for the March (moist conditions) survey, but the visual assessment of gilgai presence in EC_a during September was less defined (Fig. 2). Circular gilgai, i.e. surface features consisting of small depressions (microlows) separated by ridges (microhighs), were also associated with subsurface variability in soil properties. Because increases in clay content and organic C content in the bowls/microlows and increases in inorganic C content in the chimneys/microhighs have commonly been observed in similar soils (Wilding et al., 1989; Miller et al., 2010), the response of the EM38 to soil properties will be considered for the whole study site and by microtopography position, i.e. microhighs and microlows. The distance between these features is usually between 3 and 10 m. Figures 3 and 4 show the average of soil properties by depth increment with the standard deviation. Drier soil moisture conditions were observed in September when compared to March with the driest soil water contents at the soil surface. Soil water contents were slightly higher in the microlow microtopography position for the March survey compared with microhighs (Figure 3). Averages with depth for clay content, inorganic C content and EC_{2:1} were plotted by microtopography position and were consistent with findings by Wilding et al. (1989), with higher clay content and lower inorganic C content in the microlows (Figure 4). However, similar to soil water content, standard deviation for averages by microtopography overlapped.

The EM38 is a powerful tool for rapid mapping of field-scale soil variability; however, data interpretation is challenging due to two reasons: 1) the contribution of soil properties to the

response of the EM38 is not equal with depth and 2) the uncertainty in the specific soil property or properties driving the response. The variability in soil properties is the major driver of the spatial pattern observed in the response of the EM38, and this variability in soil properties can occur both horizontally and vertically in space. Because of this, both the horizontal and vertical distribution of soil properties should be considered when interpreting maps of EC_a as measured by the EM38.

The usual approach to comparing EC_a measurements with soil properties is to average soil properties for a single location. An alternative approach to profile-averages is to compare the EM38 response to soil properties by depth. While this type of analysis does not necessarily mean that the EM38 is most sensitive to the depth with the highest correlation, it does give some information as to what will drive the overall correlation of profile-averaged soil properties with EC_a . When calculating correlations of EC_a to soil property measurements by depth for soil water content, inorganic C content, and clay content by depth and within gilgai position, the strongest correlations for soil water content (Table 1), inorganic C content (Table 2), and clay content (Table 3) did not occur at the predicted 30 to 40 cm from the McNeil (1980) function. Additionally, drier soil moisture conditions (September survey) shifted the strongest correlations to inorganic C content deeper into the soil (Table 2), and decreased the correlation to water content (Table 1). This study area was not sufficiently large nor were enough soil samples collected to characterize the EM38 response or to shift the profile-averaging function; however, it is important when using an EM38 to map soil properties to carefully consider not only the spatial distribution but the vertical distribution of soil properties as well.

Although soil properties are often measured on discrete depth increments, to make correlations with EC_a data, soil properties are usually first vertically-averaged for a location.

The risk in calculating soil profile-averages for a location is using incorrect weights for the vertical-averaging function and obscuring the relationship of the EM38 response to a given soil property. This can be especially true in soils with high degrees of vertical heterogeneity. Correlations between EC_a measurements and soil properties at a single location are generally improved by weighted-averages of soil properties with depth based an assumed response of the instrument with depth when compared to simple averages (Harvey and Morgan, 2009). The relative influence of soil properties with depth on EC_a can be modeled by the theoretical response curve,

$$\phi_v = \frac{4z}{(4z^2 + 1)^{3/2}}, \quad [2]$$

where ϕ_v is the sensitivity function of the EM38 with depth and z is depth (m) from the soil surface (McNeil, 1980; Fig. 5). This function predicts maximum sensitivity at 35 cm from the soil surface; however, in a simulation study, the depth of exploration for electromagnetic induction instruments was shown to decrease with increasing EC_a (Callegary et al., 2007), and in clay soils may be shallower than predicted by McNeil (1980).

Profile-averages of soil water content ranged from 0.31 to 0.42 $m^3 m^{-3}$ in March and 0.16 to 0.20 $m^3 m^{-3}$ in September, and patterns of water content were largely tied to gilgai position with higher water contents found in microlows, and lower water contents on the microhighs. Profile-averages of inorganic C content for the study site ranged from 12 to 45 $g kg^{-1}$. Higher inorganic C contents were found in microhighs, and lower contents in microlows, as expected from the averages of soil properties by depth and by microtopography position in Figures 3 and 4. Electrical conductivity of the 2:1 water-soil solution ($EC_{2:1}$) ranged from 0.15 to 0.23 $dS m^{-1}$.

Clay content was high, with values between 45 and 56%. The depth to parent material was between 80 and 130 cm, with a clear boundary between the solum and weathered calcareous parent material. The spatial patterns of soil properties were consistent with previous findings (Wilding et al., 1989; Coulombe et al., 1996) and corresponded to position in the microtopography. Similarly, in a moderately fine-textured soil in undulating topography, EC_a was strongly correlated with soil water storage (Kachanoski et al., 1990), which may indicate that strongly varying topography drives EC_a response by both soil water distribution and preferential weathering patterns.

To investigate the relationship between EC_a and soil properties, correlations among profile-averages of measured soil properties and EC_a from EM38 surveys were made for both surveys (Table 4). For the September survey, only the 8 locations that had soil water content measurements were used in the correlation table. Electrical conductivity of the soil solution ($EC_{2:1}$) and clay content were both not significantly correlated with EC_a for either survey. In March (moist conditions), both soil water content and inorganic C content were significantly correlated with EC_a , but in September, only inorganic C content was significantly correlated with EC_a . A response to inorganic C was also observed by Kuhn et al. (2009) on a calcareous-sandy landscape. Clay content was significantly, positively correlated with water content in March and had a high but not significant correlation in September, likely due to clay having a high water holding capacity.

Akbar et al. (2004) observed an increase in EC_a with increasing soil depth in a Texas Vertisol; however, in our study, depth to parent material was not well correlated to EC_a . This is likely because depth to parent material occurred between 80 to 200 cm, which is deeper than the EM38's most sensitive depths and deeper than the soils in Akbar et al. (2004). In Vertisols

formed from calcareous parent materials, transition from the soil solum to parent material can be marked by a large increase in inorganic C. If EM38 measurements are related to inorganic C, we might expect the EC_a to be mapping soil depth (or thickness) if the soil depth is sufficiently shallow to be in the area of influence of the EM38. However, at this location, the calcareous parent material was sufficiently deep to be out of the range of influence of the EM38.

If higher concentrations of inorganic C were found in landscape positions that typically had lower water contents, then the response of the EM38 would not only be due to the increases in inorganic C, but also the decreases in water content. Again, this cumulative and additive response of EC_a to multiple soil properties is common in EM38 mapping (Kachanoski et al., 1990; Weller et al., 2007; Harvey and Morgan, 2009). However, the strong correlation of inorganic C content with EC_a in September (dry survey), absent of strong EC_a -water content correlation, suggests that inorganic C does have some direct effect on EC_a measurements. These results suggest that inorganic C has both a direct and indirect influence on EC_a , and is likely influencing both the water holding capacity of the soil and the surface conductivity of the solid phase. Inorganic C content is plotted against EC_a for both surveys in Figure 6. Despite the similar correlation coefficients (Table 4) and statistically significant slopes in both surveys (data not shown), the March survey had a more negative slope. This is due to the greater range in EC_a observed in March when compared with September. The relationship between EC_a and inorganic C content may be useful because inorganic C decreases shrink-swell potential of the soil (Dinka et al., 2013), and we may be able to use inorganic C content as a proxy for mapping shrink-swell potential across non-saline Vertisol landscapes.

3.2. Large field study

Point EC_a data was spatially interpolated across the study site using a tension spline on a 0.25-m grid in ArcGIS v.10.0 (ESRI, Redlands, CA). The terraces of Field 1 are visible on the EC_a maps as linear features, nonetheless the landscape trends in EC_a are still intact (Fig. 7). For example, larger EC_a values are seen along the concave portion of the footslope. In Field 2, lower EC_a values are found on the shoulders with the largest values found on the footslope (Fig. 7).

Because the purpose of the large field study was to investigate if the EM38 responds to variability in inorganic C content, only inorganic C was measured for Fields 1 and 2. Equation 2 was used to calculate profile-averages of inorganic C content for each sampling location in the two larger fields. Inorganic C content was negatively correlated with EC_a in both fields; however, there was less variability in the linear relationship in Field 2 (Fig. 8). The additional variability observed in Field 1 is likely due to the influence of terracing on soil water redistribution. Although two separate regression equations were initially calculated using least squares regression, neither the slopes (p-value = 0.51) nor intercepts (p-value = 0.65) were statistically different from each other. As a result, a single regression equation was used to map inorganic C content (Fig. 8) for Fields 1 and 2, representing both annually-cropped and grazing-land land uses.

3.3. Predicting inorganic C content

In the model from McBratney et al. (2005), which is limited to non-saline soils, EC_a measurements were suggested to be a function of clay content, when soil water content was normalized by the saturated water content (θ_s) and cation exchange capacity (CEC) was normalized to the cation exchange capacity of the reference soil (CEC_0). A fitting factor (κ , units of $mS\ m^{-1}$) was used to calibrate the model,

$$EC_a = \kappa * \frac{\text{Clay}}{100} * \frac{\theta}{\theta_s} * \frac{CEC}{CEC_0}. \quad [3]$$

The model was then used to predict clay content from EC_a data, using surveys under field capacity conditions and pedotransfer functions to calculate CEC. Because clay content was the most variable soil property in their case, McBratney et al. (2005) argued that EC_a could be used as the prediction variable.

In non-saline, calcareous Vertisols where inorganic C content is the most variable soil property driving EC_a measurements, we may be able to modify this equation and use it to spatially predict inorganic C content. Instead of using pedotransfer functions, we used data from the NRCS database for clay content, and saturated water content. Then, EC_a for each location ($EC_{a,i,j}$) is then relative to EC_{a0} of the field, where EC_{a0} is the scaling factor that represents EC_a of this soil with no inorganic C, which is calculated as the intercept of the regression of EC_a and measured inorganic C content. The resulting equation,

$$\widehat{IOC}_{i,j} = \kappa * \frac{(EC_{a0} - EC_{a,i,j})}{EC_{a0}} * \frac{\text{Clay}}{100} * \frac{\theta}{\theta_s}, \quad [4]$$

predicts inorganic C content as a function of EC_a . The fitting factor, κ , ($g\ kg^{-1}$) was used to fit the data to the model as in McBratney et al. (2005) by minimizing the model's root mean squared error (RMSE).

We used the model for the large field study, using NRCS data from soil mapping units and measurements of EC_a . Clay content was 55 and 50 (%) for Houston Black and Heiden units respectively (as mapped in Figure 1). Soil water content was assumed to be a constant $0.30\ m^3$

m^{-3} , and the saturated water content, θ_s , was reported at $0.40 \text{ m}^3 \text{ m}^{-3}$ for Houston Black map units and $0.37 \text{ m}^3 \text{ m}^{-3}$ for Heiden map units. The model of predicted inorganic C content using Eq. [4] was compared with measured values (Fig. 9); the model had an RMSE of 14.2 g kg^{-1} and tended to over-predict inorganic C content from EC_a data. In this model, clay content only varied by soil mapping unit; it is likely that improvements could be seen with a finer-scale map of clay content. Other proximal sensing instrumentation, such as gamma-ray spectrometry, has been shown to respond to clay content (van der Klooster et al., 2011) and may help improve this simple model by adding additional information.

4. Conclusions

In this study, measurements of EC_a in calcareous Vertisol landscape were correlated with inorganic C content and water content in these high-clay, moderately well drained soils when the soil was moist. Under dry conditions only inorganic C content was correlated to EC_a . Neither clay content nor depth to parent material appeared to significantly influence the response of the EM38.

In non-saline clay soil developed from calcareous parent materials, EC_a can be used to detect changes in inorganic C content at the 1-m and 10-m scale when clay content is relatively uniform. There may be co-correlation of soil water content and inorganic C content in low-lying landscape positions that are lower in inorganic C contents due to the translocation of inorganic C by water. However, it does appear that inorganic C may also have an independent effect on EC_a . Because inorganic C influences the shrink-swell potential of the soil (Dinka et al., 2013), EC_a can be used as a proximal sensing tool to map changes in cracking potential across these landscapes. These maps will be useful for predicting soil cracking potential in spatially distributed hydrology models.

5. Literature cited

- Akbar, M.A., Kenimer, A.L., and Searcy, S.W., 2004. Estimating soil profile depth with apparent electrical conductivity for a Texas Vertisol. *Trans. ASAE* 47, 1087-1092.
- Brevik, E.C., Fenton, T.E., and Lazari, A., 2006. Soil electrical conductivity as a function of soil water content and implications for soil mapping. *Prec. Agric.* 7, 393-404.
- Callegary, J.B., Ferré, P.A., and Groom, R.W. 2007. Vertical spatial sensitivity and exploration depth of low-induction-number electromagnetic-induction instruments. *Vadose Zone J.* 61, 158-167.
- Carroll, Z.L., and Oliver, M.A., 2005. Exploring the spatial relations between soil physical properties and apparent electrical conductivity. *Geoderma* 128, 354-374.
- Corwin, D. L., and Lesch, S. M., 2005. Apparent soil electrical conductivity measurements in agriculture. *Comput. Electron. Agr.* 46, 11-43.
- Dinka, T.M., Morgan, C.L.S., McInnes, K.J., Kishne, A.Sz., and Harmel., R.D., 2013. Shrink-swell behavior of soil across a Vertisol catena. *J. Hydrol.* 475, 352-359.
- Doolittle, J.A., Sudduth, K.A., Kitchen, N.R., and Indorante, S.J., 1994. Estimating depth to claypans using electromagnetic induction methods. *J. Soil Water Conserv.* 49, 572-575.
- Griffith, G., Bryce, S., Omernik, J., and Rogers, A., 2007. Ecoregions of Texas. Texas Commission on Environmental Quality. http://www.tceq.state.tx.us/assets/public/comm_exec/pubs/as/199.pdf (Accessed 18 Feb. 2014).
- Harvey, O.R., and Morgan, C.L.S., 2009. Predicting regional-scale soil variability using a single calibrated apparent soil electrical conductivity model. *Soil Sci. Soc. Am. J.* 73, 164-169.
- Holford, I.C.R., and G.E.G. Mattingly. 1975. Surface areas of calcium carbonate in soils. *Geoderma* 13:247-255.
- Johnson, C.K., Doran, J.W., Duke, H.R., Wienhold, B.J., Eskridge, K.M., and Shanahan, J.F., 2001. Field-scale electrical conductivity mapping for delineating soil condition. *Soil Sci. Soc. Am. J.* 65, 1829-1837.
- Kachanoski, R.G., DeJong, E., and van Wesenbeeck, I.J., 1990. Field scale patterns of soil-water storage from non-contacting measurements of bulk electrical conductivity. *Can. J. Soil Sci.* 70, 537-542.
- Kilmer, V.H., and Alexander, L.Z., 1949. Methods for making mechanical analyses of soil. *Soil Sci.* 68, 15-24.

- Kuhn, J., Brenning, A., Wehrhan, M., Koszinski, S., and Sommer, M., 2009. Interpretation of electrical conductivity patterns by soil properties and geological maps for precision agriculture. *Precision Agric.* 10, 490-507.
- Lund, E.D., Christy, D., and Drummond, P.E., 1999. Applying soil electrical conductivity technology to precision agriculture. in: Robert, P.C., Rust, R.H., and Larson, W.E. (Eds.), *Proceedings of the 4th International Conference on Precision Agriculture*. ASA: Madison, WI., pp. 1089–1100.
- McBratney, A.B., Minasny, B., and Whelan, B.M., 2005. Obtaining ‘useful’ high –resolution soil data from proximally-sensed electrical conductivity/resistivity (PSEC/R) surveys. in: Stafford, J.V. (Ed.), *Precision Agriculture, Papers presented at the 5th European Conference on Precision Agriculture*, Uppsala, Sweden, pp. 503-510.
- McBride, R.A., Gordon, A.M., and Shrive, S.C., 1990. Estimating forest soil quality from terrain measurements of apparent electrical conductivity. *Soil Sci. Soc. Am. J.* 54, 290-293.
- McNeil, J.D., 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Tech Note TN5. Geonics, LTD., Mississauga, Ontario, Canada. Available at: <http://www.georentals.co.uk/tn6.pdf>.
- Miller, W.L., Kishne, A.Sz., and Morgan, C.L.S., 2010. Vertisol morphology, classification, and seasonal cracking patterns in the Texas Gulf Coast Prairie. *Soil Surv. Horiz.* 51, 10-16.
- Rhoades, J.D., Raats, P.A.C., and Prather, R.S., 1976. Effects of liquid-phase electrical conductivity water content and surface conductivity on bulk soil electrical conductivity. *Soil Sci. Soc. Am. J.* 40, 651-665.
- Rhoades, J.D., 1982. Cation exchange capacity. in: Page, A.L., Miller, R.H., and Keeney, D.R., (Eds.), *Methods of soil analysis. Part 2. Agron. Monogr.* 9, ASA, Madison, WI. pp. 149-157.
- Rivera, L.D. 2011. Systematic variability of soil hydraulic conductivity across three Vertisol catenas. Master’s Thesis, Texas A&M University, College Station, TX. Available electronically from <http://hdl.handle.net/1969.1/ETD-TAMU-2010-08-8203>.
- Robinson, N.J., Rampant, P.C., Callinan, A.P.L., Rab, M.A., and Fisher, P.D., 2009. Advances in precision agriculture in south-eastern Australia. I. Spatio-temporal prediction of crop yield using terrain derivatives and proximally sensed data. *Crop Pasture Sci.* 60, 859–869.
- Serrano, J.M., Peca, J.O., Marques da Silva, J.R., and Shaidian, D., 2010. Mapping soil and pasture variability with an electromagnetic induction sensor. *Comput. Electron. Agric.* 73, 7-16.

- Sheets, K.R., and Hendrickx, J.M.H., 1995. Noninvasive soil water content measurement using electromagnetic induction. *Water Resour. Res.* 31, 2401-2409.
- Sherrod, L.A., Dunn, G., Peterson, G.A., and Kolberg, R.L., 2002. Inorganic carbon analysis by modified pressure-calimeter method. *Soil. Sci. Soc. Am. J.* 66, 299-305.
- van der Klooster, E., van Egmond, F.M., and Sonneveld, M.P., 2011. Mapping soil clay contents in Dutch marine districts using gamma-ray spectrometry. *Euro. J. Soil Sci.* 62, 743-753.
- Weller, U., Zipprich, M., Sommer, M., Castell, Zu., W. and Wehrhan, M., 2007. Mapping clay content across boundaries at the landscape scale with electromagnetic induction. *Soil Sci. Soc. Am. J.* 71, 1740-1747.
- Wilding, L.P., and Tessier, D., 1988. Genesis of Vertisols: shrink-swell phenomena. in: Wilding, L.P., and Puentes, R. (Eds.), *Vertisols: their distribution, properties, classification and management*. USDA Soil Management Support Services, Tech. Monogr. 18. Texas A&M Univ. Printing Center, College Station, TX. pp. 55-81.
- Wilding, L.P., Williams, D., Miller, W., Cook, T., and Eswaran, H., 1989. Close interval spatial variability of Vertisols: a case study in Texas. in: Kimble, J.M. (Ed.) *Proc. 6th Int. Soil Correlation Meeting (VI ISCOM), Characterization, Classification and Utilization of Cold Aridisols and Vertisols*, Aug. 6–18, 1989. USDA Soil Conservation Service, National Soil Survey Center, Lincoln, NE., pp. 232–247.
- Zhu, Q., Lin, H.S., and Doolittle, J.A., 2010a. Repeated electromagnetic induction surveys for determining subsurface hydrologic dynamics in an agricultural landscape. *Soil Sci. Soc. Am. J.* 74, 1750–1762.
- Zhu, Q., Lin, H.S., and Doolittle, J.A., 2010b. Repeated electromagnetic induction surveys for improved soil mapping in an agricultural landscape. *Soil Sci. Soc. Am. J.* 74, 1763–1774.

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492 Figure 1. Study site located near Riesel, Texas, on the USDA-ARS Grassland, Soil and Water
 493 Research Laboratory.

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497 Figure 2. Apparent electrical conductivity for the detailed field study. Apparent electrical
 498 conductivity is from moist (March) and dry (September) surveys.

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501 Figure 3. Relative response of the EM38 with soil depth (cm) based on the theoretical response
502 curve published by McNeil (1980).

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504

Figure 4. Mean volumetric water content by depth for the March and September surveys, as well as the microhighs and microlows of the March survey. Bars represent one standard deviation from the mean.

Figure 5. Mean clay content, inorganic C content, and electrical conductivity of a 2:1 water:soil solution (EC_{2:1}) by depth for microhighs and microlows of the March survey. Bars represent one standard deviation from the mean.

Figure 6. Bulk apparent electrical conductivity vs. inorganic C content measured in March (moist conditions) and September (dry conditions). Inorganic C contents are profile-averages. Both slopes are statistically significant ($p < 0.05$).

526

527 Figure 7. Apparent electrical conductivity for the large field study, Field 1 (South) and Field 2
 528 (North).

529

530

531 Figure 8. Bulk apparent electrical conductivity vs. inorganic C content for Fields 1 (annually
 532 cropped) and 2 (grazed). Inorganic C contents are profile-averages.

533

534

Figure 9. Predicted vs. measured inorganic C contents for Fields 1 (annually cropped) and 2 (grazed).

540 Table 1. Pearson's correlation coefficient between volumetric water content, measured at 10-cm
 541 depth increments and bulk apparent electrical conductivity measured using the EM38.
 542 Significance is reported at the 0.1, 0.05, and 0.001 p-value for correlation coefficients with *, **,
 543 and ***, respectively.
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545

	March (moist)	September (dry)	March (moist)	
Depth (cm)	All	All	Highs	Lows
10	0.61**	0.35	-0.04	0.28
20	0.69**	0.04	0.18	0.05
30	0.70**	-0.16	0.50	0.25
40	0.65**	-0.26	0.36	0.03
50	0.52*	0.11	0.44	-0.01
60	0.84***	0.00	0.93**	0.30
70	0.51*	0.35	0.27	-0.12
80	0.63**	0.55	0.33	0.46
90	0.13	0.35	0.53	-0.33
100	0.36	-0.18	0.79*	0.03
110	0.17	0.12	0.89**	-0.38
120	0.00	0.62*	0.91**	0.24
130	-0.26	0.26	0.94**	-0.55
140	0.33	-0.39	0.95**	-0.58
150	-0.01	0.20	0.94**	-0.70
	n = 16	n = 8	n = 7	n = 9

Table 2. Pearson's correlation coefficients between inorganic C content, measured at 20-cm depth increments, and bulk apparent electrical conductivity measured using the EM38. Significance is reported at the 0.1, 0.05, and 0.001 p-value for correlation coefficients with *, **, and ***, respectively.

	March (moist)	September (dry)	March (moist)	September (dry)		
Depth (cm)	All	All	Microhighs	Micro lows	Microhighs	Micro lows
40	-0.57*	-0.48*	-0.15	-0.71*	-0.41	-0.41
60	-0.59*	-0.50*	-0.25	-0.68*	-0.42	-0.44
80	-0.59*	-0.66**	-0.38	-0.64*	-0.51	-0.70*
100	-0.64**	-0.67**	-0.57	-0.63*	-0.64	-0.65*
120	-0.68**	-0.63**	-0.63	-0.62*	-0.67*	-0.52
140	-0.50*	-0.70**	-0.67*	-0.48	-0.85*	-0.62*
160	-0.11	-0.78***	0.00	-0.44	-0.48	-0.83**
	n = 16	n = 16	n = 7	n = 9	n = 7	n = 9

554 Table 3. Pearson's correlation coefficients between clay content, measured at 20-cm depth
 555 increments, and bulk apparent electrical conductivity measured using the EM38. No coefficients
 556 were statistically significant ($p < 0.1$).
 557

Depth (cm)	March	September
20	0.34	-0.04
40	0.36	-0.25
60	0.28	-0.27
80	0.31	-0.08
100	0.21	-0.02
120	0.07	0.03
	n=8	n=8

558

Table 4. Pearson's correlation coefficients for the detailed field study between bulk apparent electrical conductivity (EC_a) and profile-averages of soil inorganic C, soil water, and clay content, electrical conductivity of the soil solution ($EC_{2:1}$), and the depth of the soil solum for March ($n = 16$) and September ($n = 8$). Significance is reported at the 0.1 and 0.05 p-values for correlation coefficients with * and ** respectively.

		EC_a ($mS\ m^{-1}$)	Inorganic C ($g\ kg^{-1}$)	Water content ($m^3\ m^{-3}$)	Clay (%)	$EC_{2:1}$ ($dS\ m^{-1}$)	Soil depth (cm)
March ($n=16$)	EC_a ($mS\ m^{-1}$)	1					
	Inorganic C ($g\ kg^{-1}$)	-0.63**	1				
	Water content ($m^3\ m^{-3}$)	0.49*	-0.24	1			
	Clay (%)	0.30	0.24	0.49*	1		
	$EC_{2:1}$ ($dS\ m^{-1}$)	0.31	-0.39	0.39	-0.08	1	
	Soil depth (cm)	0.11	0.01	0.56**	0.44*	0.26	1
September ($n=8$)	EC_a ($mS\ m^{-1}$)	1					
	Inorganic C ($g\ kg^{-1}$)	-0.60*	1				
	Water content ($m^3\ m^{-3}$)	0.17	-0.22	1			
	Clay (%)	0.02	0.14	0.54	1		
	$EC_{2:1}$ ($dS\ m^{-1}$)	0.24	-0.49	0.57*	0.19	1	
	Soil depth (cm)	0.19	0.17	0.53	0.79	0.49	1