RESEARCH

Soybean Root Distribution Related to Claypan Soil Properties and Apparent Soil Electrical Conductivity

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ABSTRACT

Soybean [*Glycine max* (L.) Merr.] yield in claypan soils varies systematically with soil properties and landscape position. This is likely caused by soil interactions with soybean roots. Field observations of soybean root distribution are needed to reveal its effect on yield variability. This study examined profile distributions of soybean root length density (RLD) and average root diameter (ARD) as a function of landscape position, depth to claypan (DTC), apparent soil electrical conductivity (EC_a), clay-maximum translated depth (D_t), and other soil properties. A landscape of claypan soils was sampled postharvest at two sites near Centralia, MO, in 2001. Roots were washed from soil cores in 15-cm layers (15–120 cm) and measured with image analysis. Root length density and ARD were significantly related to landscape position, DTC, D_t, and EC_a. Predictions of RLD and ARD were best from 15 to 60 cm, the depths with the greatest influence from claypan soil morphology. Soil profile distributions of base cations, P, and pH matched root density profiles. Soybean roots were inhibited in E horizons above the claypan and stimulated 20 to 40 cm below it. Soybean roots below the claypan had about 20 to 30% smaller diameter. We conclude that DTC and rapid estimators of claypan morphology, such as EC_a, can be used to predict soybean root distribution in claypan soil landscapes.

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Abbreviations: ARD, average root diameter; CEC, cation exchange capacity; EC_a, apparent soil electrical conductivity; D_t, clay-maximum translated depth; DTC, depth to claypan; NA, neutralizeable acidity; OM, organic matter; RLD, root length density.

Claypan soils of northeastern Missouri and southern Illinois, the Central Claypan Areas (USDA-NRCS, 2006), possess extreme variability within the soil profile and across the landscape. As a result of this variability, soybean [*Glycine max* (L.) Merr.] plants growing in these soils must contend with starkly contrasting physical, chemical, and hydrologic environments at different depths. The dominant characteristic of soils in the Central Claypan Areas is their namesake argillic horizon, the claypan. The claypan horizon has an abrupt upper boundary, with at least 100% more clay than the superior horizon, as well as very slow permeability. Claypan horizons in these areas contain 45 to 65% clay and high concentrations of cations (K^+, Ca^{2+}, Mg^{3+}, Al^{3+}, H^+), and organic matter

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(OM) (Bray, 1935). These accumulations are preceded by a depletion of clay minerals, cations, and P, as well as low pH in the superior AE, E, or BE horizons. Depth to the claypan (DTC) varies systematically across the landform from summit to footslope. Summit soils have a moderate DTC of around 35 cm, which decreases to as little as 10 cm on eroded backslopes and increases again to between 50 and 100 cm on depositional footslope areas. This systematic soil profile variation may be an important influence on soybean root growth and development.

Soybean shoot and grain variability on claypan soils has been attributed to water redistribution and soil morphology (e.g., DTC) (Kitchen et al., 1999; Thompson et al., 1991; Yang et al., 2003b). These previous findings emphasize the importance of the root environment on aboveground plant variation and highlight some of the possible causes. However, relatively little work exists characterizing and explaining soybean root variability as influenced by these soil landscapes. Initial evidence of a secondary maximum of roots in the soil below the claypan indicates that corn (*Zea mays* L.) and soybeans grown on these soils can have a different root distribution than the exponentially diminishing form they demonstrate in ideal well-watered and well-drained soils (Fraisse et al., 2001; Wang et al., 2003; Yang et al., 2003a). This evidence also indicates that the distribution of soybean roots varies as DTC varied across the claypan landscape, with root distributions appearing more like those seen in ideal soils as DTC increased. Characterization of the physical, chemical, and hydrologic properties of claypan soil profiles is critical for understanding the possible physiological causes of root distribution adaptations.

Often referred to as the "hidden half" of plants (Waisel et al., 2002), root systems are decidedly challenging to study, particularly under field conditions. To address this difficulty, sensor-based methods are desirable. For instance, minirhizotron tubes have been used to access and image roots (Huck and Taylor, 1982; Upchurch and Ritchie, 1983). However, this technique is not acceptable for some soils. For example, argillic horizons of claypan soils have vertic properties imparted by high concentrations of smectitic clays, leading to the high possibility of soil shrinking away from tube walls. Shrinkage gaps would interfere with the natural development of roots in the claypan, possibly providing an altered pathway for water and air infiltration, nutrient mobility, and root growth. Given the special characteristics of these soils, destructive soil coring and root washing may be the most reasonable and accurate method to characterize roots, but the techniques required are labor and time inefficient. Apparent soil electrical conductivity (EC_a) is a sensor-based measurement that has been successfully used to estimate DTC (Doolittle et al., 1994). Because of the suspected relationships of root growth with DTC, EC_a could provide an alternative for rapid estimation of root distribution in claypan soils without destructive sampling.

Research is needed to improve understanding of the hidden half of soybeans. The claypan soil profile provides an interesting setting that may have implications for understanding soybean physiology. Further, understanding the interaction between soybean growth and claypan morphology will enhance the development of new soybean cultivars with specific tolerance to claypan soils. These points are important for soybean producers since soybean is grown on more than 60% of the arable land in the nearly 4 million hectares of the Central Claypan Areas (USDA-NASS, 2004). To address these research needs we used sensor measurements, soil geomorphology, and soil profile properties to characterize soybean root distribution. The specific objectives of this research were (i) to examine the relationships of DTC, EC_a, and chemical and physical properties of the soil profile to soybean root length density (RLD) and average root diameter (ARD) and (ii) to examine the relationships of these soil–root interactions to landscape position.

MATERIALS AND METHODS

Two study sites (named Sites 1 and 2) were chosen within 2 km of each other near Centralia, MO (39°13′58″ N, 92°7′57″ W), on soils predominantly classified as claypan soils. The sites are located in USDA Major Land Resource Area 113, the Central Claypan Areas (USDA-NRCS, 2006). The general landform for the region was an initially flat lobe of basal till that has undergone significant dissection and received 1 to 2 m of loess deposition into which the soils are formed (Guccione, 1982; Young and Hammer, 2000).

Soybean crops were planted on Sites 1 and 2 in 2001. Crop management practices varied between sites. Site 1 was part of a long-term replicated research project evaluating the impact of various grain and grass cropping systems over a catena of claypan soils (Kitchen et al., 1998). Two of the five cropping systems being evaluated on this site were included in this study: cropping system 1, a mulch-till (chisel plow or disk and field cultivator) corn–soybean rotation, and cropping system 2, a no-till corn–soybean rotation. Soybeans ('Maverick') were drilled in 20-cm rows at 494 000 seeds ha^{-1} on 19 June 2001. Site 2 was a uniformly managed field in a no-till corn–soybean rotation and was drilled on 18 June 2001 with the same variety, rate, and row spacing as Site 1.

Site Descriptions and Soil Sampling

For the two sites, soils on the upland interfluves and backslopes are fine, smectitic, mixed, mesic, Vertic Epiaqualfs. Various cumulic mollisols are formed in hill-slope sediments on footslopes and depositional areas (Table 1). These soils present a challenge to root investigations, primarily due to the properties imparted by the smectitic clays found at concentrations up to 65% in the claypan. Because of the vertic properties of these soils, the destructive method of coring and measurement of washed roots was employed.

Site 1

Site 1 was a subset of an existing plot experiment that had a randomized complete block design with a split-block treatment arrangement with three replications. Cropping system was randomized. Landscape position (summit, backslope) was the nonrandomized split block treatment. Detailed description of the design of Site 1 can be found in Kitchen et al. (1998).

An order-one soil survey of Site 1 was conducted in 1991 by Missouri Cooperative Soil Survey personnel. Summits were mapped as Adco silt loam (fine, smectitic, mesic Vertic Albaqualfs), 0 to 1% slopes, and backslopes mapped as Mexico silty clay loam (fine, smectitic, mesic Vertic Epiaqualf), 1 to 3% slopes, eroded (Table 1, Fig. 1). These two soils are separated by a slight convex shoulder. Curvature at the landscape positions was convex at summits, and slightly concave to linear on backslopes. Elevation difference between summit and backslope was about 0.5 m.

Triplicate cores (1.2 m by 5.9 cm) were taken within 2 wk after harvest with a hydraulic coring machine at each sampling location (Fig. 1a). Cores were cut into 15-cm segments, resulting in three 412-cm^3 subsamples for eight layers. The cores were taken within a 1.5-m distance down the slope, midway between two drilled soybean rows. This generated 288 root samples for Site 1 (2 landscape positions × 2 cropping system treatments × 3 block replications × 3 cores × 8 depths). Triplicates were used to assess local root variability, but were pooled for analysis. Pooled sample volume for each layer was 1236 cm^3. Sample cores (for both study sites) received a brief soil morphology description in the field, noting horizons and depth to clay maximum. Depth to claypan was measured as the depth (cm) to the boundary between the "topsoil" (A, AE, E, or AB horizons) and the Bt1 horizon.

Table 1. Soil taxonomy and phase with map unit key and approximate landscape position for the two study sites.

Landscape position	Map unit ID	Soil phase	Taxonomy
Summit	AdSL	Adco silt loam, 0–2% slopes	Fine, smectitic, mesic Vertic Albaqualf
	MeSL	Mexico silt loam, 1–3% slopes	Fine, smectitic, mesic Vertic Epiaqualf
Shoulder	MeSL5e	Mexico silt loam, 2–5% slopes eroded	Fine, smectitic, mesic Vertic Epiaqualf
	MeSL3	Mexico silt loam, 2–3% slopes	Fine, smectitic, mesic Vertic Epiaqualf
	MeSCLe	Mexico silty clay loam, 1–3% slopes eroded	Fine, smectitic, mesic Vertic Epiaqualf
Backslope	LeSL3e	Leonard silt loam, 1–3% slopes, eroded	Fine, smectitic, mesic Vertic Epiaqualf
	LeSCLe	Leonard silty clay loam, 1–3% slopes, eroded	Fine, smectitic, mesic Vertic Epiaqualf
	LeSL6e	Leonard silt loam, 3–6% slopes, eroded	Fine, smectitic, mesic Vertic Epiaqualf
Footslope	LeSL3	Leonard silt loam, 1–3% slopes	Fine, smectitic, mesic Vertic Epiaqualf
	AudIIFS	Argiudolls, fine-silty, 0–2% slopes	Fine-silty, smectitic, mesic Vertic Argiudolls
Upland floodplain	AabIIFS	Argialbolls, fine-silty, 0–2% slopes	Fine-silty, smectitic, mesic Albic Argialbolls
	AaqII	Argiaquolls, generic	Fine Typic Argiaquolls

Site 2

Site 2 was a 13-ha field with a long and narrow aspect cutting across a wide range of claypan landforms (Fig. 1b). The landscape ranged from a flat summit (0–2%) to convex shoulder (2–4%), to concave moderately sloping backslope (3–7%), to concave depositional toeslope and floodplain (0–3%) positions.

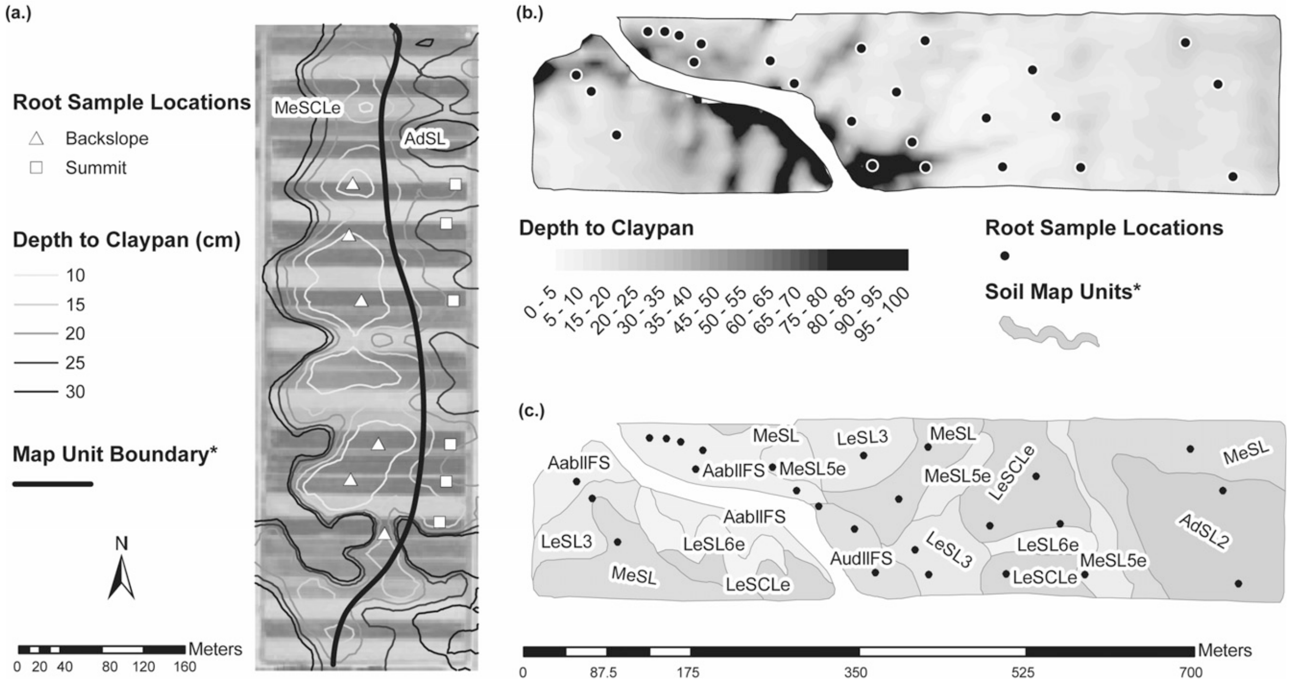

Figure 1. (a) Site 1 aerial photograph of existing research plots running east to west. Overlaid on the plot photograph are the root sampling locations, order-one soil survey, and depth to claypan (DTC) contour map. (b) Site 2 root sampling locations are overlaid on a DTC map. (c) Site 2 order-one soil survey with root sampling locations. * See Table 1 for soil map unit key with taxonomy.

Relief on this site was about 12 m. Missouri Cooperative Soil Survey personnel conducted an order-one survey on this field in 2000, classing the incised topography into 21 different soil map units (Table 1, Fig. 1c).

Within 2 wk after harvest, 26 locations were sampled for root measurement, stratifying the field based on landforms and DTC. At each sampling location a hydraulic coring machine was used to pull duplicate cores (1.2 m by 3.8 cm) from between two drilled soybean rows, cut into eight 15-cm layers, and then combined across duplicates. A total of 208 samples were taken for root analysis with a combined sample volume of 340 cm^3.

Root Measurements and Calculations

The sequence of procedures and algorithms to obtain root distribution data included washing, imaging and enhancement, debris removal via image processing, and measurement. These procedures were adapted from the published procedures of others (Dowdy et al., 1998; Murphy and Smucker, 1995; Smucker, 1982). Soil was washed from roots using a Gillison's hydropneumatic elutriator (Gillison's Variety Fabrication Inc., Benzonia, MI). Air-dried soil samples were presoaked for 15 min and then washed for 12 min. Cleaned root samples were placed in 100 mL of 30% (v/v) methanol solution for storage at 4°C. Before imaging, roots were stained with malachite green (Sigma-Aldrich Corp., St. Louis, MO) for a minimum of 30 min at 0.05% (w/v) by adding concentrated dye to the storage containers.

Stained roots were rinsed and floated in a thin film of distilled water inside 22.5 by 22.5 cm tissue culture plates. Plates were imaged in grayscale using a common flatbed scanner at 300 dpi. Image enhancement and root object discrimination was performed in image analysis software using a macro language for automated processing (Insightful Corporation, 2000). Due to the similar density of root and nonroot debris, incomplete cleaning was a problem. A linear discriminant model was developed from a training dataset of pixel measurements of root and nonroot objects to calculate a selection criterion. Objects that exceeded the discriminant threshold were deleted from the images and pixel measurements of root objects were retained for analysis.

Image vectorizing software was then used to thin root object pixels and to convert the thinned lines into vectors (Soft-Soft.net, 2004). Length of the resulting polyline vectors was calculated based on their Cartesian coordinates (ESRI, 2002). A linear calibration model based on known string lengths and surface area adjusted for the effects of increasing overlap as the density of roots on an image increased. Root length density was calculated for Sites 1 and 2 as the ratio of the calibrated vector length (L_v, cm) to the sample volume (V, cm^3).

$$\text{RLD (cm cm}^{-3}) = \frac{L_v}{V} \quad [1]$$

Projected surface area (A_p, cm^2) of unthinned root objects and measured vector length (L_v, cm) of a processed root image were used to calculate ARD (Eq. [2]) for a sampled layer for Site 2, assuming that individual root segments approximate a cylinder (Benjamin and Nielsen, 2004).

$$\text{ARD (mm)} = 10\left(\frac{A_p}{L_v}\right) \quad [2]$$

Surface soils had many undecomposed root-like plant fibers that were indistinguishable from root segments by discriminant analysis and difficult to identify even by a trained eye. A limited set of surface root measurements was obtained from Site 1. Random samples of 12 surface cores from the top 15 cm (six summit and six backslope) were manually cleaned of debris and measured. No difference was seen due to tillage or landscape position because of high variability (Myers, 2005). Therefore the surface samples were pooled within landscape position for Site 1 and no surface layers were sampled for Site 2.

EC_a Measurement

Geonics EM-38 (Geonics Limited, Mississauga, ON) and Veris 3100 (Veris Technologies, Inc., Salina, KS) ground conductivity sensors were used to survey Site 2 (Kitchen et al., 1999; Sudduth et al., 2003). EM-38 measurements ($EC_{a\text{-}em}$) were taken in the vertical dipole mode (effective depth 1.5 m) using a mobile sensor cart. The Veris Model 3100 produces two measurements; shallow ($EC_{a\text{-}sh}$, effective depth 0.3 m) and deep ($EC_{a\text{-}dp}$, effective depth 1.0 m). Both sensors were run on 10-m transects with GPS logging. Local polynomial regression was used to interpolate EC_a maps (ESRI, 2002). Based on this map, estimated EC_a was predicted at the root sampling coordinates.

Clay-Maximum Depth Translation

Depth to clay-maximum was obvious (± 2.5 cm) from field observations on soil cores by determining the moist consistency of the soil, resistance to knife insertion, and gloss of the polished core surface. Depth to clay-maximum served as a useful variable for integrating soil profile and landscape relationships. For each soil profile, clay-maximum translated depth (D_t) of a sample from layer i was calculated by Eq. [3] where clay maximum depth (cm) is the depth to maximum clay concentration and d is the midlayer depth (cm) of soil layer i.

$$D_{t,i} \text{ (cm)} = \text{clay-maximum depth} - d_i \quad [3]$$

Results of this equation indicate the distance that a given soil layer occurs either above or below its profile clay maximum. When performed on a group of soils from across a landform with varying DTC, D_t is a *coherent* linear translation, aligning profiles by the clay-maximum origin. Coherent depth translation resolves soil and root property measurements from a wide landscape onto a single scale, enhancing their comprehensive interpretation.

Soil Profile Property Measurements

Data from previous research on the study sites were used to characterize soil profile property distributions. Surface and subsoil samples taken by horizon and fixed increment were subjected to laboratory analysis as reported by previous research (Jung et al., 2005; Spautz, 1998; Sudduth et al., 2004). Included soil property measurements were: texture, buffer pH (pHs), OM, available P, cation exchange capacity (CEC), K^+, Ca^{2+}, Mg^{2+}, Na^+, Al^{3+}, and neutralizeable acidity (NA).

Statistics and Model Development

Analysis of variance, linear regression, and exploratory local regression procedures were performed in S-Plus (Insightful Corporation, 2000). For Site 1 a two-factor analysis of variance was employed to test each soil layer for the main effects of landscape position and tillage treatment, interaction of the main effects, and to determine treatment differences (Myers, 2005).

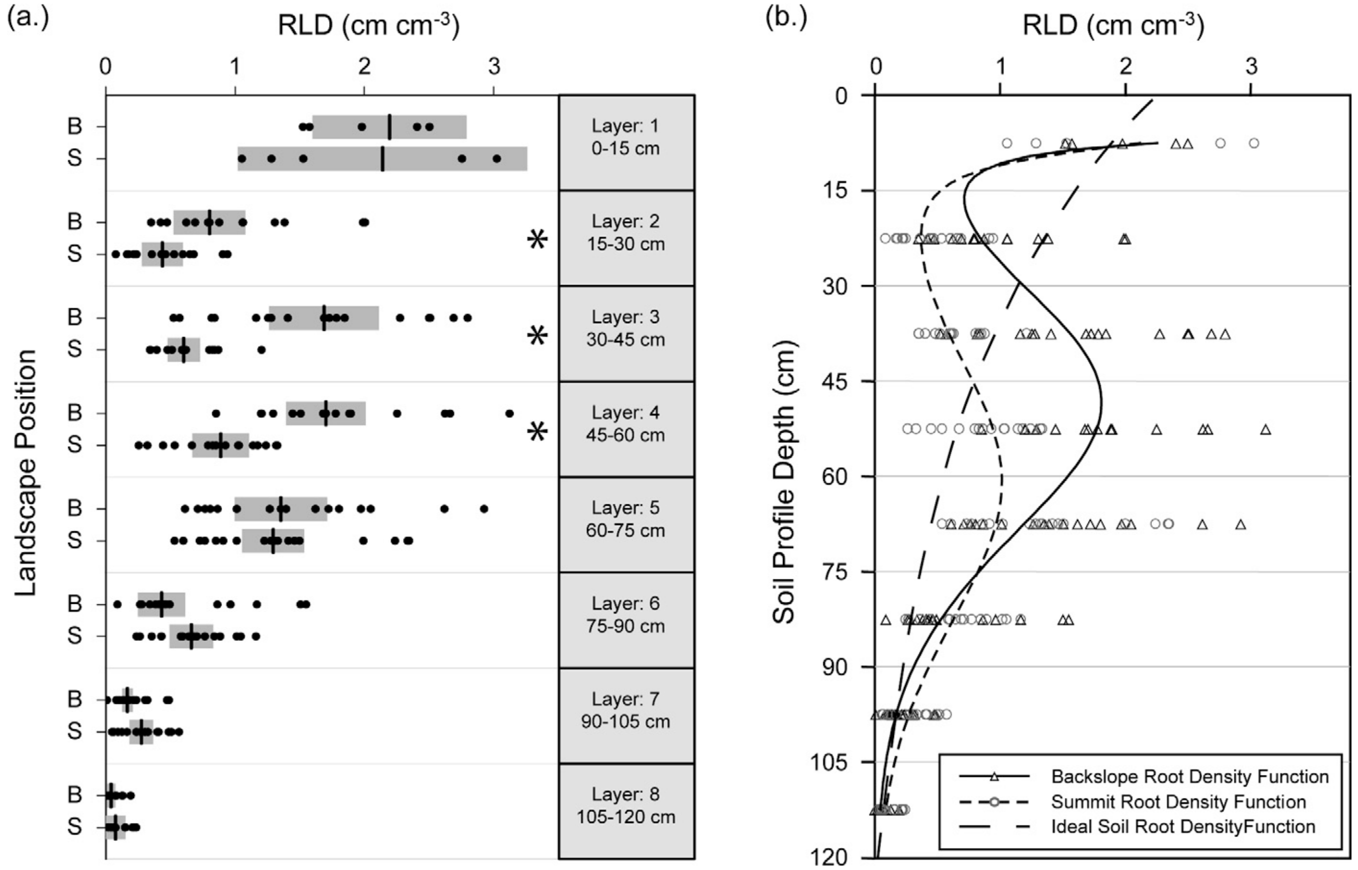

Figure 2. (a) Backslope (B) and summit (S) landscape position effects on root length density (RLD) was different for some depths on Site 1. Dot-plots indicate the sample measurements and the shaded boxes represent the 95% confidence interval of the mean. Significant differences between B and S within each soil layer are indicated with an asterisk. (b) Fitted profile models (fifth order polynomials, B $r^2 = 0.52$, S $r^2 = 0.56$; $P < 0.001$) of RLD show an initial minimum in root density and a secondary maximum and highlight the differences between summit and backslope RLD profile distributions. An exponentially decaying root distribution for ideal soils is plotted for reference (Kiniry et al., 1983).

Only the effects of landscape position comparisons are relevant to this study. Layer by layer, sampled root parameters from Site 2 were regressed as a function of DTC and EC_a. Linear and quadratic models were selected based on the significance of the overall model ($P < 0.1$), significance of the linear or quadratic parameter ($P < 0.05$), and the degree of fit ($r^2 > 0.2$). For some figures, local regression models ("loess" function; Cleveland et al., 1992), were fit to characterize D_t relationships with root and soil measurements. Local regression parameters were identified via the improved Akaike information criterion which optimizes parsimony and residual error (Hurvich et al., 1998).

RESULTS

Site 1

Landscape position and associated claypan morphology caused significant differences in RLD at some depths on Site 1 (Fig. 2a). Soybeans on summit sites produced less root length and surface area than backslope sites at 15- to 60-cm depths. This difference corresponded to variation in the depths of argillic horizons. Summit positions had an average DTC of 20 cm while the backslope sites had an average DTC of 9 cm. Due to this difference, soybeans on backslope sites were growing in a profile with relatively greater average clay content in the root zone.

Continuous profile depth models of RLD were developed for summit and backslope positions from Site 1. Fifth-order polynomial models were fit to RLD for backslope ($r^2 = 0.52$), and summit ($r^2 = 0.56$) (Fig. 2b). These models contrast the difference in amount and placement of soybean roots in the profile for the two landscape positions. Depth of the initial minimum and secondary maximum shifted upward in the profile from summit to backslope locations, following the trend of shallower DTC from summit to backslope. Root length density between 15 and 60 cm was 36% greater at backslope positions.

Site 2

For Site 2, layer-by-layer variation in RLD and ARD was examined as a function of DTC (Fig. 3). A significant curvilinear effect on RLD can be seen in response to increasing DTC between 15 and 30 cm, from 30 to 45 cm, and from 30 to 60 cm. Root length density within these layers was large when the claypan was shallow, decreased to a minimum as DTC increased, and increased again when the claypan was deep. Minimum RLD within a given layer occurred when its bottom boundary was at the claypan. In summary, RLD minimum occurred in the horizon just above the claypan, usually an E or EB horizon, and RLD increased within the Bt horizons. Depth to claypan influence on ARD was significant from 15 to 105 cm, a majority of the profile. In general, ARD within a layer increased with DTC, indicating that soil layers dominated by argillic horizons had relatively more fine roots.

Root length density and ARD were also examined as a function of EC_a and found significant for many soil layers at Site 2 (Fig. 3). Of the three EC_a measurements, $EC_{a\text{-dp}}$ produced the most significant relationships with root parameters. $EC_{a\text{-dp}}$ results were similar to DTC results. Like DTC, $EC_{a\text{-dp}}$ was most effective at predicting RLD for depths shallower than 60 cm. Similar to DTC, curvilinear forms are visible for $EC_{a\text{-dp}}$ models of RLD but are reversed due to the inverse relationship between DTC and EC_a. Likewise, ARD within a layer decreased with increasing $EC_{a\text{-dp}}$.

Once significant effects due to claypan morphology were established, a more clear and useful method of visualizing soil property influences on root distribution was desired. Therefore, translated depth was used to examine trends in RLD and ARD (Fig. 4). The use of D_t fundamentally changes the data from the layer-by-layer nature of Fig. 3 into a continuous distribution. The depth translation highlights the response of roots to the claypan morphology by compositing many root profiles onto a single scale, aligned by the depth to clay maximum. Since both sites were planted with the same variety of soybean on similar dates, in similar soils about 2 km apart, and since tillage differences were found to be insignificant at Site 1, RLD data was pooled across site. Figure 4a shows the previously identified RLD features, the initial minimum just above the claypan, and the secondary maximum 40 cm below it. For Site 2 (Fig. 4b), minimum ARD occurred within the argillic horizons 30 to 40 cm below 0-cm D_t, coinciding with maximum RLD. Translated depth results confirm and clarify landscape trends seen in the by-layer regressions, and indicate that the features of the RLD and ARD distributions vary systematically in the landscape, relative to the clay-maximum.

Soil Chemical and Physical Properties

The claypan contained 45 to 65% clay and related concentrations of cations, NA, and OM. These accumulations of soil components were accompanied by a depletion of clay minerals, base cations, and P, and by a lower pHs in the superior E or BE horizons. Translated depth profiles with exploratory local regression models emphasize the controlling nature of the claypan morphology on soil properties (Fig. 5). Throughout this landscape, the profile clay-maximum occurred 5 to 10 cm below the abrupt boundary dividing the E horizons (the eluviated zone) from the claypan horizon (the illuviated zone).

Depth-translated physical and chemical soil properties varied systematically with percentage of clay in these profiles. In general, soil properties were either minimal or maximal in the E or Bt1 horizons. For instance, clay content ranged from a minimum of 12% within E horizons just above 0-cm D_t, maximizing to 65% within Bt1 horizons, at 0-cm D_t. Silt was inversely related to clay, with maximum silt content (85%) occurring just above 0-cm D_t, and minimum silt content (32%) occurring at 0-cm D_t. Base cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were minimal in the unamended soil above the clay-maximum, but abundant in the argillic layers below 0-cm D_t. Acid cations (Al^{3+} and NA) also followed this trend. Al saturation of exchange sites of nearly 40% was present at around 0-cm D_t.

Available P and soil pHs varied similarly to cations and may have had specific implications for root growth and development. Phosphorus ranged from 0.15 to 68.5 g m^{-3}, however, most of the unamended soil above 0-cm D_t ranged from 3 to 15 g m^{-3}. This was well below the 22.5 g m^{-3} critical value recommended for soybean production by the University of Missouri (Buchholz et al., 1983). The range of soil pHs was 3.6 to 6.8. Excluding the amended surface layer, soil pHs above 0-cm D_t was 3.6 to 4.6, considerably below the University of Missouri's recommended pHs of 6.1 to 6.5 for soybean. Both pHs and available P increased to sufficiency levels below −50-cm D_t.

DISCUSSION

Soybean root distribution patterns in claypan soils are a departure from root profiles typically seen in deep, well-watered, well-drained, and otherwise nonlimiting soils (Bohm et al., 1977; Kaspar, 1985; Mitchell and Russel, 1971; Sivakumar et al., 1977; Smucker, 1985; Yang et al., 1996). In general, where claypans were present, RLD was greatest near the surface, reduced above the claypan, and increased to a secondary maximum within the argillic horizons below the claypan (Fig. 4a). Soil profiles with sufficiently deep argillic horizons had a RLD distribution that more closely matched the exponentially decaying distribution seen in ideal soils. Root growth models generally estimate a maximum potential quantity of roots and then limit root growth in soil layers where soil properties are restrictive (Jones et al., 2003; Ritchie et al., 1986; Scrivner et al., 1985; Wu et al., 1999). Because these models mimic the exponential decay form of root distribution in ideal soils, they would underpredict the RLD measured at 30 to 60 cm in claypan soils (Fig. 2b). The growth and development of the soybean root system is more plastic than these traditional models represent.

Core and minirhizotron sampling have been suggested to cause bias due to root orientation by underestimating vertically oriented roots (Bragg et al., 1983; Buckland et al., 1993; Liedgens and Richner, 2001). Due to gravitropism,

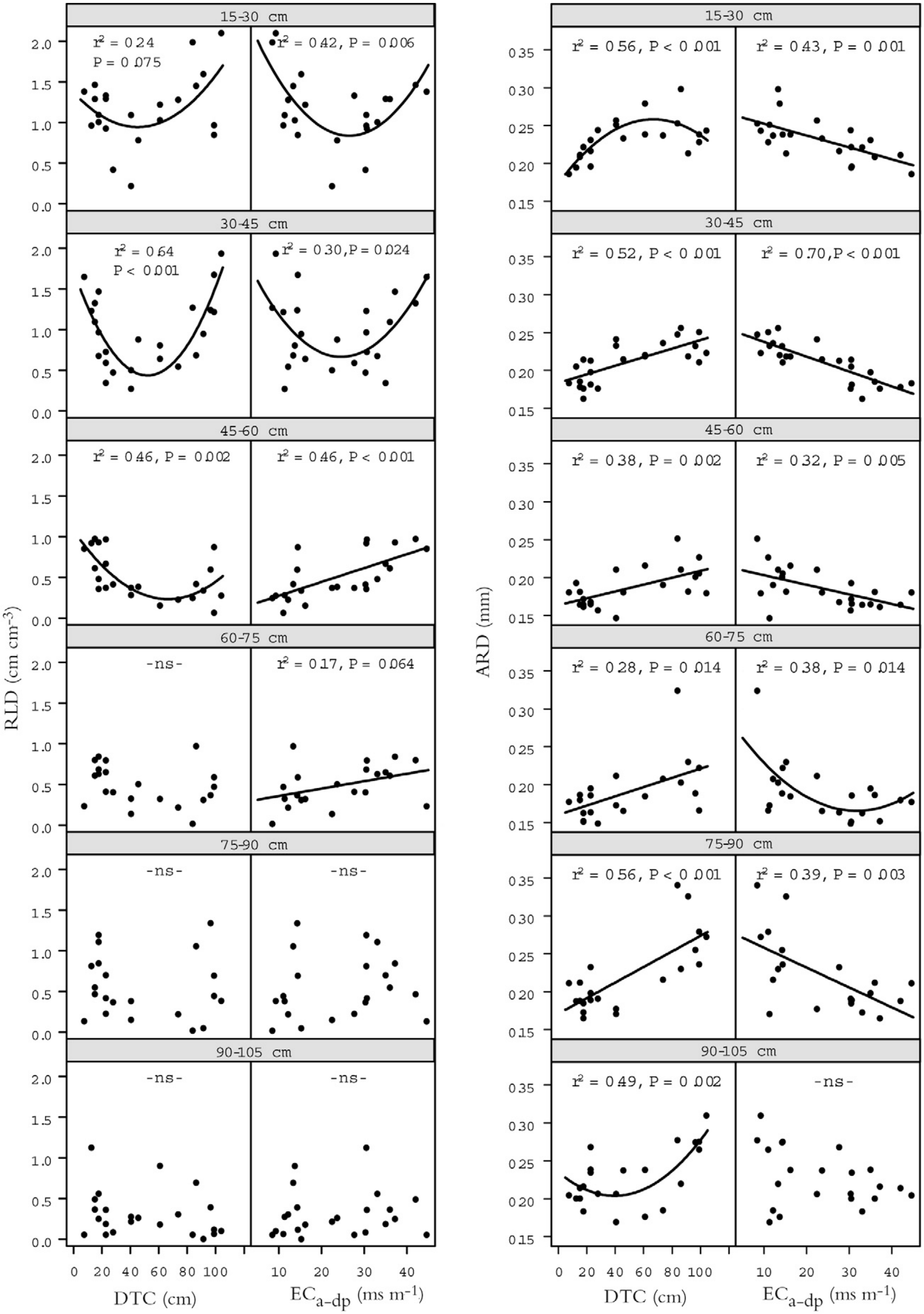

Figure 3. Site 2 root length density (RLD) and average root diameter (ARD) as a function of depth to claypan (DTC) and Veris Model 3100 deep apparent soil electrical conductivity ($EC_{a\text{-}dp}$) by sampled layer. Regression statistics and regression fit included for models with a significant linear or quadratic term ($P < 0.05$)

early lateral roots begin to grow horizontally, then orient vertically. Lateral roots deeper in the profile may grow more horizontally or be more branched. These architectural features may be emphasized as the secondary maximum seen in this study. However, core sampling bias due to vertical root orientation does not appear to be the cause of the RLD minimum since large variability would be expected there. Instead, RLD variability is low at the root minimum (Fig. 4a). Additionally, this research demonstrated that the minimum and secondary maximum follow DTC and systematically relate to D_t. If root architecture is a cause of this distributional form, then some physiological interaction with claypan soils has an effect on root architecture. It is also likely that soil profile effects on root proliferation alone are the primary cause of these distributions and that architecture driven sampling bias is not significant.

Root Distribution in Response to Soil Profile Properties

Systematic variations in soil profile properties were shown to be a function of D_t (Fig. 5). These relationships occurred because the claypan and clay-maximum are a signature of soil formation. Soil chemical properties are pedogenetically and, as a result, functionally related to clay distribution in the profile. Clay content in these profiles controls physical and hydrologic soil properties because of the high concentration and dominant chemical and physical attributes of smectite, which has a 2:1 expanding lattice structure. Coherent depth translation is useful for analysis of claypan soils because a prominent clay maximum is identifiable as the origin of the translation. It is useful in this study because the clay maximum is covariate with morphological, chemical, physical, and hydrologic soil properties that influence root growth. Depth translated profiles of soil properties can be compared to depth translated profiles of root distributions to provide a key for understanding root response (Fig. 6a, 6b).

The RLD minimum seen in these results correlates with the eluviated region above 0-cm D_t. Silt concentration is great in this layer since primary minerals rich in base cations were weathered away, leaving larger less soluble soil particles behind. Degradation components of remaining minerals are shifted toward acid cations (Bray, 1935; Lindsay, 1979). As a result of this dynamic, the eluviated layer has low pHs (~4.2) and high Al saturation of exchange sites (20–40%) (Fig. 5, 6b). Aluminum saturation can have a toxic effect on soybean roots at concentrations of 40% (Goedert, 1983). Acid cations (H^+, Al^{3+}) influence the pH of the root environment and reduce the availability of nutrients, conditions inhospitable to soybean root growth.

The illuviated argillic zone of the profile contains the weathering pulse of secondary minerals (e.g., smectite and illite) with their nutrient-rich exchange sites. The result of this accumulation is visible in D_t profiles of Ca^{2+}, Mg^{2+}, and K^+ (Fig. 5). Moderate charge and high surface area combine to give smectite a large effective CEC. Base cations (Ca^{2+}, Mg^{2+}, K^+) are important plant nutrients and therefore soybean root growth and development may be sensitive to base cation supply (Lund, 1970). Soybean roots may be avoiding the poor conditions of eluviated horizons for argillic and subargillic sources of base cations.

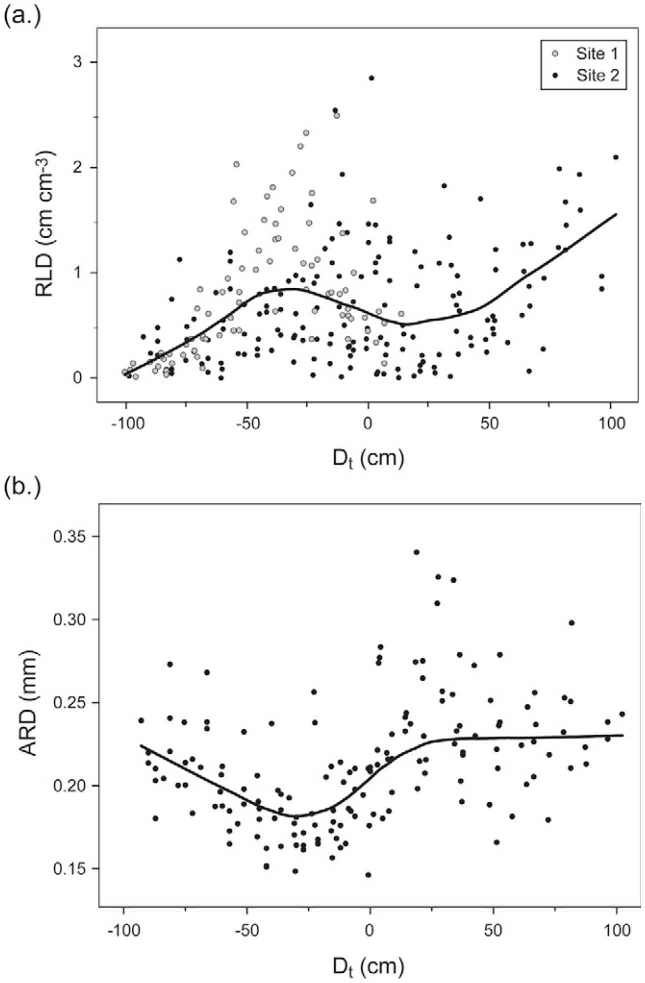

Figure 4. Clay-maximum translated depth (D_t) profiles of (a) root length density (RLD) for Sites 1 and 2, and (b) average root diameter (ARD) for Site 2. Exploratory local regression models (“loess” function; Cleveland et al., 1992) are plotted to emphasize soil morphology influence. No surface samples are included for either panel. D_t coherently aligns samples taken at any depth from across a wide claypan landscape by using the profile clay maximum as a common measurement origin.

Depth-transformed profiles of P and pHs are notably different than the clay D_t profile (Fig. 5, 6b). Phosphorous is an essential metabolite, and in P-limited soils soybean (Hallmark and Barber, 1984) and common bean (*Phaseolus vulgaris* L.) (Fan et al., 2003; Lynch and Brown, 2001; Rubio et al., 2003; Yan et al., 1996) are reported to explore P-rich soil layers. The secondary maximum in root distribution seen in this study coincides with increasing P below the 0-cm D_t. In contrast, silty horizons above the claypan have minimal available P, prob-

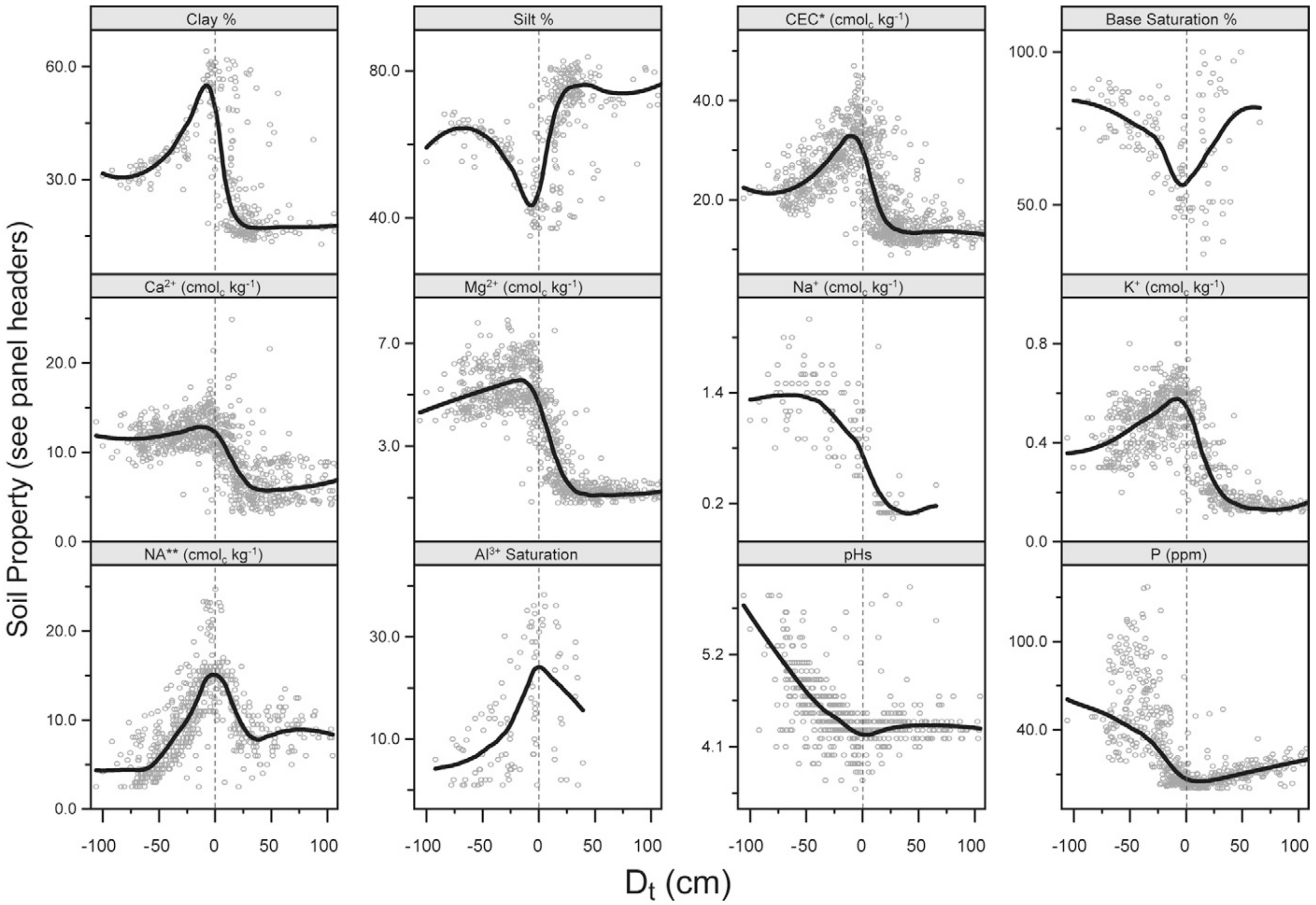

Figure 5. Clay-maximum translated depth (D_t) profiles of several key physical and chemical soil properties in claypan soils. These profiles indicate the systematic variation of soil properties relative to the claypan morphology. Exploratory local regression models ("loess" function; Cleveland et al., 1992) are plotted to emphasize soil morphology influence. See Fig. 4 for an explanation of D_t.

ably because of adsorption and occlusion by stable $Fe(PO_4)_3$, and $Al(PO_4)_3$ precipitates at acid pH. While the plow layer in claypan soils is usually amended with P and lime for crop production, the subsoil profile is not and has been shown to be an important P source for soybean in these soils (Spautz, 1998).

Hydrology Influence on Root Growth

The argillic horizons in claypan soils have very low hydraulic conductivity when saturated (Blanco-Canqui et al., 2002). The swollen smectitic clays occlude soil pores causing a perched water table and reduced conditions in the profile. These conditions are likely to occur in the spring and early summer when secondary roots are still exploring the upper portion of the profile, and evapotranspiration is greater than rainfall. Several researchers have noted that saturated soil conditions rapidly inhibit soybean root growth (Huck, 1970; Stanley et al., 1980; Taylor and Kaspar, 1985). Resumption of secondary root growth after profile drainage and evapotranspiration occurs may not completely populate the previously saturated area. Primary roots exploring deeper in the soil profile may also find the soil below the claypan to contain water late in the growing season, after surface soils are depleted. These possibly confounding effects make it difficult to identify the precise mechanism by which claypan soil morphology influences root growth and development.

Average Root Diameter Relationships

Translated depth profiles of ARD show thicker roots above the clay maximum and an ARD minimum corresponding to the RLD maximum at −40-cm D_t for Site 2 (Fig. 4b). As with RLD, this trend follows the claypan into the profile, which can also be seen in the layer-by-layer regressions for Site 2 (Fig. 3). Three possible causes of this ARD distribution are soil bulk density, root age, and root type or function.

As discussed previously, the subsoil below 0-cm D_t may be a source of subsoil cations, P, or water. Unsatisfied demand for these essentials may not have stressed soybeans until grain filling, or until late-season drought conditions occurred. Thus, roots growing below 0-cm D_t may have been stimulated late in the growing season and had a reduced time-frame to grow and develop. A root age effect on root diameter might be expected with depth even in an ideal soil as older roots near the surface become mature and suberized. Additionally fine roots in surface layers may senesce after water and nutrients are depleted, biasing the average toward thicker roots. However, the fact that ARD distribution varies relative to the claypan morphology indicates an additional influence beyond root maturity or fine root senescence.

Root function may also be different above and below 0-cm D_t. The dimensions of a root have an impact on the efficiency of its given function (i.e., exploration vs. translocation). Thicker roots above the claypan may be tasked with moving water and nutrients up to the shoot and assimilates down to an area of root expansion. Therefore, a larger cross-section with room for conductive tissues would be more efficient. Thinner roots with greater surface area would be more effective for extracting nutrients and water from soil. Smaller root diameter in combination with greater RLD below the claypan supports the conclusion that roots below the claypan are mining a nutrient or water resource.

Several researchers have noted soil strength influences on soybean root diameter, finding that as bulk density or soil strength increases, root thickness increases (Taylor and Kaspar, 1985; Unger and Kaspar, 1994; Voorhees, 1992). However, contrary to the hardpan concept, claypans in these soils are not dense. Bulk density at these sites is about 1.5 g cm^{-3} near the surface, 1.3 g cm^{-3} in the claypan, and increases linearly to 1.6 g cm^{-3} at the bottom of the root zone (Chung, 2004). Minimum bulk density in the claypan is due to the presence of expanding smectitic clays. This study found (Fig. 4b) that ARD is relatively constant with depth to 0-cm D_t where it begins to decrease until the −40-cm D_t, minimum, even as bulk density increases. Below −40-cm D_t, ARD increases back to above-claypan values. These relationships indicate that bulk density is not influencing root diameter, except perhaps at the bottom of the root-zone. This finding also supports the nutrient and water mining hypothesis.

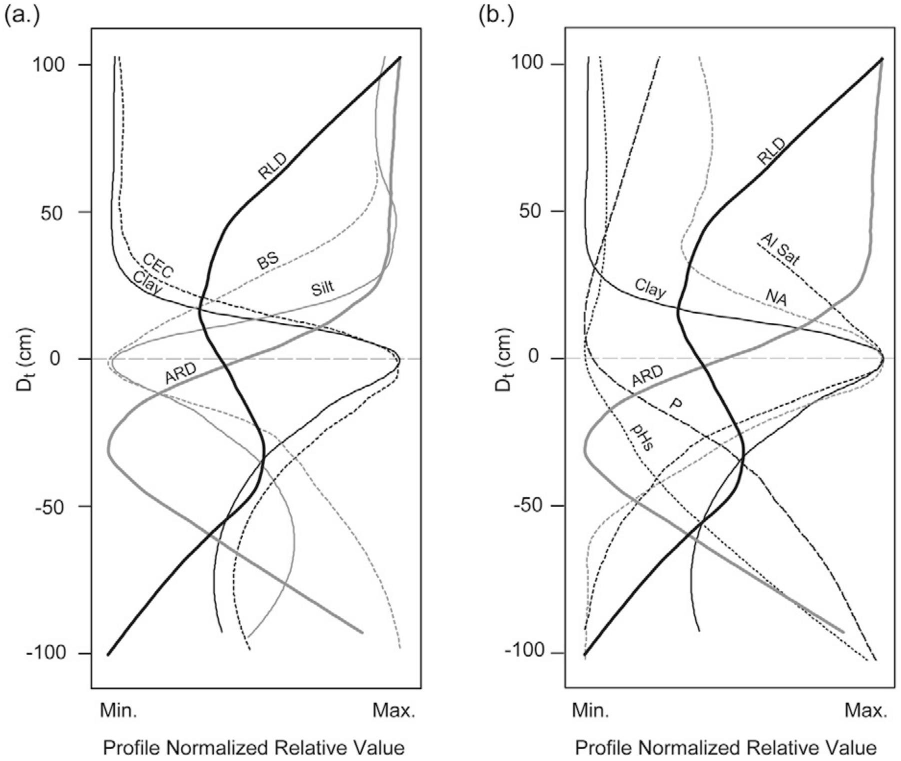

Figure 6. Clay-maximum translated depth (D_t) profiles of relative soybean root length density (RLD), average root diameter (ARD), and clay concentration, compared to relative values of (a) silt content, cation exchange capacity (CEC), and base saturation (B-Sat) of CEC, and (b) buffer pH (pHs), neutralizeable acidity (NA), Al^{3+} saturation of CEC (Al-Sat), and P. Soil properties in panel a reflect the influence of soil texture on cation supply and buffering. Soil properties in panel b generally relate to soil acidity and its influence on the distribution of available P. See Fig. 4 for an explanation of D_t.

Landscape Position and EC$_a$ Relationships

Root distribution as affected by landscape position and EC$_a$ are congruent with soil profile, D_t, and DTC effects. Since DTC varies systematically with landscape position, the effects of the profile on root density vary along with it. On Site 1, DTC was shallower on backslopes than at summits. A concomitant change in soil properties and hydrology occurred and their cumulative effect on roots was shallower initial minima and secondary maxima. Likewise, EC$_a$, as a surrogate measure of DTC, reflects the profile depth distribution of soil properties and therefore acts as a potential surrogate measure of root hospitality. This relationship makes EC$_a$ useful for developing estimations of root density distributions for the purpose of explaining yield variability, or for use in estimating root parameters for crop and hydrology models. For instance, given a within-year calibration dataset, D_t models of root density could be mapped across a claypan field using relationships of clay-maximum with EC$_a$. This would improve the spatial implementation of crop models for applications in productivity analysis or hydrology models for water quality assessments.

CONCLUSIONS

Soybean root distribution and root diameter in claypan soils can be characterized as a function of landscape position, DTC, D_t, and EC$_a$ because these variables are related to physical and chemical soil profile properties. A primary maximum, initial minimum, and a secondary maximum were confirmed as specific features of RLD distributions in claypan soils. Also characterized was a relationship of the depth of these distribution features to systematic variation in claypan landscapes. Profile distribution of exchangeable cations, pHs, and available P could all be responsible.

Declining RLD above the claypan matched the decline in pHs which likely causes decreasing availability of soil nutrients, particularly P, and reflects potentially toxic levels of Al^{3+} saturation. In contrast, increasing RLD below the clay-maximum correlated with increasing pHs, possibly causing increased P solubility and nutrient availability at around 40 cm below the claypan, as well as reduced Al^{3+} toxicity. Additional root growth at this depth could be compensating for nutrient and water deficiencies above the claypan. Reduced ARD below the claypan could be due to root age, reflecting late season foraging for nutrients or water. Alternatively, or additionally, roots may be thinner for improved function in nutrient and water absorption. Bulk density is probably not responsible for RLD or ARD distributions.

The results of this field study provide an important picture of the hidden half of soybeans on claypan soils and may be useful information for the explanation of yield variability, the calibration or validation of crop models, and the development of claypan-tolerant soybean varieties. Finally, while our study focused on the Central Claypan Areas, soils in the upland landscapes of the loess-covered till plains of Missouri, Iowa, Illinois, and Indiana have comparable soil morphology and are likely to respond similarly.

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