Critical shear stress variability in claypan soils with depth

S.E. Kulesza, M.A. Mathis II, V.J. Alarcon, and G.F. Sassenrath

Abstract: Soil erosion from land management activities reduces agricultural productivity and contaminates waterways. Understanding erosion processes within agricultural fields is critical to developing alternative management scenarios to better manage soil resources. Claypan soils comprise approximately 5% of the agronomic area in the US Midwest; however, little is understood about the erosion characteristics within the claypan soil profile. Claypan soils are defined by a dense, impermeable layer that is more resistant to erosion. In this study, we used geotechnical methods to examine claypan soils in agricultural fields in southeast Kansas that showed a rapid transition from high clay to low clay content on the soil surface. Laboratory erosion measurements with an erosion function apparatus (EFA) demonstrated a two-layer soil system at both locations. At Site 1, we found a high plasticity clay layer at 25 cm depth in the soil profile, with a hydraulic conductivity 100-fold less than the surface soil, an unconsolidated undrained triaxial strength more than double that at the surface, and a critical shear stress that was on average five times higher than that measured in the surface layer. This high plasticity clay layer dissipated, with lower elevation locations showing similarities in soil strength and critical shear stress at the surface and 25 cm in the soil profile. At Site 2, laboratory experiments showed a similar two-layer soil structure, though the clay layer did not dissipate but instead remained at a lower position in the soil profile. In situ erosion measurements with a field jet erosion test (JET) apparatus showed a higher critical shear stress and lower erosion rate in the soils above the claypan. Soils not in the claypan area showed greater similarity in critical shear stress and erosion rate with depth in the profile. Calculating erodibility coefficient as a function of critical shear stress using the JET test results identified a cluster of measurements with very high critical shear stress and low erodibility. This cluster of soils were located on the claypan as they were collected 25 cm down. These results reveal some of the sources of variability found in claypan soils and indicate the need for more careful planning to manage the soil that will result from the compositional changes. Management practices to reduce erosion will also require alternative approaches to accommodate the inherent spatial variability of soils and changes within the soil profile.

Key words: claypan soil—critical shear stress—erodibility coefficient—soil erosion

Soil erosion is a complex phenomenon that impacts the environment and society. Erosion impairs the productive capacity of agricultural lands, contaminates water resources, and damages infrastructure (Lal 2022; Alarcon and Sassenrath 2015, 2018, 2020; Tucker-Kulesza et al. 2019). Contamination of water from agriculture activities is a serious problem that can cause eutrophication due to excess sediments and nutrients (Barnes 2015) and decrease the capacity of water storage structures (Yasarer and Sturin 2015). The claypan region of southeast Kansas is particularly problematic, as water from Kansas, Missouri, Arkansas, and Oklahoma, four heavily agricultural states, flows into the Grand Lake, a major recreational area in northeast Oklahoma (Alarcon and Sassenrath 2015, 2018). Claypan soils cover approximately 4 million ha of agricultural farmlands in the US Midwest, including eastern Kansas, Missouri, Iowa, and Illinois (Jamison et al. 1968). Claypan soils are identified by the presence of an abrupt boundary layer in the soil profile that transitions to a high clay content. These soils are potentially productive, but the clay layer has distinctive different properties of infiltration, erodibility, and plant available water (Kitchen et al. 2003; Buckley et al. 2010). Claypan soils have unique challenges for crop production, with impaired crop yields in areas of high clay content (Conway et al. 2017; Sassenrath et al. 2015). The clay layer can impede root growth and alter water and nutrient cycling within the soil profile (Myers et al. 2007; Hsiao et al. 2018). Over a century of agricultural activity in the claypan region has eroded the topsoil layer, restricting the productive capacity of the land and diminishing agronomic returns (Kitchen et al. 2003, 2005; Conway et al. 2017; Sassenrath et al. 2015). The depth to clay layer has been shown to alter the productivity of the soil (Doolittle et al. 1994; Kitchen et al. 2005).

The spatial variability of crop fields has been widely reported and forms the basis for site-specific management of crop lands through precision application, delivering precise needs based on the soil properties and soil productive potential (Mueller et al. 2015). Adding to the challenges of crop production on heavy clay soils is the high spatial variability of the fields in the claypan region (Kitchen et al. 2005; Sassenrath et al. 2015; Chan et al. 2017). While these are well documented from surface measurements in the literature, there is a need to understand the changes in soil composition with depth in the soil profile for claypan soils. The changes in soil composition with depth will also impact the nutrient availability within the field, and hence crop productivity (Buckley et al. 2010; Hsiao et al. 2018).

In addition to variability in soil texture within the claypan soil profile, changes occur in the water infiltration, storage, and availability to plants in these soils. Clay layers...
can remain saturated, even after long periods of dry conditions (Buckley et al. 2010). This saturated clay layer can result in a temporary perched water table, altering water uptake and storage in the overlying soil layer (Buckley et al. 2010; Mathis II et al. 2019). Singh and Thompson (2016) established that the erodibility of surface soils is a function of the soil moisture content and that higher moisture results in greater erosion. Bockheim (2016) considers an “abrupt textural change” as an increase in clay content within 5 to 7.5 cm. Therefore, there may be a cascading effect of the abrupt increase in clay content in clayspan soils, which can cause the perched water table, resulting in surface soils with relatively higher moisture that may lead to enhanced surficial erosion.

Erosion of soil is governed by the resistive forces of the soil particles, with erosion occurring above a critical shear stress. The excess shear stress equation is the common simplified equation for estimating the erodibility of soils from overland flow, defined as equation 1:

\[ e = k_e (\tau_c - \tau)^a, \]  

where \( e \) is the rate of erosion (m s\(^{-1}\)), \( k_e \) is the erodibility coefficient (m\(^{-1}\) [N s\(^{-1}\)]), \( \tau_c \) is the effective hydraulic stress (Pa), and \( \tau \) is the critical stress (Pa). The exponent “a” is typically assumed to be one. The resistance of soil to erosion is central to this research and is a function of \( k_e \) and \( \tau \). Researchers have shown, however, that these parameters are difficult to estimate based on other soil properties (Arulananand et al. 1980; Bonilla and Johnson 2012; Shan et al. 2015; Kulesza and Karim 2021). Grabowski et al. (2011) note that the erodibility of fine-grained soil, such as the soil in a clayspan region, is difficult to predict due to the physical, geochemical, and biological relationships that interact dynamically to influence the erodibility.

It is commonly thought that topography plays a key role in soil loss and forms the basis for many soil erosion models (Borrelli et al. 2021). Our research aims to enrich the work done by the Water Erosion Prediction Project (WEPP) by providing realistic values for the erodibility parameters. The WEPP erosion model is very sensitive to the input values for baseline interrill erodibility, rill erodibility, and critical shear stress (USDA ARS 1995). Currently, those parameters are estimated using empirical equations that rely on cropland and rangeland erodibility experimental results that are not specific to clayspan soils, vegetation cover, or soil texture data (Al-Hamdan et al. 2022). Moreover, WEPP’s empirical equations do not account for erodibility that varies with depth.

Gessler et al. (1995) noted that surface water flow due to topography controls many processes within a field, including erosion. The soils in this region are near the boundary between the Osage Cuestas and the Cherokee Plains of the Central Irregular Plains of US Environmental Protection Agency (USEPA) Ecoregion III (Omernik and Griffith 2014). The area was historically dominated by tall grass prairie and oak-hickory forests, with common clayspan (Kansas Native Plant Society 2023). Given the more than a century of agricultural activity in the region, it would be expected that higher elevations within a field would have a greater potential of having an exposed clay layer due to loss of the more erodible topsoil (Bhuyan et al. 2002; Van Oost et al. 2006; Chan et al. 2017). We demonstrated that lidar-derived digital elevation maps, apparent electrical conductivity, and relative yield maps could be used to identify target areas in crop fields with a near-surface clayspan layer (Tucker-Kulesza et al. 2017). Furthermore, we established that near-surface clayspan layers, where surface soil erosion has been a problem, can occur in both the highest and relatively lower elevations in a field (Tucker-Kulesza et al. 2017).

The objective of this research is to ascertain whether soil erodibility is variable with depth in claypan soils. The driving hypothesis is that the varying degrees of erodibility with depth can be identified using electrical resistivity tomography (ERT). We seek to provide compelling evidence that recommendations for best management practices must consider changes in erosion characteristics with depth to improve soil conservation. Studies have demonstrated the limitations of accurately measuring soil erosion mechanisms in conventional replicated plots under controlled research conditions (Boix-Fayos et al. 2006; Zhao et al. 2019). Therefore, in this research we collected soil samples for laboratory erosion measurements and conducted field erosion measurements. Areas of high variability from two crop production fields were identified from electrical resistivity tests and measured with plasticity tests, saturated hydraulic conductivity (\( k_s \)) tests, and undrained shear strength tests. Unique to this study, we are the first to measure, to the best of our knowledge, erosion characteristics in situ with depth in clayspan soils. This research is needed because current agricultural management recommendations in clayspan soils are based on field-scale surface measurements. However, while producers are using no-till, reduced-till, cover crops, and other conservation management practices, there is still rapid loss of topsoil from clayspan soils.

Materials and Methods

Site Location. Two fields located in southeast Kansas were chosen for this study. Previous work in these fields identified areas with a high degree of soil variability and crop yield over a short distance. Given the extent of variability over a short distance, these areas were ideal for studying the soil variability with depth in detail. Site 1 (37.07 N, 95.22 W) is 44.2 ha, with Wagstaff silty clay loam soil (fine, mixed, thermic Oxyaquic Argiudolls) with 1% to 3% slope. Site 2 (37.08 N, 95.23 W) is 32.4 ha with a 2.2 ha grassed waterway in the southwest corner. The area of interest at Site 2 is Parsons silty loam soil (fine, mixed, active, thermic Mollic Albaqualfs), with 0% to 1% slope. The two fields are approximately 1 km apart. Both fields have been in long-term crop production, managed in the standard crop rotation of the area that produces three crops in two years: corn (Zea mays L., planted in April, harvested in September), winter wheat (Triticum aestivum, planted in October, harvested in June), and soybeans (Glycine max, planted in June, harvested in October). The production was in conventional tillage until 2013, when management was converted to no-till. Crop yields were recorded at harvest with an uncalibrated yield monitor on a commercial combine. Crop yield varied spatially by crop and year. Across the ERT survey area (described below), corn yields varied by as much as five times between the high and low yield; soybean yields varied by more than six times, depending on year. Both sites are classified as Hydrologic Group D with a very slow infiltration rate and high runoff potential according to the USDA (USDA NRCS 2024). Uncalibrated yield maps were used in conjunction with surface soil mapping of apparent electrical conductivity with a Veris soil sensor to determine areas of interest for further study (Tucker-Kulesza et al. 2017; Mathis II 2020; Sassenrath et al. 2015; Sassenrath and Kulesza 2017).
Regions of each field with unusually high variability in apparent electrical conductivity and crop yield (transitioning from very high to very low over a short distance) were selected for in-depth soil and erosion analysis using the following methodology: ERT to identify soil stratigraphy and target sampling locations, optimal soil characterization, laboratory erosion measurements, and in situ erosion measurements.

Previous research has reported the change in depth to clay as measured by apparent electrical conductivity (Tucker-Kulesza et al. 2017; Sassenrath and Kulesza 2017) and the impact of clay content on yield (Sassenrath et al. 2015) in these fields and others in the region. The specific changes in depth to claypan and changes in soil characteristics with depth are explored in greater detail in this manuscript. Landscape position of the sampling locations varied between the two sites. Site 1 was near the highest elevation in the field (267 m above sea level), with sampling conducted downhill and to the north (266 m). Sampling at Site 2 (262 m) was near the lowest elevation in the field, and ran west. Site 2 had terraces installed prior to 1992; the highest elevation in the field was 266 m.

**Electrical Resistivity Tomography**. ERT surveys were performed at both sites to determine the soil stratigraphy and to select sampling locations. An Advanced Geoscience Inc. (AGI) ‘SuperSting Earth Resistivity, Induced Polarization and Self Potential Instrument for Geo-Electrical Tomography’ (SuperSting) was used to collect all ERT data. All ERT surveys were performed using 56 electrodes with an electrode spacing of 15 cm at Site 1 and 31 cm at Site 2. Surveys were established such that the end of one survey was the starting point for the next. The 56-electrodes were attached to 56-stainless steel stakes and driven into the ground. To ensure good contact for the injection current, the stainless-steel stake/electrodes sat just above the ground surface and all debris (e.g., corn stalks as shown in figure 1a) were removed from around the base of the stainless-steel stake/electrodes. The strong gradient array, a hybrid array that combines the Dipole–dipole and inverted Schlumberger arrays, was used because it provided high vertical and horizontal resolution near-surface and minimized near-surface noise, which was useful in distinguishing near-surface stratigraphy (Tucker-Kulesza et al. 2017). The data collection time for each ERT survey using a strong gradient was approximately one hour. The red dashed rectangle in figures 1b and 1c indicates the areas of interest at both sites. Terrain analysis was conducted using a Total Station surveying system to record the ground-surface elevation at each electrode. A terrain file was created from the recorded relative elevation values and utilized for post-processing of the ERT survey data.

**Geotechnical Tests**. Undisturbed and disturbed soil samples were collected where ERT sections indicated a near-surface claypan layer (i.e., low electrical resistivity near the surface) and no near-surface claypan layer (i.e., relatively higher electrical resistivity) at both sites. All samples were collected via a direct push method using a tractor mounted Giddings soil sampler (Giddings Machine Comp, Windsor, Colorado). The undisturbed soil samples were collected in stainless steel Shelby tubes (Humboldt Mnf, Elgin, Illinois) at depths between 30 and 72 cm (ASTM D1587/D1587M-15 2016). Undisturbed soil samples were used to determine undrained shear strength (ASTM D2850-15 2015), k_s, (ASTM D5084-16a 2016), and laboratory erosion tests. Disturbed soil samples were collected adjacent to the undisturbed samples in clear plastic tubes from the surface to a depth of 76 cm. Disturbed soil samples were used to classify soil samples according to the Unified Soil Classification System using Atterberg Limits (ASTM D2487-17 2018) and to observe horizons. Although there is no unifying equation for predicting critical shear stress based on soil properties, these measurements provide the soil properties commonly explored when trying to make such a prediction (Arulananand et al. 1980; Bonilla and Johnson 2012; Shan et al. 2015; Kulesza and Karim 2021). Physical measurements in the undisturbed samples were conducted in the horizons where two distinct horizons were observed in the disturbed samples, referred as the Top (T) of sample and Bottom (B) of sample.

**Laboratory Measurement: Erosion Function Apparatus**. The goal of the EFA testing plan was to measure the anticipated high critical shear stresses in the claypan layer and to contrast this with surface measurements. Other erosion devices cannot induce the relatively high (i.e., above 25 Pa) hydraulic shear stress that have been measured in claypan soils (Tucker-Kulesza et al. 2017). The EFA test directly measures the erosion rate and critical shear stress of undisturbed soil samples (Briaud et al. 2001). In an EFA test, the Shelby tube containing the soil sample is placed on a platform and oriented such that the top portion of the sample is flush with a small flume. Water flows over the soil sample through a rectangular flume at various velocities controlled by a pump. All samples were tested for one hour at six different velocities from 1.0 to 6.0 m s−1, in 1 m s−1 increments. As soil erodes from the Shelby tube, the sample is extruded using a piston such that the sample remains flush with the bottom of the flume; the erosion rate is calculated by tracking the extrusion over time. A photo of the soil surface was taken after each velocity and processed using a custom photogrammetry computational program to quantify the surface roughness for determining the applied hydraulic shear stress (Tran et al. 2017). Prior to testing at the next velocity, the top portion of the sample was trimmed level to the Shelby tube and...
bottom of the flume. This process was then repeated for each flow velocity. The applied hydraulic shear stress for each velocity was estimated using equation 2:

\[
\tau = \frac{1}{2} f \rho v^2, \tag{2}
\]

where \( \tau \) is the shear stress on the sample surface (Pa), \( f \) is the friction factor obtained from the Moody chart (Moody 1944) using the soil roughness from the photogrammetry, \( \rho \) is the mass density of water (kg m\(^{-3}\)), and \( v \) is the flow velocity (m s\(^{-1}\)). These data were used to create a plot of erosion and shear stress for each sample. The critical shear stress is the stress at which erosion initiates, assumed to be the hydraulic stress at 0.1 mm h\(^{-1}\) according to Briaud et al. (2001). EFA tests were performed on Shelby tube samples tested from the top of the sample, to indicate a surface measurement. EFA tests were also performed with the samples inverted such that the bottom was measured to indicate a measurement at depth within the claypan layer. It was not possible to sample only within the claypan layer using the Giddings sampler and direct push method without disturbing the surface of the claypan layer, thus sample integrity was ensured with this method. Sample locations were guided by the ERT surveys and the choice of a Top or Bottom test was further supported by observing two distinct horizons in the adjacent disturbed samples collected in the clear plastic tubes.

**Field Measurement: “Mini” Jet Erosion Test.** The “mini” jet erosion test (JET) (Al-Madhkhachi et al. 2013) was performed at the surface and 25 cm below the surface at locations where ERT sections indicated a transition from a near-surface claypan layer and no near-surface claypan layer (figure 2). Although the claypan layer may not have been exactly at 25 cm, this was the deepest the ring could be placed while keeping the hole stable. The JET foundation ring was driven into the soil surface using a rubber mallet to minimize soil disturbance and the submerged tank (containing the rotatable plate and depth gauge) was attached to the foundation ring. The rotatable plate with the jet nozzle was closed before test initiation. A hose connected the water supply tank to the water flow pump, the water flow pump to the head tank, and the head tank to the JET apparatus water inlet. Two excess flow ports located at the top of the head tank controlled the water level inside the head tank. The head tank was attached to a tripod stand such that the height measured from the excess flow ports to the top of the rotatable plate was between 2.1 and 2.4 m. The initial depth to the surface was recorded using the depth gauge before test initiation. At test initiation, the jet was opened and scour of the soil surface was recorded at the following time intervals: 1, 2, 3, 4, 5, 10, 15, 20, and 30 minutes. When three consecutive scour measurements were recorded for the same time interval, the time interval was increased. For example, a scour depth of 52 mm was recorded three consecutive times using a 2-minute time interval, so the time interval was increased to 3 minutes. This measurement process was performed for all JET tests with a maximum data collection of two hours per test at both sites.

All JET data analysis followed the scour depth solution as described by Daly et al. (2013). The soil erodibility was determined using the measured scour depth and total time of the experiment. The scour depth solution was selected for JET data analysis because observed scour depth measurements closely correlated to the predicted scour depth solution measurements. The critical shear stress was determined as equation 3:

\[
\tau_c = \tau_0 (J_0/J_e)^2, \tag{3}
\]

where \( \tau_c \) is the critical shear stress (Pa), \( \tau_0 \) is the maximum shear stress due to the jet velocity at the nozzle (Pa), \( J_0 \) is the potential core length from the jet origin (cm), and \( J_e \) is the equilibrium scour depth (cm). The erodibility coefficient was determined using equation 3, the applied shear stress, and the observed scour depth data as described by Daly et al. (2013). The goal of the JET measurements was to show how rapidly the critical shear stress increased with depth in this claypan region; effects of sample disturbance were minimized by running the test in situ.

**Statistical Design and Analysis.** The inherent variability of soil properties means that each location was a unique replicate. To improve the accuracy of measurements, multiple runs of each testing method were conducted at each site, with the exception of the initial electrical resistivity surveys. All ERT data were processed using AGI’s EarthImager 2D software. A Smooth Model inversion method (Constable et al. 1987) was selected for all data processing. The forward modeling utilized the Finite Element Method with the Cholesky Decomposition Method equation solver and a mixed boundary condition. The root mean square error (RMSE) and L2-norm error metrics were used to characterize the goodness-of-fit between measured and calculated electrical resistivity of the reconstructed model. Where RMSE represents an average data misfit over
all data points, L2-norm accounts for the weighted data errors. An RMSE of less than 5% and an L2-norm close to unity (1.0) but not exceeding the most accurate representation of the subsurface. All electrical resistivity surveys converged in three iterations, with RMSE less than 5% and L2 norms near unity, indicating excellent fit between the collected and modeled data.

Results and Discussion

Site One. Four ERT surveys in our target area of Site 1 were performed with an electrode spacing of 0.15 m, and positioned such that the end of Survey 1A was the beginning of Survey 1B and so on, with an overall survey length of 33.4 m (figure 3). Survey 1A started at the highest elevation, with a relative elevation change of 0.62 m across the survey. The overall slope of the line was 1.86%. All surveys converged in three iterations, with RMSE less than 5%, and L2 norms near unity, indicating excellent fit between the collected and modeled data. In Survey 1A, electrical resistivity measurements indicated a distinct low resistivity layer (10 Ohm-m or less), shown in purple, at the surface to a depth of ~0.48 m below the surface, indicating a very near surface claypan layer. A transition area was measured in Survey 1B, where the low resistivity layer (10 Ohm-m or less) thinned from 89 cm to less than 15 cm in thickness as the measurements transitioned toward a high electrical resistivity area. Electrical resistivity measurements in Survey 1C highlighted a thin surface layer (approximately 15 cm) of relatively higher electrical resistivity averaging around 15 Ohm-m. Survey 1D had a discontinuous and relatively higher electrical resistivity in the upper 15 cm, which appeared to dissipate across the profile.

Based on these profiles, multiple soil samples were collected across Survey 1B for laboratory characterization in two horizons where they were observed within the upper 62 cm. Furthermore, areas with relatively large areas of low resistivity from Surveys 1A and 1B were used to select areas for JET tests where the claypan was suspected to be near the surface. Additional JET tests were performed across Survey 1D where the claypan was suspected to have dissipated based on the ERT results. The black arrows in figure 3 denoted with “S” indicate where JET tests were performed at the surface. The red arrows denoted with “L” indicate where JET tests were performed in the lower layer, 25 cm from the surface. The filled in arrows indicate testing in an area suspected to have near surface claypan and open arrows in an area where the claypan was suspected to have dissipated. Tests were performed in similar areas in series of three for replication, but a third test was not run on the surface measurements in the region where the claypan was suspected to have eroded.

The soil analysis of samples collected from Survey 1B highlighted the two distinct horizons within the soil profile (table 1). At the surface 0 to 25 cm, the soil was a low plasticity clay with an average k_{sat} of 4.27 × 10^{-5} cm s^{-1}, an average undrained shear strength (S) of 40 kPa, and an average critical shear stress (\(\tau_c\)) measured in the EFA of 19.1 Pa. The lower horizon at 25 to 61 cm, was a high plasticity clay, CH, with a k_{sat} of 9.1 × 10^{-7} cm s^{-1}, an average undrained shear strength of 100 kPa, and an average critical shear stress measured in the EFA of 96.3 Pa. For the lower horizon, the EFA test was the 61 cm sample tested "bottom up." All soil index and strength parameters at Site 1 are shown in table 1; note that we were not able to obtain a replicate for the lower k_{sat} conductivity test as the specimen was damaged during extrusion. The results highlighted the presence of a relatively more impermeable and stiffer high plasticity clay horizon at 25 cm depth in the soil profile of Survey 1B. This high plasticity clay horizon had a critical shear stress that was on average five times higher than that measured in the surface horizon.

Six in situ JET tests were performed in Surveys 1A and 1B, and five in Survey 1D (figure 3). The critical shear stress measured in the JET tests as a function of the location along the profile demonstrated the two distinct horizons observed in the area with the relatively low resistivity and near surface claypan layer in Surveys 1A and 1B (figure 4a). The lower horizon 25 cm below the soil surface (L1.1, L1.2, and L1.3) had an average critical shear stress of 15.4 Pa (red diamonds). This was nearly twice as high as that measured at the surface (S1.1, S1.2, and S1.3), which had an average critical shear stress of 7.71 Pa (black diamonds). A similar trend was noted in the measured erosion rates (figure 4b, filled diamonds), with the upper surface (black) eroding faster than the lower soil (red). The measurements 25 cm below the surface in Surveys 1A and 1B (L1.1, L1.2, and L1.3), where the electrical resistivity was relatively low (figure 3), had the lowest erosion rate compared to that measured at the surface. In contrast, the region of the survey (Survey 1D) without claypan showed nearly identical critical shear stress measurements at both upper and lower horizons (figure 4a, open squares), and minimal difference in erosion rates between the surface and 25 cm deep layer of the tests (figure 4b).

Site Two. The target area at Site 2 was identified as a region that changed quickly from high apparent electrical conductivity and low yield, to lower apparent electrical conductivity and higher yield (Mathis II 2020). This area was near the lowest elevation in the field. Two ERT surveys were performed in this target area (figure 5). A shorter survey line was required at Site 2 because there was a more rapid transition in apparent electrical conductivity and yield. Furthermore, the presence of an overhead power line through this field caused noise in the ERT results. The shortened survey lines distanced the surveys from the noise source. The 0.15 m electrode spacing at Site 1 also did not highlight the very shallow, distinct soil horizons above the relatively conductive near-surface claypan layer. Utilizing an electrode spacing of 0.31 m, ERT surveys were performed such that the end of Survey 2A was the beginning of Survey 2B. In Survey 2A, electrical resistivity measurements highlighted a low resistivity layer (10 Ohm-m or less), shown in purple, with an overall depth of 1.3 m (note difference in depth scale between sites). Survey 2B showed a dissipation of the low resistivity layer at the soil surface similar to that observed at Site 1 (Survey 1B). However, instead of the continued diminution of the lower resistivity layer as seen at Site 1, a low electrical resistivity layer (10 Ohm-m or less) remained approximately 0.5 m below the surface (Survey 2B). Samples were collected for laboratory analysis and characterized with replicates at two depths from Survey 2B. An additional sample was collected and tested at 61 cm from Survey 2A for EFA testing. Black and red arrows indicate JET tests at the surface and at 25 cm, respectively. Filled arrows indicate JET tests in the area suspected to have claypan at the surface and open arrows in the area suspected to not have a claypan surface. The two-layer soil laboratory testing showed the surface soils at Site 2 classified as low plasticity clay, with an average k_{sat} conductivity of 2.9 × 10^{-5} cm s^{-1}, undrained shear strength of 35 kPa, and critical shear stress of
Figure 3
Site 1 electrical resistivity tomography (ERT) survey line: (a) Survey 1A, (b) Survey 1B, (c) Survey 1C, and (d) Survey 1D. Undisturbed samples were collected in Shelby tubes across Survey 1B for the erosion function apparatus (EFA) test and geotechnical analysis in the lab. Additional samples were collected in clear plastic tubes for soil classification. Arrows in survey lines 1A, 1B, and 1D indicate where in situ jet erosion tests (JET) were performed at the surface (S) and 25 cm from the surface (L). Replicates are grouped by filled (in claypan) or open (not in claypan) arrows.

(a)  
[ERT survey line image with legend: Ohm-m, Iteration = 3 RMS = 3.03% L2 = 0.95 Electrode spacing = 0.15 m]

(b)  
[ERT survey line image with legend: Ohm-m, Iteration = 3 RMS = 3.47% L2 = 0.94 Electrode spacing = 0.15 m]

(c)  
[ERT survey line image with legend: Ohm-m, Iteration = 3 RMS = 4.25% L2 = 0.92 Electrode spacing = 0.15 m]

(d)  
[ERT survey line image with legend: Ohm-m, Iteration = 3 RMS = 3.94% L2 = 0.92 Electrode spacing = 0.15 m]
5.43 Pa (table 2). The lower horizon classified as clay; however, the replicates classified differently, with one as a low plasticity clay and one as a high plasticity clay. The average ksat of the lower layer was 4.2 × 10⁻⁵ cm s⁻¹ and undrained shear strength of 53.5 kPa. Only one EFA test could be conducted on the lower layer at Site 2 due to sample disturbance from difficulty sampling. Again, the critical shear stress measured in the EFA was from an undisturbed sample tested “bottom up.” Unlike Site 1, although the critical shear stress at the lower horizon was nearly four times that at the surface, the other soil parameters did not indicate two distinct layers.

Ten JET tests were performed at Site 2 to measure the critical shear stresses and erosion rates at the surface and at 25 cm within the soil profile (figure 6). The average critical shear stress at the surface at Site 2 was 5.18 Pa and 4.23 Pa in Surveys 2A and 2B, respectfully (S2.1 to S2.6 in figure 6a). However, the average critical shear stress 25 cm below the surface was very similar at locations both with and without a claypan (15.19 Pa in Survey 2A and 15.62 Pa in Survey 2B), unlike those measured at Site 1. As observed in Site 1, the upper soil layer had a higher rate of erosion than the lower layer (figure 6b), though erosion rates were similar at locations both with and without a claypan. Two distinct horizons can be seen in the measured erosion rates at Site 2, though sample S2.5 was an extreme outlier with an erosion rate of 61 mm h⁻¹. Overall, the field erosion results presented in figure 6 are similar to the laboratory erosion in that there were two horizons of different erodibility, despite the similarities in other soil properties (table 2).

To further delineate differences in soil erosion with depth, we compared the erodibility coefficient, kEFA, to the critical shear stress, τc, measured with the JET (figure 7). Although there is scatter in the data, which has commonly been reported with JET tests (Daly et al. 2015; Enlow et al. 2017; Mahalder et al. 2018), the unique measurements 25 cm below the surface tested from soils on the claypan layer identified in the ERT surveys clearly form a cluster with distinct characteristics of high critical shear stress and low erodibility coefficient, highlighting the nonerodible nature of this layer.

Discussion. We have observed that the depth to the clay layer varies across a field (Tucker-Kulesza et al. 2017; Mathis II et al. 2019) (figures 3 and 5). The original motivation of this research was to understand the cause of variable topsoil loss leading to different depth to clay layer that was quantitatively

### Table 1

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>LL</th>
<th>PI</th>
<th>USCS</th>
<th>Ksat (cm s⁻¹)</th>
<th>Su (kPa)</th>
<th>τc_EFA (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 25</td>
<td>30</td>
<td>14</td>
<td>CL</td>
<td>2.2 × 10⁻⁵</td>
<td>47</td>
<td>19.4</td>
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<tr>
<td></td>
<td>38</td>
<td>21</td>
<td></td>
<td>6.04 × 10⁻⁵</td>
<td>33</td>
<td>18.7</td>
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<tr>
<td>25 to 61</td>
<td>53</td>
<td>29</td>
<td>CH</td>
<td>9.1 × 10⁻⁷</td>
<td>97</td>
<td>118.0</td>
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<tr>
<td></td>
<td>73</td>
<td>52</td>
<td></td>
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<td>103</td>
<td>74.5</td>
</tr>
<tr>
<td>25 cm 1A</td>
<td>76</td>
<td>51</td>
<td></td>
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</tbody>
</table>

et al. 2002; Van Oost et al. 2006; Chan et al. 2017), we expected that the exposed clay layer would be at the highest elevation in the fields. As noted by Mathis II (2020), Site 1 was at the highest elevation in the field, and that is where Survey 1A started. Although the field had a very modest 1.8% slope, the more productive surface soils were likely slowly removed after repeated tillage operations, bringing the claypan layer closer to the surface, as has been shown in other studies (Gerontidis et al. 2001; Van Oost et al. 2006).

A clear two layered system was observed in Survey 1A and Survey 1B using ERT. The soil analysis also supported this interpretation with $k_{sat}$ measurements at a relatively shallow depth (25 cm) that were two orders of magnitude lower (i.e., more impermeable) than the surface measurements. Previous researchers have evaluated the role of low and high plasticity on erodibility as well as shear strength (Shan et al. 2015; Kulesza and Karim 2021). While there is no direct equation to determine critical shear stress from these properties, the high plasticity clay with the lower $k_{sat}$ measurement and higher undrained shear strength were observed to have higher critical shear stress. Similarly, the field and laboratory erosion measure-

**Table 2**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>LL</th>
<th>PI</th>
<th>USC</th>
<th>$k_{sat}$ (cm s$^{-1}$)</th>
<th>$S_u$ (kPa)</th>
<th>$\tau_{c,EFA}$ (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 25</td>
<td></td>
<td></td>
<td>CL</td>
<td>$3.3 \times 10^{-5}$</td>
<td>28</td>
<td>5.52</td>
</tr>
<tr>
<td>30</td>
<td>31</td>
<td>14</td>
<td>CL</td>
<td>$2.2 \times 10^{-5}$</td>
<td>42</td>
<td>5.43</td>
</tr>
<tr>
<td>25 to 61</td>
<td>56</td>
<td>37</td>
<td>CH</td>
<td>$1.7 \times 10^{-6}$</td>
<td>60</td>
<td>20.6</td>
</tr>
<tr>
<td>240</td>
<td>40</td>
<td>22</td>
<td>CL</td>
<td>$8.2 \times 10^{-6}$</td>
<td>47</td>
<td>20.6</td>
</tr>
</tbody>
</table>


Figure 5

Site 2 electrical resistivity tomography (ERT) survey line: (a) Survey 2A and (b) Survey 2B. Arrows indicate where jet erosion tests (JET) were performed at the surface (S) and 25 cm below the surface (L). Replicates are grouped by filled (in claypan) or open (not in claypan) arrows.

Table 2

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noted based on crop yields; both study areas have much greater yield variability relative to the rest of the field (Tucker-Kulesza et al. 2017; Mathis II 2020; Sassenrath and Kulesza 2017). In this study, we highlight the rapid changes in soil physical characteristics with depth to delineate changes in erodibility that could explain the variability in surface soil characteristics at these sites. We also show how these changes with depth can be extrapolated beyond point measurements using ERT. Here, we first interpret our results at the two sites and then discuss the implications for erosion research, soil conservation, and agricultural management.

The unique experimental design in this study begins by using electrical resistivity to visualize the claypan layer with depth, rather than traditional bulk surface measurements obtained with an apparent electrical conductivity mapper (e.g., a Veris mapper). An advantage of ERT is the depth image shown in figures 3 and 5, rather than a surface profile more commonly performed through grid or zone soil sampling to identify variability in agricultural fields (Mueller et al. 2015). Based on results from other research studies (Bhuyan et al. 2002; Van Oost et al. 2006; Chan et al. 2017), we expected that the exposed clay layer would be at the highest elevation in the fields. As noted by Mathis II (2020), Site 1 was at the highest elevation in the field, and that is where Survey 1A started. Although the field had a very modest 1.8% slope, the more productive surface soils were likely slowly removed after repeated tillage operations, bringing the claypan layer closer to the surface, as has been shown in other studies (Gerontidis et al. 2001; Van Oost et al. 2006).
Figure 6
In situ erosion measurements from the jet erosion test (JET) at Site 2: (a) critical shear stress and (b) erosion rates at the surface (blue) and at 25 cm in the profile (green) for surveys with a clay layer (solid symbols; low electrical resistance, figure 5) and without (open symbols; higher electrical resistance, figure 5).

Legend
- Surface 2A
- 25 cm 2A
- Surface 2B
- 25 cm 2B

Test ID
S2.1 to S2.3, L2.1 to L2.3, S2.4 to S2.6, L2.4 to L2.5

Conversely, the area of interest at Site 2 was near the lowest elevation in the field. This was a major shift from previous research studies. Erosion in Site 1 occurred as expected, with the highest elevation having the greatest loss of silt loam topsoil, most likely the result of erosion from the upper landscape position. The presence of the exposed claypan layer at the lowest field elevation in Site 2 indicated an alternative cause of the exposed claypan, and the great variability in the claypan depth within the region. A similar experimental design was used at Site 2 where a very near surface claypan layer was observed in figure 5a based on ERT (approximately 10 Ohm-m) that then continued but was slightly deeper at about 0.5 m in figure 5b. Although we anticipated a continuous transition from claypan to no claypan, this was not observed at Site 2. Rather than a dissipation of the clay layer as seen at Site 1, the clay layer at Site 2 continued, though at deeper depth. The ERT showed claypan across both surveys and this was similarly observed with the critical shear stress measured via the EFA and JET tests. The EFA tests at Site 2 showed that the assumed claypan layer had critical shear stresses that were four times higher than the surface measurements, though the magnitude was five times lower than the average critical shear stress on the claypan at Site 1. The average critical shear stresses measured with the JET at the surface and 25 cm below the surface in Survey 2B were similar to the average critical shear stress values obtained in Survey 2A, again supporting the results from the ERT profile.

To further delineate soil variability, we grouped the in situ erosion tests in figure 7 as guided by ERT, where critical shear stress was measured with depth in areas with relatively low electrical resistivity (approximately 10 Ohm-m). While the erodibility coefficient had a range of values for most of the measured soils, those on the claypan had much lower erodibility coefficient and higher critical shear stress. Therefore, this showed that a claypan layer can be found at both the highest elevation and lowest elevation in a crop production field as supported by soil property analysis, field erosion tests, and laboratory erosion tests, indicating that processes other than erosion of topsoil due to topography contributed to the soil variability. It is worth noting that the erosion characteristics of the topsoil were relatively consistent across the sites, regardless of elevation or the presence of a claypan layer as measured. It is likely that the natural topsoil erosion at Site 1 in the claypan area was greater than at Site 2 because the k_sat of the lower horizon was two orders of magnitude lower than at the surface. The reduced k_sat results in lateral flow that exacerbates surface runoff (Anderson 2011; Blanco-Canqui et al. 2002). Although we measured the change in erosion characteristics with depth, a limitation of this study was that our measurements only alluded to enhanced erosion due to lateral flow from the measured increase in critical shear stress on the claypan and the supporting hydraulic conductivity measurements. The measurements did not account for the influence of subsurface flow on the erodibility coefficient or erosion rates.
Site-specific management recognizes the inherent variability of soils across an agricultural field. However, current measurements tend to generalize surface measurements, treating the soil horizon as one uniform layer, irrespective of variability with depth. The size of agricultural fields, time, and resource constraints often limit the ability to map an entire field with depth. Here, we employ a unique approach to guide the in-depth measurements. After identifying areas of unique variability, we performed the ERT surveys and other tests in the areas of interest. The ERT was able to clearly delineate where there was reduced critical shear stress. The ERT tests took an hour, while the detailed investigation took longer. Thus, this research highlights how ERT can be used to quickly identify where to sample for more detailed analysis. This is becoming increasingly common in geotechnical site investigations to guide sampling locations across large projects. The Federal Highway Administration’s Advanced Geotechnical Methods in Exploration (A-GaME) represents a national initiative to reduce geotechnical risks with effective site characterization guided by applied geophysical methods, including ERT (FHWA 2023). Furthermore, the changes in the ERT profile were correlated with the measured, rapid change in erosion characteristics with depth. Karim and Tucker-Kulesza (2018) showed that ERT alone can be used to identify erosion variability in near surface soils, which is further supported in this research.

Our data not only showed the variability of the depth to claypan but also the variability of the claypan layer within the soil profile. Furthermore, erosion varied with depth in a claypan soil. These results demonstrated the need to better understand dimensional variability in nonhomogeneous soils. Soils in the region were historically tall grass prairie. Deep-rooted grasses and perennial systems have root systems that are better able to grow into the claypan (Clark et al. 1998; Rachman et al. 2004). Establishment of perennial crops, especially grasses, may be better suited to utilize the clay layer, extracting nutrients and water from deeper within the soil profile than annual crops (Hsiao et al. 2018; Alagele et al. 2020). Research has shown changes in soil properties and improved soil health with use of perennial crops and forages for biomass and grain production (Daly et al. 2023; Rakkar et al. 2023). Changes in soil biochemistry with management practices is only beginning to be understood as we explore the soil microbiome. Changes in soil biochemistry with depth may be even more important in stabilizing the soil system to reduce soil and nutrient losses. In addition to being more suited to production on clay soils, these perennial systems may provide greater stability of the soil, reducing nutrient and sediment losses and preserving the shallow topsoil. Incorporation of cover crops may also enhance the soil microbiome and create more rooting structure into the clay layer; however, this is challenging due to the tight crop rotation of the region that produces three crops in two years. Future research is needed to examine the impact of vegetative systems with alternative root systems that mimic tallgrass prairie and better manage the whole soil profile in the claypan region.

An additional consideration is that the abrupt textural change between the claypan and surface soils may make the surface soils more susceptible to erosion (Buckley et al. 2010; Bockheim 2016). The combination of a distinct textural change and surface soils with relatively higher moisture may augment erosion at the surface (Singh and Thompson 2016). Studies are needed to further examine erosion processes within the clay soil to measure the potential for undermining of the topsoil at the claypan interface. Additionally, the erosion data on the claypan can be used in erosion models to more accurately predict sediment transport. Accurate erodibility coefficients calculated in this study can be used for more precise erosion modeling (Alarcon 2021).

Summary and Conclusions

Understanding the inherent soil properties within the soil profile are critical in developing appropriate crop management protocols. Accurate knowledge of soil properties is also critically important to develop conservation management practices that will address the nonpoint source pollution from potential nutrient and sediment losses from agricultural fields (Lohani et al. 2020). Integrative approaches to land and soil management can result in better and more site-specific adaptation of management practices (Sassenrath et al. 2010; Lal 2022). In this paper, we demonstrate that claypan soil erodibility is highly variable both laterally and with depth. We have also shown that varying degrees of erodibility can be identified using ERT, which confirms our hypothesis. Previous research has focused on the lateral variability as a means to improve crop management practices. We identified areas of interest based on known lateral variability in a site and then further showed variability with depth within those specific sites. We used unique erosion tests in the lab and in the field to capture this change in soil erosion characteristics with depth. We also show the extent of these soil characteristics using electrical resistivity, which can be employed significantly faster to obtain similar information.

Figure 7

Erodibility coefficient, \( k_d \), as a function of critical shear stress, \( \tau_c \), measured with the jet erosion test (JET). All points within the black box are located in the high resistivity area (i.e., claypan).

Legend

- **Surface surveys**
- **25 cm surveys**

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\( k_d \) (cm\(^3\) [N-s]\(^{-1}\))

\( \tau_c \) (Pa)

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Another unique finding in this research was that the exposed claypan layer can be found at the lowest elevation in a field, which is contrary to common knowledge.

Because of the inherent variability of claypan soils, this research showed that we need to better understand the variability with depth in nonhomogeneous soils as well as surface variability. Alternative agronomic systems, incorporating more deep-rooted plants such as grasses and perennial systems for forage or biomass production may be more suitable for production in the claypan region. The deeper-rooted vegetation and permanent root structures would stabilize the soil system. Perennial roots are also better able to grow into the clay layer, extracting nutrients and water from deeper in the soil profile. Unlike the deep loessial or alluvial soils, claypan soils have a restrictive soil layer. The clay layer is not a temporary layer, such as a plow layer that can be disrupted with deep tillage. As demonstrated here, the clay layer also varies in depth across a field. Alternative management practices that incorporate grasses and perennial crops and forages applicable to claypan soils need to be designed.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the research reported in this manuscript.

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