Compaction Susceptibility of Select Alabama Piedmont and Upper Coastal Plain Ultisols

by

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A thesis submitted to the Graduate Faulty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
December 15, 2018

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ABSTRACT

The U.N. categorizes soil compaction as the most important type of physical soil degradation because of soil productivity and quality loss. Subsoil compaction causes great concern because it is difficult to remediate, particularly in forested settings. Soils vary in their reaction to applied dynamic and static forces and susceptibility to compaction based on physical, chemical, biological, and morphological properties. Soil mechanical approaches have developed indices and parameters that describe a soil's behavior upon compaction for largely engineering applications, while little work has related these to soil morphological and pedological measures. Soil surveys and on-site pedological investigations describe soil morphological properties (e.g. horizonation, structure, consistence) that we hypothesize to be related to soil compaction susceptibility. In order to more fully understand relationships between soil properties and response to applied static and dynamic forces, a two-fold approach utilizing field-based trafficking and laboratory-based consolidometer experiments was used.

In the first study, recently developed sensors were used to measure stress transferred through soil with depth during trafficking events for nine Alabama Piedmont sites where soils were Typic, Oxyaquic, and Rhodic Kanhapludults. Soils were described, sampled, and several near surface (0-40 cm) properties were measured. Sites were trafficked with five passes using a CAT 535D forestry skidder and soil morphological and physical properties were related to the resulting compactive forces. Sensors placed in subsurface (~12.5 cm) and subsoil (~25 cm) horizons (measured stress) responded systematically with depth to trafficking pressures. Bulk density increased (6% and 16% for overall and surface horizons, respectively) following trafficking. Soil texture (e.g. clay content, Atterberg limits) correlated with several other near surface properties ($r = 0.21$ to 0.77, $p<0.10$). Using principal components, loading factors indicated that textural properties (USDA texture, Atterberg limits) and volumetric water content described the majority of soil property variability. Stepwise linear and principal component regression indicated that soil physical properties (e.g. texture, volumetric water content, and bulk density) and, to a lesser extent, morphological properties (e.g. argillic depth, stratification ratios, and horizonation) were related to measured dynamic stress. In these select Alabama Kanhapludults, soil texture is highly related to sensor-based stress measurements, but morphological properties also describe a portion of variability. These properties are provided in soil surveys and soil descriptions, illustrating their utility in determining compaction susceptibility.

In the second study, a consolidometer (static loads from 10-800 kPa) was used to develop compression indices and relate these to soil morphological and physical properties for surface (A), subsurface (E, BE) and subsoil (Bt) horizons (34) collected from Alabama Upper Coastal Plain and Piedmont Ultisols. Soils were described, sampled, and several near surface (0-40 cm) properties were measured. Surface horizons were more susceptible to bulk density change caused by compression (~35% vs ~20%) and had higher compression indices (C_P) (0.24 vs 0.19) than subsurface or subsoil horizons. Uncorrelated factors developed using factor analysis indicated that textural

properties (USDA texture, Atterberg limits, and Coefficient of Curvature) and dynamic properties (soil organic carbon (SOC), water content at 0.3 bar) described a significant portion of soil property variability. Stepwise linear and factor regression suggested that dynamic properties (SOC, bulk density), static properties (texture), and morphological properties (structure grade) affected compaction susceptibility. Compression indices were largely affected by SOC and texture (e.g. coefficient of curvature, % coarse fragments). Maximum bulk density (to 800 kPa) and bulk density change (from initial to 800 kPa) increased with greater SOC and decreased with structure grade development.

The goal of these studies was to better understand compaction susceptibility of select southeastern U.S. Piedmont and Coastal Plain soils through relationships between near-surface soil properties and applied dynamic (soil stress translation) and static compression (consolidometer) measurements. In general, soil textural attributes describe approximately 15-30%, dynamic properties (SOC, WSA) describe approximately 40%, and morphological properties (structure grade) describe approximately 15% of compaction susceptibility variability.

The aggregate results from this study illustrate that soil compaction susceptibility is influenced by static, dynamic, and morphological properties. Combining this understanding with pre-existing tools, such as soil surveys, can provide producers—particularly in the forest industry—with valuable information on which sites are more susceptible to compaction. This can contribute to an overall management plan that seeks to minimize the degradation of a precious, life supporting, finite resource—our soil.

Acknowledgements

I am beyond grateful for and blessed by my wonderful husband, Mr. P.Lane, who has contributed an immense amount of time and energy towards supporting me through this M.S. Thank you for all of your help in the lab and field, with technology, with cooking, and for the abundance you contribute to my life.

I want to extend appreciation of the highest degree to Dr. Joey N Shaw, the fearless leader of the Pedology Lab. Thank you for encouraging me to pursue an M.S. and for offering me the opportunity to earn it. I am beyond thankful for your guidance in all things Pedology. I appreciate and respect your commitment to excellence and holding me to high standards. Thank you for continuing to offer patience and advice when I did not know where to turn next. Finally, thank you for your dedication to helping your students develop.

I would like to thank my committee, Drs. Carter, Gallagher, and Knappenberger, for their guidance, patience, resources, and help–particularly during the long days spent trafficking in the summer heat. I would not have been able to complete this work without each of you.

I would like to thank the USDA Forest Service for their partial funding of this project.

I would like to thank the Pedology Lab group for their help: Wade Gossett, Jessie Curl, Brooke Johnson, Patrick, Ashleigh Van Cleave, and Jenna Platt. Each of you made my day-to-day job so much easier and more enjoyable. Thank you for assisting me through the learning curve of managing a lab.

I would like to acknowledge Dr. Yucheng Feng and Liz Smith for their advisement and encouragement during my time at Auburn.

I would like to express my deepest appreciation to my family for the support they have provided in my life and in this part of the journey. Mom and Dad, thank you for investing in me and my education. Grandaddy, thank you for your presence, wisdom, and support. Aunt Meg, thank you for being so interested in my success that you have already read (and provided feedback on) this thesis.

Finally, to the late Jody Sohr – thank you for introducing me to the field of soil science. I am in this field that I love because you told me that Soils was the hardest subject. With your prompting, I was determined to master soils. Now, I literally have.

soli Deo gloria.

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List of Abbreviations

Cc	Coefficient of Curvature
C_P	Compression Index
Cu	Coefficient of Uniformity
LL	Liquid Limit
PL	Plastic Limit
PI	Plasticity Index
SOC	Soil Organic Carbon
WSA	Water Stable Aggregates
WDC	Water Dispersible Clay

List of Symbols

ρ_b Bulk Density (g cm^{-3})

σ Stress (psi)

θ_V Volumetric Water Content

Chapter 1. Literature Review

INTRODUCTION

Soil compaction has been recognized as a critical issue in agriculture, even recognized as the "most serious environmental problem caused by conventional agriculture" (McGarry, 2001; Hamza and Anderson, 2005) and "the most important type of physical soil deterioration" (Oldeman et al., 1991). The Soil Science Society of America (1996) defines soil compaction as "the process by which soil grains are rearranged to decrease void space and bring them into closer contact, thereby increasing bulk density." Compaction effects are both immediate and long-lasting with increases in bulk density, soil strength, runoff and erosion and decreases in porosity, gas diffusivity, air permeability, hydraulic conductivity, available water, and overall soil quality (Keller et al., 2017; Zhai and Horn, 2017).

Southeastern Piedmont and Coastal Plain Soil Quality

Stable landscapes within the southeastern U.S. Piedmont and Coastal Plain are dominated by Ultisols (Buol et al., 2011). Historically, these landscapes have been subjected to intensive cultivation, leaving landscapes susceptible to soil loss via erosion (Trimble, 1974; Daniels, 1987). Consequently, soils in this region generally have thin A (surface) and E (subsurface) horizons (Markewich et al., 1990).

The climate and geology of the southeastern U.S. is conducive to the formation of argillic and kandic subsoil horizons dominated by highly weathered clays (e.g. kaolinite), quartz, and iron and aluminum oxides (Markewich et al. 1990; Shaw, 2002; Shaw et al.,

2010) with naturally high acidity and low cation exchange capacity and base saturation (Daniels, 1987; Shaw et al., 2010; Soil Survey Staff, 2014). The highly weathered mineralogy and thermic, udic climate of the U.S. Piedmont and Coastal Plain contribute to soils that are relatively infertile with little ability to sustain production without amendments (Shaw, 2002; Shaw et al., 2010). Soil organic carbon stores, the most important soil quality indicator, have been depleted and are not readily restored (Causarano et al., 2008, Levi et al., 2010). Protecting these soils from further degradation is vital.

Soil Compaction Effects

Many studies have highlighted the largely negative effects of compaction on crop productivity (Unger and Kaspar, 1994). Zhai and Horn (2017) found decreased air permeability, total porosity, and air diffusivity in remolded sand, silt loam and clay loam soils in response to compression. Douglas and Crawford (1998) found that decreased nitrogen uptake in ryegrass was closely related to increased compaction, which was closely related to the amount of vehicle traffic in fields with clay loam surface textures.

Roots are physically restricted by compacted soils (Unger and Kaspar 1994), and yield reductions are associated with increased bulk density (Greacen and Sands, 1980; Hammel, 1994; Hamza and Anderson, 2003). Research has indicated that increased soil strength physically limits root growth, while increased bulk density limits hydraulic conductivity and porosity which limits root intakes of air, water, and nutrients (Unger and Kaspar, 1994). Correspondingly, the USDA-NRCS recognizes threshold bulk densities for each soil texture that affect or restrict root growth (USDA, 1999).

Compaction in Forested Systems

Compaction issues in forested systems are similar to agronomic systems, although the relationship between forestry operations and soil compaction is a bit more complex. Compaction in forested systems is often significant due to heavy equipment and heavy loads during forestry operations (Horn et al. 2004). Forestry equipment has become heavier over the years causing increases in soil mechanical resistance and bulk density and decreases in porosity and hydraulic conductivity (Greacen and Sands 1980). Due to the size of timber crops, trees and tree roots have also been shown to cause compaction (Greacen and Sands 1980).

Covering trafficking routes (e.g. skid trails) with a thick layer of logging residue (i.e., a slash-road) is commonly used to protect soil from disturbance and degradation (McDonald and Seixas, 1997; Wood et al., 2003). Parkhurst et al. (2018) examined trafficking in a forested setting with silt loam textured soils. They found that slash placed on trafficking routes had an “interesting and unexpected” result on soil properties (Parkhurst et al., 2018).

Summarized research findings indicate that compaction is persistent in forested settings (Kozlowski, 1999). While remediation can be effective when used properly, research indicates that amelioration in forested situations is not always effective, especially in the subsoil (Kozlowski, 1999). Furthermore, remediation efforts have been known to immediately harm and interminably restrict root growth in woody plants (Kozlowski, 1999).

In *Compaction of Forest Soils, a Review,* Greacen and Sands (1980) found 117 studies on 24 different tree species where soil compaction caused yield reduction, and several studies that demonstrated soil compaction caused growth reduction in "economically significant" species. As opposed to agronomic soils, forest soils are often not uniformly compacted, with some areas of forest soils left virtually undisturbed while skid trails and logging decks are heavily compacted with slow natural recovery times (McDonald et al., 2002). Tillage has been identified and implemented as a possible solution to compaction issues (Froelich et al. 1985). In summary, compaction is a soil problem and not just an agricultural or forest production problem.

Soil Compaction Remediation

Historically, agronomists have relied on mechanical means of remediation to combat the negative effects of soil compaction. However, conventional tillage is responsible for inducing massive amounts of erosion in the southeastern U.S. Piedmont (Trimble, 1974) and for decreasing soil organic carbon in many physiographic regions (Cannell and Hawes, 1994). Therefore, with the harmful effects on soil quality (USDA, 1999), conventional tillage is not a sustainable option for remediation of compaction in Alabama Kanhapludults.

Research has demonstrated that the use of deep ripping, or subsoiling, to alleviate compaction without disturbing the topsoil has mixed results. A study on a Decatur silt loam in North Alabama found that cotton (*Gossypium hirsutum* L.) yields associated with a conservation tillage system—subsoiling combined with a cover crop—were comparable to yields in a conventional tillage system (Raper et al., 2000). The researchers noted that the soil quality benefits associated with the conservation tillage system, such as decreased soil strength, were persistent for almost a year following subsoiling.

However, in a cotton study in Alabama by Touchton et al. (1986) on a Decatur silt loam and a Dothan sandy loam, deep ripping treatments yielded consistently lower-than-conventional tillage treatments. Additionally, deep ripping had no effect on cotton yields in the Dothan (Coastal Plain) soil, while it had a negative effect on yields in the Decatur (Tennessee Valley) soil compared to no-till systems (Touchton et al. 1986). In a series of soybean (*Glycine max* L. Merr.) studies on a Goldsboro sandy loam in South Carolina, deep ripping decreased soil strength and increased yields. Remediation benefits were not persistent and deep ripping had to be frequently repeated to maintain yield recovery (Frederick et al. 1998; Busscher et al. 2000; Busscher et al. 2002).

While evaluating deep ripping effects on a clay soil in Australia, Hamza and Anderson (2002) found that deep ripping with and without gypsum application resulted in increases in wheat (*Triticum aestivum* L.) yields and decreases of soil bulk density. In addition to bulk density, these researchers observed improvements to various physical soil properties in both sandy and sandy clay loam soils in response to deep ripping, including porosity, water holding capacity, hydraulic conductivity, infiltration rate, cation exchange capacity, and water stable aggregates (Hamza and Anderson, 2003). However, three years after deep ripping (with continued annual cropping), the bulk density was higher than the initial values measured before the experiment began (Hamza and Anderson, 2002).

Similarly, when Raper and Arriaga (2007) conducted trafficking in a soil bin using a sandy loam textured surface horizon collected from a southeastern Coastal Plain soil, they found that when the soil was tilled prior to being subjected to wheeled loads of 19 or 37 kN, the soil lost upwards of 60% of its initial volume. Decreased soil strength and structure caused soil loosened by tillage and subsoiling to compact past its initial compacted condition (Håkansson and Petelkau, 1994) and increased the soil's susceptibility to compaction (Spoor, 1995). Because of the potential for re-compaction following tillage, annual remediation is required in many systems to minimize compaction and maximize productivity (Hamza and Anderson, 2002; Busscher et al., 2002).

Additionally, subsoil compaction tends to be persistent (Etana and Håkansson, 1994), while its remediation can be cost prohibitive (Werner, 1989; Horn et al., 2000). Etana and Håkansson (1994) noted that trafficking increased soil strength and bulk density within the subsoil up to 50 cm. The consequences of compaction were particularly persistent below 35 cm, showing no trends of recovery after 11 years (Etana and Håkansson, 1994). Subsoiling between 15-30 cm can cost upwards of 50% more in energy costs when compared to subsoiling above 15 cm, with energy costs continuing to rise with deeper subsoiling (Raper et al., 2000).

Mechanical remediation of soil compaction has mixed effects on soil quality and crop yield, while subsoil compaction is often persistent, and its remediation can be cost prohibitive. As such, remediation cannot be relied upon as the solution to this form of soil deterioration. As Benjamin Franklin put it, "an ounce of prevention is worth a pound of cure," and this holds altogether true in the realm of soil compaction. Identifying the properties that increase a soil's susceptibility is essential to preventing compaction.

Properties Affecting Compaction

A load placed on soil by machinery during a trafficking event is the most easily identifiable factor affecting compaction (Raper, 2005). These loads translate stress through the soil that can alter the soil state accordingly depending on magnitude, duration, and frequency (Raper and Arriaga, 2007).

Soil water content has a unique relationship with soil compaction and is recognized as the driving factor behind susceptibility to compaction (Larson et al., 1980; Lebert and Horn, 1991; Smith et al., 1997a & b; Sánchez-Girón et al., 1998). Compaction susceptibility increases with water content until the soil water content reaches a critical point where water molecules are supporting a portion of the load and further compaction is limited by drainage (Proctor, 1933; Greacen, 1960 a & b).

Soil organic matter content also has a significant impact on soil compressibility, especially in sandier soils (Smith et al., 1997a & b; Sánchez-Girón et al., 1998). High soil strength and bulk density have been shown to prevent further compaction to a point at which an increase of force is necessary for further compaction to occur. However, increased soil strength and bulk density can be root limiting and are therefore undesirable in many cases (Lebert and Horn, 1991).

Mathematic Models to Estimate Soil Stress

Mechanistic models are one way of estimating soil compaction. They often include wheel contact area and load as input parameters combined with equations describing volume change (O'Sullivan and Simota, 1995). Examples are mechanistic models based on Boussinesq's point load equation (O'Sullivan and Simota, 1995). These models assume soils are "homogenous, isotropic, and continuous" and are better suited for comparing trafficking loads than estimating compaction (McCarthy, 2007). Therefore, types of analytical models are frequently used to estimate stress translation, but do not accurately predict the amount of compaction that will occur (O'Sullivan and Simota, 1995). Empirical models can be used to model the expected compaction at a particular site but can be difficult to develop because they require large amounts of site-specific data (O'Sullivan and Simota, 1995).

Researchers have developed texture-based models that estimate how much trafficking load a soil can sustain before compacting (Horn, 1981 in Lebert and Horn, 1991). Soils were characterized by degree of physical change that occurred upon experiencing loads smaller than pre-consolidation according to the Cassagrande method (Cassagrande, 1936; Horn, 1981; Lebert and Horn, 1991). These researchers were able to relate soil properties including cohesion, angle of internal friction, bulk density, water holding capacity, saturated hydraulic conductivity, and organic matter content to pre-consolidation load, dependent on soil texture (Lebert and Horn, 1991).

Sensors for Measuring Trafficking Stress

While stress translation and compaction susceptibility can be estimated using various models, without verification, the accuracy of the estimates are unknown. Nichols et al. (1987) developed a Stress State Transducer (SST) to measure pressures exerted by machinery. The SST measures pressures across six planes, which likely allows this measurement to provide better information than theoretical equations (Bailey et al., 1995).

Raper and Arriaga (2007) noted that the Nichol et al. (1987) SST was a "milestone" in the realm of soil compaction research, but that it was complex in the amount of electronics it required. Turner and Raper (2001) developed and tested a bulb filled with water and connected by a hose to a needle gauge. In experiments comparing the sensor bulb to Nichol et al.'s (1987) SST, Raper and Arriaga (2007) found that the SST was unable to measure the difference between the stress translated by a 19 kN load and a 37 kN load to a buried depth of 23 cm. The sensor bulbs were more sensitive than the SST and were able to detect different stresses produced by varying loads when buried at 23 cm. The stresses measured by the SST were of a higher magnitude than those measured by the sensor bulbs. So, while the bulbs measured lower pressures when compared to the SST, the bulbs maintained precision of measurement at deeper depths (Raper and Arriaga, 2007).

Parkhurst et al. (2018) utilized sensor bulbs (Ag Tech Sensors) similar to those developed by Raper et al. (Turner and Raper, 2001; Raper and Arriaga, 2007) at a site in Virginia. The bulbs were buried to 12 cm in a silt loam textured soil in a forested setting, and used to evaluate soil response to trafficking by wheeled and tracked machinery on slash roads and bare ground. They found that the increase of soil stresses remaining upon trafficking, or the stress residuals, were higher in the bare ground treatments than in slash treatments. The first pass, for the slash treatment, and the third pass, for the bare treatment, produced the largest amount of change in soil stress residuals. They noted that the AgTech sensors needed more research under field conditions in order to examine their reliability as a data-collection tool. The newly developed sensors can provide insight into the magnitude of stress that is exhibited at depths within the soil, but do not necessarily inform how the soil will respond to that stress.

Compression Indices and Susceptibility to Compaction

Compression indices indicate how readily a soil compresses, and therefore illustrate how susceptible it is to compaction. Compression indices are developed using a one-dimensional consolidation test. In the engineering standard, the sample is saturated and void ratio is plotted against the logarithm of the applied pressure to develop consolidation curves (ASTM D2435/D2435M, 2011). Engineers often estimate compression indices of saturated soil using liquid limits and clay content (McCarthy, 2007). In agricultural situations, soils are rarely trafficked at saturation, and soil water content affects the response of soil to stress (Greacen, 1960a & b; Larson et al. 1980). Therefore, to more accurately reflect field conditions found in agricultural and forested settings, consolidation curves and compression indices are developed for unsaturated soils by plotting bulk density versus the logarithm of applied pressure (Gupta et al., 2002).

Consolidation tests have been used to evaluate a soil's susceptibility to compaction in several studies. In 1960, Greacen used one-dimensional and triaxial consolidation tests to examine the effects of water content and aggregate strength on soil compaction using aggregates of two types of clay with differing plasticity. He concluded that in the soils evaluated, compression was a function of aggregate strength.

Larson et al. (1980) analyzed compression indices for 36 soil samples from eight orders at four water contents. The compression tests were run using dried, sieved, and remolded (disturbed) samples. They found that compression indices increased with clay content and leveled off somewhere between 30-35% clay. They also found that the virgin compression curves for a soil were essentially parallel at different water contents, but that soils at higher water contents would achieve a higher bulk density when subjected to a certain stress than a drier soil subjected to the same stress, up to a certain water content. These authors also found Andepts behaved differently than soils from other orders and maintained a lower bulk density under similar stress. These authors identified four groups characterizing mineralogical and textural effects on soil compressibility, with southeastern Piedmont and Coastal Plain Kanhapludults (evaluated in this study) most commonly categorized into two groups: 1) medium textured soils with highly weathered clays that have moderate to high bulk density when subjected to stress and, 2) poorly graded, coarse textured soils where particle size distribution controls compressibility.

A study on South African soils from several orders found that soil texture, soil organic carbon, and water content were significantly related to the susceptibility of a soil to compaction (Smith et al., 1997). Disturbed samples were evaluated after being sieved through a 2 mm sieve, thus destroying natural soil-structure effects. The results found that: 1) texture had a strong influence on compression indices 2) soil organic carbon had a significant impact in sandier soils, and 3) water content was often the most significant factor on compressibility.

Sanchez-Girón et al. (1998) evaluated the compaction response of five different agricultural soils from Spain using confined uniaxial compression tests. They measured several chemical and physical properties including cation exchange capacity, soil organic matter, specific gravity of solids, electric conductivity, pH, lime content, water content and Atterberg limits. They evaluated disturbed samples and found the compression index was dependent on water content, texture, and soil organic carbon content, with sandy loam soils of higher carbon being the most susceptible to compaction (Sanchez-Girón et al., 1998). Canarache et al. (2000) performed compression tests using undisturbed cores equilibrated at a constant moisture content below saturation. These researchers found that water stable aggregates, bulk density, resistance to penetration, and mean weight diameter of aggregates were correlated to pre-compression stress, but only resistance to penetration had a significant correlation with compression index (Canarache et al., 2000).

Although the researchers treated texture as a constant in the experiment, they noted a considerable amount of soil variability within the field where samples were obtained. However, the soil morphological variability was not reported—and therefore not considered as a factor that could have influenced the compression indices (Canarache et al., 2000).

RATIONALE AND OBJECTIVES

Soil compaction contributes to the global problem of soil degradation. Due to inherently poor soil quality of southeastern U.S. Piedmont and Coastal Plain Ultisols, any further decrease of dynamic soil quality can be devastating. Forest production systems, which are critical to the region, are susceptible to and negatively impacted by compaction. Mechanical remediation is not always effective and can leave soil particularly susceptible to re-compaction; making reliance on tillage an unsustainable approach to soil compaction. Therefore, compaction must be prevented.

The magnitude, duration, and frequency of the stress produced by trafficking loads impacts the amount of compaction that will occur. Predicting a soil's response to this stress is an important part of preventing compaction. Historically, soil stress has been estimated using often overly simplified models. However, recent technologic development of sensor bulbs allows stresses to be measured *in situ*. This allows for development of approaches to relate measured stress to soil properties to potentially develop methods to reduce compaction.

Soil texture, water content, Atterberg limits, and other properties are known to affect a soil's response to stress. Soil surveys contain valuable data about soil morphological and physical properties that influence the behavior of soils to stress and compaction. In addition, soil surveys provide soil horizon data (e.g. depth and thickness), potentially offering information of layer effects on stress and compaction. Therefore, soil survey data is valuable for determining soil susceptibility to compaction.

Therefore, the objectives of this study are to: 1) Utilize in-ground sensors to measure machine pressures and compactive forces with depth for select soils in the southeastern U.S. Piedmont 2) Relate soil morphological and management-dependent (dynamic) properties to measured machine pressures and compactive forces 3) Develop susceptibility to compaction models using consolidometer data to develop compression curves for unsaturated soils.

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Chapter 2. Relating Sensor-Based Soil Stress Measurements to Soil Properties in Southeastern U.S. Piedmont Kanhapludults

ABSTRACT

The U.N. categorizes soil compaction as the most important type of physical soil degradation because of the loss of soil productivity and quality. Subsoil compaction causes great concern because it is difficult to remediate, particularly in forested settings. Soils vary in their reaction to applied dynamic forces based on physical, chemical, biological, and morphological properties. Soil mechanical approaches have developed indices and parameters that describe soil behavior upon compaction primarily for engineering applications, while little work has related these to soil morphological and pedological measures. Soil surveys and on-site pedological investigations describe soil morphological properties (e.g. horizonation, structure, consistence) that that we hypothesize to be related to soil compaction susceptibility. The objective of this study is to relate soil morphological and physical properties to measured stress and compactive forces for select sites in the southeastern U.S. Piedmont. Nine Alabama Piedmont sites were selected along three transects, and soils were described (to 40 cm), sampled, and several soil physical properties were measured. Recently developed hydraulic sensor bulbs were used to measure the stress transferred through soil with depth. Sites were trafficked with five passes using a CAT 535D forestry skidder. Soils consisted of Typic, Oxyaquic, and Rhodic Kanhapludults in fine particle size families with thin surface horizons (A) overlaying subsurface (E and BE) and subsoil (Bt) horizons. Sensors placed

in subsurface and subsoil horizons responded systematically with depth to trafficking pressures. Bulk density increased (6% and 16% for overall and surface horizons, respectively) following trafficking. Soil textural attributes were correlated with several other near surface properties ($r= 0.21$ to 0.77, $p<0.10$). When principal components were developed, loading factors indicated that textural properties (USDA texture and Atterberg limits) and volumetric water content described the majority of soil property variability. Stepwise linear regression and principal component regression indicated that soil physical properties (esp. texture, volumetric water content, and bulk density) and, to a lesser extent, morphological properties (esp. argillic depth, stratification ratios, and horizonation) are related to measured stress. In these select Alabama Kanhapludults, soil texture is highly related to sensor-based stress measurements, but morphological properties also describe a portion of variability. These static properties are described in soil surveys and soil descriptions, illustrating their utility in determining compaction susceptibility.

INTRODUCTION

Global Soil Quality Issue

Compaction has been recognized by the Food and Agriculture Organization as a widespread global soil quality issue—"the most important subtype of physical soil deterioration" (Oldeman et al., 1991)—affecting soil health and productivity. Soil compaction occurs when soil particles are rearranged in a way that results in a loss of void space and an increase of bulk density. This usually occurs in conjunction with a disturbance caused by the application of a stress-producing load onto the soil, such as passes of heavy agricultural/forestry equipment or trampling by livestock (Soil Science

Society of America, 1996). Soil compaction negatively impacts several soil properties affecting soil-water relations, root growth, plant health and productivity—all essential to soil quality and soil health. Compaction often increases soil strength, runoff, and erosion and decreases available water, hydraulic conductivity, and porosity (Zhai and Horn, 2017; Keller et al., 2017; Douglas and Crawford, 1998; Unger and Kaspar, 1994).

Several methods have been developed to alleviate compaction including conventional tillage or deep ripping, but these methods are not comprehensive solutions. Remediation of compaction is less effective in subsoil than surface horizons (Etana and Håkansson, 1994), and is not always practical as it can be cost prohibitive or otherwise inefficient (Raper et al., 2000). Additionally, remediation can leave soil susceptible to re-compaction which can be worse than initial compaction (Håkansson and Petelkau, 1994; Turner and Raper, 2001; Busscher et al., 2002). For these reasons, prevention rather than remediation is the preferred method of addressing the soil compaction issue. Therefore, in order to effectively prevent compaction, it is critical to understand causes.

Compactive Forces and Soil Properties

Several studies have looked at the causes of soil compaction. The main causes in agronomic and forested settings are related to trafficking loads. These loads translate stress through the soil profile that can alter the soil state depending on magnitude, distribution, duration, and frequency. Soil water content is extremely influential on soil compressibility, with the total amount of compression increasing as water content approaches a critical water content, often resulting in the soil approaching saturation following compaction (Proctor, 1933; Larson et al., 1980; Lebert and Horn, 1991; Smith et al., 1997a; Sánchez-Girón et al., 1998). Additionally, soil texture is an extremely influential static soil property affecting compaction. with clay contents to approximately 35% increasing compression susceptibility (Larson et al., 1980).

Other soil properties also influence soil compressibility. Soil organic matter content impacts soil compressibility in coarser soils but does not significantly contribute to the compressibility of finer soils (Smith et al., 1997b). Relatively high soil strength and bulk density can initially prevent further compaction to a point where an increase of force is necessary for further compaction to occur (Lebert and Horn, 1991). However, high soil strength and bulk density can be root limiting and are therefore undesirable (Lebert and Horn, 1991).

Southeastern Piedmont Soils

Soils found in the Southeastern Piedmont U.S. tend to be highly weathered, significantly eroded, and of poor soil quality (Trimble, 1974; Markewich et al., 1990; Buol et al., 2011). Ultisols, with low base saturation and inherently poor fertility dominate dissected landscapes. These Piedmont Ultisols generally have thin A and E horizons overlaying argillic and/or kandic horizons. Historic land use that included clear-cutting forests to produce decades of continuous cotton left these soils vulnerable to erosion and removed nutrients essential to plant growth (Trimble, 1974). However, Kanhapludults found in the Southeastern Piedmont are only suited for agronomic crops with the addition of amendments and proper management (Markewich et al., 1990; Buol et al., 2011). Therefore, these soils are well suited for pine tree production, which requires less intensive management and less nutrient additions than agronomic crops.

Innovative Techniques to Measure Soil Stress

Demands for agricultural and forest products have led to increased loads placed on the soil during planting, maintenance, and harvesting. Stresses occurring from these loads can be estimated using empirical models (McCarthy, 2007; O'Sullivan and Simota, 1994). Recent technological advances have allowed these stresses to be measured rather than estimated. A recently developed hydraulic bulb sensor, connected via a hose to a pressure transducer, can be inserted into the soil allowing trafficking load stresses to be measured *in situ* (Turner and Raper, 2001; Raper and Arriaga, 2007; Parkhurst et al., 2018). This allows for improved understanding of stresses that are translated through soils that are neither isotropic or homogenous, such as would be found in agricultural and forested settings. These sensors are sensitive to pressure changes (Raper and Arriaga, 2007), but more research is needed to determine their reliability in field situations (Parkhurst et al. 2018).

Forestry in Southeastern Piedmont

The forest industry in the Southeastern U.S. is responsible for more than 40% of the timber produced in the U.S. In Alabama, approximately 23 million acres are forested, with the industry generating $12 billion annually (U.S. Forest Service, 2014; Auburn University, 2013). Soil compaction causes tree growth reduction and yield losses in economically significant species, while harming the environment and forest industry (Greacen and Sands, 1980). The complexity of soil compaction increases in forest production. Compaction in commercial forested systems is greater than agronomic or pasture systems due to heavier equipment and loads, and the repetitive trafficking that occurs during planting, maintenance, and harvesting (Greacen and Sands, 1980). In addition, mechanical remediation can usually only be advantageously performed prior to planting of new stands (i.e. site preparation).

RATIONALE

In order to meet the growing global population's demand for agricultural and forest products with shrinking arable lands, soils must be protected against degradation. Compaction has been identified as a key part of physical soil degradation, and the expense and effectiveness of remediation—particularly in forested systems—is suspect. It is said, "an ounce of prevention is worth a pound of cure," and this rings particularly true in the realm of soil compaction. Soil surveys contain valuable information on soil morphological and physical properties that we hypothesize may be related to trafficking stress and susceptibility to compaction. Understanding how these near-surface soil properties affect stress translation in select southeastern U.S. Piedmont Kanhapludults would be useful in the pursuit of protecting this valuable resource.

OBJECTIVES

1) Utilize in-ground sensors to measure machine pressures and compactive forces with depth for select soils in the southeastern U.S. Piedmont.
2) Relate soil morphological and management-dependent (dynamic) properties to measured machine pressures and compactive forces.

MATERIALS AND METHODS

Site Selection and Soil Descriptions

Three hillslope transects with soils representative of the southeastern U.S. Piedmont region were selected at the Piedmont Research Substation in Camp Hill, Alabama (Figure 2.1). The first hillslope was mapped Gwinnett (Fine, kaolinitic, thermic

Rhodic Kanhapludults), the second Cecil (Fine, kaolinitic, thermic Typic Kanhapludults), and the third Hard Labor (Fine, kaolinitic, thermic Oxyaquic Kanhapludults) (Soil Survey Staff, accessed 2017). On each hillslope transect, sites were selected on the summit, backslope, and footslope for a total of nine sites. Slopes were measured at each site using a clinometer.

Excavations were made at each site to 40-cm, and soil morphological properties were described including horizonation, Munsell color, texture, structure grade and shape, moist consistence, presence of clay films, presences of redoximorphic features, mica presence, boundary distinction, and horizon depth (Schoeneberger et al., 2012). An index was developed and used for quantitative measure of soil structure grade. The index correlated to NCSS categories of structure grade with zero corresponding to structureless, one to three corresponding to weak structure, four to six corresponding to moderate structure, and seven to nine corresponding to strong structure (Schoeneberger et al., 2012). Each site contained three to four horizons for a total of 28 horizons.

Soil Measurements

Bulk density (ρ_b) measurements pre- and post-trafficking were taken by horizon in triplicate using a drop hammer and ring of known volume (Blake and Hartge, 1986). Measurements were corrected for rock fragments, and replicate values were averaged. Bulk and undisturbed samples were collected from each horizon. Bulk samples were air-dried, lightly crushed using a rolling pin, and sieved to separate the coarse fragments from the fine-earth fraction using a 2-mm sieve, and percent coarse fragment was determined. Particle size analysis was conducted on each horizon in duplicate using the pipette method (Kilmer and Alexander, 1949); duplicates were averaged. Water dispersible clay (WDC) was measured by horizon in duplicate (Miller and Miller, 1987), and reported as percent of fine earth fraction (< 2 mm) and of clay fraction (<0.002 mm). Atterberg limits, including liquid limit (LL), plastic limit (PL), and plasticity index (PI), were measured on each horizon (ASTM D4318, 2017). Replicates for LL and PL were averaged, and PI values were calculated. Soil organic carbon (SOC) was determined by horizon in duplicate using the dry combustion method with a Costech CHNSO Elemental Analyzer (Valencia, CA) (Yeomans and Bremner, 1991). Water stable aggregates (WSA) were measured by horizon in triplicate and averaged (Kemper and Rosenau, 1986).

Prior to and following trafficking, soil strength measurements were obtained using a Rimik CP20 Cone Penetrometer (Agridry Rimik PTY LTD, Australia; ASAE 313.3). Nine insertions close to the soil sampling location were performed and data collected every centimeter from the surface to 30 cm. Measurements from each of the insertions were compiled into 0-10 cm, 10-20 cm, and 20-30 cm depth increments, and averaged. At the time of trafficking, soil samples taken from each horizon using three auger holes were composited by horizon, and a sub-sample was taken to obtain gravimetric water content (θ_g) (Soil Survey Staff, 2014). Field obtained values of θ_g and ρ_b were used to calculate θ_v (Soil Survey Staff, 2014)

Trafficking Experiments

Sensors—developed by Turner and Raper (2001), modified by the U.S. Forest Service Research Lab (Auburn, Alabama) and utilized by Parkhurst et al. (2018)—were used to measure soil stress at two depths at each location. The sensor system consisted of a pressure transducer connected to a 2.54 cm rubber bulb by a hydraulic hose of 3.35 m in length (water filled) and data recorded by a logger, powered by a battery and housed in a protective case. In order to place the sensors in undisturbed soils, a hole was drilled at an angle using a drilling guide to insert bulbs at specific depths. The sensor bulbs were inserted using a modified PVC pipe which allowed the sensor to stay in place when the PVC pipe was removed. Four sensors were installed at each site; two at approximately 12.5 cm (subsurface) and two at approximately 25 cm, resulting in 36 total sensor placements. The four sensors at each site were placed in a straight vertical line spaced approximately 30 cm apart in vertical distance. The data loggers in the sensors were connected to software (OMEGA Engineering, INC.) using a laptop computer and set to collect one data point per second.

Over the course of August 15-17, 2017, each of the nine sites was trafficked with five passes. All trafficking was conducted using a skidder (Caterpillar 535D) weighing 20,692 kg (45,620 lbs) travelling between 1-2 ms^{-1} (3-5 mph). The timing of skidder passes was recorded to the nearest half minute to aid in data interpretation. Passes occurred at least one minute apart. After the initial pass, data were reviewed to ensure sensors were recording properly before commencing subsequent passes. Following trafficking, the soil was excavated to the sensor and sensor depths were measured.

Sensor data were recorded as micro-amperages and converted to pounds per square inch (psi) using calibration curves provided by Omega and verified by a dead weight gauge tester (American Schaeffer & Budenberg Corporation). The data points were analyzed to determine pressures corresponding to soil stress for each of the five trafficking passes at both depths. These stresses were reported as maximum stress, mean stress, median stress and first pass stress.

Data Organization

To address the non-homogenous nature of multiple soil horizons above the sensor, several steps were taken to prepare data for analyses. Stratification ratios were calculated by dividing a soil property in a horizon by the same property in the subjacent horizon for all soil properties measured by horizon (Franzluebbers, 2002). Ratios were calculated for adjacent horizons from the surface to the horizon where the sensor was seated. The average of properties measured by horizon were calculated using a weighted mean from the surface to each specific sensor depth. The total mass of clay, sand, and water above the sensor on a g cm^{-3} basis were calculated using bulk density and horizon thickness. Depths to the argillic horizon and epipedon thickness were also included in the analyses.

Statistical Analyses

Data were analyzed using SAS Statistical Software (SAS Institute, Cary, NC). Paired t-tests were used to compare pre- and post ρ_b. Pearson linear correlation coefficients (r) were calculated to relate soil properties within horizons ($p \leq 0.10$).

Stepwise multiple linear regression ($p<0.15$) was used to relate measured compactive forces (dependent) to soil properties (independent) by measurements both at the sensor and weighted average of properties above the sensor; stratification ratios and mass above sensor values were included with weighted averages. Regression models were developed overall and by horizon (subsurface, subsoil).

Many of the soil properties (independent) were correlated, so data were analyzed using multivariate principal component analysis (PCA). Principal components were developed to create uncorrelated variables that could be related to compactive forces using stepwise regression. Soil property data were standardized, and components with eigenvalues >1 that explained >5% of the data variance were related to compactive forces using stepwise regression. Loading factors were evaluated to determine the most significant soil properties within each individual component.

RESULTS AND DISCUSSION

Soils

At the nine sites evaluated (Table 2.1), surface horizons were thin (5-8 cm) with loamy textures. All nine sites had Ochric epipedons. The sites mapped Gwinnett and Hard Labor generally had E horizons, with E horizons being slightly thicker at the Hard Labor sites. The sites mapped Pacolet and the Gwinnett on the backslope had transitional horizons (e.g. BE) in lieu of fully expressed E horizons. Thin surfaces with a general lack of E horizon expression is due to the historical erosion in the region (Markewich et al., 1990). Soils had moderate amounts of soil organic carbon (SOC) (2-3% in surface horizons), as they had been in pasture and hay systems for several years. Most of the sites had relatively high bulk density in subsurface horizons, likely due to a plow pan persisting from historic land use.

Soil Property Correlation

Soil texture was significantly correlated with several soil properties in all horizons (Table 2.2). In general, as sand content increased, structure grade, water content, liquid limit (LL), and plasticity index (PI) decreased. The inverse was generally true for clay content. Additionally, in these nine sites, water stable aggregates (WSA) and soil organic carbon (SOC) were negatively related to clay content (Table 2.2). This is in disagreement with previous studies that indicate a positive correlation between SOC and clay content, particularly in surface horizons (Hassink, 1997; Causarano et al., 2008).

Generally, structure grade was positively correlated with clay and negatively correlated with sand content, possibly due to increased aggregation in clayey versus sandy textures. Similarly, structure grade was negatively correlated with D_{10}, D_{30}, and D_{60} (which represent diameter (mm) that 10%, 30%, and 60% of soil grains are finer than, respectively); while structure grade was positively correlated with the coefficient of curvature (C_c).

Atterberg limits have a strong relationship with USDA texture. The LL and PI increased with increasing clay content and decreased with increasing sand content; PL decreased with increasing D_{30}. This is in agreement with previous studies that found PL is not as strongly correlated to texture as PI and LL (Keller and Dexter, 2012). The SOC content was negatively correlated with pre-and post-trafficking ρ_b, and positively correlated with percent ρ_b increase. Soils with lower ρ_b are more susceptible to compaction, and previous literature suggests that higher SOC can protect soil from reaching root limiting ρ_b (Soane, 1990).

Bulk density (ρ_b) before and after trafficking was negatively correlated with volumetric water content taken directly before trafficking. The negative relationship between pre-trafficking ρ_b and water content is consistent with studies that have shown that increased ρ_b causes decreased porosity and water holding capacity (Larson et al., 1980).

Sensor Data

Following trafficking, sensor depths were measured to verify locations (Table 2.3). Measured sensor stresses were found to be variable, with coefficients of variation (% CV) greater than 100% in one case. Subsoil stresses were more variable than subsurface stresses. This variability is likely due to the experimental nature of the sensor bulbs, as well as potential inconsistencies in trafficking paths. The variation occurred despite trafficking each site five times to minimize noise from trafficking path variation and other factors. Despite variation, trends in stress measured with depth suggested systematic response of sensor bulbs to trafficking.

Additionally, measured replicate stresses (maximum, mean, median, and first pass) were highly correlated. The first pass stress and maximum stress showed the least correlation with each other and therefore were chosen to be the dependent variables in stepwise multiple linear regression. Additional consideration in selecting maximum stress and first stress was that soils compact most readily during the first few passes (Carter et al., 1999).

Soil Response to Trafficking

Overall, there was a significant increase in soil bulk density following the five-pass trafficking (Figure 2.2). There were also significant increases in bulk density on the summit and backslope hillslope positions (Figure 2.2). When averaged by horizon, surface horizons showed a significant increase in bulk density following trafficking (Figure 2.3). Therefore, for these select Kanhapludults, the majority of trafficking impacts on bulk density was observed in surface horizons. This is similar to previous studies that indicate the highest compaction susceptibility, in terms of bulk density increase, exists at the surface (Gent et al., 1984; Shaw and Carter, 2002). Relatively high pre-trafficking bulk density (USDA, 1999) in subsurface horizons (corresponding to a persisting plow pan) may have essentially “protected” the subsurface and subsoil from further compaction (USDA, 1999).

Linear Regression to Relate Soil Properties to Stress

Stepwise linear regression was utilized to relate stress (maximum and first pass stress) to soil properties above and at the sensor (Table 2.4). Overall, soil property data described 26 to 70% of stress variability. Sensor depth was the most significant property ($p<0.15$) related to maximum stress in both models (partial $R^2 = 0.51$), and sensor depth within the argillic was the most significant property related to first pass stress (partial $R^2 = 0.22$). Volumetric water content (θ_v) at the sensor and stratified θ_v above the sensor were significantly related to stress (partial R^2 between 0.09 and 0.13). Additionally, argillic depth and textural attributes (e.g. PL, Cc, Cu, WDC) were each significant in one of the four models. Regression models illustrate that sensor depth, to a larger extent, and θ_v, to a lesser extent, are the most influential properties on measured stress magnitude.

In order to better understand which soil physical and morphological properties influenced stress translation, stepwise linear regression models were developed for subsurface (~12.5 cm) and subsoil (~25 cm) stress. Soil property data described 80 to 99% of subsurface stress variability. Subsurface stress was related to several soil physical properties that predominated: ρ_b (partial R^2 between 0.12 and 0.17) and textural attributes (e.g. sand mass, WDC, clay %, Cc, LL [partial R^2 between 0.13 and 0.52]).

Soil property data described 98 to 99% of subsoil stress variability. Similar to models examining subsurface and subsoil stresses, θ_v was significant in various capacities in three of four models. Stratified θ_v above the sensor decreased stress translation (partial R^2 between 0.03 and 0.33), while higher subsoil θ_v (measured at the bulb) resulted in higher stress translation (partial $R^2 = 0.11$). Similar to subsurface models, several textural properties (e.g. sand%, WDC, LL, Cu) were also significant (partial R^2 between 0.15 and 0.50). Surface SOC also played a significant role in reducing subsoil stress (partial R^2 between 0.10 and 0.44).

Several soil physical and morphological properties were significantly related to stress translation. Although significant properties varied by model, textural attributes, ρ_b, and θ_v were predominate. Several soil properties including θ_v, texture, SOC, and ρ_b are known to affect a soil's susceptibility to compaction (Greacen, 1960 a & b; Larson et al. 1980; Smith et al., 1997a & b). These same properties affect stress translation.

Principal Component Analysis to Relate Soil Properties to Stress

Multivariate analyses using principal components (PC) was utilized to develop uncorrelated variables (components) to relate to sensor data (first peak and maximum stress) through stepwise regression. Standardized data were used to develop PC scores and loading factors for soil properties associated with the subsurface (~12.5cm) and subsoil (~25cm) sensor placements.

The first six principal components (PC) (eigenvalues >1) described 94% of the subsurface (~12.5cm) soil property variability (Table 2.5.). Component 1 (PC1) described 53% of data variability, and loading factors indicated that textural attributes (e.g. clay and sand content, PL, LL, PI) and θ_V at the sensor were the most significant soil properties of PC1 (Table 2.5). Component 2 (PC2), which described an additional 14% of data variability, was dominated by PL, LL, soil carbon, and WSA both above and at sensor. Component 3 (PC3), which described an additional 10% of data variability, was dominated by volumetric water content and Cc at the sensor. Component 4 (PC4) (8% of data variability) was dominated by morphological properties, particularly soil structure grade.

Utilizing the first six components, PC regression indicated that PC1 (53%), PC6 (21%), PC2 (14%), and PC5 described 96% (R^2=0.96) of subsurface first pass stress variability (Table 2.6). The discussion above illustrated that PC1 was dominated by textural attributes, while PC 6 was dominated by morphological properties including depth to argillic, stratification of sand content (difference between horizons), and the horizon number where sensor was placed. None of the PC's were significantly related to maximum peak at sensor in the subsurface. Considering PC1 described most soil property variability and subsurface first pass stress variability, it is apparent textural properties at the sensor play a significant role in measured subsurface horizon stress. Although to a lesser degree, morphological properties related to horizonation also play a role.

The first six components (eigenvalues >1) described 95% of subsoil (~25cm) property variability (Table 2.5). Principal component 1 (PC1), that described 37% of the data variability, was dominated by soil textural attributes and volumetric water content above the sensor (Table 2.5). Component 2 (PC 2) described 25% of data variability and was dominated by textural attributes at the sensor. Component 3 (PC 3) described an additional 11% of data variability and was dominated by physical properties including soil strength, Cc at sensor, and WSA averaged above sensor. Component 4 (PC 4) (9% of variability) was dominated by physical properties including volumetric water content and soil strength.

Utilizing the first six components for subsoil sensor placement (~25cm), PC regression indicated that PC 6 described 33% of first pass stress variability, and PC5 (40%) PC2 (24%), PC1 (21%), and PC6 (11%) described 96% (R^2=0.96) of maximum stress variability (Table 2.6). Components 5 and 6 were dominated by bulk density both above sensor and at sensor, while PC2 and PC1 loadings are described above. The aggregate of this indicates that soil physical properties, including texture and bulk density, are significantly related to measured subsoil stress.

CONCLUSION

USDA soil texture is correlated with several other near-surface physical properties, including Atterberg limits, bulk density, water holding capacity, water stable aggregates, structure grade, and soil organic carbon in these southeastern U.S. Piedmont Kanhapludults. Data collected by recently developed sensors, though highly variable, showed a systematic response to trafficking suggesting their validity as a method for measuring soil stress. Following trafficking, bulk density increased on average, 6 % and 16% overall and in surface horizons, respectively. The relatively high pre-trafficking bulk densities likely reduced trafficking effects.

Stepwise linear regression indicates both soil physical and morphological properties affect stress translation. Physical properties, including θ_v, ρ_b, and textural properties, influenced stress translation to a greater extent than morphological properties. Principal components were developed that described a high degree of soil property variability. Similar to stepwise regression, principal component regression models were developed that described a high amount of subsurface first pass stress and subsoil maximum stress. These models also illustrated that textural attributes, θ_v, and ρ_b were highly related to stress variability.

Previously, soil physical properties were utilized to estimate soil stress translation (Lebert and Horn, 1991). Our study illustrates that morphological soil properties also play a role in stress translation, albeit to a lesser degree than measured physical properties. Nonetheless, soil surveys provide in depth information on morphological and physical properties related to stress translation; making soil surveys a useful tool to combine with onsite dynamic physical property (e.g. θ_v, ρ_b) evaluation for insight to stress translation at a specific site.

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TABLES

Table 2.1. Summary of select soil properties separated by hillslope component and horizon in nine Alabama Piedmont Kanhapludults.

	Variable	All			Summit			Backslope			Footslope		
		Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev	N
Surface	Horizonation	Ap											
	Soil Organic Carbon (%)	2.8	0.5	18	3.0	0.4	6	3.0	0.3	6	2.3	0.4	6
	Clay (%)	19.3	5.7	18	16.0	7.1	6	21.9	5.2	6	20.1	5.1	6
	Sand (%)	57.2	8.2	18	61.8	8.5	6	52.4	10.0	6	57.5	5.8	6
	Structure Grade (scale 0-9)	4.2	1.2	9	4.3	0.6	3	3.7	1.5	3	4.7	1.5	3
	Bulk Density (g cm^{-3})	1.22	0.11	27	1.10	0.06	9	1.27	0.01	9	1.28	0.12	9
	Volumetric Water Content (g cm^{-3})	0.32	0.08	9	0.29	0.08	3	0.33	0.04	3	0.33	0.13	3
	Liquid Limit	48.3	5.7	18	48.9	8.7	9	50.9	0.7	9	45.1	5.3	9
	Plastic Limit	35.3	3.1	36	35.5	4.2	12	36.3	3.1	12	34.0	2.6	12
	Water Stable Aggregates (%)	93.9	4.3	27	92.0	7.5	9	95.0	1.8	9	94.8	2.0	9
	Water Dispersible Clay (%)	12.9	6.5	18	10.8	6.1	6	10.9	8.2	6	17.1	4.8	6
Subsurface	Horizonation	E or BE			E or BA			AE or BE			BE		
	Clay (%)	16.7	6.8	18	13.6	8.4	6	19.6	7.9	6	17.7	4.2	6
	Sand (%)	62.9	8.8	18	67.2	7.6	6	59.3	13.9	6	61.2	5.6	6
	Structure Grade (scale 1-9)	3.6	1.0	9	2.8	1.0	3	4.3	0.6	3	4.0	0.8	3
	Bulk Density (g cm^{-3})	1.69	0.10	27	1.74	0.14	9	1.62	0.08	9	1.70	0.07	9
	Volumetric Water Content (g cm^{-3})	0.27	0.07	9	0.26	0.10	3	0.28	0.06	3	0.28	0.05	3
	Liquid Limit (%)	31.7	7.9	18	28.2	8.9	9	31.5	8.9	9	35.4	6.6	9
	Plastic Limit	21.1	4.6	36	20.3	6.1	12	21.8	4.5	12	21.3	4.4	12
	Water Stable Aggregates (%)	87.0	9.1	27	82.2	12.0	9	88.5	10.0	9	90.7	4.2	9
	Water Dispersible Clay (%)	12.5	5.7	18	11.0	6.6	6	15.3	5.5	6	11.9	5.6	6

(continued)

	Variable	All			Summit			Backslope			Footslope		
		Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev	N
Subsoil	Horizonation	Bt											
	Clay (%)	35.9	6.1	20	38.5	9.7	8	35.4	1.2	6	32.9	6.0	6
	Sand (%)	42.8	6.2	20	40.5	6.8	8	43.0	6.1	6	46.0	8.3	6
	Structure Grade (scale 1-9)	5.1	1.1	10	5.0	1.0	4	6.0	1.0	3	4.0	0.0	3
	Bulk Density (g cm^{-3})	1.60	0.06	30	1.61	0.04	12	1.57	0.07	9	1.64	0.03	9
	Volumetric Water Content (g cm^{-3})	0.33	0.04	10	0.35	0.02	4	0.30	0.05	3	0.32	0.01	3
	Liquid Limit	53.6	8.9	20	53.0	13.0	8	54.0	8.5	9	54.1	8.3	9
	Plastic Limit	27.1	4.0	40	26.2	6.9	16	27.4	2.5	12	27.9	1.2	12
	Water Stable Aggregates (%)	80.6	9.5	30	77.0	8.6	12	79.9	13.0	9	87.3	4.2	9
	Water Dispersible Clay (%)	14.4	11.4	20	16.4	10.9	8	16.2	15.2	6	8.7	11.4	6

*Standard deviation calculated on the average of replicates.

Table 2.2. Pearson Linear Correlation Coefficients (p < 0.10) relating select soil properties by horizon in the top 40 cm of nine Alabama Piedmont Kanhapludults.

.	Clay (%)	Sand (%)	Silt (%)	D_{60}	D_{30}	D_{10}	Cu	Cc	Structure	CF	ρ_b (pre)	ρ_b (post)	ρ_b (% change)	θv	LL	PL	PI	WSA	SOC	WDC	WDC/Clay
Clay (%)	1.00	-0.91	NS	-0.82	-0.75	-0.52	NS	NS	0.52	-0.35	NS	NS	NS	0.59	0.74	NS	0.84	-0.44	-0.34	NS	-0.50
Sand (%)	-0.91	1.00	-0.43	0.95	0.81	0.56	NS	NS	-0.47	0.37	NS	NS	NS	-0.55	-0.67	NS	-0.71	0.21	0.19	NS	0.50
Silt (%)	NS	-0.43	1.00	-0.51	-0.32	NS	-0.43	-0.41	NS	NS	NS	-0.34	NS	NS	NS	NS	NS	0.45	NS	NS	NS
D_{60}	-0.82	0.95	-0.51	1.00	0.67	0.42	0.39	NS	-0.36	0.34	NS	NS	NS	-0.43	-0.56	NS	-0.64	NS	NS	NS	0.53
D_{30}	-0.75	0.81	-0.32	0.67	1.00	0.80	NS	0.32	-0.39	0.40	NS	NS	NS	-0.57	-0.64	-0.39	-0.58	NS	NS	-0.35	0.34
D_{10}	-0.52	0.56	NS	0.42	0.80	1.00	-0.43	NS	-0.40	0.39	NS	NS	NS	-0.41	-0.37	NS	-0.32	NS	NS	NS	NS
Cu	NS	NS	-0.43	0.39	NS	-0.43	1.00	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.44	NS
Cc	NS	NS	-0.41	NS	0.32	NS	NS	1.00	0.38	NS	NS	0.32	NS	NS	NS	NS	NS	NS	NS	0.40	0.37
Structure	0.52	-0.47	NS	-0.36	-0.39	-0.40	NS	0.38	1.00	-0.50	NS	NS	NS	NS	0.38	NS	0.39	NS	NS	0.48	NS
CF	-0.35	0.37	NS	0.34	0.40	0.39	NS	NS	-0.50	1.00	0.41	0.34	NS	NS	-0.58	NS	-0.40	NS	NS	NS	0.35
ρ_b (pre)	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.41	1.00	0.84	-0.70	NS	-0.44	-0.85	NS	-0.45	-0.89	NS	NS
ρ_b (post)	NS	NS	-0.34	NS	NS	NS	NS	0.32	NS	0.34	0.84	1.00	NS	NS	-0.43	-0.74	NS	NS	-0.73	NS	NS
ρ_b (% change)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	-0.70	NS	1.00	NS	NS	0.54	NS	0.38	0.64	NS	NS
θv	0.59	-0.55	NS	-0.43	-0.57	-0.41	NS	NS	NS	NS	NS	NS	NS	1.00	0.51	0.46	0.33	NS	NS	0.49	-0.11
LL	0.74	-0.67	NS	-0.56	-0.64	-0.37	NS	NS	0.38	-0.58	-0.44	-0.43	NS	0.51	1.00	0.71	0.81	NS	NS	NS	-0.65
PL	NS	NS	NS	NS	-0.39	NS	NS	NS	NS	-0.49	-0.85	-0.74	0.54	0.46	0.71	1.00	NS	NS	0.77	NS	NS
PI	0.84	-0.71	NS	-0.64	-0.58	-0.32	NS	NS	0.39	-0.40	NS	NS	NS	0.33	0.81	NS	1.00	-0.51	NS	NS	-0.70
WSA	-0.44	NS	0.45	NS	NS	NS	NS	NS	NS	NS	-0.45	NS	0.38	NS	NS	NS	-0.51	1.00	0.57	NS	0.33
SOC	-0.34	NS	NS	NS	NS	NS	NS	NS	NS	NS	-0.89	-0.73	0.64	NS	NS	0.77	NS	0.57	1.00	NS	NS
WDC	NS	NS	NS	NS	-0.35	NS	0.44	0.40	0.48	NS	NS	NS	NS	0.49	NS	NS	NS	NS	NS	1.00	0.63
WDC/Clay	-0.50	0.50	NS	0.53	0.34	NS	NS	NS	NS	0.35	NS	NS	NS	NS	-0.65	NS	-0.70	0.33	NS	0.63	1.00

* D_N: diameter in mm that N% of soil grains are finer than; Cu: Coefficient of uniformity; Cc: Coefficient of curvature; Structure: Structure grade on a scale of 1-9; ρ_b (pre): bulk density prior to trafficking; ρ_b (post): Bulk density in wheel track prior to five passes during trafficking event; ρ_b (% increase): Percent bulk density change; θ_v : Volumetric water content; LL: Liquid limit; PL: Plastic limit; PI: Plasticity index; WSA: Percent water stable aggregates; WDC: Water dispersible clay as a percent of the whole soil; WDC/Clay: Water dispersible clay as a percent of the clay fraction; NS: Not significant at the $p \leq 0.10$ level.

Table 2.3. Data collected by in-situ sensors at nine sites during a skidder trafficking event in the southeastern U.S. Piedmont.

Placement	Variable	Mean	N	Standard Deviation	Coefficient of Variation %	Minimum	Maximum
Subsurface (~12.5cm)	Sensor Depth (cm)	12.1	18	1.5	7.5	7.8	14.0
	Max Stress (psi)	18.81	18	13.11	63.50	3.18	49.41
	Mean Stress (psi)	10.80	18	7.13	59.40	2.41	32.72
	First Pass Stress (psi)	7.83	18	9.78	60.80	2.27	41.09
	Median Stress (psi)	9.64	18	6.92	56.40	2.27	30.82
Subsoil (~25 cm)	Sensor Depth (cm)	24.0	18	1.8	12.3	20.0	28.5
	Max Stress (psi)	8.74	18	5.55	69.70	3.33	26.03
	Mean Stress (psi)	7.02	18	4.17	66.00	2.23	18.51
	First Pass Stress (psi)	5.73	18	3.49	125.00	0.67	14.38
	Median Stress (psi)	6.82	18	3.85	71.80	2.14	16.35

Table 2.4. Stepwise Linear regression relating measured soil stress (psi) from a five-pass trafficking event involving a CAT 535D forestry skidder to soil properties in nine Alabama Piedmont Kanhapludults.

Horizon	Property Analyzed	Stress	N	R^2	Linear Formula
All	Average	Max	18	0.69	98.22 - (1.44) Sensor Depth - (0.36) WDC - (0.27) θ_v Strat
	Average	First Pass	18	0.26	(1.29) PL - 27.88
	Sensor	Max	18	0.70	(1.26) θ_v - (1.54) Sensor Depth + (0.64) Depth to argillic - 2.83
	Sensor	First Pass	18	0.67	(0.82) θ_v + (0.02) Cu + (0.58) Cc - (1.21) Depth of sensor into argillic - 19.14
Subsurface	Average	Max	9	0.80	302.75 – (1.00) Mass of Sand – (1.62) WSA – (0.56) ρ_b
	Average	First Pass	9	0.98	236.73 + (0.23) ρ_b Strat – (1.63) – θ_v Strat – (48.97) ρ_b
	Sensor	Max	9	0.97	(5.96) θ_v - (3.65) LL + (0.29) WDC + (1.04) Clay % - 71.24
	Sensor	First Pass	9	0.98	137.78 + (1.26) Cc - (1.39) WSA + (0.27) Depth to argillic
Subsoil	Average	Max	9	0.98	15.83 - (0.35) Slope% + (0.34) Sand % + (0.0087) Cu + (0.078) Surface SOC - (0.36) θ_v Strat
	Average	First Pass	9	0.98	75.39 - (1.30) Surface SOC - (0.07) LL - (37.40) ρ_b - (0.039) θ_v Strat
	Sensor	Max	9	0.99	(0.078) WSA + (0.55) WDC + (0.051) Slope% - 33.10
	Sensor	First Pass	9	0.99	(0.19) WDC + (0.135) LL + (0.033) Sand % + (0.084) θ_v + (0.48) Depth to argillic - 16.37

* Average, Weighted averages of property measured at each horizon above the sensor; Cc, coefficient of curvature; Cu, coefficient of uniformity; First, First stress measured by the sensors during the trafficking event; LL, water content at liquid limit; Max, Maximum stress measured by the sensor during trafficking event; PI, plasticity index; PL, water content at plastic limit; Sensor, Value of property measured in the horizon where the sensor was seated; Slope, slope of site; SOC, percent soil organic carbon; Strat (i.e. Clay, density, etc.) Stratification ratio of property measure of the superjacent horizon to the horizon where the sensor is seated; Surface Strat, Stratification ratio of the property measure in the surface horizon vs. the subsurface horizon; WDC, water dispersible clay; WSA, water stable aggregates; θ_v, volumetric water content; ρ_b, soil bulk density.

Table 2.5. Principal component (PCs) loading factors for subsurface and subsoil properties of nine Alabama Piedmont Kanhapludults

	Subsurface (0 – 12.5 cm)						Subsoil (0 – 25 cm)					
Property*	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
Horizon	0.16	0.20	-0.08	0.13	0.18	-0.41	-0.05	0.28	-0.10	-0.06	0.32	0.13
Argillic Depth, cm	-0.16	-0.14	-0.08	-0.07	0.37	0.35	-0.20	-0.20	0.01	-0.07	-0.25	-0.09
SOC, surface	-0.08	0.25	-0.09	0.21	-0.24	0.00	-0.08	0.24	0.15	-0.21	-0.18	0.21
θ_v, surface	0.18	-0.01	0.30	-0.15	-0.08	0.00	0.22	-0.01	-0.07	0.31	0.14	-0.13
Clay (g cm^{-3}), avg	0.22	-0.13	0.04	0.10	-0.04	0.08	0.28	0.00	-0.01	-0.01	-0.02	0.04
Sand (g cm^{-3}), avg	-0.19	0.14	0.10	0.08	-0.11	-0.14	-0.25	0.03	0.13	0.12	0.16	-0.06
Water (g cm^{-3}), avg	0.20	0.01	0.20	-0.22	-0.08	0.01	0.27	-0.01	-0.08	0.09	0.02	-0.19
Clay %, avg	0.23	-0.10	0.03	0.05	0.05	0.06	0.28	0.00	-0.01	-0.01	-0.06	0.02
Sand %, avg	-0.19	0.23	0.01	-0.03	0.10	-0.18	-0.25	0.04	0.16	0.12	0.08	-0.14
Structure, avg	0.07	-0.09	-0.27	0.32	0.41	0.17	0.20	-0.03	0.23	-0.03	-0.16	0.30
LL, avg	0.19	0.27	-0.03	0.05	-0.06	0.06	0.28	0.05	0.08	0.00	0.04	-0.01
PL, avg	0.10	0.34	0.08	-0.20	0.03	0.25	0.24	0.06	0.06	-0.02	-0.09	-0.22
PI, avg	0.20	0.15	-0.10	0.22	-0.11	-0.09	0.26	0.04	0.09	0.01	0.12	0.13
θ_v, avg	0.20	0.01	0.20	-0.22	-0.08	0.01	0.27	-0.01	-0.08	0.09	0.02	-0.19
ρ_b, avg	0.04	-0.24	0.14	0.22	-0.45	0.17	-0.06	-0.02	-0.08	0.01	0.52	0.38
WSA, avg	-0.09	-0.38	-0.10	0.10	0.04	-0.09	-0.07	-0.22	-0.31	-0.11	-0.06	0.21
Cu, avg	0.15	0.12	0.05	0.00	0.39	0.13	0.17	-0.11	0.31	0.12	0.14	-0.25
Cc, avg	-0.07	0.10	0.41	0.29	0.15	-0.10	0.07	0.14	0.22	0.28	-0.28	0.11
Clay %, sensor	0.23	0.00	-0.03	0.10	0.03	-0.12	0.01	0.34	-0.11	-0.02	0.02	-0.02
Sand %, sensor	-0.22	0.12	0.09	-0.07	0.08	-0.05	0.00	-0.28	0.26	0.10	0.02	-0.03
LL, sensor	0.23	-0.03	-0.08	0.01	-0.02	-0.17	-0.02	0.33	0.00	0.15	0.07	0.05
PL, sensor	0.22	-0.04	-0.06	-0.18	-0.01	-0.07	0.09	0.27	-0.05	-0.11	-0.10	-0.10
PI, sensor	0.21	-0.01	-0.08	0.15	-0.02	-0.23	-0.08	0.28	0.03	0.25	0.15	0.13
θ_v, sensor	0.22	0.00	-0.08	-0.15	0.04	-0.16	0.11	0.19	-0.18	-0.12	0.12	-0.29
WSA, sensor	-0.13	-0.35	0.04	0.16	0.01	-0.07	0.07	-0.28	-0.20	0.00	-0.15	0.24
Structure, sensor	0.16	0.09	0.14	0.40	0.09	-0.01	0.16	0.24	0.01	-0.07	-0.17	0.25
ρ_b, sensor	-0.21	0.02	-0.08	-0.04	-0.19	-0.01	-0.02	-0.23	0.24	0.16	0.31	0.03
Soil Strength, sensor	-0.16	0.14	-0.18	0.27	-0.25	-0.01	-0.03	0.06	0.40	-0.35	-0.06	0.04
Clay, Strat	-0.20	-0.05	0.19	-0.14	0.08	-0.18	-0.24	0.05	-0.15	0.19	-0.12	-0.17
Sand, Strat	0.09	0.19	-0.29	-0.01	-0.18	0.46	0.09	-0.03	0.27	-0.30	0.26	-0.01

(continued)

Property*	Subsurface (0 – 12.5 cm) PC1	PC2	PC3	PC4	PC5	PC6	Subsoil (0 – 25 cm) PC1	PC2	PC3	PC4	PC5	PC6
ρ_b, Strat	0.18	-0.14	0.22	0.20	-0.05	0.24	0.21	-0.10	-0.03	0.23	0.01	0.33
SOC, Strat	-0.14	0.33	0.12	0.16	0.08	0.12	-0.16	0.14	0.34	0.12	-0.11	0.00
θ_v, Strat	-0.05	0.03	0.48	0.14	0.05	0.17	-0.05	0.05	0.04	0.48	-0.19	0.15
	0.16	0.20	-0.08	0.13	0.18	-0.41	-0.05	0.28	-0.10	-0.06	0.32	0.13
Eigenvalue	17.31	4.642	3.415	2.561	1.833	1.386	12.45	8.06	3.67	3.01	2.40	1.69
Proportion of variance explained, %	52	14	10	8	6	4	38	24	11	9	7	5
Cumulative variance explained, %	52	67	77	85	90	94	38	62	73	82	90	95

*Horizon, numeric horizon where sensor is seated; Surface, property in surface horizon; Avg, property average above sensor; Sensor, property at sensor; Strat, property surface and subjacent horizon stratification ratio; SOC, soil organic carbon %; θ_v, volumetric water content; WSA, water stable aggregates ; Cc, coefficient of curvature; Cu, coefficient of uniformity; Structure, structure grade; ρ_b, soil bulk density; LL, liquid limit; PL, plastic limit; PI, plasticity index.

Table 2.6. Principal component regression relating stress to components described in Table 2.5.

Depth	**Stress (dependant)**	**Variable**	**Partial R^2**	**Model R^2**	**Pr > F**
Subsurface (12.5 cm)	First Pass Stress	PC1	0.527	0.527	0.027
		PC2	0.211	0.738	0.071
		PC6	0.138	0.875	0.066
		PC5	0.089	0.964	0.035
	Maximum Stress	NS			
Subsoil (25cm)	First Pass Stress	PC6	0.330	0.330	0.106
	Maximum Stress	PC5	0.401	0.401	0.067
		PC2	0.237	0.638	0.095
		PC1	0.212	0.849	0.045
		PC6	0.108	0.958	0.033

FIGURES

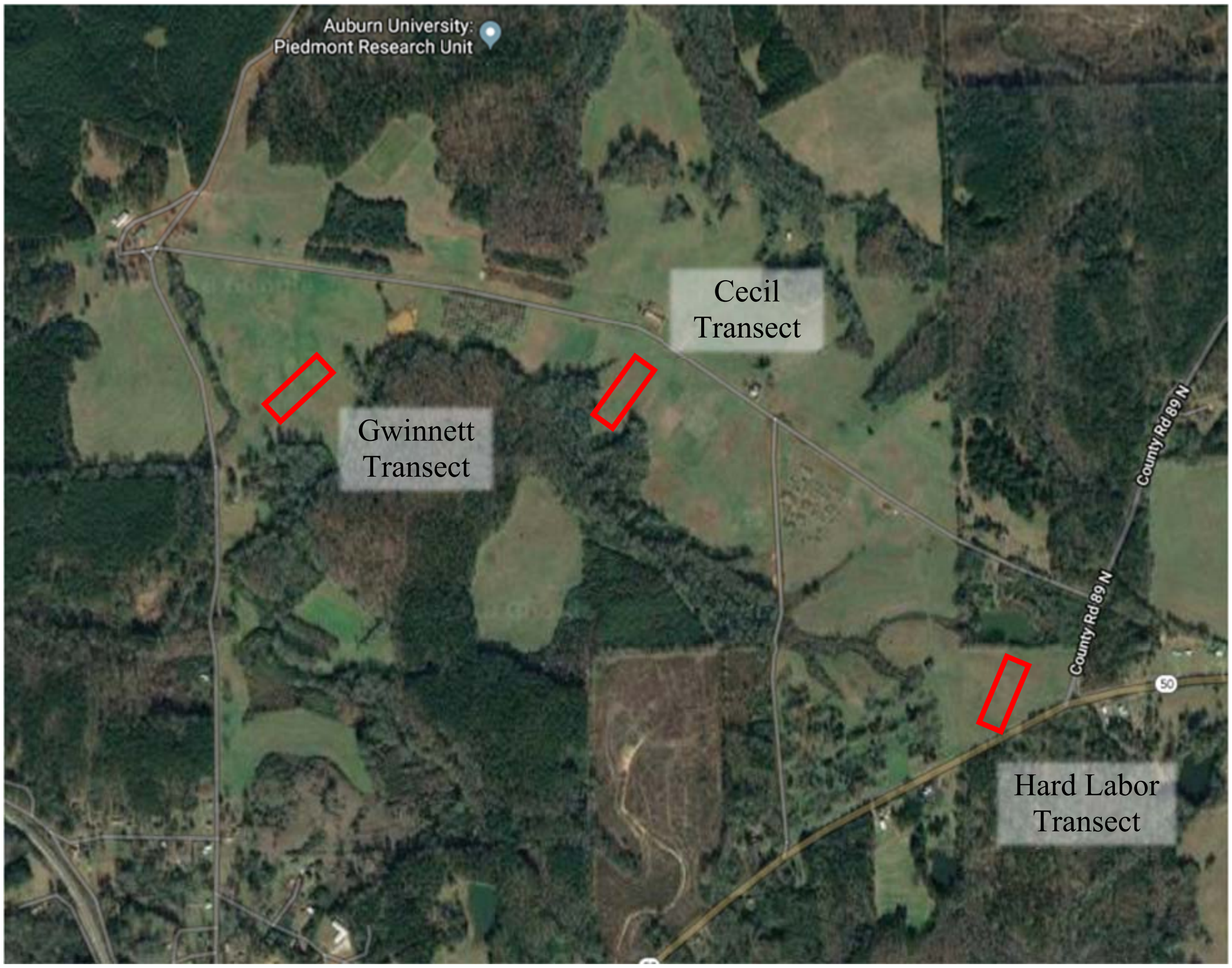

Figure 2.1. Locations of three transects on the Piedmont Substation Research Center used in a trafficking study looking at soil stress translation in nine select Alabama Kanhapludults.

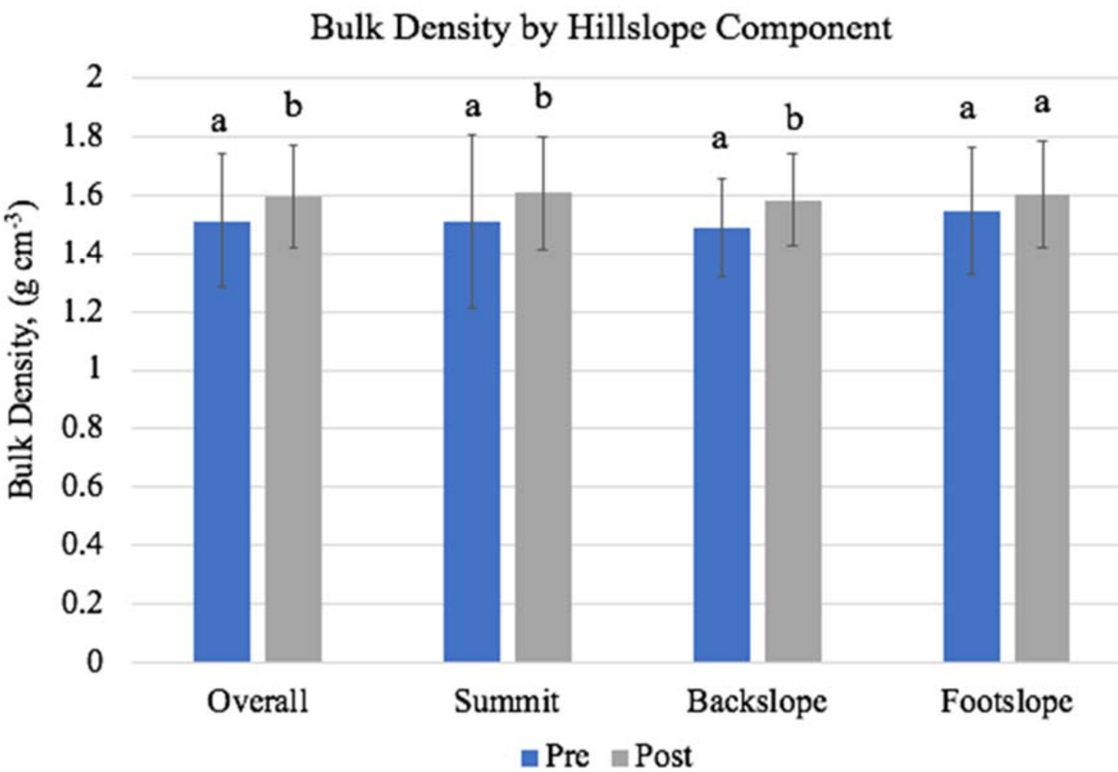

Figure 2.2. Soil bulk density (g cm^{-3}) before and after a five-pass trafficking event involving a CAT 535D forestry skidder in nine select Kanhapludults in the Alabama Piedmont. Data averaged by hillslope component and compared using paired t-tests. *Letters indicate significant difference ($p \leq 0.10$). Error bars indicate standard deviation.

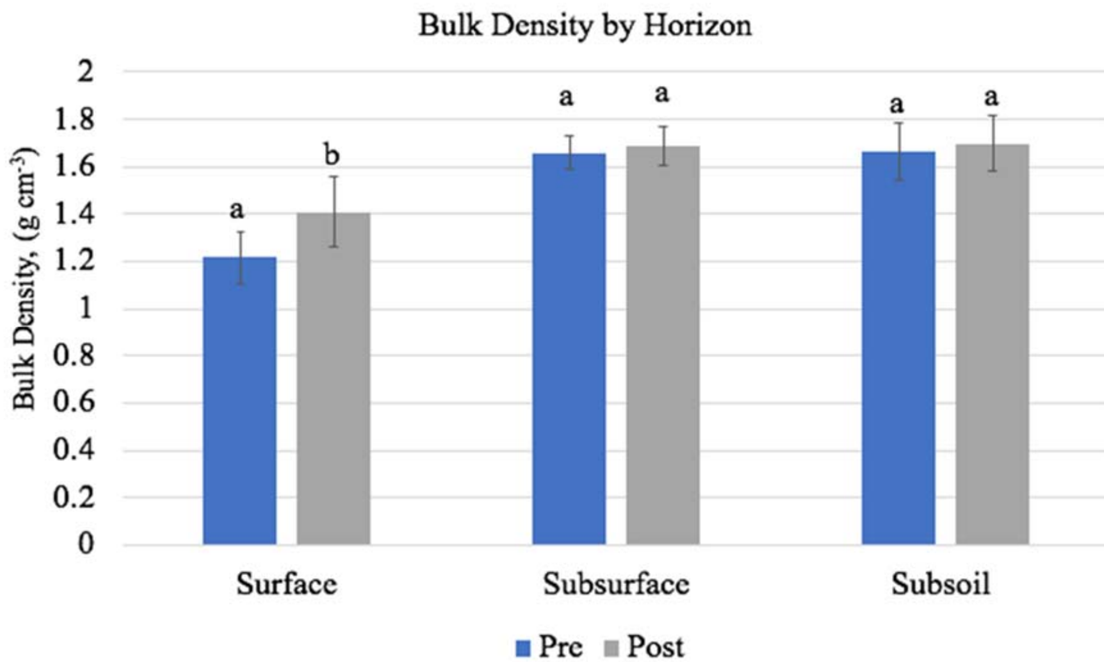

Figure 2.3. Soil bulk density (g cm^{-3}) before and after a five-pass trafficking event involving a CAT 535D forestry skidder in nine select Kanhapludults in the Alabama Piedmont. Data averaged by horizon and compared using paired t-tests.
*Letters indicate significant difference ($p \leq 0.10$). Error bars indicate standard deviation.
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Chapter 3. Evaluating Compaction Susceptibility of Southeastern U.S. Piedmont and Coastal Plain Ultisols with Compression Curves

ABSTRACT

The inherently poor soil quality of southeastern U.S. Piedmont and Coastal Plain Ultisols means that further decrease of dynamic soil quality can be devastating. Soil compaction contributes to the global problem of soil degradation and the solution is prevention, not remediation. Soil surveys provide information about near surface soil morphological and physical properties that we hypothesize can provide information about soil compaction susceptibility. Little research has been conducted that relates these properties to compaction susceptibility of southeastern Ultisols. This study seeks to evaluate compression indices and changes in density of near-surface horizons and relate soil physical and morphological properties to compaction susceptibility using compression indices for select southeastern U.S. Coastal Plain and Piedmont Ultisols. Four representative Coastal Plain and seven representative Piedmont sites were described (to 40 cm), sampled, and several soil physical properties were measured. Compression indices were determined from curves developed using a consolidometer. Results indicate texture and soil organic carbon were correlated to several other near-surface properties (r=|0.33 to 0.88|). Surface horizons (A) were more susceptible to bulk density change caused by compaction (~35% vs ~20%) and had higher compressions indices (C_P) (0.24 vs 0.19) than subsurface (E, BE) or subsoil horizons (Bt). Dynamic properties (e.g. soil organic carbon [SOC], bulk density, structure grade) and static properties (e.g. texture), to a lesser extent, affected compaction susceptibility; compression indices were related

to texture (e.g. coefficient of curvature, coarse fragments) and SOC. Factor analyses indicated that texture, dynamic properties (SOC, WSA, WDC, water content at 0.3 bar), and morphological properties (structure grade) described most of the soil property data variability. Stepwise linear and factor regression suggested that dynamic properties (e.g. SOC, bulk density), static properties (e.g. texture), and morphological properties (e.g. structure grade) affected compaction susceptibility. Compression indices were largely affected by soil organic carbon and texture (e.g. coefficient of curvature, % coarse fragments). Maximum bulk density (to 800 kPa) and bulk density change (from initial to 800 kPa) increased with greater soil organic carbon and decreased with structure development. In summary, our study found soil compaction susceptibility is influenced approximately 15-30% by static, 40% by dynamic, and 10% by morphological properties.

INTRODUCTION

Compaction as a Global Issue

Soil compaction affects over 68 million hectares worldwide (Oldeman et al., 1991). Soil compaction affects many soil properties vital to soil quality and causes increases in runoff, loss of nutrients via erosion, and decreases in available water, hydraulic conductivity and porosity (Unger and Kaspar, 1994; Douglas and Crawford, 1998; Zhai and Horn, 2017; Keller et al., 2017). Compaction increases bulk density and can limit root growth (Unger and Kaspar, 1994; Soil Science Society of America, 1996). As root growth is stunted, crop productivity decreases (Greacen and Sands 1980). Remediation of compaction is complex, not always efficient or effective, and can leave soils susceptible to future compaction (Håkansson and Petelkau, 1994; Busscher et al., 2002). Due to widespread negative effects on crop production, plant growth, soil microbial communities, and soil health, compaction has been recognized as a widespread global soil quality issue and has been called “the most important subtype of physical soil deterioration” (Oldeman et al., 1991).

Properties Affecting Soil Compaction

Increasing demands for global food and fiber production has resulted in increased soil trafficking (Raper, 2005). Several soil properties are related to inherent compaction susceptibility. Compaction susceptibility increases with clay content to approximately 35% clay (Larson et al., 1980). Compaction susceptibility, highly influenced by water content, increases as soil approaches a critical water content, near saturation, where soil water contributes support and further compaction is controlled by hydraulic conductivity (Proctor, 1933; Larson et al., 1980; Lebert and Horn, 1991; Smith et al., 1997 a & b; Sánchez-Girón et al., 2000). Soil organic carbon increases the compressibility of sandier soils (Smith et al., 1997 a & b). High bulk density and soil strength protect soils from further compaction, but also limit a soil’s ability to support plant and microbial communities (Lebert and Horn, 1991).

Compression Curves

When pressure greater than the soil’s internal strength is applied, bulk density increases (Greacen, 1960 a & b). Soil is not a perfectly elastic material and does not fully rebound from a load (van den Akker, 2004). The highest load which a soil has been exposed, prior to a consolidation test, is called pre-consolidation stress (Gupta et al., 2002). A plot of void ratio or bulk density vs log of applied pressure is called a compression curve (Gupta et al., 2002). The linear portion of a compression curve, termed the virgin compression curve, indicates how a soil will respond past pre-consolidation stress. The slope of the virgin compression curve, the compression index (C_P), indicates the soil's potential response to stress (Gupta et al, 2002).

Measuring Compaction Susceptibility with Compression Curves

Compression curves and indices have been used to estimate soil response to applied mechanical stress in agronomic situations (Larson et al., 1980). In agricultural soils, bulk density is often used to develop the compression index rather than void ratio, as saturated soils are not representative of field conditions at trafficking (Greacen 1960 a & b; Gupta et al., 2002). The majority of studies that use compression indices to evaluate soil compressibility have used disturbed samples (Larson et al., 1980; Smith et al., 1997 a & b; Sanchez-Girón et al., 1998). Many physical and morphological properties, such as structure, moist consistence, water stable aggregates, and bulk density, affect soil behavior. Those effects are likely diminished upon disturbance that occurs in sample preparation. Therefore, compression indices developed from undisturbed samples are more useful for understanding agricultural soil behavior.

Southeastern Piedmont and Coastal Plain Soils

Southeastern U.S. Piedmont and Coastal Plain landscapes are dominated by Ultisols (Buol et al, 2011). These landscapes have experienced intense historical erosion due to intensive cultivation (Trimble et al., 1974). Coastal Plain soils tend to have sandy to sandy loam textured epipedons overlying loamy textured argillic and kandic horizons. Piedmont soils tend to have sandy loam to loamy textured epipedons overlying a sandy clay loam to clay textured Bt (argillic and/or kandic) horizon (Markewich et al., 1990). Both regions have lost vital soil organic stores, rendering them degraded with poor dynamic soil quality. The climate and geology of the Piedmont and Coastal Plain is conducive to the formation of argillic and kandic subsoil horizons dominated by highly weathered clays (e.g. kaolinite), quartz, and iron and aluminum oxides (Markewich et al., 1990; Shaw et al., 2010). The high acidity, low cation exchange capacity and base saturation create soils that are relatively infertile and unable to rebound from further degradation.

RATIONALE

In order to meet the growing demand for agricultural and forest products with declining arable lands, soils must be protected against degradation. Compaction has been identified as a key part of physical soil degradation; the expense and effectiveness of remediation (e.g. tillage) of compaction renders it unsustainable in many situations. Therefore, the solution to soil compaction is prevention, not remediation. Soil surveys contain valuable information on soil morphological and physical properties that we hypothesize may be related to compaction susceptibility. Understanding these relationships in select southeastern U.S. Piedmont and Coastal Plain Ultisols would be useful in making management decisions to protect this valuable resource.

OBJECTIVES

1) Evaluate compression indices and changes in density of near-surface horizons, and

2) Relate soil physical and morphological properties to compaction susceptibility using compression indices for select southeastern U.S. Coastal Plain and Piedmont soils

MATERIALS AND METHODS

Site Selection and Soil Descriptions

Sites were selected that were representative of Alabama Piedmont and Coastal Plain soils. Four sites were selected within the Coastal Plain and seven sites were selected within the Piedmont. The Coastal Plain sites were mapped as Marvyn (Fine-loamy, kaolinitic, thermic Typic Kanhapludults), Sacul (Fine, mixed, active, thermic Aquic Hapludults), Uchee (Loamy, kaolinitic, thermic Arenic Kanhapudults), and Cowarts (Fine-loamy, kaolinitic, thermic Typic Kanhapludults). The Piedmont sites were mapped as Pacolet (Fine, kaolinitic thermic Typic Kanhapludults), Gwinnett (Fine, kaolinitic, thermic Rhodic Kanhapludults), Cecil (Fine, kaolinitic, thermic Typic Kanhapludults), and Hard Labor (Fine, kaolinitic, thermic Oxyaquic Kanhapludults).

Excavations were made at each site to 40-cm, and soil morphological properties were described (Schoeneberger et al., 2012). Soil morphological properties included horizonation, Munsell color, texture, structure grade and shape, moist consistence, presence of clay films, presences of redoximorphic features, presence of mica, boundary distinction, and depth. An index was developed and used for quantitative measure of soil structure grade. The index correlated to NCSS categories of structure grade with zero corresponding to structureless, one to three corresponding to weak structure, four to six corresponding to moderate structure, and seven to nine corresponding to strong structure

(Schoeneberger et al., 2012). Two to four horizons from above 40 cm were utilized from each site for a total of 34 horizons.

Soil Measurements

Bulk density (ρ_b) measurements were taken by horizon in triplicate using a drop hammer and ring of a known volume (Blake and Hartge, 1986). Measurements were corrected for rock fragments, and replicate values were averaged. Bulk and undisturbed samples and undisturbed cores were collected from each horizon. Bulk samples were air-dried, lightly crushed using a rolling pin, and sieved to separate the coarse fragments from the fine-earth fraction using a 2-mm sieve, after which percent coarse fragments were determined. Particle size analysis was conducted on each horizon in duplicate using the pipet method (Kilmer and Alexander, 1949); duplicates were averaged. Water dispersible clay (WDC) was measured by horizon in duplicate (Miller and Miller, 1987), averaged, and reported as percent of the fine earth (< 2mm) and clay fraction. Atterberg limits, including liquid limit (LL), plastic limit (PL), and plasticity index (PI), were measured on each horizon (ASTM D4318, 2017). Replicates for LL and PL were averaged, and PI values were calculated. Soil organic carbon (SOC) was determined by horizon in duplicate using the dry combustion method with a Costech CHNSO Elemental Analyzer (Valencia, CA) (Yeomans and Bremner., 1991). Water stable aggregates (WSA) were measured by horizon in triplicate and averaged (Kemper and Rosenau, 1986).

Consolidometer Tests

Undisturbed soil samples were collected in duplicate from each horizon using a 7.5 cm diameter ring for a total of 68 samples. Samples were equilibrated to 0.3 bar pore pressure using tempe cell apparatuses. Subsamples were collected from the rings using 6.3 cm diameter brass ring. One dimensional consolidation tests were run on subsampled soils using a fixed ring consolidometer (ELE International, Loveland, CO) (ASTM D2435/D2435M, 2011; Larson et al., 1980). Soils were subjected to stresses (σ) of 10, 25, 50, 100, 250, 500, and 800 kPa for five hours duration at each stage, which preliminary tests indicated brought the sample to a nearly constant volume (Larson et al., 1980).

Compression curves were developed by plotting bulk density (ρ_b) vs. logarithm of stress (log σ) (Gupta et al., 2002. Compression indices (C_P) were calculated using equation 1 for the virgin portion of the curve.

$$C_P = \frac{\delta \rho_b}{\delta log \sigma} \quad \text{(eq. 1)}$$

Where C_P = compression index, δ = change, ρ_b = bulk density (g cm^{-3}), and logσ = log of stress (kPa) (examples of representative curves: Figure 3.1-3.6).

Statistical Approach

Data were analyzed using SAS Statistical Software (SAS Institute, Cary, NC). Pearson linear correlation coefficients (r) were calculated to relate soil properties within horizons ($p \leq 0.10$ significance level). Averages for horizons (surface, subsurface, subsoil) of Cp, maximum density (800 kPa), and change in bulk density (initial vs 800 kPa) were analyzed using analysis of variance ($p<0.10$). Mean separation was conducted using Duncan's multiple range test.

Stepwise multiple linear regression ($p<0.15$) was used to relate compression parameters—C_P, $\delta\rho_{b\,(\%)}$, ρ_b at 800 kPa, load (kPa) resulting in ρ_b affecting root growth (derived from USDA, 1999)—(dependent) to soil properties (independent).

Many soil properties (independent) were correlated, so data were analyzed and reduced using multivariate factor analyses (FA). Factors were developed to create uncorrelated variables that could be related to consolidometer data using stepwise regression. Soil property data were standardized, and factors with eigenvalues >1 that explained >5% of the data variance were related to consolidometer data using stepwise regression. Loading factors were evaluated to determine the most significant soil properties within each individual factor.

RESULTS AND DISCUSSION

Soil Properties

The sampled soils were mostly Kanhapludults. Soils sampled from the Coastal Plain generally had coarser textures than sampled Piedmont soils, with sand contents of near surface horizons averaging 76% in the Coastal Plain compared to 55% in the Piedmont (Table 3.1). Due to coarser texture, the Coastal Plain soils had higher *in situ* bulk density values averaging 1.61 g cm^{-3} versus a lower, but more variable, average of 1.39 g cm^{-3} in the Piedmont. The finer-textured Piedmont soils had higher LL, PL, and PI. These Piedmont and Coastal Plain soils had similar values of WSA, WDC/Clay, and C_P.

Piedmont soils (Table 3.1) had thin Ap (surface) horizons ranging from 5 to 10 cm thickness with loamy sand to sandy clay loam textures, SOC around 3-4%, and relatively low ρ_b (average 1.08 g cm^{-3}). Underlying E or BE (subsurface) horizons were thin with higher ρ_b, compared to surface horizons, likely due to a persistent plow pan from decades of past cotton production. The Bt (argillic and/or kandic subsoil) horizon came in between 10 and 20 cm with increased clay (~35%) and structure grade (~5).

The Coastal Plain soils (Table 3.1) had slightly thicker surface horizons compared to Piedmont soils, ranging from 7 to 20 cm. Coastal Plain surface (Ap) horizons had relatively coarse loamy sand to sandy loam textures with clay content averaging ~5%. Surface horizon soil organic carbon averaged between 1-2%. Eluvial horizons (E) had coarse textures, with a weak structure grade (2-3). Thick subsoil (Bt) horizons came in between 16 and 33 cm, and clay content (~20%) and structure grade (~5) increased.

Soil Property Correlation

In these Piedmont and Coastal Plain soils, texture was significantly correlated with several soil properties (Table 3.2). In general, structure grade, LL, PL, PI, WDC, and gravimetric water content at 0.3 bar all increased as clay increased and increased as sand decreased.

Structure grade was positively correlated with LL ($r = 0.29$), PI ($r = 0.38$), and clay content ($r = 0.60$), and negatively correlated with sand content ($r = -0.46$). Additionally, structure grade was negatively correlated with WDC/clay ($r = -0.42$), suggesting dispersion of clay decreases soil structure

Bulk density was negatively correlated with gravimetric water content at 0.3 bar ($r = -0.67$); this is in agreement with findings that increased bulk density causes decreased porosity and water content (Unger and Kaspar, 1994). Additionally, bulk density was negatively correlated with SOC ($r = -0.80$); this is similar to findings that increased SOC contents leads to soil resilience against bulk density increases and an increased propensity to “rebound” (Larson and Allamaras, 1971; Soane, 1990). SOC also contributed to increasing WSA ($r = 0.40$) and water holding capacity ($r = 0.55$). This reinforces the concepts that SOC is the most important soil quality indicator (Causarano et al., 2008, Levi et al., 2010).

Linear Regression Relating Soil Properties to Compaction Metrics

Stepwise linear regression was utilized to relate C_P, $\delta\rho_{b\,(\%)}$, ρ_b at 800 kPa, and load (kPa) resulting in ρ_b, affecting root growth (dependent), to soil morphological and physical properties (independent) (Table 3.3). Soil property data described 52% ($p< 0.15$, $R^2 = 0.52$) of C_P variability. SOC was most significant (partial $R^2 = 0.44$), and texture parameters, in the form of Cc and coarse fragment content, were also significant.

Soil property data described 82% of bulk density following consolidation at 800 kPa ($\rho_{b\,max}$) variability. (Table 3.3). Initial bulk density ($\rho_{b\,ini}$) and SOC were positively related, while structure grade was negatively related to $\rho_{b\,max}$. Initial ρ_b was the most significant property (partial $R^2 = 0.72$). While it is possible that higher $\rho_{b\,ini}$ causes higher $\rho_{b\,max}$, it is probable that higher $\rho_{b\,ini}$ largely results in higher potential ρ_b values.

Soil property data described 79% of percent bulk density change ($\delta\rho_{b\,\%}$) variability during the consolidation test at loads from 10-800 kPa (Table 3.3). Structure grade and initial bulk density were negatively related, and SOC and Cc were positively related to $\delta\rho_{b\,\%}$. Soil property data described 80% of variability related to soil reaching a critical ρ_b threshold that affects root growth (USDA, 1999). Texture was the main factor affecting the amount of pressure required to reach the threshold, with higher clay content, D_{30}, and coarse fragment content resulting in lower pressures where root limiting bulk density occurs.

Higher soil organic carbon (SOC) increased compaction susceptibility in relation to several compression parameters (e.g. C_P, $\delta\rho_{b\,\%}$, $\rho_{b\,max}$). Smith et al. (1997 a & b) found similar interactions between SOC and compaction susceptibility, especially in sandier soils. Relatively better soil structure grade improved soil compaction resistance (e.g. lower $\delta\rho_{b\,\%}$, $\rho_{b\,max}$). These results complement findings indicating that aggregate strength increases compaction resistance, and soil morphological data are useful for determining susceptibility to compaction (Greacen, 1960) and tillage leaves soil susceptible to re-compaction (Håkansson and Petelkau 1994; Spoor, 1995; Raper and Arriaga, 2007).

The aggregate of these regression findings is that static (e.g. texture), dynamic (e.g. SOC), and morphological properties (e.g. structure grade) all influence compaction susceptibility.

Factor Analysis Relating Soil Properties to Compaction Metrics

Factor analyses was utilized to develop uncorrelated variables (factors) to relate to compression measures (C_P, $\delta\rho_{b\,\%}$) through stepwise linear regression. Standardized data were used to develop factors and correlated soil properties were evaluated. The first four factors described 78% of the soil property data variability (Table 3.4). Factor 1 described 28% of the data variability and was highly related to textural properties (e.g. sand and clay content, PL, LL, PI) and water content at 0.3 bar (W%). Factor 2 described 19% of the data variability and was highly related to dynamic properties (e.g. WSA, SOC, W%), morphological properties (e.g. structure grade), and static properties (e.g. coarse fragment, PL, clay content). Factor 3 (16% of data variability) was dominated by textural measures (e.g. Cc, Cu, coarse fragment, D_{60}) and SOC. Factor 4 (15% of data variability) was related with textural properties (e.g. silt, Cc, PI, D_{60}) and dynamic properties, namely WDC and SOC.

Utilizing the first four factors, regression indicated that Factor 3 (22%), Factor 2 (16%), and Factor 4 (5%) described 43% (R^2=0.43) of C_P variability (Table 3.5). Utilizing the first four factors, regression indicated that Factor 3 (43%), Factor 1 (7%), Factor 2 (5%), and Factor 4 (5%) described 60% (R^2=0.60) of $\delta\rho_{b\,\%}$ variability (Table 3.5). Considering that Factor 3 explained a significant part of both C_P and $\delta\rho_{b\,\%}$ variability, it is apparent that textural standards, such as those commonly used by engineers (e.g. Cc, Cu, D_{60}), and SOC impact soil compaction susceptibility. The inclusion of Factor 2 suggests that structure grade was also influential, although to a lesser extent.

Consolidation Metrics Comparisons Among Horizons

Analysis of Variance was used to compare compression parameter means among horizon types (Table 3.6). Surface horizons were significantly ($p<0.10$) more susceptible to compaction — higher C_P and $\delta\rho_{b\,\%}$ — than subsurface and subsoil horizons. Surface C_P values averaged 0.24 and $\delta\rho_{b\,\%}$ averaged 35%, while subsurface and subsoil C_P values averaged 0.19 and $\delta\rho_{b\,\%}$ averaged 19-20% Although not significant (p=0.11), maximum ρ_b was also higher in surface horizons.

Similar to past studies, surface horizons are more susceptible to compaction than subsurface and subsoil horizons (Shaw and Carter, 2002). Although proximity to the load surely increases this risk, results from this study suggest that soil properties present in surface horizons (e.g. increased SOC, decreased structure grade) may contribute to susceptibility. It is important to note however, that SOC is known to increase a soil's elasticity and ability to rebound from compactive events as well as contribute to overall soil health (Soane, 1990).

CONCLUSIONS

USDA texture largely influences soil behavior and is highly correlated to several near-surface physical properties including Atterberg limits, bulk density, structure grade, and water content at 0.3 bar. In these southeastern Piedmont and Coastal Plain Ultisols, SOC is correlated with properties indicative of better soil quality including low bulk density, increased water stable aggregates, and increased water content at 0.3 bar.

Several soil properties influence compaction susceptibility in these Alabama Piedmont and Coastal Plain Ultisols. Better structure prevents bulk density increases in response to loads. Higher initial bulk density was related to higher maximum bulk density but dampened potential bulk density increases; likely initial bulk density is more an expression of how particular soils in the region reacted to compactive events in the past than if a soil will compact further under larger loads. Soil organic carbon increased compaction susceptibility, although none of the soils used had independently “high” SOC. Soil texture and coarse fragment content also influenced compaction susceptibility.

Uncorrelated factors developed using factor analysis indicated that textural properties are important to soil behavior. Similar to stepwise linear regression, textural properties as well as SOC were most important to compaction susceptibility; to a lesser extent, morphological properties (structure grade) also influenced compaction susceptibility. The aggregate of these regression findings suggests that static (e.g. texture), dynamic (e.g. SOC), and morphological properties (e.g. structure grade) all influence compaction susceptibility variability.

On average, surface horizons in Piedmont and Coastal Plain Ultisols are more susceptible to compaction (higher C_P and $\delta\rho_{b\,\%}$). As previously found, surface horizons suffered the most from compaction. Other literature suggests that this is due to the proximity to the load. However, our results suggest that dynamic soil properties—higher SOC, lower structure grade—may play a role in making surface soil more susceptible to compaction. However, as previous literature suggests, as SOC increases, overall bulk density decreases—attributed to SOC's higher elasticity—and increasing soil quality.

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Tables

Table 3.1 Summary of select soil properties by region and horizon in 11 Alabama Piedmont and Coastal Plain Ultisols.

	Variable	All			Coastal Plain			Piedmont		
		Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev	N
Ap (Surface)	Soil Organic Carbon (%)	2.8	1.8	22	1.2	0.8	8	3.7	1.6	14
	Clay (%)	12.0	6.9	22	5.0	0.8	8	16.0	5.2	14
	Sand (%)	67.2	13.7	22	82.9	1.1	8	58.3	7.4	14
	Structure Grade (scale 1-9)	3.3	1.6	11	3.0	0.8	4	3.4	1.9	7
	Bulk Density (g cm-3)	1.21	0.24	33	1.44	0.15	12	1.08	0.16	21
	Water Content at 0.3 bar (g cm^{-3})	0.20	0.08	22	0.11	0.02	8	0.25	0.04	14
	Liquid Limit	41.7	14.6	22	25.0	3.6	8	51.2	7.7	14
	Plastic Limit	31.4	10.3	44	20.4	3.3	16	37.7	6.5	28
	Water Stable Aggregates (%)	91.3	7.1	33	88.3	10.8	12	93.1	4.1	21
	Water Dispersible Clay (%)	9.3	5.8	22	4.4	0.7	8	12.1	5.5	14

(continued)

	Variable	All			Coastal Plain			Piedmont		
		Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev	N
E or BE (Subsurface)	Upper Depth (cm)	8.8	4.3	12	11.8	5.9	4	7.1	2.1	7
	Clay (%)	10.3	6.5	24	4.7	0.6	8	13.6	6.1	16
	Sand (%)	69.9	12.3	24	81.5	0.9	8	63.3	10.6	16
	Structure Grade (scale 1-9)	3.2	1.1	12	3.0	1.2	4	3.3	1.1	8
	Bulk Density (g cm-3)	1.62	0.19	36	1.65	0.11	12	1.60	0.23	24
	Water Content at 0.3 bar (g cm^{-3})	0.12	0.05	24	0.08	0.01	8	0.15	0.04	16
	Liquid Limit	24.6	8.3	24	17.6	5.2	8	28.6	7.0	16
	Plastic Limit	18.4	4.8	48	14.6	1.8	16	20.6	4.6	24
	Water Stable Aggregates (%)	82.3	13.8	36	82.8	19.3	12	82.0	11.3	24
	Water Dispersible Clay (%)	8.4	5.0	24	4.1	0.6	8	10.8	4.7	16
Bt (Subsoil)	Upper Depth (cm)	22.2	8.5	11	29.3	9.4	5	18.1	4.8	6
	Clay (%)	27.8	12.5	22	19.8	10.0	10	33.6	11.3	12
	Sand (%)	52.3	14.5	22	66.2	8.1	10	42.3	7.8	12
	Structure Grade (scale 1-9)	5.0	1.3	11	5.0	1.6	5	5.0	1.3	6
	Bulk Density (g cm-3)	1.58	0.18	33	1.71	0.16	15	1.49	0.15	18
	Water Content at 0.3 bar (g cm^{-3})	0.17	0.06	22	0.13	0.05	10	0.20	0.05	12
	Liquid Limit	43.5	16.4	22	30.5	10.7	10	52.9	13.1	12
	Plastic Limit	24.5	7.0	44	21.0	8.7	20	26.9	4.6	24
	Water Stable Aggregates (%)	77.4	11.0	33	74.1	13.3	15	79.8	9.3	18
	Water Dispersible Clay (%)	10.6	9.7	22	6.5	6.2	10	13.6	11.0	12

*Standard deviation calculated using average of replicates.

Table 3.2. Pearson Linear Correlation Coefficients ($p < 0.10$) relating select soil properties of 34 soil samples from horizons in the top 40 cm of four Coastal Plain and seven Piedmont Ultisols.

	C_P	Clay %	Sand %	Silt %	Struc	CF%	ρ_b	LL	PL	PI	WSA	SOC	WDC	WDC / Clay	Θ_g	cm	D60	D30	D10	Cu	Cc	ρ_b max	$\delta\rho_b$ %
C_P	1.00	NS	NS	0.41	NS	0.36	-0.58	0.35	0.54	NS	0.32	0.66	NS	NS	0.41	-0.47	NS	NS	NS	NS	NS	NS	0.75
Clay %	NS	1.00	-0.88	NS	0.60	NS	NS	0.76	0.40	0.88	NS	NS	0.30	-0.61	0.52	0.40	-0.48	-0.71	-0.62	0.45	NS	NS	NS
Sand %	NS	-0.88	1.00	-0.64	-0.46	-0.34	0.31	-0.80	-0.55	-0.81	NS	NS	-0.46	0.43	-0.67	NS	0.39	0.84	0.74	-0.52	NS	NS	NS
Silt %	0.41	NS	-0.64	1.00	NS	0.58	-0.54	0.43	0.48	NS	NS	0.43	0.45	NS	0.54	NS	NS	-0.59	-0.53	0.35	NS	NS	0.40
Struc	NS	0.60	-0.46	NS	1.00	NS	NS	0.29	NS	0.38	NS	NS	NS	-0.42	NS	0.43	-0.46	-0.42	-0.42	NS	NS	NS	-0.43
CF%	0.36	NS	-0.34	0.58	0.29	1.00	-0.48	0.30	0.34	NS	NS	NS	NS	NS	0.42	NS	0.52	NS	NS	0.58	NS	NS	0.41
ρ_b ini	-0.58	NS	0.31	-0.54	NS	-0.48	1.00	-0.59	-0.83	NS	-0.42	-0.80	NS	NS	-0.67	0.51	NS	NS	NS	NS	NS	0.42	-0.72
LL	0.35	0.76	-0.80	0.43	NS	0.30	-0.59	1.00	0.84	0.85	NS	0.48	NS	-0.47	0.81	NS	NS	-0.67	-0.57	0.46	NS	-0.28	0.30
PL	0.54	0.40	-0.55	0.48	NS	0.34	-0.83	0.84	1.00	0.44	NS	0.79	NS	NS	0.82	-0.32	NS	-0.53	-0.47	0.41	NS	NS	0.54
PI	NS	0.88	-0.81	NS	0.38	NS	NS	0.85	0.44	1.00	NS	NS	NS	-0.57	0.56	NS	-0.36	-0.60	-0.50	0.37	NS	NS	NS
WSA	0.32	NS	NS	NS	NS	NS	-0.42	NS	NS	NS	1.00	0.40	NS	NS	NS	-0.32	NS	NS	NS	NS	-0.33	NS	0.41
SOC	0.66	NS	NS	0.43	NS	NS	-0.80	0.48	0.79	NS	0.40	1.00	NS	NS	0.55	-0.62	NS	NS	NS	NS	NS	-0.30	0.74
WDC	NS	0.30	-0.46	0.45	NS	NS	NS	NS	NS	NS	NS	NS	1.00	0.42	0.36	NS	NS	-0.45	-0.45	0.28	NS	NS	NS
WDC/ Clay	NS	-0.61	0.43	NS	-0.42	NS	NS	-0.47	NS	-0.57	NS	NS	0.42	1.00	NS	-0.53	0.34	0.40	0.36	NS	NS	NS	NS
Θ_g	0.41	0.52	-0.67	0.54	NS	0.42	-0.67	0.81	0.82	0.56	NS	0.55	0.36	NS	1.00	NS	NS	-0.66	-0.61	0.60	NS	-0.34	0.41
cm	-0.47	0.40	NS	NS	0.43	NS	0.51	NS	-0.32	NS	-0.32	-0.62	NS	-0.53	NS	1.00	NS	NS	NS	NS	NS	NS	NS
D60	NS	-0.48	0.39	NS	-0.46	0.52	NS	NS	NS	-0.36	NS	NS	NS	0.34	NS	NS	1.00	0.44	0.36	0.35	NS	NS	NS
D30	NS	-0.71	0.84	-0.59	-0.42	NS	NS	-0.67	-0.53	-0.60	NS	NS	-0.45	0.40	-0.66	NS	0.44	1.00	0.92	-0.58	NS	NS	NS
D10	NS	-0.62	0.74	-0.53	-0.42	NS	NS	-0.57	-0.47	-0.50	NS	NS	-0.45	0.36	-0.61	NS	0.36	0.92	1.00	-0.63	NS	NS	NS
Cu	NS	0.45	-0.52	0.35	NS	0.58	NS	0.46	0.41	0.37	NS	NS	0.28	NS	0.60	NS	0.35	-0.58	-0.63	1.00	NS	NS	NS
Cc	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	-0.33	NS	NS	NS	NS	NS	NS	NS	NS	NS	1.00	0.85	-0.79
ρ_b max	NS	NS	NS	NS	NS	NS	0.42	-0.28	NS	NS	NS	-0.30	NS	NS	-0.34	NS	NS	NS	NS	NS	0.85	1.00	-0.36
$\delta\rho_b$ %	0.75	NS	NS	0.40	-0.43	0.41	-0.72	0.30	0.54	NS	0.41	0.74	NS	NS	0.41	NS	NS	NS	NS	NS	-0.79	-0.36	1.00

* C_P, compression index; Cu, Coefficient of uniformity; Cc, Coefficient of curvature; cm, lower horizon depth in cm; D_N, Diameter in mm that N% of soil grains are finer than; Struc, Structure grade on a scale of 0-9; $\rho_{b\ ini}$, Bulk density preceding compression test; ρ_b

(max), Bulk density after consolidation test with a max stress of 800 kPa; $\delta\rho_b$ %, Percent bulk density increase during consolidation test; θ_g , Gravimetric water content at 0.3 bar; LL, Liquid limit; PL, Plastic limit; PI, Plasticity index; WSA, Percent water stable aggregates; WDC, Water dispersible clay as a percent of the whole soil; WDC/Clay, Water dispersible clay as a percent of the clay fraction; NS, Not significant at the $p \leq 0.10$ level.

Table 3.3. Stepwise Linear regression relating soil physical and morphological properties to compression parameters obtained from one-dimensional consolidation tests on 34 soil samples from horizons in the top 40 cm of four Coastal Plain and seven Piedmont Ultisols with loading stresses of 10, 25, 50, 100, 250, 500, and 800 kPa

Dependent Variable	Independent Variables	Model R^2
Compression Index (Cp)	0.15 + 0.0013 CF% + 0.029 SOC+ 0.00032 Cc	0.52
Bulk Density (800 kPa)	0.53-0.019 Struc + 0.030 SOC + 0.87 $\rho_{b\ ini}$	0.82
Bulk Density Change (%)	67.44-1.41 Struc+2.78 SOC-31.49 $\rho_{b\ ini}$ + 0.033 Cc	0.79
Pressure Affecting Root Growth (kPa)	3640.62 - 1088.49 C_P-7.06 Clay % -14.58 CF -2068.40 $\rho_{b\ ini}$ + 669.00 D_{60} -1748.26 D_{30}	0.80

*CF %, Coarse fragment content; SOC, % soil organic carbon; Cc, coefficient of curvature; Struc, structure grade on a scale of 0-9; C_p, compression index; $\rho_{b\ ini}$, initial bulk density; D_N, diameter in mm

Table 3.4. Uncorrelated factors for soil properties of 34 soil samples from four Coastal Plain and seven Piedmont Ultisols.

	Factor1	Factor2	Factor3	Factor4
CF	0.38608	0.5597	0.53776	0.26044
clay	0.80743	-0.46018	-0.09644	0.28188
sand	-0.9347	0.18636	-0.03747	-0.04896
silt	0.62762	0.3649	0.23612	-0.35954
Structure	0.42294	-0.59276	-0.04451	0.03844
LL	0.8951	0.10032	-0.27204	0.19411
PL	0.74142	0.44932	-0.28792	-0.04777
PI	0.7785	-0.26945	-0.17602	0.3706
WSA	-0.03808	0.56947	-0.44285	-0.0115
SOC	0.34923	0.69762	-0.34588	-0.34178
WDC	0.47137	0.00321	0.11638	-0.47284
Water	0.84799	0.34972	-0.15415	0.05311
D60	-0.3086	0.66932	0.45428	0.38786
D30	-0.88782	0.19069	-0.12719	0.19555
D10	-0.82525	0.18246	-0.27092	0.26652
Cu	0.63446	0.19261	0.54796	0.28537
Cc	-0.10501	-0.21317	0.61261	-0.35813
Eigenvalue	4.7511293	3.2791431	2.7476181	2.47211
Proportion	0.27947397	0.19288785	0.16162215	0.14541603
Cumulative	0.27947397	0.47236182	0.63398397	0.7794

Table 3.5. Factor analysis regression relating compression metrics to factors described in Table 3.4

Compression Metric (dependent)	**Variable (independent)**	**Partial R^2**	**Model R^2**
Compression Index	Factor 3	0.22	0.22
	Factor 2	0.16	0.38
	Factor 4	0.05	0.43
Bulk Density Change	Factor 3	0.43	0.43
	Factor 1	0.07	0.50
	Factor 2	0.05	0.55
	Factor 4	0.05	0.60

Table 3.6 Analysis of variance for means of Cp, maximum bulk density (800 kPa), and change in bulk density (between initial and 800 kPa) developed from consolidometer data for 34 soil samples from horizons in the top 40 cm of four Coastal Plain and seven Piedmont Ultisols

Horizon depth	Horizonation	Cp	Bulk Density maximum (g cm^{-3})	Bulk Density change (%)
Surface	A	0.24a	1.7	34.9a
Subsurface	E, BE, EB	0.19b	1.65	20.7b
Subsoil	Bt	0.18b	1.58	19.0b
	P>F	0.047	0.112	<0.0001

*Means followed by the same letter are not significantly different (p<0.05) using Duncan's multiple range test.

FIGURES

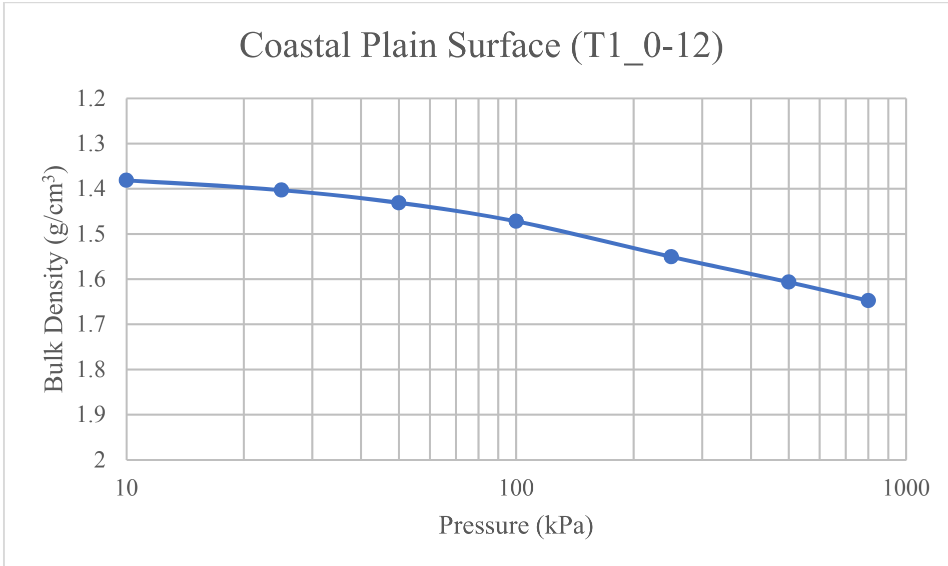

Figure 3.1. Compression curve of a representative Coastal Plain Surface horizon

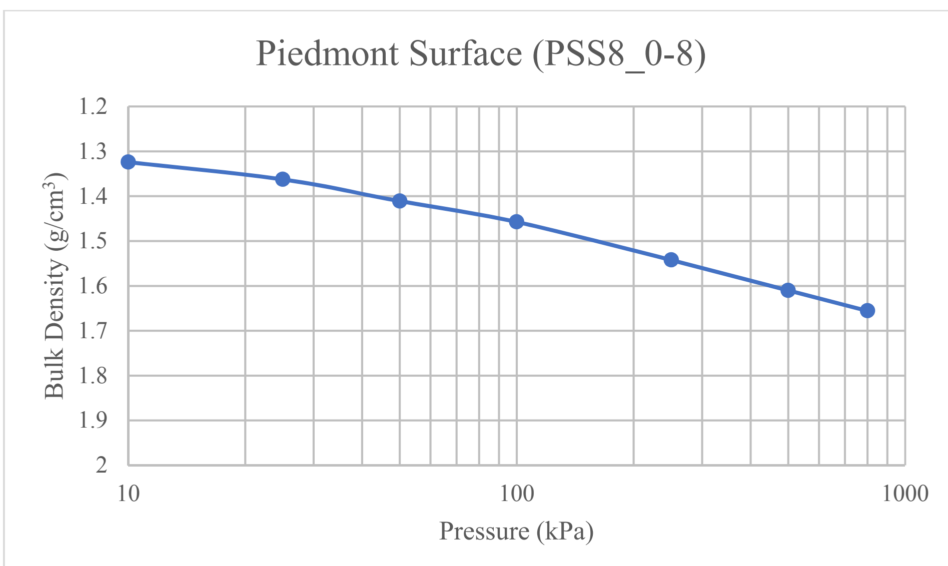

Figure 3.2. Compression curve of a representative Piedmont surface horizon

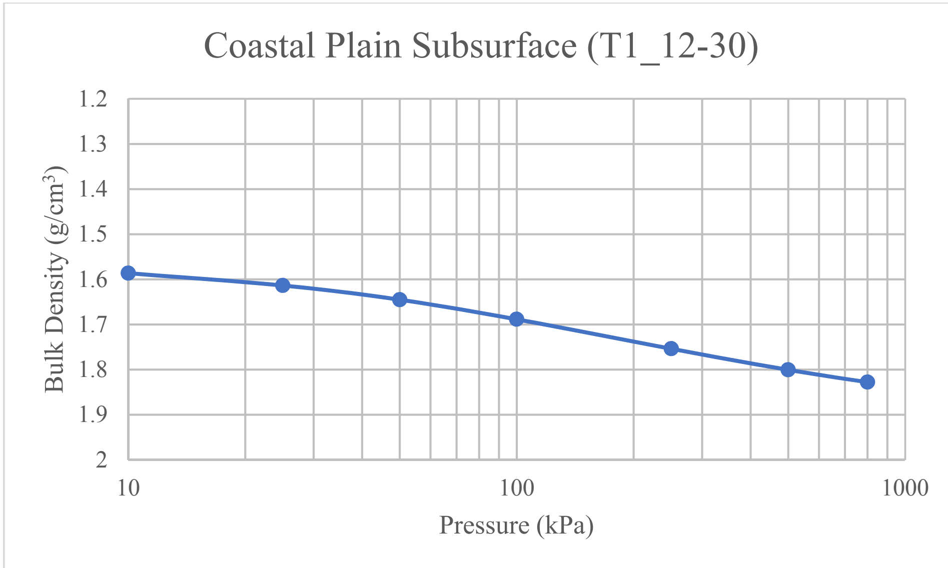

Figure 3.3. Compression curve of a Coastal Plain subsurface horizon

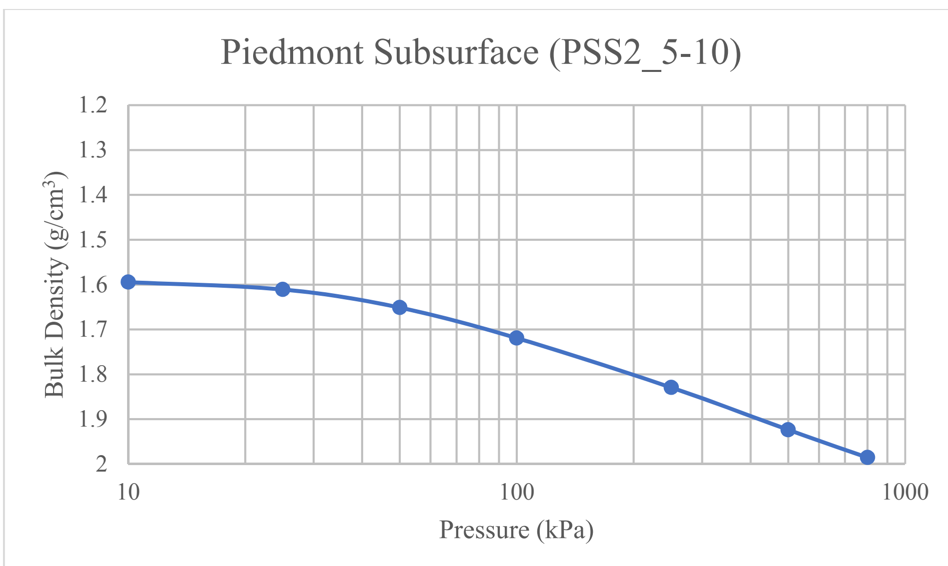

Figure 3.4. Compression curve of a representative Piedmont subsurface horizon

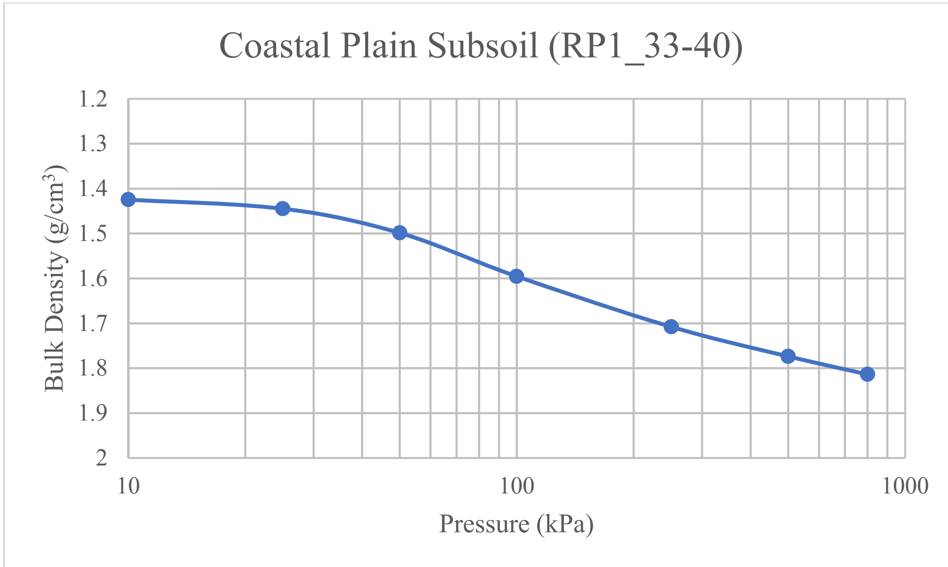

Figure 3.5. Compression curve of a representative Coastal Plain subsoil horizon

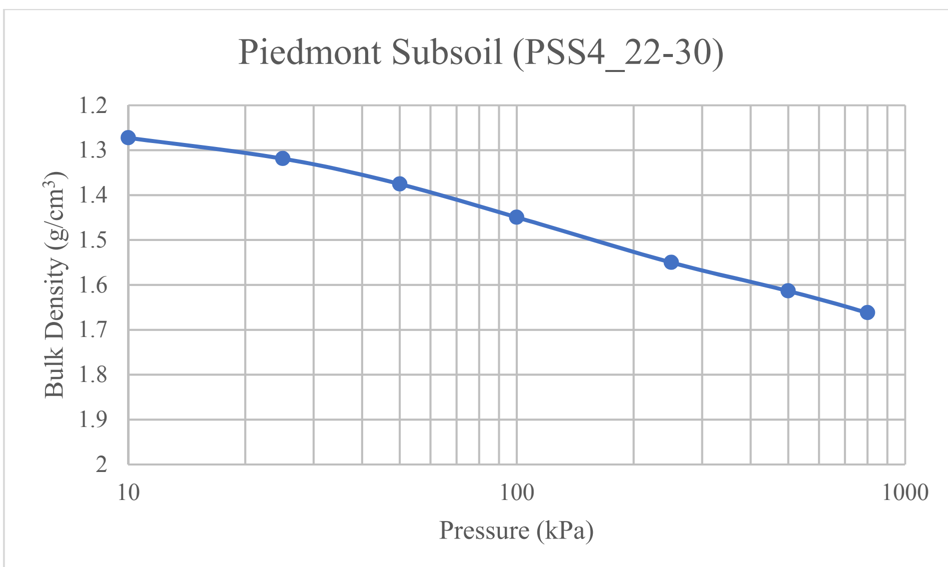

Figure 3.6. Compression curve of a representative Piedmont subsoil horizon

THESIS CONCLUSIONS

1) USDA soil texture is an important static property that is correlated with several other static and dynamic properties. Soil texture can provide insight to many properties in these Alabama Piedmont and Coastal Plain Ultisols.
2) Although data are variable, recently developed sensor bulbs are satisfactory tools for detecting trends in stress translation with depth under field conditions.
3) Surface horizons are most susceptible to compaction compared to subsurface and upper subsoil horizons. Surface horizons are subjected to higher stress (as measured by sensor bulbs) and possess properties leaving the soil susceptible to greater increases in bulk density (trafficking and consolidometer experiments).
4) Physical soil properties previously found to affect compaction susceptibility (e.g. soil texture, bulk density, and water content) also influence soil stress translation. Soil morphological properties related to horizonation (e.g. argillic depth, stratification ratios) influence stress translation, although to a lesser extent than measured physical properties.
5) Compaction susceptibility in select Alabama Piedmont and Coastal Plain Ultisols is affected by both near surface physical (major) and morphological (minor) properties, including soil texture (clay content, coefficient of curvature, coarse fragment %, D_{60}, D_{30}), soil organic carbon, bulk density, and structure grade. In general, soil textural attributes describe approximately 15-30% of the variability in compaction metrics, dynamic properties (SOC, WSA) describe approximately 40% of the variability in

compaction metrics and morphological properties (structure grade) describe approximately 10% of the variability in compaction metrics.

6) The aggregate results from this study illustrate that soil compaction susceptibility is influenced by static, dynamic, and morphological properties. Combining this understanding with pre-existing tools, such as soil surveys, can provide producers—particularly in the forest industry—with valuable information on which sites are more susceptible to compaction. This will allow for the prioritization of trafficking these more susceptible sites when moisture content is more advantageous. This can contribute to an overall management plan that seeks to minimize the degradation of a precious, life supporting, finite resource—our soil.

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APPENDICES

Appendix 1. Research Site Soil Descriptions

PSS_1 Gwinnett Summit (pasture)

Ap-- 0-6 cm; dark reddish brown (2.5 YR 3/4), moderate (4) granular structure; very friable; clear boundary.

BA-- 6-11 cm; reddish brown (2.5 YR 4/4) sandy clay loam (26% clay); moderate (4) subangular blocky structure; friable; common mica flakes; clear wavy boundary.

Bt-- 11-30+; dark red (2.5 YR 3/6) sandy clay (37% clay); moderate (6) subangular blocky structure; friable; common mica flakes; common clay films; few lithorelics.

PSS_2 Gwinnett Backslope (pasture)

Ap-- 0-5 cm; dark reddish brown (2.5YR 3/4); moderate (5) granular structure; very friable; clear wavy boundary.

AE-- 5-10cm; reddish brown (2.5YR 4/4); moderate (4) subangular blocky structure; few faint clay films; common mica; clear wavy boundary.

Bt-- 10-30+; dark red (2.5YR 3/6); strong (7) subangular blocky structure; friable; many mica; common clay films.

PSS_3 Gwinnett Footslope (pasture)

Ap-- 0-8 cm; dark reddish brown (2.5YR 3/4); weak (3) granular structure; very friable; clear wavy boundary.

EB-- 8-13cm; red (2.5YR 4/6); moderate (4) subangular blocky structure; friable; common mica; few faint clay films; clear wavy boundary.

Bt-- 13-30+, red (2.5YR 4/6) moderate (5) subangular blocky structure; friable to firm; common clay films;

PSS_4 Cecil Summit (pasture)

Ap-- 0-5 cm; dark reddish brown (5YR 3/4); moderate (5) fine granular structure; very friable; abrupt smooth boundary.

E-- 5-22 cm; reddish brown (2.5YR 4/4); weak (2) subangular blocky structure; very friable; clear smooth boundary.

Bt-- 22-30+, red (2.5YR 4/6); moderate (4) subangular blocky structure; friable;

PSS_5 Cecil Backslope (pasture)

Ap-- 0-5 cm; reddish brown (2.5YR 4/3); moderate (4) granular structure; very friable; clear smooth boundary.

AE-- 5-20 cm; reddish brown (2.5YR 4/4); moderate (4) subangular blocky structure; friable; approximately 10% gravels; clear wavy boundary.

Bt— 20-30+ cm; red (2.5YR 4/6); moderate (6) subangular blocky structure; friable; common clay films;

PSS_6 Cecil Footslope (pasture)

Ap-- 0-8 cm; dark reddish brown (5YR 3/3); moderate (6) fine granular structure; very friable; clear wavy boundary.

AE-- 8-34 cm; reddish brown (5YR 4/4); weak (3) subangular blocky structure; friable; few clay films; clear wavy boundary.

Bt-- 34-40+; yellowish red (5YR 4/6) moderate (4) subangular blocky structure; friable.

PSS_7 Hard Labor Summit (pasture)

Ap-- 0-8; very dark grayish brown (10 YR 3/2); moderate (4) medium subangular blocky structure; very friable; abrupt smooth boundary.

E -- 8-18; yellowish brown (10 YR 5/4) loamy sand (6% clay); weak (2) fine subangular blocky parting to moderate (4) granular structure; very friable; clear wavy boundary.

BE-- 18-24 cm; light yellowish brown (10 YR 6/4 or 6/6) sandy loam (12% clay); weak (3) subangular blocky structure; firm; compact in place; clear smooth boundary.

Bt-- 24-36+ cm; strong brown (7.5 YR 5/6) clay (50% clay); moderate (4) subangular blocky structure; firm; common redox concentrations (2.5 YR 4/6); common clay films;

PSS_8 Hard Labor Backslope (pasture)

Ap-- 0-8 cm; very dark grayish brown (10 YR 3/2); moderate (5) fine granular structure; very friable; clear smooth boundary.

E-- 8-20 cm; dark yellowish brown (10 YR 4/4) sandy loam (10% clay); weak (2) subangular blocky structure; very friable; clear boundary.

Bt-- 20-35+ cm; strong brown (7.5 YR 5/6) sandy clay (36% clay); moderate (5) subangular blocky structure; friable; common redox concentrations (2.5 YR 4/6); common clay films;

PSS_9 Hard Labor Footslope (pasture)

Ap-- 0-6 cm; dark brown (10 YR 3/3); moderate (5) fine granular structure; very friable; clear wavy boundary.

E-- 6-19 cm; strong brown (7.5 YR 5/6); moderate (5) subangular blocky structure; friable; common iron and manganese concentrations; clear wavy boundary;

Bt-- 19-35+ cm; strong brown (7.5 YR 4/6); moderate (4) subangular blocky structure; friable; common redox concentrations; faint redox depletions; common clay films.

MOT_1 Pacolet (forest)

Ap-- 0 to 5 cm; reddish brown (5YR 4/3) sandy loam (15.7% clay); weak (3) granular structure; friable; clear smooth boundary.

E -- 5 to 14 cm; red (2.5YR 5/6) loam (16.8% clay); weak (3) subangular blocky structure; friable; clear wavy boundary.

Bt-- 14-35+ cm; red (10R 4/6) clay (44.6% clay); moderate (6) subangular blocky structure; firm; common mica flakes; common clay films.

MOT_2 Pacolet Backslope (forest)

Ap-- 0 to 9 cm; brown (7.5YR 4/3) sandy loam (14.4% clay); moderate (5) granular structure; friable; clear smooth boundary.

E -- 9 to 19 cm; yellowish red (5YR 5/6) loam (13.6% clay); moderate (4) subangular blocky structure; friable; clear wavy boundary.

Bt-- 19-35+ cm; yellowish red (5YR 4/6) loam (21.9% clay); moderate (5) subangular blocky structure; friable; common mica; common rock fragments.

MOT_3 Pacolet Footslope (forest)

Ap-- 0 to 10 cm; dark brown (7.5YR 3/3) sandy loam (14.2% clay); massive parting to weak (2) granular structure; friable; many gravels;

Bt1-- 10 to 19 cm; reddish brown (5YR 4/4) sandy clay loam (17.7% clay); weak (3) subangular blocky structure; friable; many gravels

Bt2-- 19 to 35+ cm; yellowish red (5YR 4/6) sandy loam (15.7% clay); moderate (5) subangular blocky structure; friable; many gravels

RP Marvyn (forested)

Ap-- 0-7 cm; brown (10YR 4/3) loamy sand (4.7% clay); weak (3) granular structure; very friable; clear smooth boundary.

AE-- 7-16 cm; dark yellowish brown (10YR 4/4) loamy sand (4.8% clay); weak (2) subangular blocky structure; very friable; clear smooth boundary.

BE-- 16-33 cm; strong brown (7.5YR 4/6) loamy sand (5.4% clay); moderate (4) subangular blocky structure; very friable; clear smooth boundary.

Bt-- 33-40+ cm; strong brown (7.5YR 5/6) sandy loam (10.6% clay); moderate (5) subangular blocky structure; friable; weak thin clay films; less than 5% iron stone.

SCW Sacul (pasture/roadside)

Ap-- 0-8 cm; dark yellowish brown (10YR 4/4) loamy fine sand (4.8% clay); weak (2) granular structure; very friable; less than 5% angular gravels; clear smooth boundary.

E-- 8-19 cm; yellowish brown (10YR 5/4) fine sandy loam; weak (2) subangular blocky structure; friable; compacted in place; approximately 10% angular gravels; clear smooth boundary.

Bt1-- 19-36 cm; dark yellowish brown (10YR 4/6) fine sandy loam (18.6% clay); moderate (4) subangular blocky structure; friable; common clay films; 5% gravels. clear smooth boundaries.

Bt2-- 36-45+ cm; dark yellowish brown (10 YR 4/6) fine sandy clay (36.8%); strong (7) angular and subangular blocky structure; firm; many thick clay films; common redox concentrations (2.5YR 4/6).

T_1 Cowarts (field)

Ap-- 0-12; brown (10YR 4/3) loamy sand (4.4% clay); weak (3) subangular blocky structure; very friable; tillage pan present; clear wavy boundary.

E-- 12-30; yellowish brown (10YYR 5/4) loamy sand (3.9% clay); moderate (4) subangular blocky structure; very friable; clear wavy boundary.

Bt-- 30-40+; dark yellowish brown (10YR 4/6) sandy loam (17.9 % clay); moderate (6) subangular blocky structure; friable; few gravels; few faint clay films;

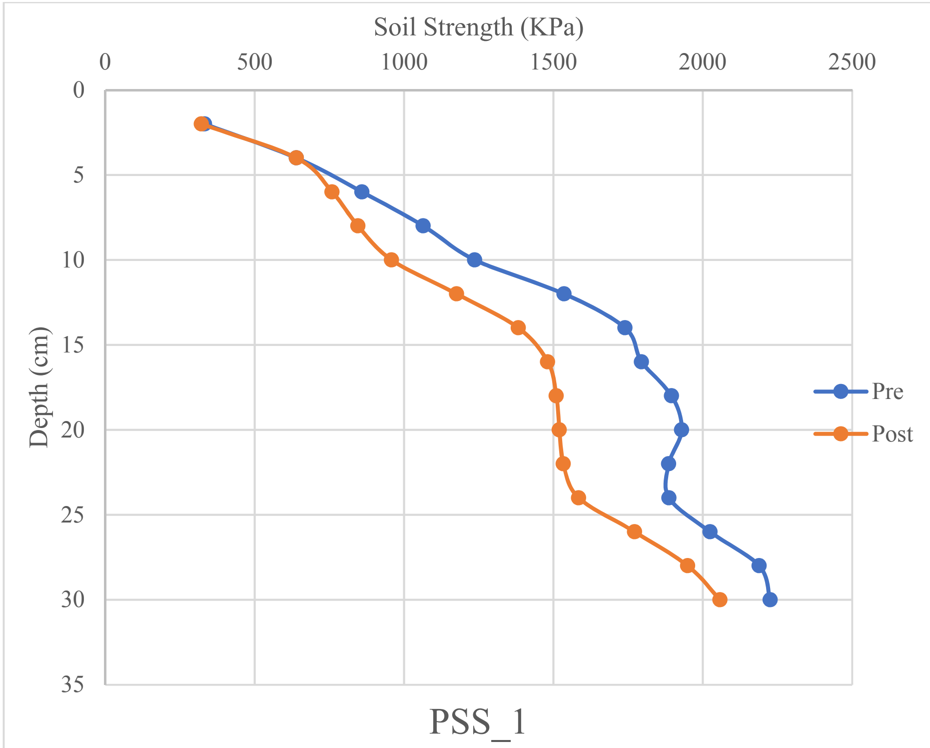
T_2 Uchee-Maryn (forested)

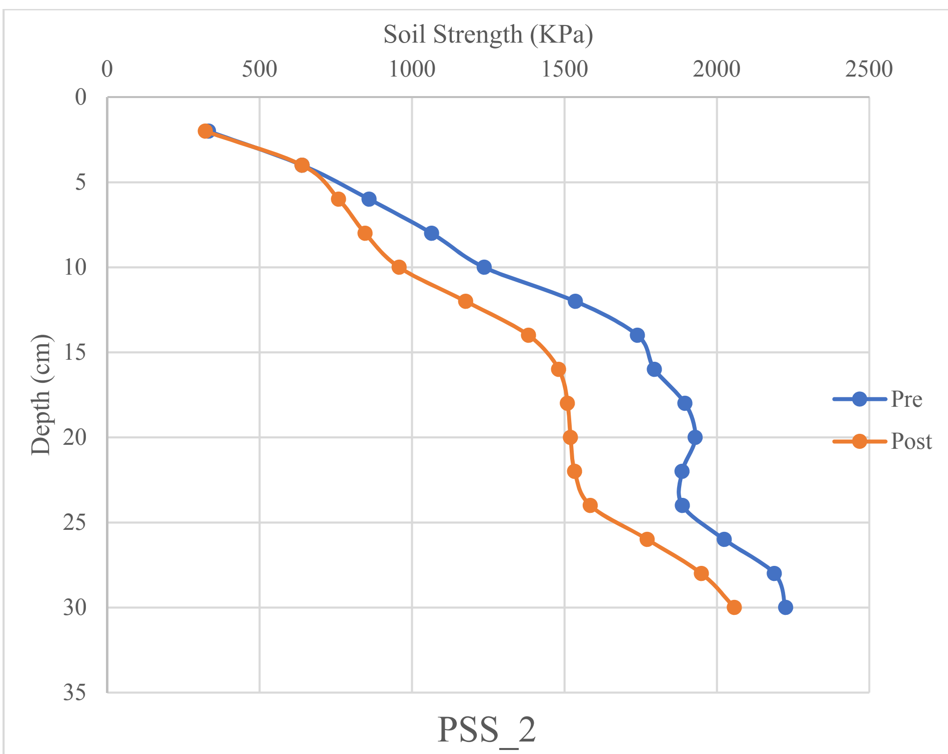
Ap-- 0-20; dark brown (10YR 3/3) loamy sand (6.2% clay); moderate (4) subangular blocky structure; very friable; few gravels; gradual wavy boundary (thin transitional underneath, too thin to describe).

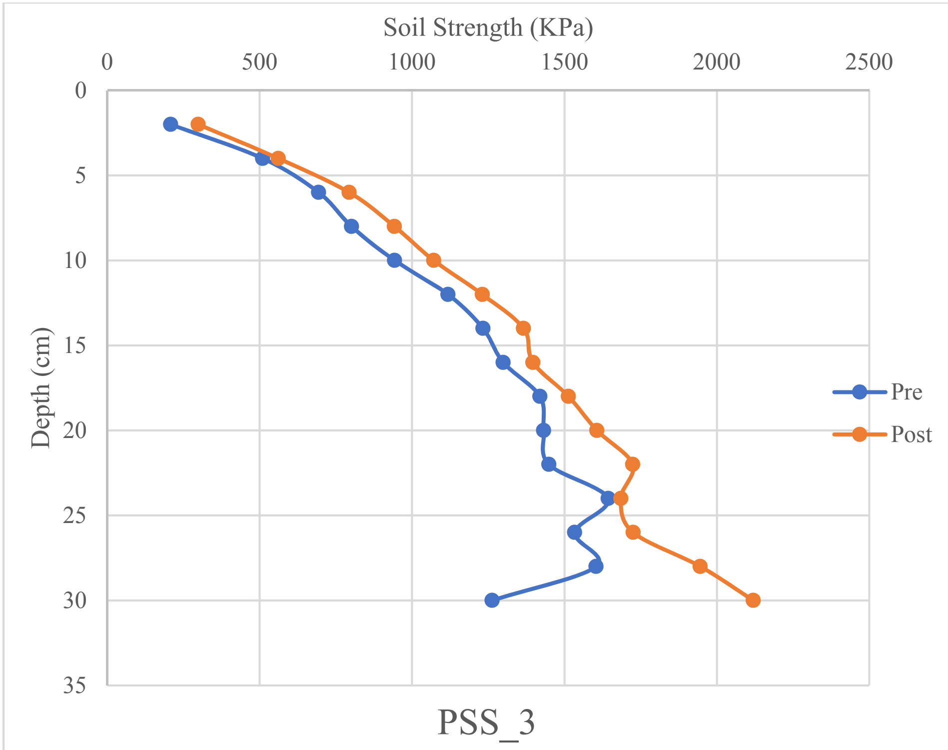
E— 20-38; yellowish brown (10YR 5/6) loamy sand (4.5% clay); weak (5) subangular blocky structure; very friable; few gravels; clear wavy boundary.

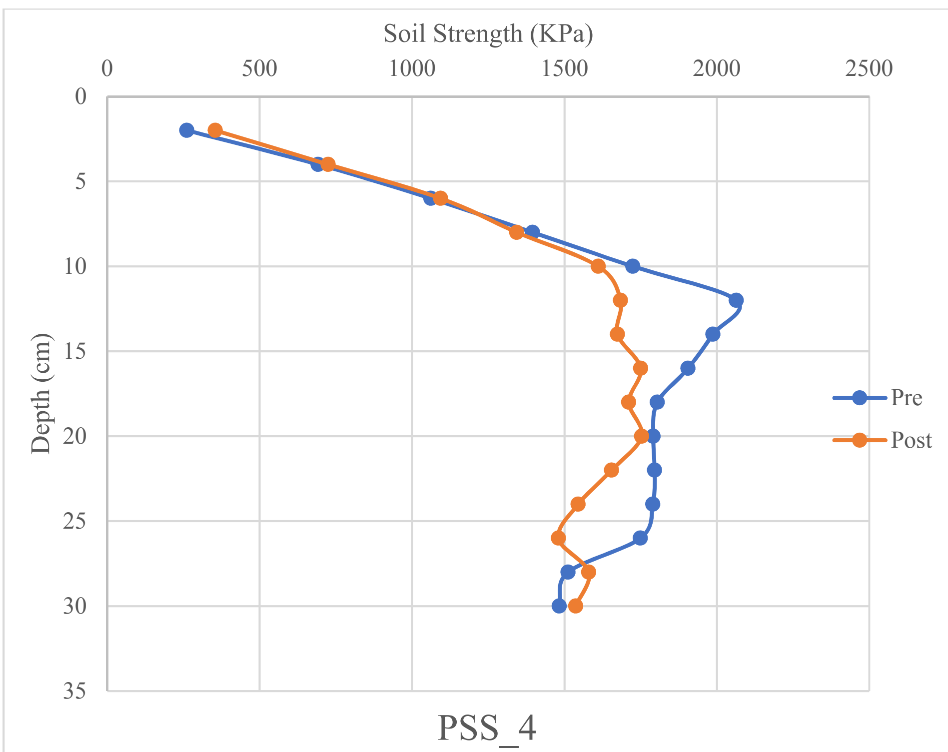
Bt-- 38-40+; strong brown (7.5YR 5/6) sandy loam (14.95% clay); moderate subangular blocky structure; friable; common soft iron nodules; few faint clay films;

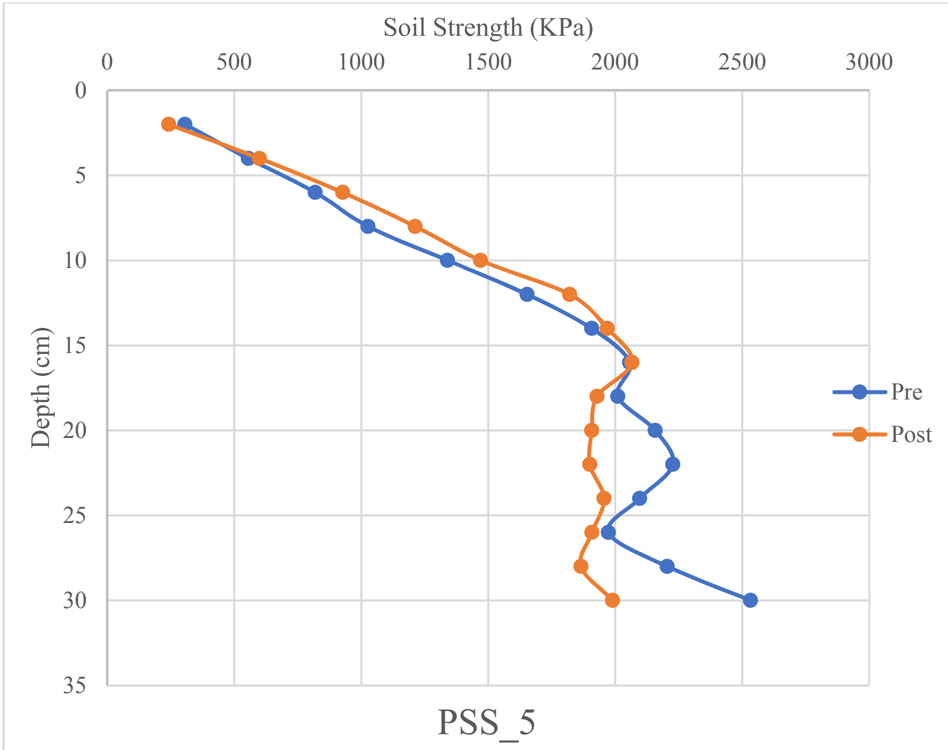
Appendix 2. Charts Comparing Soil Strength Before and After Trafficking



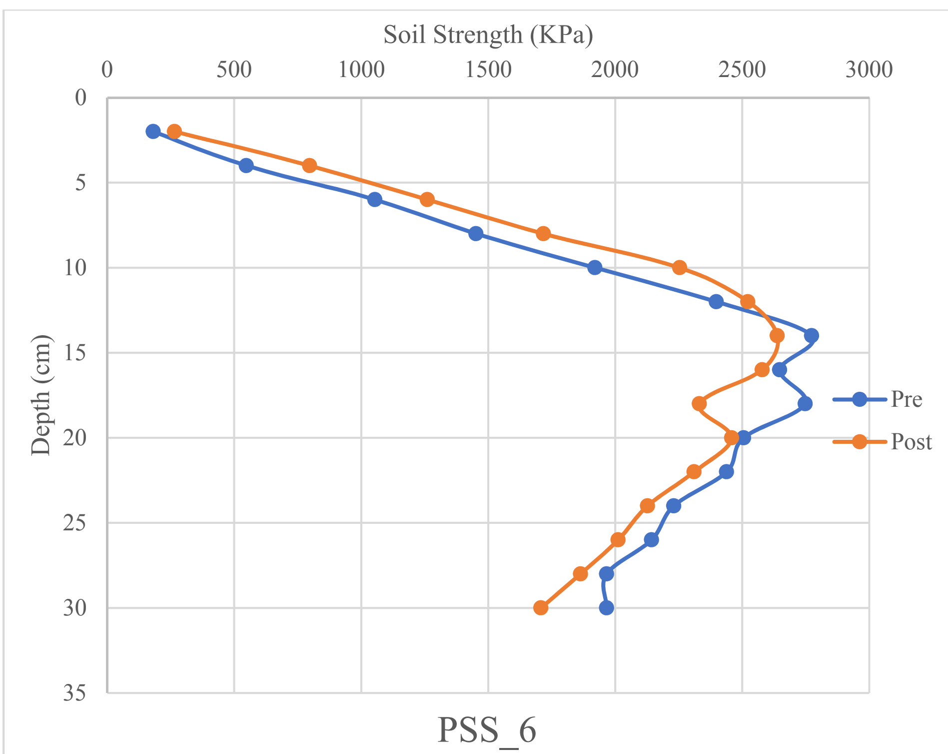



Soil Strength (KPa)
0
500
1000
1500
2000
2500
0
5
10
15
20
25
30
35
Depth (cm)
Pre
Post
PSS_3

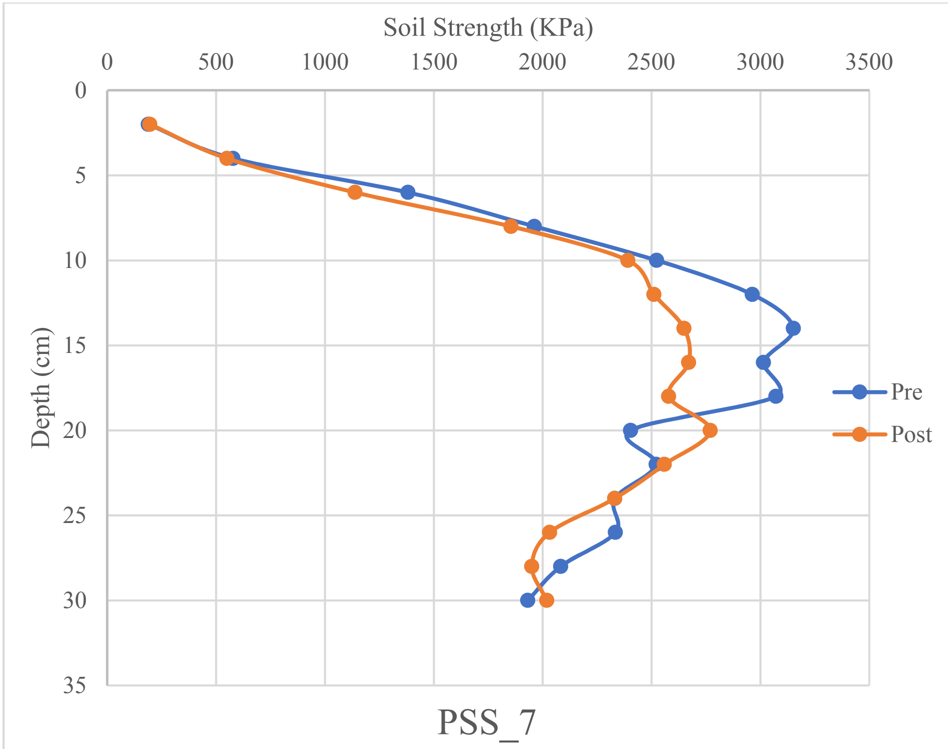

Soil Strength (KPa)
0
500
1000
1500
2000
2500
0
5
10
15
20
25
30
35
Depth (cm)
Pre
Post
PSS_4

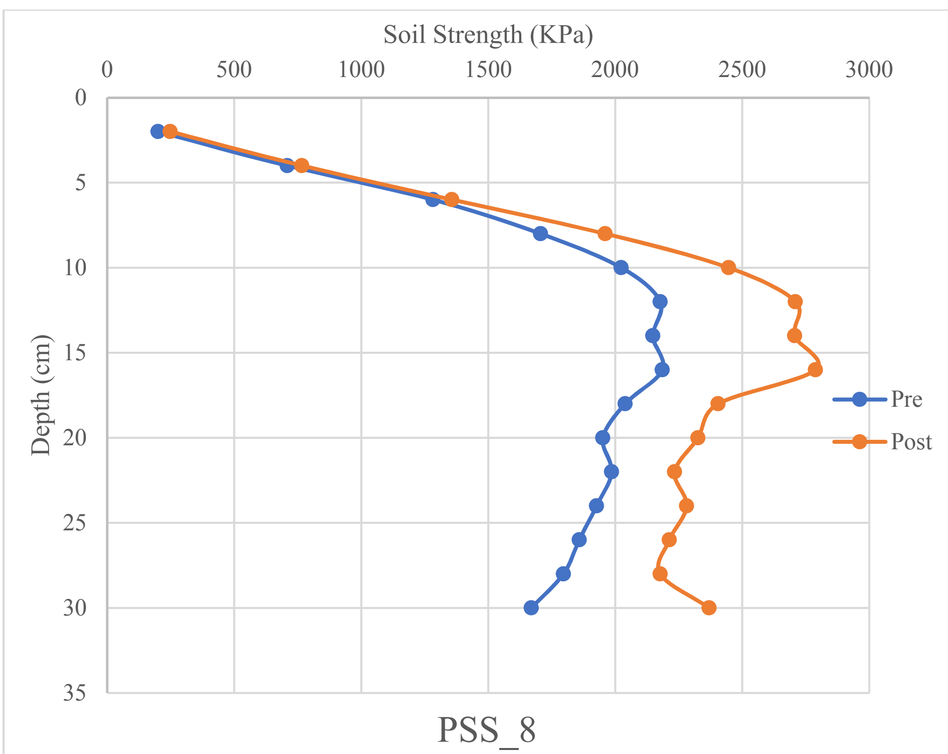


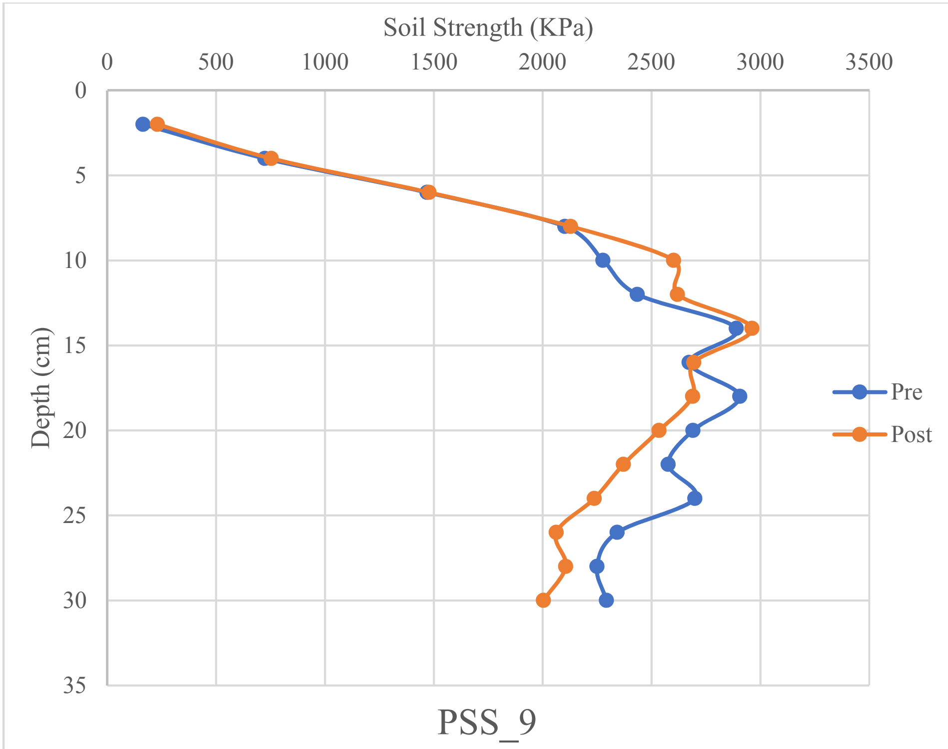
Soil Strength (KPa)
0
500
1000
1500
2000
2500
3000
0
5
10
15
20
25
30
35
Depth (cm)
Pre
Post
PSS_5



Soil Strength (KPa)
0
500
1000
1500
2000
2500
3000
0
5
10
15
20
25
30
35
Depth (cm)
Pre
Post
PSS_6


Soil Strength (KPa)
0
500
1000
1500
2000
2500
3000
3500
Depth (cm)
0
5
10
15
20
25
30
35
Pre
Post
PSS_7


Soil Strength (KPa)
0
500
1000
1500
2000
2500
3000
Depth (cm)
0
5
10
15
20
25
30
35
Pre
Post
PSS_8


Soil Strength (KPa)
0
500
1000
1500
2000
2500
3000
3500
0
5
10
15
20
25
30
35
Depth (cm)
Pre
Post
PSS_9