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nEstablishing soil compaction thresholds for the M1A1 Abrams tank at Camp Minden, Louisiana

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ESTABLISHING SOIL COMPACTION THRESHOLDS FOR THE M1A1 ABRAMS TANK AT CAMP MINDEN, LOUISIANA

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ABSTRACT

Soil compaction is a primary impediment to vegetation regeneration on military land used for M1A1 Abrams tank training. As such, there is a need to identify soil compaction thresholds and develop guidelines with which military range managers can determine appropriate timing and intensity of training exercises using the 63-ton M1A1 tank. A study was initiated at the Camp Minden Louisiana Training Site (CMTS) to develop guidelines which will allow for maximum utilization of the land resource with minimum degradation. The study was designed to evaluate soil moisture content and traffic rates as experimental variables using a replicated 3 x 3 x 3 factorial design with 3 soil 'moisture ranges' (< 20%; 20 to 30%, and > 30% water fraction by volume, wfv) and 3 'traffic load rates' (3, 6, or 9 passes) on 5 m^2 plots. Comparison of pre- and post-trafficked soil bulk density (BD), soil penetration resistance (PR), and soil-moisture retention characteristics (SMR) were used to evaluate the effects of soil moisture and traffic rates on relative compaction. Post-trafficked BD increased in all treatment combinations with root-limiting thresholds of 1.65 g/cm^3 exceeded at the 20 cm depth in the Mid (20% to 30%) moisture range plots with as few as 6 passes and in the Hi (>30%) moisture range plots with as few as 3 passes. SMR curve data indicate a reduction in total porosity from 0.44 to 0.38 cm^3/cm^3 in soil cores from Hi moisture treatment plots with a corresponding shift in pore size distribution toward a predominance of smaller pores across the range of pressures investigated to 12.5 bars.

We conclude that training exercises are best when moisture contents for 'silty' and 'loamy' soils are at or below 20% on a volume basis. Furthermore, training exercises should be avoided at moisture contents above 30% to prevent root limiting compaction levels.

Soil moisture levels exceeding the recommended thresholds commonly occur between December and April at CMTS annually. Suspending training maneuvers for this period is impractical. Therefore, we recommend range management plans include disking operations to loosen soil in tank trafficked areas when compaction levels exceed 1.65 g/cm^3.

CHAPTER 1

INTRODUCTION

1.1 GENERAL BACKGROUND

Training in accordance with doctrinally based standards and under realistic combat conditions is necessary to produce military forces of the highest quality to insure for the national defense. In recent years, increased potential for environmental impacts on many U.S. military installations can be attributed to a variety of factors including: increased mechanization, heavier and faster vehicles, combined arms exercises, testing requirements for advanced weapon systems, and more concentrated training because of base realignment and closure (CECER website, 1995). Intensive, realistic military training activities frequently result in land degradation which can negatively affect long term training use capability of the land in addition to a broad range of deleterious environmental and ecosystem impacts.

In an era of growing environmental awareness the U.S. Army recognized the need to address the growing environmental impacts on natural resources while insuring no net loss of training capabilities. In response, the U.S. Army Construction Engineering Research Laboratories (CERL) developed the Integrated Training Area Management (ITAM) program as a comprehensive approach to land management on all military installations. As stated on the U.S. Army Sustainable Range Program website (2008), the objectives of the ITAM program are to achieve optimal sustained use of lands for realistic training and testing by providing a sustainable core capability that balances usage, condition, and level of maintenance; implement a management and decision-making process that integrates Army training and other mission requirements for land use with sound natural resources management; and advocate proactive conservation and land management practices by aligning Army training land management priorities with the Army training and readiness priorities.

ITAM consists of four subprograms or major components designed to facilitate these objectives. The subprograms are: 1) Range and Training Land Assessment (RTLA), which is the ecological monitoring component to characterize and monitor installation natural resources both geospatially and temporally. It is the natural resources data collection and analysis component of the program and is used to establish essential natural resource baseline information needed to effectively monitor and manage training lands; 2) Training Requirements Integration (TRI), which uses information generated from RTLA to assist with military exercise scheduling and logistics so as to minimize harmful practices or activities in training areas; 3) Land Rehabilitation and Maintenance (LRAM) provides mitigation measures and land rehabilitation where needed or desired; and 4) Sustainable Range Awareness (SRA), which serves to promote awareness of environmentally sensitive issues and instill a stewardship ethic among unit commanders, soldiers, and neighboring communities. As such, ITAM is a management tool developed to maximize the benefits of training activities on military readiness while simultaneously minimizing the detrimental effects on natural resources and the environment. Preventing degradation of military lands will not only prolong the time these lands can be used for training activities, but also preserve thousands of acres of natural ecosystems that serve as home to numerous plants and animals, some of which are classified as threatened or endangered. When instituted properly, this program should enable its users to make educated, environmentally sound decisions about suitable levels and types of uses of particular training lands based on the capabilities and limitations of these areas (U.S. Army Environmental Command website, 2009).

Military training exercises using heavy tracked vehicles is an intensive land use activity that results in vegetation disturbance and soil compaction which can have long lasting environmental effects (Althoff and Thien, 2005; Palazzo et al., 2003, 2005; Fehmi et al., 2001; Diersing and Severinghaus, 1988). The termination of training activities short of obvious serious damage to natural resources may not stop certain long-term damage to the soil resource. Continuous long-term, or intense short-term, traffic by military tanks can cause soil compaction and changes in soil bulk density and soil strength that adversely affect the soil's ability to sustain those functions considered to be indicative of a soil in good condition (Horn et al., 1995). Furthermore, these changes may remain virtually invisible until secondary indicators start to appear. These secondary indicators are most often expressed as altered soil-water relationships, reduced aeration, reduced vigor in plant growth, impaired vegetation regeneration capabilities, altered plant community composition and diversity, and increased runoff and soil erosion (Palazzo et al., 2003; Johnson and Bailey, 2002; Brady and Weil, 2002; Ayers, P.D., 1994; Diersing and Severinghaus, 1984; Goran et al., 1983). Soil compaction or densification and the resulting associated negative effects on other soil physical, chemical, biological and hydrologic properties is widely recognized as the primary factor in reduced soil quality and function where tank training activities occur (Prose and Wilshire, 2000).

In a 2005 review of the relevant military vehicle impact literature, Anderson et al., indicated that a number of knowledge gaps still exist even though considerable research has focused on assessing the impact of military vehicles on natural resources since the early 1980s. They also indicate that the bulk of the research to date had been conducted on military lands in the Southwestern United States while other regional areas like the Southeast and Northeast remain largely under studied. Due to significant regional ecosystem differences it is unlikely that study results from one region will directly apply to others. As such, the environmental impacts of military tank maneuvers upon training land's soils and vegetation are identified as a priority issue at military installations across the country (Althoff and Thien, 2005).

1.2 STUDY BACKGROUND

The Louisiana Army National Guard (LAARNG) Camp Minden Training Site (CMTS) was chosen in 2001 to serve as an M1A1 battle tank training facility. CMTS sought to implement a soil and vegetation resilience study to comply with ITAM program regulations designed to maintain training lands in a condition that will accommodate long-term sustainability. The study falls under the RTLA component of the ITAM program. Knowledge derived from the study will be applied via the TRI component of ITAM and will allow Army Range Officers to make land management decisions that meet both mission requirements and natural resource conservation objectives. This study would be among the first of its kind in the southeast region.

Camp Minden is the LAARNG's second largest training site. It is approximately 13,682 acres in size and is located approximately 16 miles east of Bossier City, Louisiana on the Bossier/Webster Parish line. Approximately 50 M1A1 tanks were scheduled for detailed training and maneuvers at this facility. The potential for damage to soil and vegetation is significant and may be irreparable if a soil and vegetation stewardship program is not implemented. In order for any such program to be successful, the resilience of the soil and vegetation with respect to tank maneuvers must be ascertained. The primary measure of soil resilience with respect to this study is governed by soil compaction levels under varying rates of tank traffic at different soil moisture content levels.

1.3 STUDY OBJECTIVES

The main objectives of the tank study were to (1) establish soil compaction thresholds for the M1A1 battle tank for soil resilience, and (2) develop guidelines based upon the above referenced thresholds that will allow Army Range Managers to determine appropriate timing and intensity levels for tank training maneuvers at the facility that will allow for maximum utilization of the land resource with minimal degradation.

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CHAPTER 2

IMPACTS OF TRACKED MILITARY VEHICLE MANEUVERS ON SOILS AND VEGETATION – A REVIEW

2.1 INTRODUCTION

Military training exercises using heavy tracked vehicles is an intensive land-use activity that results in vegetation disturbance and soil compaction which can have long lasting environmental effects (Palazzo et al., 2003; Johnson and Bailey, 2002; Brady and Weil, 2002; Ayers, P.D., 1994; Diersing and Severinghaus, 1984; Goran et al., 1983). Continuous long-term, or intense short-term, traffic by military tanks can cause soil compaction and changes in soil bulk density and soil strength that adversely affect a soil's ability to sustain those functions considered to be indicative of a soil in good condition. Furthermore, these changes may remain virtually invisible until secondary indicators start to appear (Horn et al, 1995). These secondary indicators are most often expressed as reduced soil structure and porosity, altered soil-water relationships, reduced aeration, increased runoff and soil erosion, reduced vigor in plant growth, impaired vegetation regeneration capabilities, altered plant community composition and diversity, and altered bird and mammal species diversity and distribution (Palazzo et al., 2003; Johnson and Bailey, 2002; Brady and Weil, 2002; Ayers, P.D., 1994; Diersing and Severinghaus, 1984; Goran et al., 1983). Soil compaction and the resulting associated negative effects on other soil physical, chemical, biological and hydrological properties is widely recognized as the primary factor in reduced soil quality and function where tank training activities occur (Prose and Wilshire, 2000).

A review of soil compaction processes and their effects on the environment is presented by Horn, et al (1995). Additionally, a rather extensive review of the literature pertaining to the impacts of military vehicle traffic on natural areas can be found in a special issue of the Journal of Terramechanics (Anderson, et al., 2005). The disturbance impact of military tank maneuvers upon training lands soils and vegetation, and specific management guidelines for achieving long-term sustainability of those training lands, are identified as priority issues at military installations across the country (Althoff and Thien, 2005). Whereas a significant proportion of the military vehicle impact research has been conducted in the Southwestern United States, other regions of the country remain largely understudied (Anderson, et al., 2005).

An opportunity to further the study of the impacts of military tank traffic in the Southeastern United States arose when the Louisiana Army National Guard's (LAARNG) Camp Minden Training Site (CMTS) was chosen in 2001 to serve as an M1A1 battle tank training facility. Approximately 50 M1A1 (A1) tanks were scheduled for detailed training and maneuvers at this facility. The CMTS sought to implement a soil and vegetation resilience study to comply with Integrated Training Area Management (ITAM) program regulations designed to maintain training lands in a condition that accommodates future long-term sustainability. The overall objective of this present study was to establish critical soil compaction thresholds with respect to trafficking by the M1A1 battle tank in an effort to minimize soil physical property degradation that would negatively impact natural vegetation regeneration, soil erosion potential , and potential siltation of waterways on and surrounding the training facility. The hypothesis was that management of M1A1 training maneuver timing and intensity levels, as determined by soil moisture conditions and the number of passes with the tank, could effectively reduce soil compaction levels and the associated deleterious effects on overall soil quality, vegetation regeneration capabilities, and ecosystem degradation.

2.2 FACTORS AFFECTING ENVIRONMENTAL IMPACTS OF M1A1 MANEUVERS

2.2.1 Factors Affecting Soil Compaction and Strength

Soil compaction is generally defined as the process by which a mass of soil, consisting of solid soil particles, air voids, and water, is reduced in volume by mechanical means thereby increasing dry density or bulk density (Shroff and Shah, 2003). Soil bulk density is defined as the mass per unit volume of dry soil, wherein the volume is inclusive of solid particles and pore space (Brady and Weil, 2002). As bulk density increases, there is frequently a corresponding increase in soil mechanical strength resulting from the closer packing orders of the soil particles. In turn, soil strength can generally be defined as the minimum stress required that will cause a soil body to fail by means of fragmentation, rupture or flow. There are complex interrelationships among soil compaction, strength, bulk density, porosity, soil water content and aeration, and soil-plant interactions. These properties are influenced by factors such as soil texture, structure, mineralogy, organic matter content, and the type and amount of external force applied.

Soil compaction is a more or less rapid process of volume reduction and soil densification resulting from dynamic loading, usually resulting in substantial rearrangement of soil particles and the expulsion of air from the soil voids. Soil consolidation is similar to soil compaction; however it is a gradual process of volume reduction and densification under sustained static loading with little rearrangement of soil particles, typically accompanied by the expulsion of air and water (USDA-SCS-NEDS, 1988).

Three primary variables that interact to determine the dry unit weight or bulk density of a compacted soil mass are: 1) moisture content at which the soil is compacted, 2) type of soil being compacted, and 3) the amount and type of energy applied (USDA-SCS-NEDS, 1988). In the following discussion the focus is on characteristics of fine-grained soils comparable to those encountered at the site selected for the present study.

A soil's resistance to compaction is a function of soil strength. As mentioned previously, soil strength can generally be defined as the minimum stress required that will cause a soil body to fail by means of fragmentation, rupture or flow. Soil strength can be difficult to measure because of the high variability of the property which can change during the process of measurement. During measurement, the deformed soil body may increase or decrease its resistance to further deformation depending on other conditions, particularly moisture content. Illustration of this point can be made by considering that the strength of an unsaturated soil may increase as the soil becomes compacted, while transient stress may cause a saturated soil to experience loss of cohesion, and possibly liquefaction (Hillel, 1998). As such, the moisture content at which a soil is compacted is particularly important. For any given compaction effort, the resulting bulk density is largely dependent upon the soil moisture content or wetness. Starting from a dry condition, the attainable bulk density initially increases with soil wetness and then reaches a maximum at a wetness referred to as 'optimum' moisture content. Beyond this 'optimum' moisture, additional water decreases the resulting attainable density. This typical soil moisture to compaction trend can be explained by the fact that dry soils are typically resistant to compaction due to their stiff matrix and high degree of particle to particle bonding, interlocking, and frictional resistance to deformation (Hillel, 1998). As soil moisture increases, the thicker films of water weaken the interparticle bonds in low charge particles by means of expansion of the diffuse double-layer. This results in a corresponding reduction in attractive forces between particles or an increased interparticle repulsion which permit the particles to slide past one another into a more uniformly oriented or denser packing state. Additionally, initial increments of water tend to reduce interparticle friction between coarser, less electro-chemically active particles, thus serving as a lubricant. However, beyond the previously mentioned optimum soil moisture content, the incremental fractional volume of air expelled is reduced and the addition of water may actually start to reduce soil bulk density and apparent soil strength (Shroff and Shah, 2003).

The second primary variable in soil compaction, ‘type of soil’, is characterized by the particle size distribution, pore size distribution, and the electro-chemical properties of soil particle surfaces. The soils of our study site are considered fine-grained soils and consist of various percentages of silt and clay fines with small percentages of sand -sized particles. Classification of soils under the Unified Soil Classification System (USCS) uses a combination of letters to describe soil properties that primarily affect engineering properties. The soils at the Camp Minden study site are classified as ML, CL, and CL-ML under the USCS. These soils are dominated by CL, and to a lesser degree, ML soils. The abbreviation for a soil group in the USCS consists of two or more letters. The two-letter abbreviations for the classification groups encountered at the Camp Minden site are modifiers used to describe the plasticity characteristics and liquid limit values. A summary of the definition of each letter is as follows: C = fines with plastic characteristics (clay influenced); M = fines with non-plastic to slightly plastic characteristics (silt influenced); L = fine-grained soils with low liquid limit values less than 50; and H = fine-grained soils with high liquid limit values greater than 50 (Brady and Weil, 2002).

Generally, non-plastic soils derive strength from internal friction and plastic soils derive strength from cohesion (PCA, 1992). Coarse-grained soils derive their strength or resistance to compaction primarily from internal friction resistance as coarser particles tend to interlock as they slide past each other. Fine-grained soils derive their strength primarily from cohesion due to electro-chemical properties of the silt + clay fraction. Cohesion results from inherent molecular attractions bonding soil particles together and provides strength or shear resistance. It is highly dependent upon moisture content and, to some degree, on its density. Soils having high percentages of clay sized particles are typically classified as CL or CH and tend to be strongly influenced by the high electrical charge to surface area ratio. The cohesive strength of clays with finer structure and higher electrical charge, such as montmorillonite, are most affected; whereas clays with coarser lattice structure and less electrical charge, such as kaolinite, are somewhat less affected. The silt size particles, however, are relatively inert and the soils classified as ML and CL-ML, which are dominated by silt, exhibit limited internal friction or cohesion (USDA-SCS-NEDS, 1988). Any soil with moisture contents above its liquid limit would have no cohesion. Alternatively, as soil dries, cohesion and soil strength increase.

Clay size particles have a high attraction to water and to each other. They can only be readily compacted over a very narrow range of water content. At very low water content there is insufficient water for lubrication and to generate interparticle attraction. Compaction is made more difficult at very high water content in clayey soils due to their inherent low permeability, resulting from small soil pore or void sizes, making expulsion of water difficult (USDA-SCS-NEDS, 1988). In general, the higher the liquid limit and the higher the plasticity index, the more difficult a fine-grained soil is to compact and the more important water content is to effective compaction. Medium- and fine-textured soils, e.g., loam and clay soils, are resistant to mechanical pressure at low moisture content, but are highly susceptible to severe compaction at higher moisture content between their plastic and liquid limits. The soils at the Camp Minden study site are dominated by soils classified as CL and to a lesser degree ML. These soils are relatively easy to compact, particularly when wet, due to the low internal friction, moderate to low cohesion, low liquid limit and low plasticity index.

Type and amount of organic matter (OM) affect initial soil strength due to the potential binding effect OM contributes to soil structural units (Brady, 2002). Moderately decomposed OM has a higher binding capacity than does highly decomposed humus. Soil aggregates tend to be larger, stronger, and more stable in soils with high OM content. Soils with low organic matter content tend to be more susceptible to compaction (Daum, 1996).

The amount and type of mechanical energy applied is the third primary variable of importance in the final compaction density of a soil. The total amount of mechanical energy applied by a given vehicle is a function of the vehicle weight, weight distribution or ground pressure, and to a lesser degree, trafficking rates or number of passes with the vehicle (Bedard et al, 1997; Daum, 1996). Daum (1996) indicates that it is generally accepted that ground contact pressure of 0.27 kg/cm^2 (4 psi) or more can produce compaction with economic implications for most soils. All other factors being equal, the main impact of traffic rate or number of passes on compaction, as reflected in bulk density, occurs during the first few trips (Horn et al, 1995; Lenhard, 1986). In a study of rut formation under multiple passes by wheeled vehicles, rut depth increased with each pass at a deceasing rate with approximately 90 percent of the total rut depth caused by the first pass (Taylor et al, 1982). Similarly, Daum (1996) suggests that 80 percent of the potential compaction occurs during the first pass with subsequent passes causing additional, but progressively less, compaction. He also suggests that after four passes, the additional compaction becomes negligible. Horn et al (1995) indicate that if soils are trafficked under favorable conditions (e.g., matric potential between -10 and -30 kPa), only the upper 30 cm will be deformed and compacted while the deeper soil layers are strong enough to withstand all applied stresses. However, if the soil is slightly wetter (e.g., matric potential of -6 kPa), the applied stress can equal or exceed the internal soil strength resulting in soil compaction to greater depths.

The primary types of mechanical energy application are grouped as follows: 1) static load application or live weight, 2) kneading action, 3) vibratory action, 4) impact load application, or 5) a combination of two or more of the above. The M1A1 Abrams Main Battle tank (A1) is described by military experts as the backbone of the armored forces for the United States military and several US allies as well. It has been in service for over three decades. The M1A1 series, produced between 1985 and 1993, replaced the M1. The M1A1 replaced the M1's 105 mm main gun with a 120 mm gun and numerous other enhancements including a new turret, improved suspension, and increased armor protection. With the enhancements, the M1A1 weighs approximately 61 mt (67 tons). It has a dual track drive system with 7 independently sprung road wheels per track. Each track measures approximately 64 cm (25 in.) wide by 457.5 cm (180.1 in.) long producing an average ground pressure of 1.05 kg/cm^2 (15.0 psi) (U.S. Army Fact Files, www, 2009).

The amount and type of mechanical energy produced by the A1 is similar to that of a heavy crawler tractor (bulldozer). It imparts a combination of static live load, and to a lesser degree, vibratory action resulting from engine vibration and kneading as a result of the track grousers (USDA-SCS-NEDS, 1988). For most soils, and with all methods of compaction, an increase in compaction effort results in an increased bulk density with a corresponding reduction in optimal water content. However, at water content above the optimum, soil particles may simply be realigned without significantly altering particle spacing; and no substantial increase in bulk density will result from additional compaction effort (Gill and Vanden Berg, 1968). Alternatively, Horn et al (1995) state that retarded water fluxes, at high water content, in conjunction with soil loading at high dynamic forces, can result in a completely homogenized soil; characterized by a lower bulk density and a predominance of fine pores. Whether bulk density increases or soil is homogenized with a greater predominance of finer pores, there is a corresponding decrease in mass flow and diffusion of water and gases, and an increase in penetration resistance, each of which results in impeded root development.

For a tracked vehicle, pressure distribution under a track is an important performance parameter. The large ground contact area of the track results in high tractive efficiencies, high dynamic traction ratios, good stability on steep slopes and most importantly, low relative ground pressures (Marsili, 1998). Deformation of the soil layer beneath the tracks is dependent on the pressure distribution over the entire track length. Track-type vehicles have the potential for causing less relative compaction as compared to wheeled vehicles of the same weight due to the greater surface area and load distribution of the tracks (Brown et al, 1992). However, the duration of loading is longer than that under wheels and more vibration may be transmitted to the soil (Hakansson et al, 1988).

A standardized laboratory test method is commonly used to determine ideal soil moisture conditions to insure adequate soil compaction for road construction. This test procedure, known as the Standard Proctor Method (ASTM D 698, 2000), is determined by compaction of a sample of soil in a 944 cm^3 (1/30 ft^3) mold using standardized compaction effort of 600 kN-m/m^3 (12,400 ft-lbf/ft^3) at varying moisture content. Compaction effort is applied to the soil using a set number of standardized blows from a ramming hammer. The procedure is repeated for a series of water content to develop a 'Proctor compaction curve' to identify the optimum water content corresponding to the maximum bulk density for a given soil subjected to a given amount of energy. For dry soils, the unit weight increases as water is added to the soil because the water lubricates the particles making compaction easier. At water contents above the optimum, excess water in the soil pore space acts as an incompressible fluid and resists maximum compaction (Shroff and Shah, 2003; Marshall and Holmes, 1979). Because of the modern use of heavier compaction equipment and the desirability of having greater load-bearing fill, a Modified Proctor test was developed using more compactive effort. The modified test uses the same compaction mold volume but the compactive effort applied to the sample is increased to 2,700 kN-m/m^3 (56,000 ft-lbf/ft^3) with the use of a larger ramming hammer and longer fall distance (Day, 2002). While the Proctor method is used to identify the moisture-density relationship of a soil for a given compactive effort, the method cannot be directly correlated to specific vehicular compaction effort. The test does give insight into the moisture-density characteristics of a soil. As such, the relative degree of soil compaction induced by tank traffic on soils of this study site needed to be determined using similar field plot methods as those described in following chapter sections.

2.2.2 Effects of Compaction on Soil Properties and Vegetation

Recent reviews of soil compaction and the resulting effects are available (Anderson et al, 2005; Lipiec and Hatano, 2003; Johnson and Bailey, 2002; Fehmi et al, 2001; Worrell and Hampson, 1997; Horn et al, 1995; Sloan, 1990; Hakansson et al, 1988; Greacen and Sands, 1980; Gill and Vanden Berg, 1968). These publications address a broad range of compaction related topics and offer a comprehensive list of related references.

As indicated previously, the physical manifestation of soil compaction is most easily recognized as the reduction in bulk volume of a soil mass, resulting in increased dry density, or bulk density. Increased bulk density is achieved by alteration of soil structure and the overall reduction in porosity, or total pore volume (Brady and Weil, 2002; Johnson and Bailey, 2002). Small increases in bulk density can cause disproportionate decreases in infiltration rate and a corresponding increased potential for runoff and soil erosion (Palazzo, et al, 2003; Halvorson, et al, 2001). Decreased infiltration rate can be directly attributed to reductions in porosity. As such, one of the primary effects of compaction is reduced pore volume and redistribution among pore size groupings and inter- and intra-aggregate pore continuity (Horn, 1990). These changes affect many soil physical properties and processes, in varying degrees. Included are infiltration, water retention and hydraulic conductivity; air capacity and gaseous exchange; and soil strength and mechanical impedance to root growth. In turn, these changes indirectly affect numerous chemical and biological processes such as, nutrient availability for plants and soil microbial populations, soil redox status, and root penetration and elongation (Assouline, 2004; Johnson and Bailey, 2002; Glinski and Lipiec, 1990; Hakansson et al, 1988).

When applied stresses exceed the internal soil strength, compaction generally results from soil structural deterioration in two stages. First, the deterioration of secondary, coarse inter-aggregate pores results in the reduction of macropores and a corresponding increase in micropores. This is followed by the deterioration of the individual soil aggregates and the associated finer inter-aggregate pores. As such, the soil pore distribution tends to become more homogenized; with a corresponding reduction in total pore space, a relative increase in microporosity, and reduced pore continuity (Marsili et al, 1998; Horn et al, 1995). The resulting increase in mechanical impedance, and decrease in air permeability and hydraulic conductivity, negatively affect soil-plant relationships and alter numerous physical-chemical processes (Horn et al, 1995).

Increasing soil compaction reduces water infiltration, primarily as a result of the loss of larger macro pores; which, in turn, results in increased risk of surface runoff, soil erosion, and reduced water storage in the root zone (Lipiec et al, 1998; Lal, 1986; Lindstrom and Voorhies, 1980). Additionally, the loss of larger pores results in a corresponding reduction in soil drainage and unsaturated hydraulic conductivity (Lipiec et al, 1998; Lin et al, 1996). The relative increase in micropore space tends to result in increased water retention at low capillary heads (Hill and Sumner, 1967). Lipiec and Hotano (2003) report that hydraulic conductivity, as a function of soil wetness, generally decreases with compaction; however, at some compaction range and low water potentials, the conductivity is higher in compacted than non-compacted soils. They also report that “some studies indicate that an increase in soil compaction results in lower gravimetric water content at high matric potentials (from 0 to approximately -16 kPa) and higher at low matric potentials (from -50 to -1550 kPa, with only slight effect at the intermediate potential range". These are reflected in the flattening of the soil water retention curve (SWRC) and indicate a proportional reduction in large pore spaces with a corresponding increase in small pore spaces.

Increasing soil compaction and wetness are directly correlated with decreased oxygen diffusion rates (ODR) in soils. Decreased ODR results from smaller average pore diameters and reduced air permeability in compacted soils. Air permeability is directly related to the square of the diameter of the air-filled pores (Stepniewski et al, 1994).

Plants require water, essential minerals and nutrients, and anchorage from the soil. For plants to derive benefits from water and nutrients in the soil, plant roots must be able to reach them. Plant roots extract water from soil, excrete mucilage from their tips, and swell when physically impeded (Bengough and Mullin, 1990). Soil strengths that prevent root penetration or reduce root elongation rates may reduce plant development and yields. Taylor and Brar (1991) published an excellent overview and review of the effect of soil compaction on root development. They state that changes in soil compactness may influence fluxes and concentrations of each of the requirements furnished by plant roots. However, those changes will not affect plant growth unless the particular requirement becomes a limiting agent. A review of the 'biological effects of soil compaction' by Whalley et al (1994) provides an extensive list of references pertaining to soil-plant relationships of compacted soils. They also provide in-depth discussion of soil compaction and plant growth, compaction and soil fauna, compaction and microbial activity, and biological interactions. They conclude that the effects of soil compaction on biological processes are complex. However, they stated that it is clear that, in general, soil compaction reduces biotic activity, particularly in the case of roots, earthworms, and other fauna. In the case of microbial activity, the emphasis tends to be changed from aerobic to anaerobic with compaction.

Excessive compaction reduces plant emergence in the seedbed and also impedes plant rooting. It also furthers denitrification by decreasing oxygen diffusion and leads to reduction in infiltration and, thus, increases runoff risk (Defossez et al, 2003). Anoxic soil environment can adversely affect root growth directly as a result of deficient oxygen supply and indirectly as a result of anaerobic soil processes that develop in many soils (Startsev and McNabb, 2001). Uptake of ammonium nitrogen and photosynthesis activity were shown to decrease with decreasing soil redox potential in cherrybark oak and overcup oak (Delaune et al, 1998).

2.3 MEASUREMENT AND PREDICTION OF SOIL COMPACTION

Common direct measures of a soil's state of compaction include dry bulk density, void ratio, and porosity. Direct measures generally yield reliable estimates of soil compaction but can be time consuming and expensive. Indirect measures of a soil compaction typically rely on a reduction in pore space or increase in soil strength when soil is compacted. Common indirect measures include permeability to water or air, which reflects the pore space and the interconnectivity of the pores; and penetration resistance, which reflects the soil's resistance to penetration, due to closer packing orders of soil particles. Interpretation of indirect measures can be influenced by changes in soil not related to soil compaction. For instance, a reduction in measured soil permeability may be due to plastic flow or deformation of a soil body with a disruption in pore continuity without an increase in compaction. Additionally, increased penetration resistance may be due to changes in moisture content with no corresponding reduction in total pore volume or compaction (Johnson and Bailey, 2002; Soane and Van Ouwerkerk, 1995, 1994; Hakansson et al, 1988). Another relative compaction value is the ratio of actual bulk density and the maximum bulk density obtained in the Proctor compaction test. This ratio has been useful in the characterization of compaction levels in numerous field studies (Lipiec and Hatano, 2003). An estimate of the relative change in pore size distribution can be indirectly measured by evaluation of the soil moisture retention curves of compacted and non-compacted soils (Assouline et al, 1997).

2.4 STUDY OBJECTIVES AND GENERAL COMPACTION ASSESSMENT METHODS

The primary objective of this study was to determine the relative degrees of compaction induced by varying tank traffic rates on these soils under varying moisture conditions. Specifically, the goal was to determine the critical soil moisture content and number of passes with the A1 tank required to induce compaction levels that could be expected to substantially impede vegetation regeneration following tank training exercises. It was hypothesized that the relative amount of applied external forces exerted by the A1 tank, in conjunction with the relative moisture content of the soil at the time the force is applied, would determine the degree to which the soil is compacted.

Inferences about compaction levels, resulting from A1 tank maneuvers, were drawn from a combination of direct and indirect measures of soil compaction. Soil bulk density, soil moisture retention curves, and soil penetration resistance were used. Each set of methods yielded uniquely valuable information that allowed assessment of compaction parameters and fulfillment of the primary study objectives. Field extracted soil cores were used for soil bulk density measurements and to develop soil moisture retention curves. Together, these methods allow interpretation of soil volume changes and alteration in pore size distribution, resulting from compaction, and are presented together in chapter 3. Soil penetration resistance, as measured by soil penetrometer, yields a relative measure of change in soil strength, resulting from soil compaction, and is presented separately in chapter 4. Summary conclusions for all compaction measurements are presented in chapter 5.

The primary objectives of this study were to (1) establish soil compaction thresholds for the M1A1 battle tank for soil resilience and vegetation regeneration, and (2) develop guidelines based upon the above referenced thresholds, that will allow Army Range Managers to determine appropriate timing and intensity levels for tank training maneuvers, at the facility that will allow for maximum utilization of the land resource, with minimal degradation.

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CHAPTER 3

INFLUENCE OF TRAFFIC RATE AND SOIL MOISTURE CONTENT ON SOIL BULK DENSITY AND MOISTURE RETENTION CURVES

3.1 INTRODUCTION

Military training exercises using heavy tracked vehicles is an intensive land use activity that results in vegetation disturbance and soil compaction, which can have long lasting environmental effects (Althoff and Thien, 2005; Palazzo et al., 2003, 2005; Fehmi et al., 2001; Diersing and Severinghaus, 1988). Mobile tracked vehicles crush and shear woody and herbaceous vegetation during maneuvers with potentially long-lasting damage depending on use intensity. Additionally, the resulting soil compaction can alter soil physical, chemical, biological, and hydrologic properties of the soil to the extent that vegetation regeneration is impaired; and can ultimately lead to a shift in plant community composition and productivity (Althoff and Thien, 2005; Halvorson et al, 2003; Prosser et al, 2000; Johnson and Bailey, 2002; Prose and Wilshire, 2000; Diersing and Severinghaus, 1984).

Preliminary evaluation of the “soil factors” that affect plant growth and natural vegetation regeneration at Camp Minden Louisiana led investigators to conclude that soil compaction would be the primary factor of investigation. A brief listing of effects of soil compaction is as follows:

- ✓ Increased soil strength and bulk density,
- ✓ Increased mechanical impedance,
- ✓ Alteration and/or destruction of soil aggregate structure,
- ✓ Decreased total pore volume,
- ✓ Changes in pore size distribution percentage,
- ✓ Reduced water infiltration, drainage, and aeration,
- ✓ Potential increased frequency and duration of anaerobic conditions

Impaired soil and soil-plant processes resulting from soil compaction include, but are not limited to:

- ✓ Reduction or prevention of root penetration and root elongation,
- ✓ Limited water, aeration and nutrient availability for plants and microbes,
- ✓ Potential redox implications due to modified hydrology,
- ✓ Potential alteration of organic matter decomposition rate and release of plant nutrients.

The objectives of this research were to study the effects of M1A1 tank traffic on soil compaction as influenced by soil moisture and traffic rate. We utilized field extracted soil cores taken immediately prior to and following tank traffic passes for the determination of bulk density changes as one of the indicators of soil compaction. Additional field extracted soil cores taken from trafficked and non-trafficked areas were utilized to develop soil moisture retention curves to evaluate changes in pore size distribution resulting from soil compaction.

3.2 REVIEW - SOIL COMPACTION AND ITS RELATION TO OTHER FACTORS

Soil compaction is generally defined as the process by which a mass of soil consisting of solid soil particles, air, and water is reduced in volume by mechanical means thereby increasing dry density or bulk density (Shroff and Shah, 2003). As bulk density increases, there is frequently a corresponding increase in soil mechanical strength, resulting from the closer packing orders of the soil particles. Soil compaction is a relatively rapid process of volume reduction, caused by dynamic loading; usually resulting in substantial rearrangement of soil particles and the expulsion of air from the soil voids. Soil consolidation is similar to soil compaction. However, it is a gradual process of volume reduction and densification, under sustained static loading, with little rearrangement of soil particles. Soil consolidation is typically accompanied by the expulsion of air and water (USDA-SCS-NEDS, 1988).

Three primary variables that interact and determine the dry unit weight, or bulk density, of a compacted soil mass are: 1) moisture content at which the soil is compacted, 2) type of soil being compacted, and 3) the amount and type of energy applied (USDA-SCS-NEDS, 1988). In the following discussion, the focus is on characteristics of fine-grained soils comparable to those encountered at the site selected for the present study.

A soil's resistance to compaction is a function of soil strength. Soil strength can generally be defined as the minimum stress required that will cause a soil body to fail by means of fragmentation, rupture or flow. Soil strength can be difficult to measure because of the high variability of the property which can change during the process of measurement. During measurement the deformed soil body may increase or decrease its resistance to further deformation depending on other conditions. Illustration of this point can be made by considering that the strength of an unsaturated soil may increase as the soil becomes compacted, while a saturated soil may experience loss of cohesion and possibly liquefaction (Hillel, 1998). As such, the moisture content at which a soil is compacted is particularly important. At any given compaction effort, the resulting bulk density is dependent upon the soil moisture content or wetness. Starting from a dry condition, the attainable bulk density initially increases with soil wetness and then reaches a maximum at a wetness referred to as 'optimum' moisture content. Beyond this 'optimum' moisture content, additional water decreases the resulting attainable bulk density. This typical soil moisture to compaction trend can be explained by the fact that dry soils are typically resistant to compaction due to their stiff matrix and high degree of particle to particle bonding, interlocking, and frictional resistance to deformation (Hillel, 1998). Initial increments of water tend to reduce interparticle friction between coarser, less electro-chemically active particles, thus serving as a lubricant. As soil moisture increases, the thicker films of water weaken the interparticle bonds, in low charge particles, by means of expansion of the diffuse double-layer. This results in a corresponding reduction in attractive forces between particles, or an increased interparticle repulsion, which permit the particles to slide past one another into a more uniformly oriented, or denser, packing state. However, beyond the previously mentioned optimum soil moisture content, the incremental fractional volume of air expelled is reduced and the addition of water may actually start to reduce soil bulk density and apparent soil strength. At water contents above the optimum, the air voids approach a constant value and additional increases in water content cause no appreciable reduction in the air voids, though a more orderly arrangement of soil particles may exist at the higher water contents (Shroff and Shah, 2003).

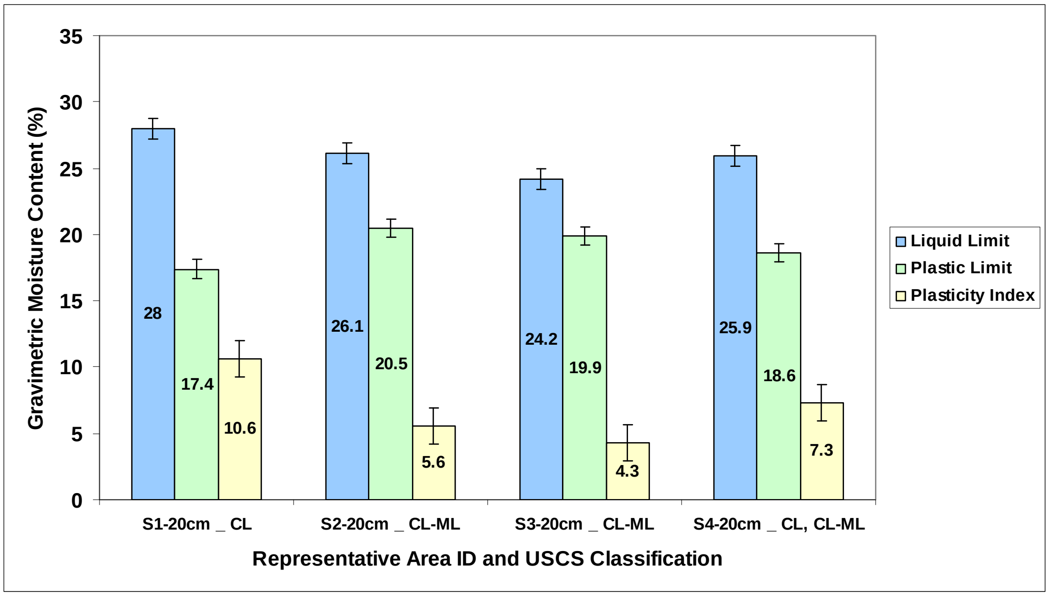
The second primary variable in soil compaction, 'type of soil', is characterized by the particle size distribution, size and distribution of void spaces, and the electro-chemical properties of soil particle surfaces. The soils of our study site are considered fine-grained soils and consist of various percentages of silt and clay fines with small percentages of sand sized particles. Classification of soils under the Unified Soil Classification System (USCS) uses a combination of letters to describe soil properties that primarily affect engineering properties. The soils at the Camp Minden study site are classified as ML, CL, and CL-ML under the USCS. These soils are dominated by CL and to a lesser degree ML soils. The abbreviation for a soil group in the USCS consists of two or more letters. The two-letter abbreviations for the classification groups encountered at the Camp Minden site are modifiers used to describe the plasticity characteristics and liquid limit values. A summary of the meaning of each letter is as follows: C = fines with plastic characteristics; M = fines with non-plastic to slightly plastic characteristics; and L = fine-grained soils with low liquid limit values less than 50. The USCS classification and Atterberg limits of the Camp Minden soils are found in Table 3.1 and graphically displayed in Figure 3.1a and b.

Table 3.1. Atterberg limits (LL, PL, and PI) and Unified Soil Classification System (USCS) class for shallow (20 cm) and deep (50 cm) horizons by site area.

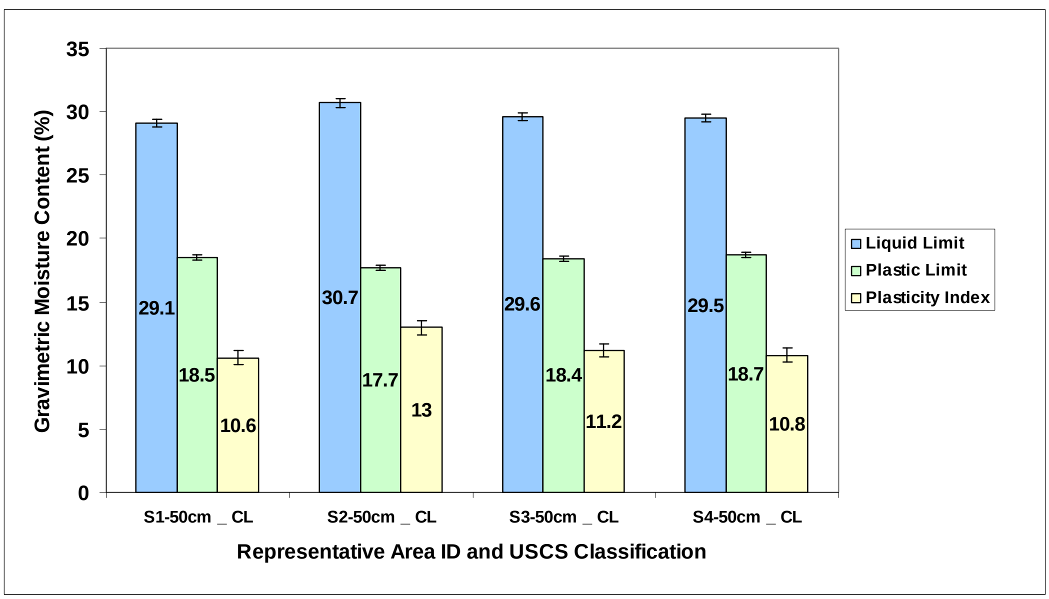
Site Area ID†	Liquid Limit	Plastic Limit	Plasticity Index	USCS Class
S1-20cm	28	17.4	10.6	CL
S2-20cm	26.1	20.5	5.6	CL-ML
S3-20cm	24.2	19.9	4.3	CL-ML
S4-20cm	25.9	18.6	7.3	CL, CL-ML
S1-50cm	29.1	18.5	10.6	CL
S2-50cm	30.7	17.7	13	CL
S3-50cm	29.6	18.4	11.2	CL
S4-50cm	29.5	18.7	10.8	CL

† Site Area ID denotes plots associated with data loggers S-(1-4) and depth (cm).

Coarse-grained soils derive their strength or resistance to compaction primarily from internal friction resistance as coarser particles tend to interlock as they slide past each other. Fine-grained soils derive their strength primarily from cohesion due to electro-chemical properties of the fine fraction. Soils having high percentages of clay sized particles are typically classified as CL or CH and tend to be strongly influenced by the high electrical charge to surface area ratio. The cohesive strength of clays with finer structure and higher electrical charge such as montmorillonite are most affected; whereas clays with coarser lattice structure and less electrical charge, such as kaolinite, are somewhat less affected. The silt size particles, however, are relatively inert and the soils classified as ML and CL-ML, which are dominated by silt, exhibit little internal friction or cohesion (USDA-SCS-NEDS, 1988).



a)



b)

Figure 3.1. Atterberg Limits and USCS Classification for a) EBg horizon and b) Btg/E1 horizon. Error bars represent standard error.

Clay size particles have a high attraction to water and to each other. They can only be readily compacted over a very narrow range of water content. At very low water content there is insufficient water for lubrication and to generate interparticle attraction. Compaction, in clayey soils, is made more difficult at very high water content due to their inherent low permeability, resulting from small soil pore or void sizes, making expulsion of water difficult (USDA-SCS-NEDS, 1988). In general, the higher the liquid limit and the higher the plasticity index, the more difficult a fine-grained soil is to compact and the more important water content is to effective compaction. As seen in Table 3.1, the soils at the study site are dominated by soils classified as CL and to a lesser degree ML. These soils are relatively easy to compact, particularly when wetted, due to the lack of internal friction, moderate to low cohesion, low liquid limit and low plasticity.

The amount and type of mechanical energy applied is the third primary variable of importance in the final compaction density of a soil. The primary types of mechanical energy application are grouped as follows: 1) static load application or live weight, 2) kneading action, 3) vibratory action, 4) impact load application, or 5) a combination of two or more of the above. The A1 tank weighs 63 tons (57 mt) and has a ground pressure of 15.0 psi (1.05 kg/cm^2). The amount and type of mechanical energy produced by the A1 is similar to that of a heavy crawler tractor (bulldozer). It imparts a combination of static live load, vibratory action and some degree of kneading as a result of the track grousers (USDA-SCS-NEDS, 1988). For most soils, and with all methods of compaction, an increase in compaction effort results in an increased bulk density, with a corresponding reduction in optimal water content. However, at high water content at or near saturation, soil particles may simply be realigned, with a more orderly arrangement of particles, and no substantial increase in bulk density will result from additional compaction effort (Shroff and Shah, 2003). At very high water content e.g., ≥ 90% pore volume, energy has little effect on compacted density of a fine textured soil because water is an incompressible fluid and takes the applied energy without compacting the soil (Gresser, 2008).

The primary objective of this study was to determine the relative degrees of compaction induced on the soils at the Camp Minden Training Site, by varying tank traffic rates under varying moisture conditions. Specifically, the goal was to determine the critical soil moisture content and number of passes, with the M1A1 tank, required to induce maximum compaction. It was hypothesized that the relative amount of applied external forces exerted by the M1A1 tank, in conjunction with the relative moisture content of the soil at the time the force is applied and the soil particle size distribution, would determine the degree to which the soil is compacted. With this knowledge, training officers can avoid these conditions during training maneuvers.

Initial efforts to evaluate the soils compaction behavior was accomplished using a laboratory test method commonly used to determine ideal soil moisture conditions that insure adequate soil compaction for road construction. This test procedure known as the Proctor Method (ASTM D 698, 2000) was determined by compaction of a sample of soil in a cylinder under a set number of standardized blows from a sliding hammer. The procedure was repeated for a series of water content to develop a 'Proctor standard energy maximum dry density curve' to identify the optimum water content (gravimetric %) corresponding to the maximum dry bulk density (g/cm^3) for a given soil subjected to a given type and amount of energy. For the Standard Proctor test the maximum dry bulk density and optimum water content for the study site soils were 1.71 g/cm^3 at 15.3%, and 1.79 g/cm^3 at 14.7% for the 20cm and 50cm depth intervals respectively (Figure 3.2). At water contents above the optimum, excess water in the soil pore space resists maximum compaction and can cause soil instability and pumping (Gresser, 2008).

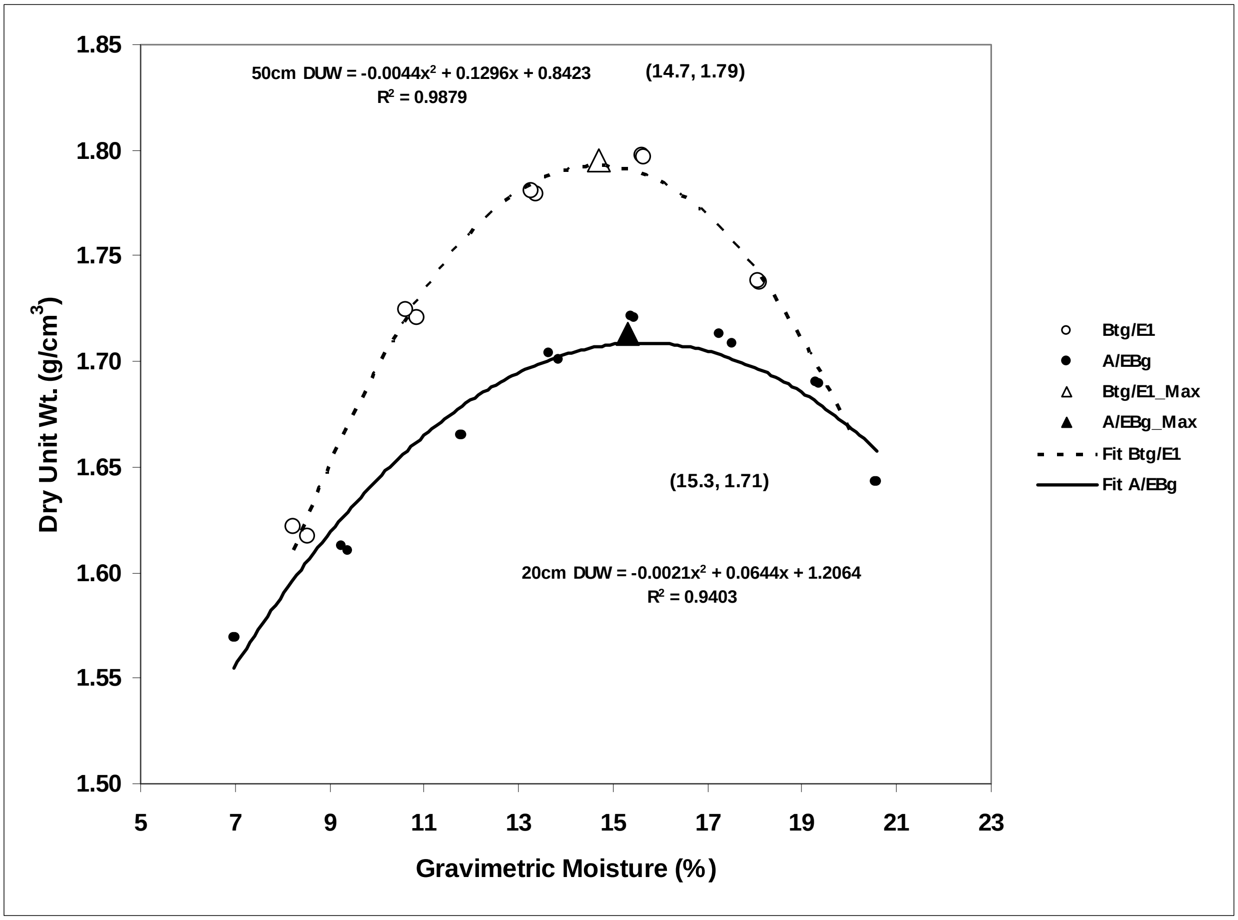


Figure 3.2. Proctor standard energy maximum dry density (MDD) curves.

Water contents below the optimum are resistant to maximum compaction due to greater cohesion and internal friction between particles and aggregates (Shroff and Shah, 2003; USDA-SCS-NEDS, 1988; Marshall and Holmes, 1979). While the Proctor method is used to identify a critical compaction threshold for a given soil, the method cannot be directly correlated to vehicular compaction effort. The results of the laboratory compaction test are used primarily to form the basis for the design of compacted fill in engineering projects (USDA-SCS-NEDS, 1988). The test provides a uniform reference base for a specific soil, and field control can then be tied to this reference base. As such, the relative degree of soil compaction induced by tank traffic on soils of this study site needs to be determined using similar field plot methods as those described below.

3.3 MATERIALS AND METHODS

3.3.1 Study Area

The location selected for the study was the Camp Minden Training Site (CMTS) which is the Louisiana Army National Guard's (LAARNG) second largest training site. The CMTS is located approximately 16 miles east of Bossier City, Louisiana on the Bossier/Webster Parish line and covers approximately 13,682 acres (Fig. 3.3). The CMTS was selected because it had been designated as an A-1 tank training facility and was to have approximately 50, A-1 tanks available for detailed training and maneuvers. Camp Minden is located in the Western Coastal Plain Major Land Resource Area (MLRA 133B) and in the Coastal Plain Province physiographic region. Camp Minden is situated on Quaternary geologic sediments. These sediments were the braided stream terrace deposits of ancient river systems. The sediments were subdivided according to different interglacial periods. Camp Minden is on two of the five divisions, the Montgomery and Prairie Terraces. The surface landscape is comprised of nearly level to rolling topography with relatively broad, nearly level to gently sloping ridge tops and gently to moderately sloping sideslopes. The area is dissected by several drainageways. Elevation ranges from about 184 feet on the eastern boundary along Bayou Dorcheat to about 225 feet near the geographic center of the facility. Air temperature averages from 7 to 28 degrees C (44 to 82 degrees F) and precipitation averages about 120 centimeters (48 inches) annually. The frost-free season is about 233 days (Web Soil Survey-USDA. 2007).

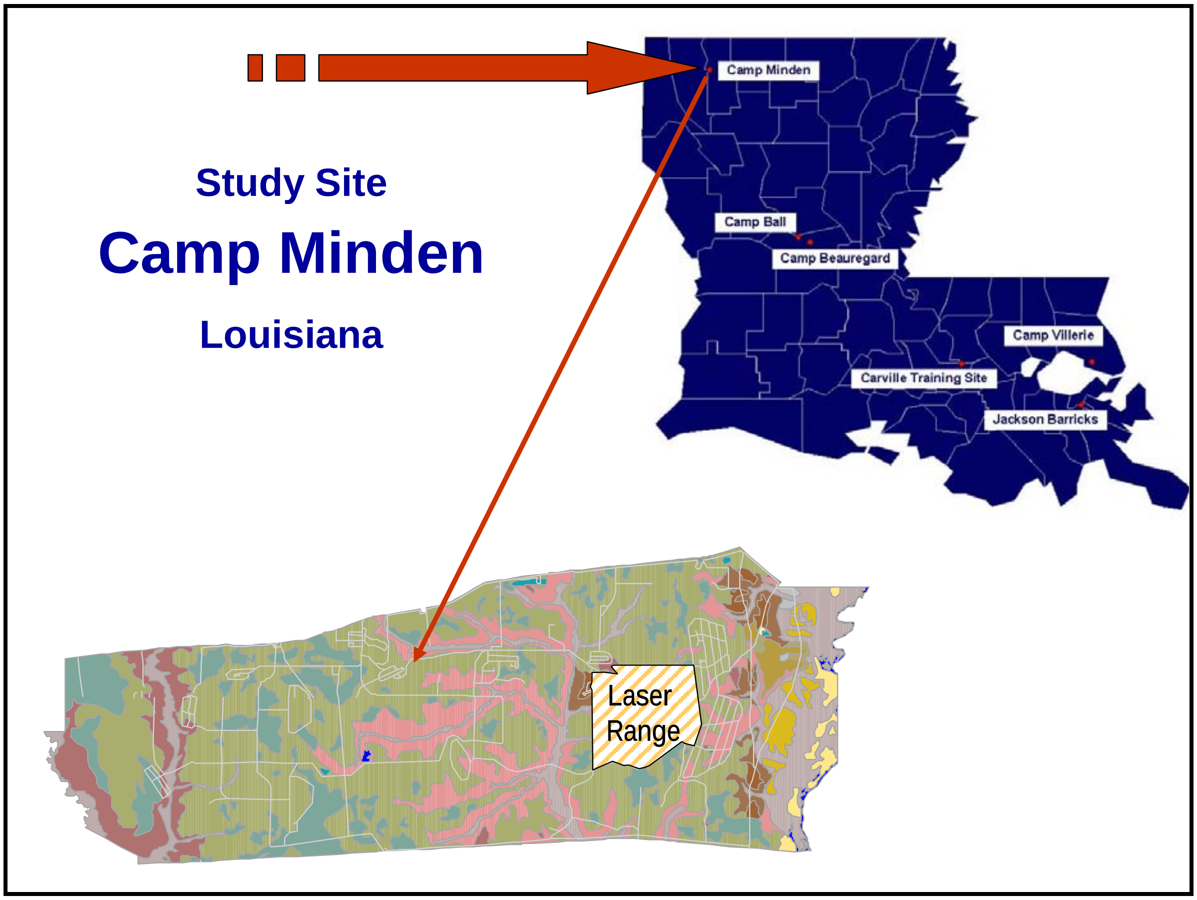


Figure 3.3. Map of Louisiana Army National Guard facilities and the Camp Minden Tank Trafficability and Soil Resilience Study Site.

3.3.2 Soil Type

The soils at the experimental test site at the CMTS are mapped Kolin silt loam (Fine-silty, siliceous, active, thermic Oxyaquic Glossudalfs) (Soil Data Mart-USDA, 2007). These soils are on uplands and terraces of Pleistocene Age. The Kolin soil series consists of very deep, moderately well drained, very slowly permeable soils that formed in loamy sediments overlying clayey sediments. A perched water table exists above the argillic horizon (45 to 90 cm) from December through April in most years.

Most of the areas of this soil are in mixed hardwood and pine woodland. A small acreage is used for pasture and cultivated crops. The soils at the study site have a complex landscape micro-topography of mounds and inter-mounds, with the mounds having better drainage (Web Soil Survey-USDA, 2007). During the initial phases of this study, the dominant proportion of inter-mound area was identified as inclusions of Wrightsville (Fine, mixed, active, thermic Typic Glossaqualfs) that is less well drained. The Wrightsville series consists of very deep, poorly drained, very slowly permeable soils with slow runoff that formed in old silty and clayey alluvium. Slopes are less than 1 percent. These soils are on level to depressional areas on old stream terraces. As a result, the soil is wet in the layers below a depth of 15 to 45 cm (6 to 18 inches) and above the Btg horizon during December through April in normal years (Web Soil Survey-USDA, 2007).

The Wrightsville soil is in land capability subclass IIIw and as such has severe limitations due to wetness that reduce the choice of plants or that require special conservation practices, or both. The soil is used mainly as woodland and is moderately well suited as pine woodland. The main concerns in producing and harvesting timber are severe equipment use limitations and severe seedling mortality caused by wetness. When the soil is moist, methods of harvesting timber that use standard wheeled and tracked vehicles causes rutting and soil compaction (Soil Data Mart-USDA, 2007). Because of this high susceptibility to wetness and the associated negative affects of soil compaction that would result from heavy mechanized maneuvers, the study plots were established in the inter-mound Wrightsville soils.

A soil characterization pit was excavated (Figure 3.4) in the spring of 2006 to facilitate detailed soil profile description and soil sample collection and analysis. The

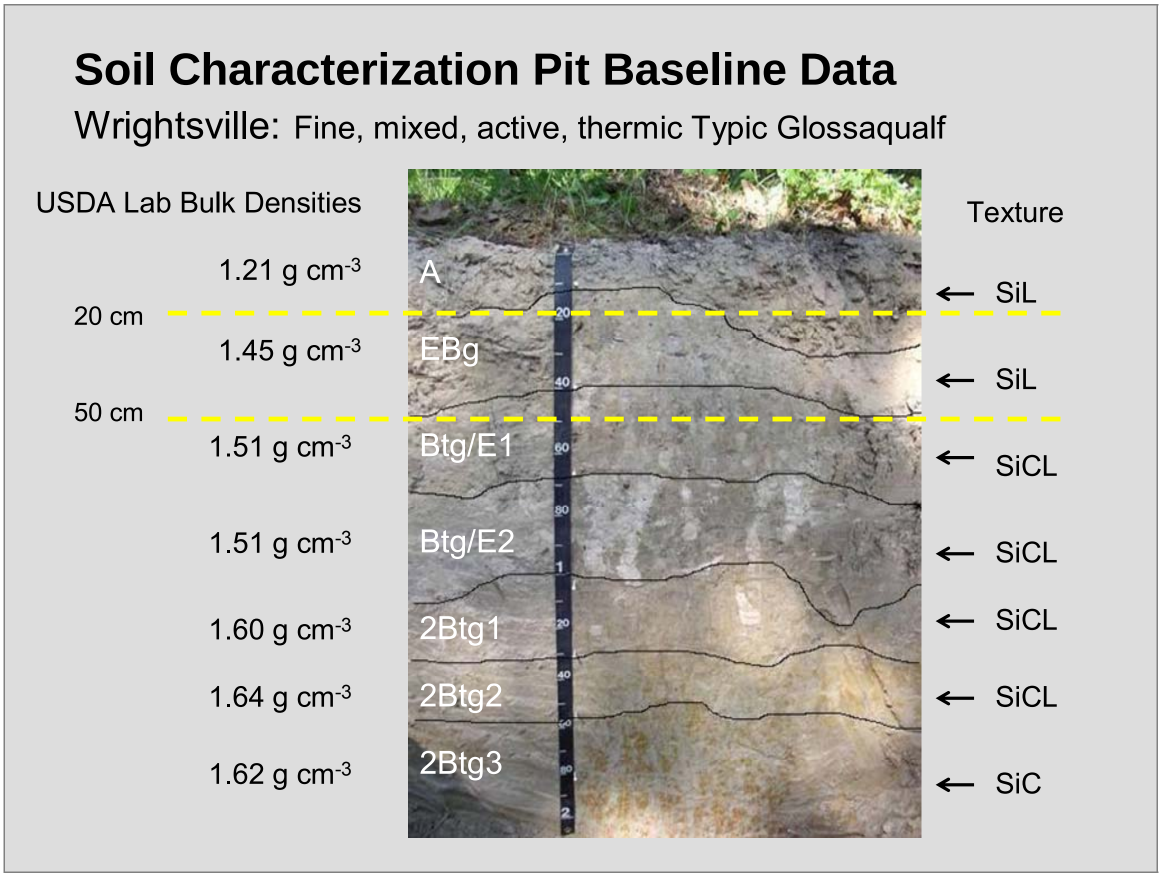


Figure 3.4. Wrightsville characterization pit photograph with horizon designations, USDA lab bulk densities, horizon textures, and critical investigation depths.

soil pit was in a wooded area adjacent to the study site and located at Lat: 32° 33' 55.50"north, Long: 93° 24' 24.60" west, NAD 83, MLRA 133B. Soil samples were shipped to the USDA-NRCS National Soil Survey Center - Soil Survey Laboratory in Lincoln NE for detailed analysis. The Site ID and Pedon No. on record are 06LA119001 and 06N0859 respectively. The soil was taxonomically identified as Wrightsville Fine, mixed, active, thermic Typic Glossaqualf. Detailed USDA soil lab characterization data can be accessed via the internet from the National Cooperative Soil Survey Soil Characterization Database (http://ssldata.nrcs.usda.gov/querypage.asp).

Of potential relevance to this study was the identification of soil textures in the A, EBg, and Btg/E horizons. Soil particle size distribution was determined by hydrometer method (Gee and Bauder, 1986). Generalized USDA soil textures were as follows: (i) A horizon – silt loam; (ii) EBg horizon – silt loam and silty clay loam; and (iii) Btg/E horizon – silty clay loam and silt loam. The EBg horizon textures tend toward the upper clay threshold of silt loam while the Btg/E horizon textures tend toward the lower clay threshold of silty clay loam. The less than 2mm fine earth fractions, particle densities, and USDA textural classes are illustrated in Table 3.2. Plot textures were grouped and averaged by 'Site Area' (1-4) which corresponds to centralized data loggers around which individual plots are distributed.

Table 3.2. Mean particle-size fractions, particle density and USDA class.

Site Area ID†	Clay	Silt	Sand	Particle Density	USDA Texture
	(< 2μm)‡	(2-50μm)‡	(>50μm)‡		
	-------------------- %	--------------------	--------------------	g cm^{-3}	
A-8cm	15±3	71±6	14±5	2.71	SiL
S1-20cm	28±3	66±5	6±2	2.69	SiL, SiCL
S2-20cm	24±3	68±3	8±2	2.69	SiL
S3-20cm	23±2	62±3	15±3	2.69	SiL
S4-20cm	24±3	61±4	15±4	2.69	SiL
S1-50cm	28±7	62±2	10±8	2.69	SiCL, SiL
S2-50cm	26±3	66±4	8±5	2.69	SiL, SiCL
S3-50cm	27±4	57±4	16±6	2.69	SiCL, SiL
S4-50cm	27±6	56±2	17±6	2.69	SiCL, SiL

† Site Area ID denotes plots associated with data loggers S-(1-4) and depth (cm).
‡ Values following ± represent standard deviation.

3.3.3 Site Preparation and Plot Establishment

In March of 2003, 48 plots measuring 5 meters by 5 meters square were established in the intermound areas of the selected study site which was in a managed pine forest stand. The plots were distributed over an area of approximately 2.6 hectares

(6.4 acres) and were permanently located by driving 1.5 meter by 1.6 centimeter diameter steel rebar rods into the ground at the plot corners. A numerically stamped metal identification tag was affixed to one corner rod of each plot and a GPS reading was taken at the center point. The trees were subsequently removed from the study site between March and July of 2003. Special instructions were issued to the harvesting personnel to avoid driving equipment on, or allowing harvested trees to fall on, the individual plots to minimize compaction or other disturbance. The site remained undisturbed for four years (June 2007) to allow establishment of early succession vegetation.

3.3.4 Experimental Design

The experimental design was a completely randomized factorial design that attempted to evaluate the effects of soil moisture content (Factor 1) and tank traffic rates (Factor 2) on soil compaction and soil strength. Factor 1 was split into three levels as determined by volumetric water fraction (wfv): (i) Dry or 'Lo' (0.05 to 0.20 wfv); (ii) Intermediate or 'Mid' (0.20 to 0.30 wfv); and (iii) Wet or 'Hi' (>0.30 wfv). Factor 2 was split into three levels: (i) 3; (ii) 6; and (iii) 9 passes with the M1A1 battle tank in crisscross configuration to achieve complete coverage of each plot. Each treatment combination was replicated 3 times resulting in a total of 27 experimental plots. A single representative replicate is illustrated in Table 3.3. Treatment combinations were randomly assigned to 27 plots with the remaining 21 plots available as control checks in follow-up evaluations (Figure 3.5).

Tank runs were conducted between August and October 2007. Specific dates of individual runs are presented in Table A.3.1 in the appendix. Average monthly temperature and precipitation data are presented in Table A.3.2 of the appendix.

Table 3.3. Single replicate of soil moisture and traffic rate treatment combinations. Soil moisture = volumetric water fraction (wfv), Passes = passes with Abrams tank in crisscross configuration.

Soil Moisture†	Passes	Passes	Passes
Lo = Dry (< 0.20 wfv)	3	6	9
Mid = Intermediate (0.20 to 0.30 wfv)	3	6	9
Hi = Wet (> 0.30 wfv)	3	6	9
Control = Not applicable	0	0	0

†wfv - volumetric water fraction

3.3.5 Site Instrumentation

In June 2007, a Campbell Scientific, Inc. (Logan, UT), CR-10X datalogger with CSI AM16/32 multiplexer (Figure 3.6) was installed at each of four site station locations distributed across the larger study area and was linked by means of radio telemetry and satellite uplink equipment to facilitate daily soil moisture and temperature monitoring via internet website. A tipping bucket rain gauge and Campbell Scientific Inc., Model# 107 air temperature sensor were wired into the datalogger at site 1 for atmospheric environmental monitoring purposes. Dataloggers were powered by 12 volt batteries charged by solar panels. In May and June 2007, Stevens 'Hydra Probe II' soil moisture, temperature and salinity sensor probes (Stevens Water Monitoring Systems, Beaverton, OR) were modified to facilitate long cable runs from the experimental plots to the centralized Campbell dataloggers. Each Hydra Probe II sensor had a seven wire cable which was extended to accommodate plot distances of up to 46 meters (150 feet). Individual wires within the cable were spliced, soldered, and sealed with heat shrink tubing. In addition, each cable was then water-tight sealed with heat shrink tubing and silicone and wrapped with duct tape. Each sensor was tested before and after splicing, in open air and in tap water, to insure acceptable operation across moisture ranges.

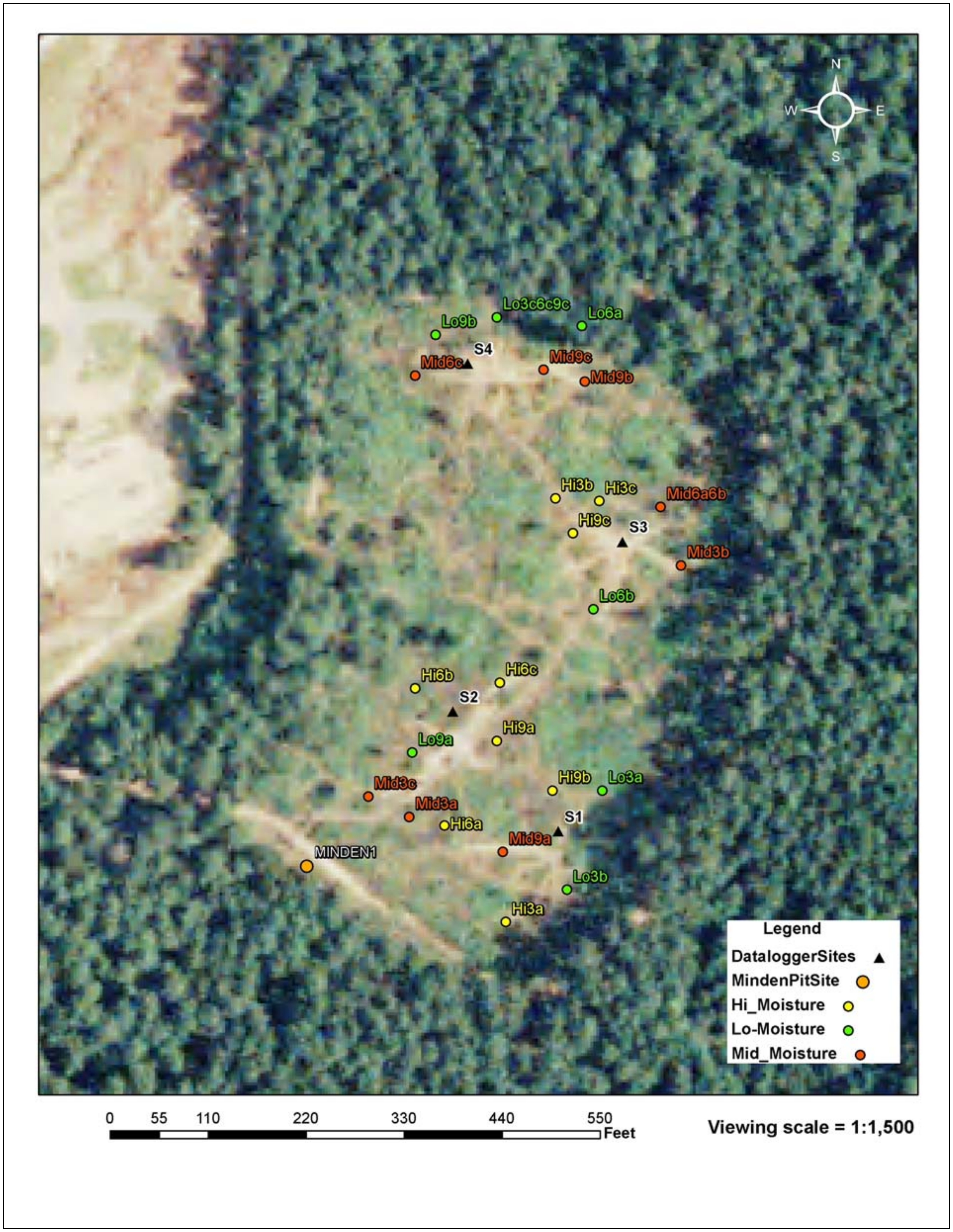


Figure 3.5. Map of Camp Minden tank study site.

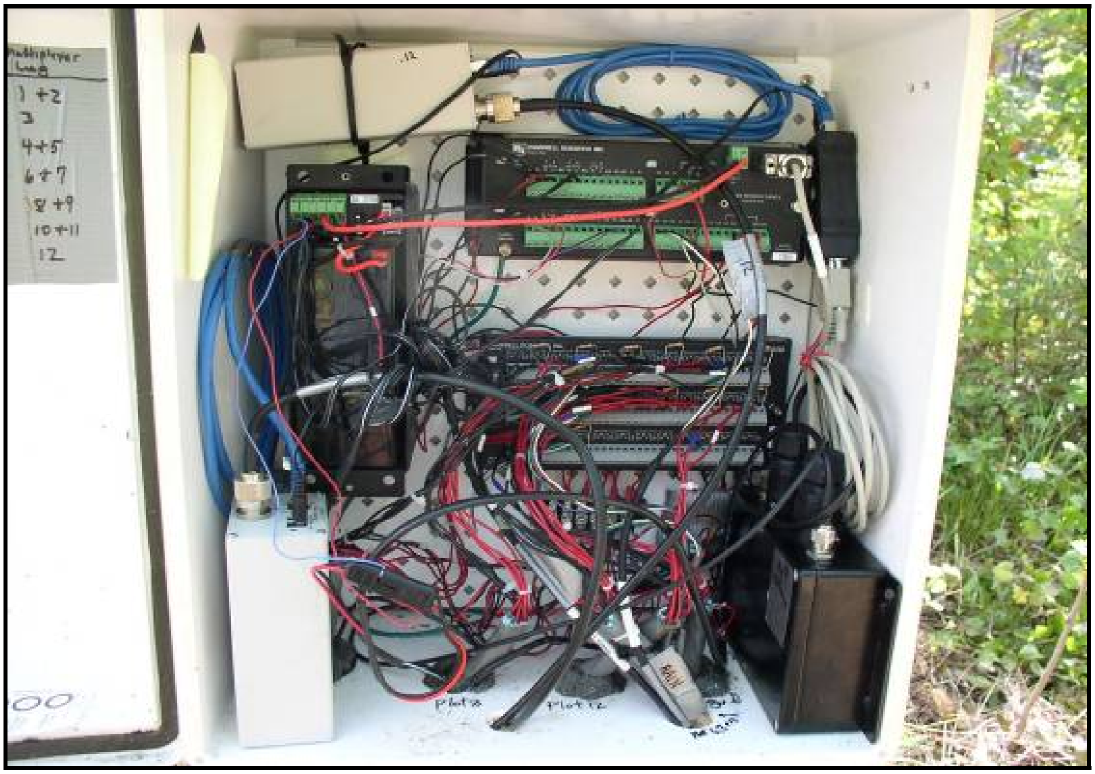


Figure 3.6. Primary site data logging station with Campbell Scientific CR-10X® datalogger, CSI AM16/32 multiplexer, radio telemetry, satellite uplink, and atmospheric environmental monitoring equipment.

In June, July, and August 2007, the modified Hydra Probe II sensors were installed at depths of 20 and 50 cm within 18 of the 30 plots (Figure 3.7). Sensors were installed at 50 cm only in the remaining 12 plots. Installation depths of 20 and 50 cm were chosen to yield information on soil moisture content of the epipedon (A and EBg horizons) and the argillic subsoil (Btg/E horizons). Sensor installation was facilitated by excavating a 30 cm diameter hole to a depth of approximately 60 cm deep. The sensor tongs were inserted into the soil bore wall (Figure 3.7) and the sensors were connected to Campbell dataloggers.

Sensors were allowed to “equilibrate” for 5 to 7 days in the soil environment and test readings were taken for each sensor to insure proper operation. Sensor cables were buried in 60 cm deep trenches to protect them from being damaged by tank traffic.

The soil bore holes were then backfilled with soil material to approximate original soil density. Hydra Probe II moisture and temperature readings were to be taken hourly and averaged daily. The dataloggers were equipped with satellite remote download capabilities so that soil moisture levels could be remotely monitored on a daily basis to determine appropriate timing for tank runs. The location of the four datalogger stations, the study plots with treatment combination identification, and the site characterization pit is illustrated in the map shown in Figure 3.5. The map base is 2007 ortho imagery.

Figure 3.7. Stevens Vital soil moisture, temperature, and salinity sensor with depiction of typical installation in excavation wall at 20 cm and 50 cm depths. Cables were buried in trenches.

Soil moisture was initially to be determined by averaging moisture content of the upper 50 cm of the plot soil profile as indicated by soil moisture sensor readings, as described above, and verified by soil core extraction to a depth of 50 cm and microwave drying to a stable soil weight. However, soil moisture sensor readings became erratic and unreliable following thunderstorm activity in early September 2007 and soil moisture content was subsequently determined by microwave drying extracted soil cores to a depth of 50 cm. A soil core with a volume of 142 cm^3, measuring 1.9 cm diameter by 50 cm deep, was taken from the center of each plot prior to tank runs with an Oakfield tube sampler. The bulk sample was microwave dried to a constant weight to determine volumetric moisture content. Treatment level average moisture contents with standard deviations and ranges are presented in Table 3.4.

3.3.6 Soil Compaction Measurement - Pre and Post Tank Bulk Density

Three soil bulk density core sample replicates were taken from each plot, as each Hydra Probe moisture sensor was installed, within 30 cm of each sensor, at the 20 and 50 cm depths (June – August 2007). The bulk density cores were taken by driving a 68.7 cm^3 (3 cm long x 5.4 cm diameter) brass cylinder horizontally into the bore hole wall. These cores were used to establish pre-traffic soil bulk densities of the individual plots. Post-traffic soil bulk densities were determined, subsequent to tank passes, by excavating the original bore hole and taking an additional three cores within 30 cm of the original core samples (August – December 2007). In all, a total of twelve bulk density cores were extracted from each of the 27 plots for a total of 324 core samples. Figure 3.8 illustrates the sampling location of bulk density cores from each plot.

3.3.7 Soil Moisture Retention Curves

Soil moisture retention curves were developed for a subset of field extracted soil cores utilizing the ceramic pressure plate method described by Klute (1986). The moisture retention curves were utilized to evaluate changes in pore size distribution of the soils resulting from tank traffic induced soil compaction. Twelve soil cores with a volume of 40.5 cm^3 (2.0 cm long x 5.08 cm diameter) were extracted from the 20 and 50 cm depth intervals of two Hi moisture 9 pass treatment plots and adjacent non-trafficked control areas on September 15-16, 2009. The extracted cores were wrapped in cellophane to prevent moisture loss during transport to the soil physics lab at LSU.

Prior to placement on the pressure plate apparatus the cores were shaved at both ends of the core cylinder to ensure maximum surface contact with the ceramic pressure plates. The moisture characteristic curves were developed using a range of moisture levels which included 0, 0.1, 0.3, 0.5, 1.0, 3.0, 5.0, 10.0, and 12.5 bars pressure. No data was collected at a pressure of 15.0 bars due to a malfunctioning valve on the compressor that supplies air to the pressure plate apparatus at the time the curves were developed.

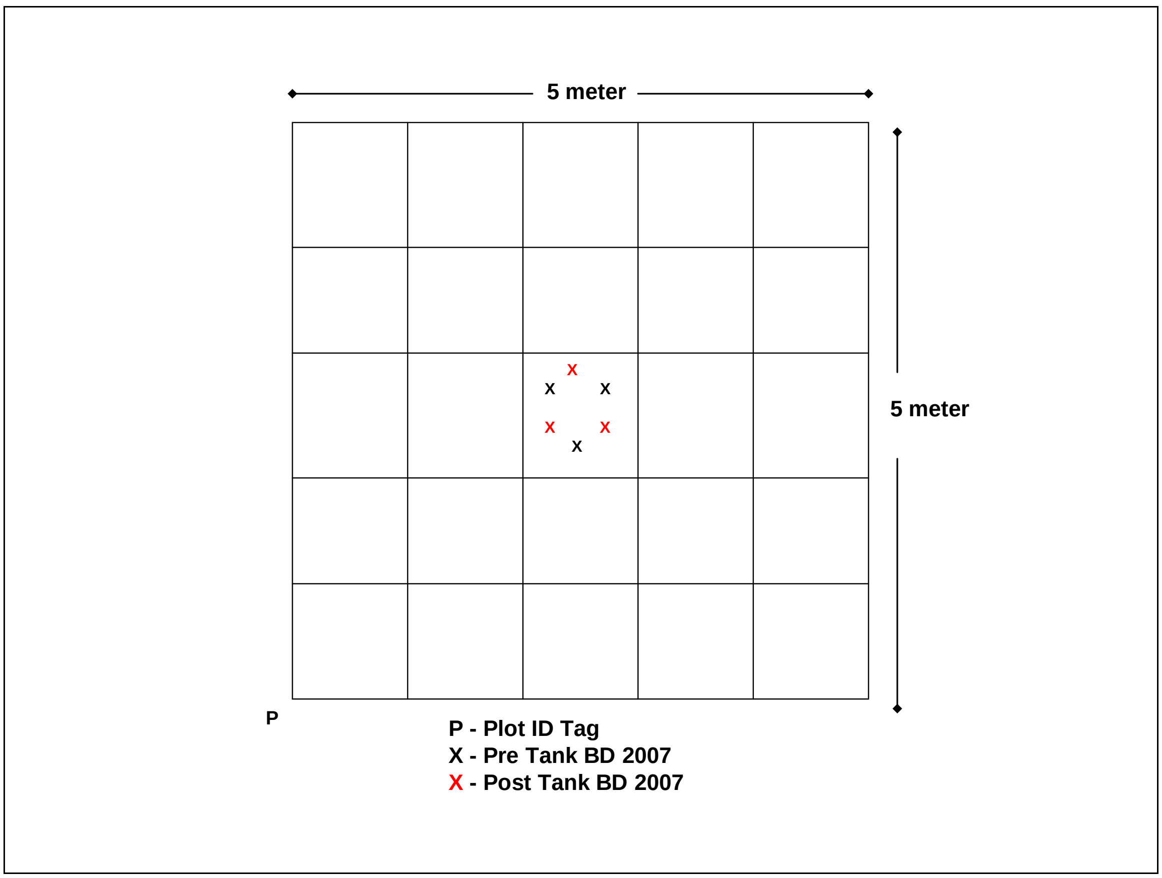


Figure 3.8. Plot grid diagram of bulk density sampling location. Cores taken at depths of 20 and 50 cm.

We utilized two models to fit the curve of the experimentally derived moisture retention data. The first was Rosetta Version 1.0 program which is capable of predicting, or more precisely, estimating the van Genuchten water retention and unsaturated hydraulic conductivity parameters (van Genuchten, 1980) from surrogate soil data (M.G. Schapp, 1999). Known sand, silt, and clay percentages, bulk density, 0.3 bar and estimated 15 bar water content of the soil cores were used as input data for Rosetta. The van Genuchten water retention parameters generated are Θ_r and Θ_s (cm^3/cm^3) which represent residual and saturated water contents, respectively, and α (1/cm) and *n*, which represent curve shape parameters. These four parameters can then be used to graph the van Genuchten water retention function, where $\Theta(h)$ represents the water retention curve defining water content Θ (cm^3/cm^3) for a given soil water pressure head *h* (cm).

The van Genuchten water retention function is given by:

$$\Theta(h) = \Theta_r + (\Theta_s - \Theta_r) / (1+(\alpha * h)^n))^m$$

Where $m = 1 - 1/n$ is assumed (van Genuchten, 1980).

Therefore, the above moisture retention equation requires only four parameters; Θ_r, Θ_s, α, and *n*. Additionally, we utilized Microsoft Excel Solver, an add-in analysis tool incorporated into Microsoft Excel (2007) for Windows, to obtain best-fit estimates of these parameters. Using Solver, an iterative, non-linear least square optimization procedure was used to obtain best-fit parameter estimates for two soil-moisture retention data sets and for two different depths.

3.3.8 Statistical Analysis of Bulk Density Measures

Statistical analysis of pre and post tank traffic soil bulk density core measurements was accomplished using JMP Statistical Software, Version 5.0.1.2. JMP was developed by SAS Institute Inc., Cary NC., and is a business unit of SAS. Exploratory statistical analysis of all bulk density data was conducted to screen for extreme outliers that could lead to false interpretation of data results. Evaluation of JMP box and whisker plots (not shown) indicated that no sample values were considered extreme outliers. Analysis of variance (ANOVA) and Tukey-Kramer HSD (honest significant differences) statistical analysis were utilized for treatment means comparisons. Results of the ANOVA (box and whisker plots) and Tukey-Kramer HSD (comparison circles) are shown graphically in Figures 3.9 thru 3.14 and in tabular form in Tables 3.7 thru 3.12. Interpretation of the box and whisker plots is such that the ends of the box are the 25th and 75th percentiles, also called quartiles. The difference between the 25th and 75th percentiles is the interquartile range. The line across the middle of the box identifies the median sample value and the means diamond indicates the samples mean and 95% confidence interval. The whiskers extend from the ends of the box to the outer-most data point that falls within a distance computed to be equal to the upper or lower quartile +/- 1.5 times the interquartile range. The accompanying data tables give basic statistics and means comparisons. Treatment combination means that are not significantly different at P = 0.05 are represented by the same letter.

3.4 RESULTS AND DISCUSSION

3.4.1 Measured Pre-Traffic Soil Moisture Levels

Soil moisture was initially to be determined by averaging moisture content of the upper 50 cm of the plot soil profile as indicated by soil moisture sensor readings and verified by soil core extraction to a depth of 50 cm and microwave drying to a stable soil weight. However, soil moisture sensor readings became erratic and unreliable following thunderstorm activity in early September 2007 and soil moisture content was subsequently determined solely by microwave drying extracted soil cores to a depth of 50 cm. A soil core with a volume of 142 cm^3, measuring 1.9 cm diameter by 50 cm deep, was taken from the center of each plot prior to tank runs with an Oakfield tube sampler. The bulk sample was microwave dried to a constant weight to determine volumetric moisture content. Average volumetric moisture contents for each moisture treatment level with standard deviations and ranges are presented in Table 3.4 below.

Table 3.4. Measured pre-traffic soil moisture levels.

Moisture Treatment Level	**Volumetric Moisture Content** Mean ± Std. Dev.	**Moisture Range**
Hi	0.38 ± 0.02	0.34 - 0.41
Mid	0.27 ± 0.02	0.24 - 0.30
Lo	0.18 ± 0.01	0.17 - 0.21

3.4.2 Bulk Density Measure Analysis

Tables 3.5 and 3.6 show the average post tank bulk density values of the study site plots as grouped by 'Moisture' and 'Traffic Rate' treatment levels for the 20cm and 50cm depth intervals respectively. The treatment level average bulk density is shown with standard deviation in brackets. These tables illustrate the average trends of the treatment levels without consideration of treatment interactions and are presented as a simplified overview of the tank traffic experiment results.

At the 20cm depth interval it can be seen that moisture treatment effect followed the trend Hi > Mid > Lo moisture levels with average bulk density values of 1.65, 1.61, and 1.57 g/cm^3 respectively. At the same depth interval the traffic rate treatment effect followed the trend 6 >3 = 9 passes with average bulk density values of 1.63, 1.60, and 1.60 g/cm^3 respectively. At the 50 cm depth interval, the moisture treatment effect followed the trend Mid > Hi > Lo, with average bulk density values of 1.61, 1.60, and 1.56 g/cm^3 respectively. The traffic rate treatment effect in the 50cm interval was 3 = 6 > 9 with average bulk density values of 1.61, 1.61, and 1.56 g/cm^3 respectively.

Table 3.5. 20 cm depth post-traffic average bulk density. Values in brackets = standard deviation.

20 cm Depth Average Bulk Density (g/cm^3) by Moisture and Traffic Rate Level					
		Traffic Rate (Passes)			
	20cm Depth	3	6	9	***Moisture mean***
Moisture Treatment (WFV%)	Hi	1.64 (0.07)	1.63 (0.06)	1.67 (0.08)	*Hi mean = 1.65 (0.07)*
	Mid	1.58 (0.11)	1.68 (0.07)	1.58 (0.09)	*Mid mean = 1.61 (0.09)*
	Lo	1.58 (0.08)	1.59 (0.11)	1.55 (0.10)	*Lo mean = 1.57 (0.09)*
	Rate mean	*3 mean = 1.60 (0.08)*	*6 mean = 1.63 (0.08)*	*9 mean = 1.60 (0.08)*	

Table 3.6. 50 cm depth post-traffic average bulk density. Values in bracket = standard deviation.

50 cm Depth Average Bulk Density (g/cm^3) by Moisture and Traffic Rate Level					
		Traffic Rate (Passes)			
	50cm Depth	3	6	9	***Moisture mean***
Moisture Treatment (WFV%)	Hi	1.64 (0.07)	1.61 (0.04)	1.57 (0.05)	*Hi mean = 1.60 (0.05)*
	Mid	1.61 (0.05)	1.60 (0.05)	1.62 (0.05)	*Mid mean = 1.61 (0.05)*
	Lo	1.58 (0.06)	1.61 (0.05)	1.48 (0.08)	*Lo mean = 1.56 (0.06)*
	Rate mean	*3 mean = 1.61 (0.06)*	*6 mean = 1.61 (0.05)*	*9 mean = 1.56 (0.06)*	

Figures 3.9 and 3.10 illustrate the comparative sampling distributions, and the pre and post traffic means and sample distribution of the 20 cm depth bulk density cores respectively. Figures 3.11 and 3.12 illustrate the comparative sampling distributions,

and the pre and post traffic means and distribution of the 50 cm depth bulk density cores respectively. These graphs illustrate that there is a high degree of variability among the bulk density measures at all treatment combination levels, particularly at the shallower 20 cm depth. It can also be observed that at both the 20 cm and the 50 cm depths the post-traffic bulk densities are consistently higher than the pre-traffic bulk densities for virtually all treatment combinations. Figures 3.13 and 3.14 illustrate the relative percent change in bulk density for each treatment combination at the 20 and 50 cm depth respectively. There appears to be greater variability in 20 cm depth cores than the deeper 50 cm cores, as indicated by the size of the box and whiskers.

It should be noted that the family particle size classification of the Wrightsville soil is technically considered 'fine', as based on the particle size control section (38 to 88 cm depths). However, the textures of the Camp Minden study site soils at the depths of our investigation (0 to 50 cm) are typically characterized as being fine-silty.

The primary concern of the study is to indicate whether bulk density levels in excess of some threshold level that inhibit plant root extension and growth are met or exceeded. The USDA-NRCS National Soil Survey Handbook (2008) indicates that root extension 'restriction' is initiated at dry bulk density values of 1.54 g/cm^3 and that dry bulk density values of ≥ 1.65 g/cm^3 are considered root extension limiting.

All of the pre-traffic soil bulk densities sampled tended to be at or above the root restriction-initiation level of 1.54 g/cm^3. The pre-traffic mean responses were 1.54 g/cm^3 with a range of 1.49 to 1.60 g/cm^3 at the 20 cm depth and 1.56 g/cm^3 with a range of 1.49 to 1.59 g/cm^3 at the 50 cm depth (Tables 3.7 and 3.9). As such, it is expected that most of the site should exhibit some root extension restriction prior to tank traffic.

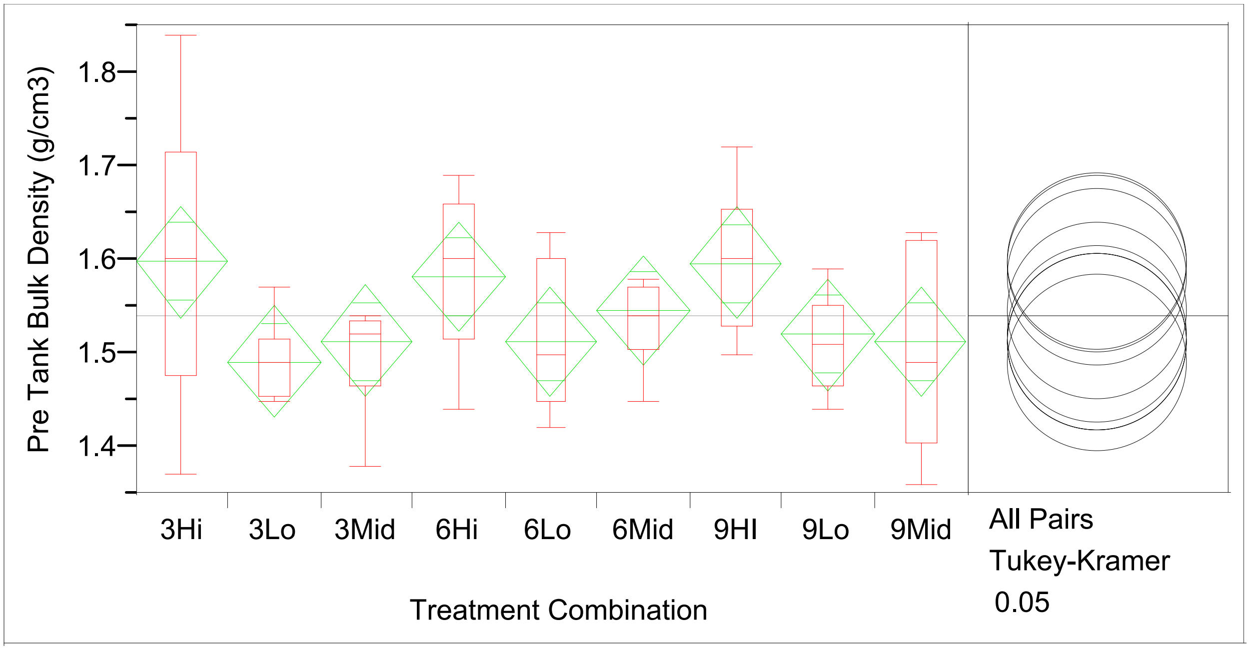


Figure 3.9. Pre tank bulk density ANOVA box plots and Tukey-Kramer HSD means comparisons for 20 cm depth.

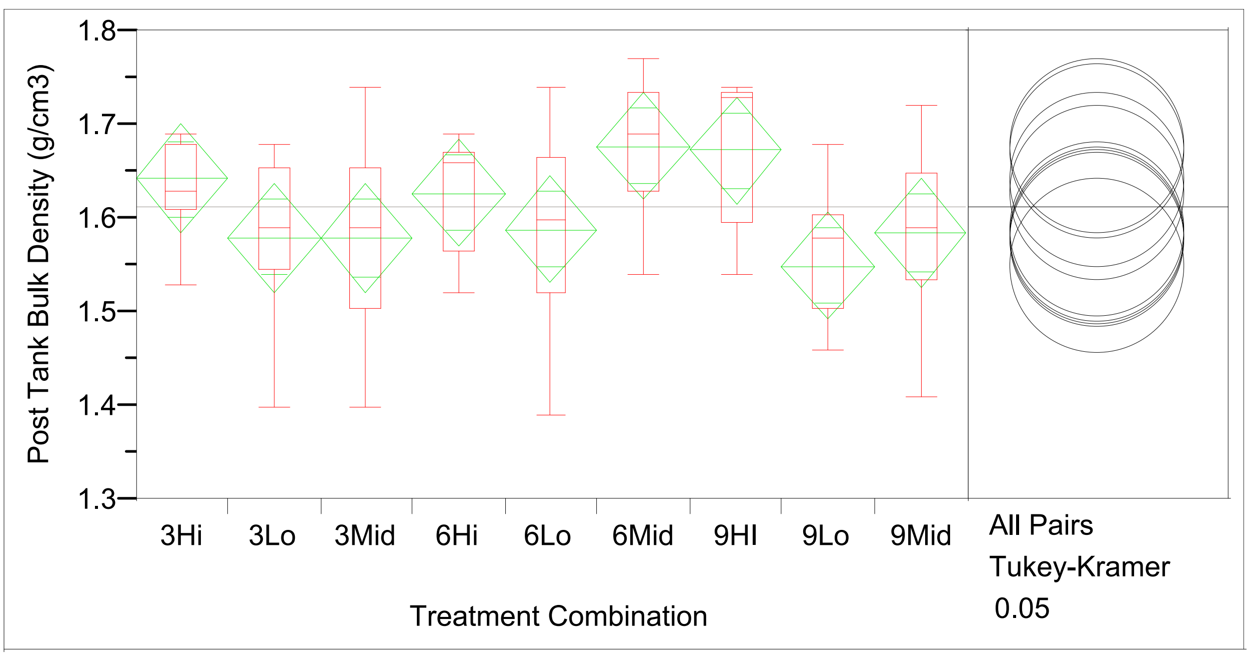


Figure 3.10. Post tank bulk density ANOVA box plots and Tukey-Kramer HSD means comparisons for 20 cm depth.

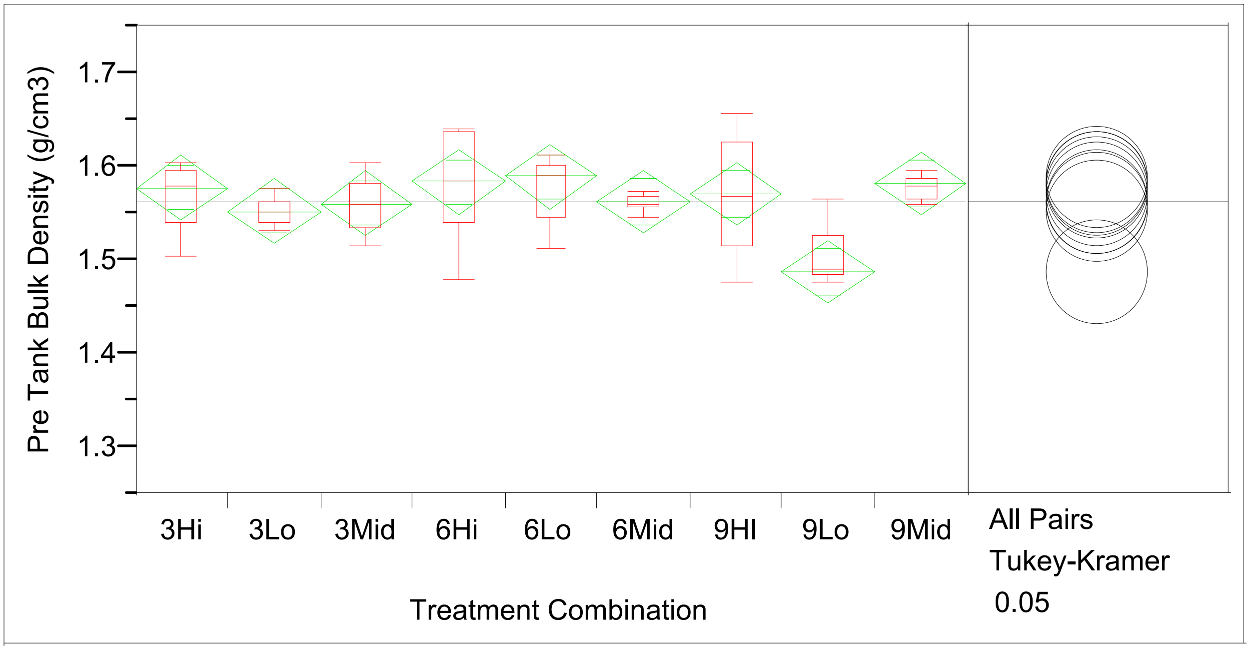


Figure 3.11. Pre tank bulk density ANOVA box plots and Tukey-Kramer HSD means comparisons for 50 cm depth.

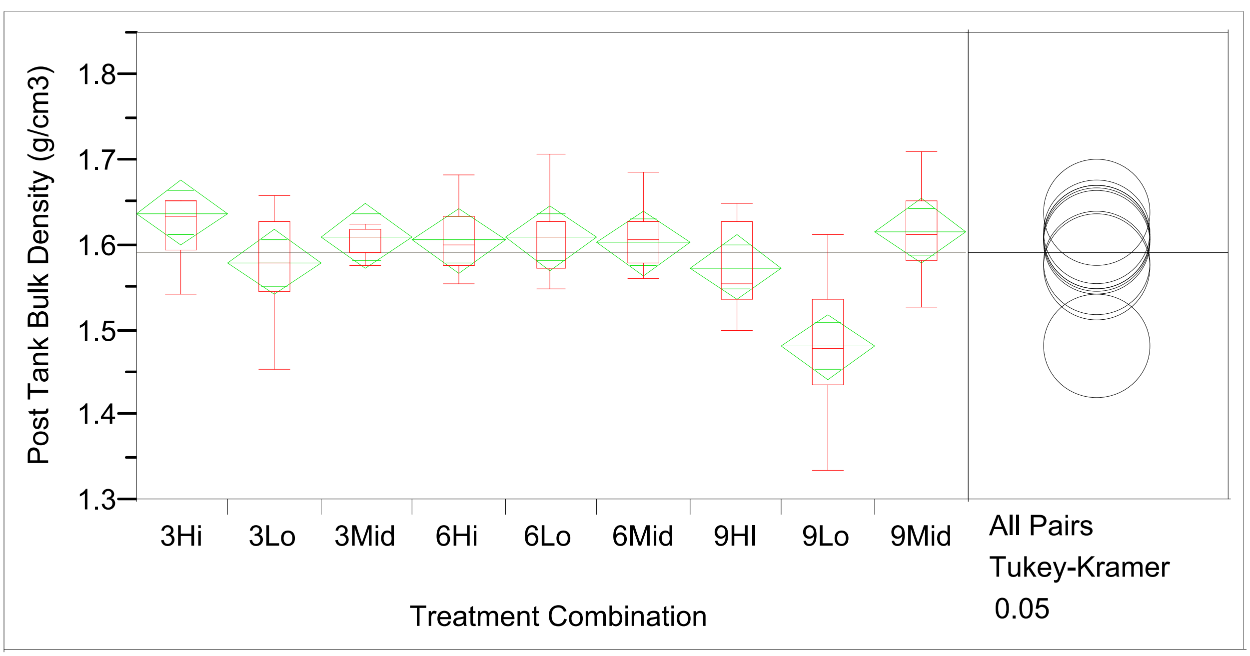


Figure 3.12. Post tank bulk density ANOVA box plots and Tukey-Kramer HSD means comparisons for 50 cm depth.

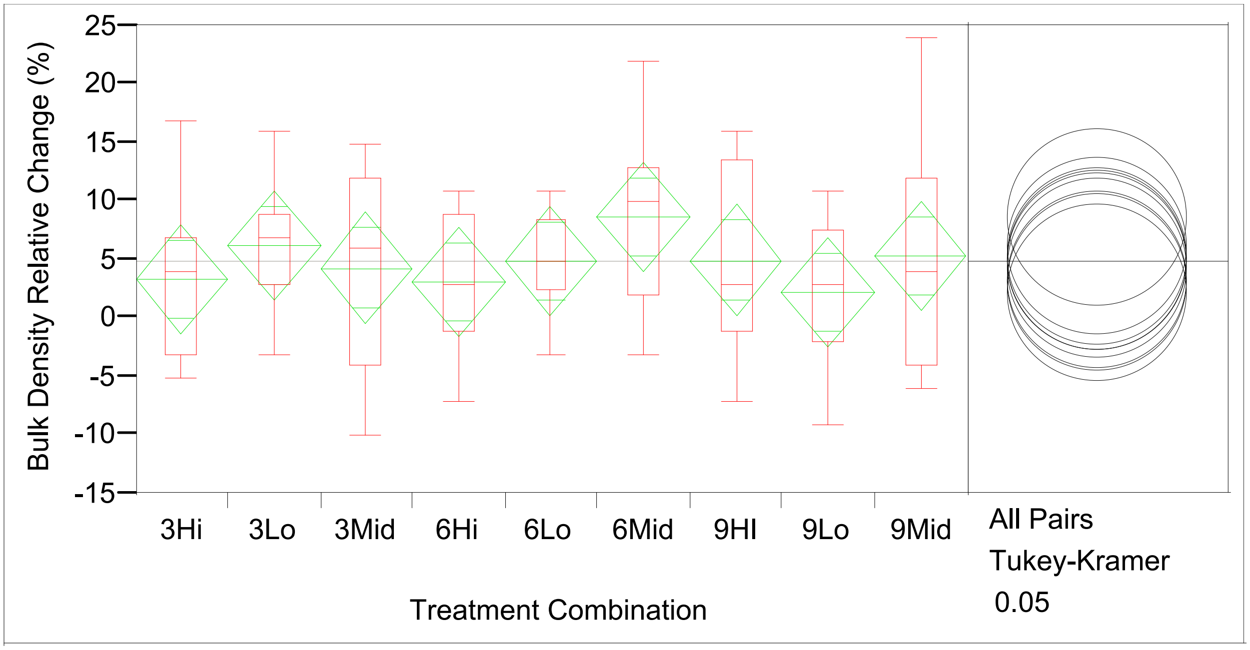


Figure 3.13. **Pre vs. post tank bulk density relative change (%) ANOVA box plots and Tukey-Kramer HSD means comparisons for 20 cm depth.**

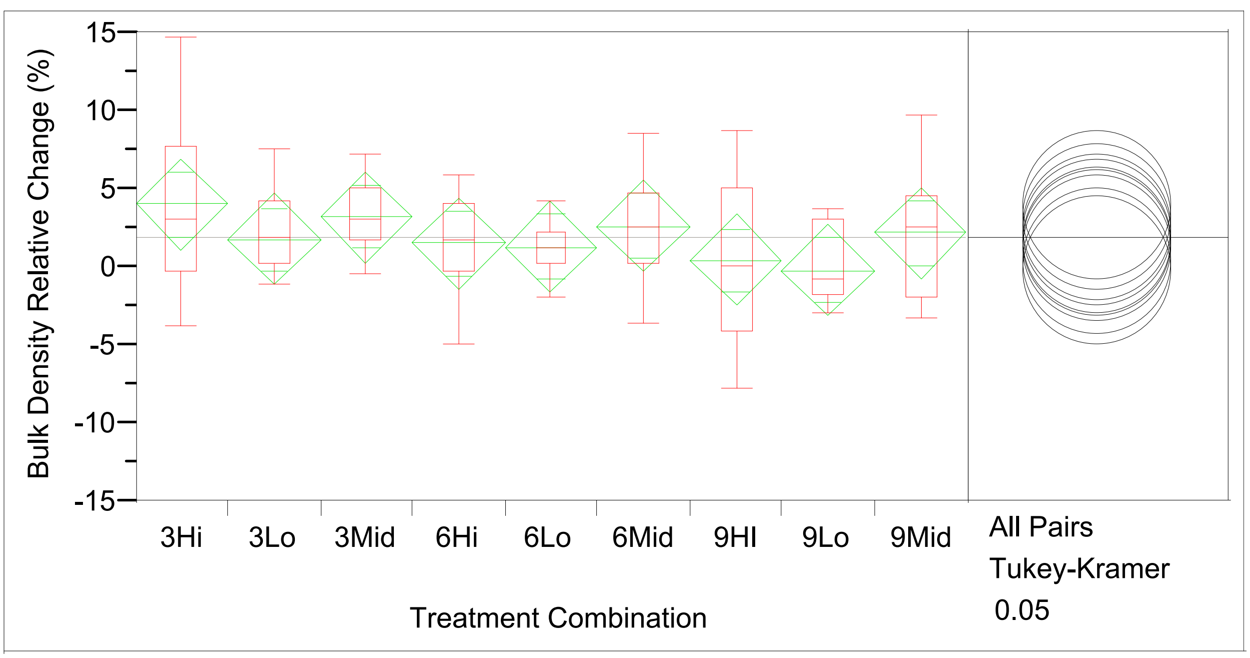


Figure 3.14. **Pre vs. post tank bulk density relative change (%) ANOVA box plots and Tukey-Kramer HSD means comparisons for 50 cm depth.**

Table 3.7. Pre tank bulk density ANOVA and Tukey-Kramer HSD means comparisons by treatment combination for the 20 cm depth.

Summary of Fit

Rsquare	0.174378
Adj Rsquare	0.082642
Root Mean Square Error	0.089033
Mean of Response	1.541235
Observations	81

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Treatment Combination	8	0.12	0.02	1.9009	0.073
Error	72	0.57	0.01		
C. Total	80	0.69			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
3Hi	9	1.60	0.03	1.5386	1.6569
3Lo	9	1.49	0.03	1.4319	1.5503
3Mid	9	1.51	0.03	1.4542	1.5725
6Hi	9	1.58	0.03	1.5231	1.6414
6Lo	9	1.51	0.03	1.4531	1.5714
6Mid	9	1.55	0.03	1.4864	1.6047
9HI	9	1.60	0.03	1.5375	1.6558
9Lo	9	1.52	0.03	1.4608	1.5792
9Mid	9	1.51	0.03	1.4531	1.5714

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
3Hi	A	1.60
9HI	A	1.60
6Hi	A	1.58
6Mid	A	1.55
9Lo	A	1.52
3Mid	A	1.51
6Lo	A	1.51
9Mid	A	1.51
3Lo	A	1.49

Levels not connected by same letter are significantly different

Table 3.8. Post tank bulk density ANOVA and Tukey-Kramer HSD means comparisons by treatment combination for the 20 cm depth.

Summary of Fit

Rsquare	0.211087
Adj Rsquare	0.12343
Root Mean Square Error	0.08745
Mean of Response	1.611358
Observations	81

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Treatment Combination	8	0.15	0.02	2.4081	0.0231
Error	72	0.55	0.01		
C. Total	80	0.70			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
3Hi	9	1.64	0.03	1.5841	1.7003
3Lo	9	1.58	0.03	1.5219	1.6381
3Mid	9	1.58	0.03	1.5208	1.637
6Hi	9	1.63	0.03	1.5697	1.6859
6Lo	9	1.59	0.03	1.5308	1.647
6Mid	9	1.68	0.03	1.6197	1.7359
9HI	9	1.67	0.03	1.6141	1.7303
9Lo	9	1.55	0.03	1.4919	1.6081
9Mid	9	1.58	0.03	1.5263	1.6426

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
6Mid	A	1.68
9HI	A	1.67
3Hi	A	1.64
6Hi	A	1.63
6Lo	A	1.59
9Mid	A	1.58
3Lo	A	1.58
3Mid	A	1.58
9Lo	A	1.55

Levels not connected by same letter are significantly different

Table 3.9. Pre tank bulk density ANOVA and Tukey-Kramer HSD means comparisons by treatment combination for the 50 cm depth.

Summary of Fit

Rsquare	0.262233
Adj Rsquare	0.180258
Root Mean Square Error	0.051425
Mean of Response	1.562926
Observations	81

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Treatment Combination	8	0.07	0.01	3.199	0.0037
Error	72	0.19	0.00		
C. Total	80	0.26			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
3Hi	9	1.58	0.02	1.5433	1.6116
3Lo	9	1.55	0.02	1.5185	1.5868
3Mid	9	1.56	0.02	1.5264	1.5947
6Hi	9	1.58	0.02	1.5494	1.6177
6Lo	9	1.59	0.02	1.5549	1.6233
6Mid	9	1.56	0.02	1.5281	1.5964
9Hi	9	1.57	0.02	1.5364	1.6047
9Lo	9	1.49	0.02	1.4536	1.5219
9Mid	9	1.58	0.02	1.5483	1.6166

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
6Lo	A	1.59
6Hi	A	1.58
9Mid	A	1.58
3Hi	A	1.58
9Hi	A	1.57
6Mid	AB	1.56
3Mid	AB	1.56
3Lo	AB	1.55
9Lo	B	1.49

Levels not connected by same letter are significantly different

Table 3.10. Post tank bulk density ANOVA and Tukey-Kramer HSD means comparisons by treatment combination for the 50 cm depth.

Summary of Fit

Rsquare	0.382391
Adj Rsquare	0.313768
Root Mean Square Error	0.057699
Mean of Response	1.59137
Observations	81

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Treatment Combination	8	0.15	0.02	5.5723	<.0001
Error	72	0.24	0.00		
C. Total	80	0.39			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
3Hi	9	1.64	0.02	1.6008	1.6775
3Lo	9	1.58	0.02	1.5418	1.6185
3Mid	9	1.61	0.02	1.5727	1.6493
6Hi	9	1.61	0.02	1.5684	1.6451
6Lo	9	1.61	0.02	1.5709	1.6476
6Mid	9	1.60	0.02	1.5648	1.6415
9HI	9	1.57	0.02	1.5364	1.6131
9Lo	9	1.48	0.02	1.4431	1.5198
9Mid	9	1.62	0.02	1.5784	1.6551

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level			Mean
3Hi	A		1.64
9Mid	A		1.62
3Mid	A		1.61
6Lo	A		1.61
6Hi	A		1.61
6Mid	A		1.60
3Lo	A		1.58
9HI	A		1.57
9Lo		B	1.48

Levels not connected by same letter are significantly different

Table 3.11. Pre vs. post tank bulk density relative change (%) ANOVA box plots and Tukey-Kramer HSD means comparisons for 20 cm depth.

Summary of Fit

Rsquare	0.065975
Adj Rsquare	-0.03781
Root Mean Square Error	7.184947
Mean of Response	4.790123
Observations	81

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Treatment Combination	8	262.54	32.82	0.6357	0.7452
Error	72	3716.89	51.62		
C. Total	80	3979.43			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
3Hi	9	3.33	2.40	-1.441	8.108
3Lo	9	6.22	2.40	1.448	10.997
3Mid	9	4.33	2.40	-0.441	9.108
6Hi	9	3.11	2.40	-1.663	7.885
6Lo	9	4.89	2.40	0.115	9.663
6Mid	9	8.67	2.40	3.892	13.441
9HI	9	5.00	2.40	0.226	9.774
9Lo	9	2.22	2.40	-2.552	6.997
9Mid	9	5.33	2.40	0.559	10.108

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
6Mid	A	8.67
3Lo	A	6.22
9Mid	A	5.33
9HI	A	5.00
6Lo	A	4.89
3Mid	A	4.33
3Hi	A	3.33
6Hi	A	3.11
9Lo	A	2.22

Levels not connected by same letter are significantly different

Table 3.12. Pre vs. post tank bulk density relative change (%) ANOVA box plots and Tukey-Kramer HSD means comparisons for 50 cm depth.

Summary of Fit

Rsquare	0.082173
Adj Rsquare	-0.01981
Root Mean Square Error	4.392836
Mean of Response	1.882012
Observations	81

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Treatment Combination	8	124.39	15.55	0.8058	0.5996
Error	72	1389.38	19.30		
C. Total	80	1513.78			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
3Hi	9	4.00	1.46	1.084	6.9218
3Lo	9	1.77	1.46	-1.153	4.6849
3Mid	9	3.24	1.46	0.325	6.1631
6Hi	9	1.55	1.46	-1.369	4.4691
6Lo	9	1.30	1.46	-1.622	4.2164
6Mid	9	2.63	1.46	-0.285	5.5531
9HI	9	0.43	1.46	-2.491	3.3472
9Lo	9	-0.17	1.46	-3.093	2.7445
9Mid	9	2.19	1.46	-0.729	5.1089

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
3Hi	A	4.00
3Mid	A	3.24
6Mid	A	2.63
9Mid	A	2.19
3Lo	A	1.77
6Hi	A	1.55
6Lo	A	1.30
9HI	A	0.43
9Lo	A	-0.17

Levels not connected by same letter are significantly different

The probable explanation for this condition can be attributed to past logging operations. Although operators were instructed to avoid trafficking in the pre-delineated plots it is likely that there was some degree of disturbance. While only the 9 pass Hi moisture and 6 pass Mid moisture treatment levels produced average post bulk densities in excess of the root-limiting ≥ 1.65 g/cm^3, post-treatment bulk density levels in all treatment combinations exceeded the 1.54 g/cm^3 root restriction initiation level except the 9 pass Lo moisture treatment.

3.4.3 Soil Moisture Retention Curves

Analysis of the soil moisture retention curves of the Camp Minden soils indicate that changes in pore size distribution in the tank trafficked soils occurred across the range of pore sizes (144 to 0.1 μM) associated with the pressures evaluated (0 to 12.5 bars). This observation is more accentuated at the shallower 20 cm depth than the deeper 50 cm depth as illustrated in Figures 3.15 and 3.16 respectively. In samples taken from a depth of 20 cm, the larger pores (>15 μM) corresponding with pressures >0.3 bars are collapsed in the tank trafficked soils and are significantly different from the non-trafficked control samples (Figure 3.15). A review of the data presented in Table 3.13 will illustrate the point that as the satiation water content nears 0.0 bars, the control samples averaged 0.44 cm^3/cm^3, whereas the satiation water content of the tank trafficked samples averaged 0.38 cm^3/cm^3, a decrease of 0.06 cm^3/cm^3. This equates to approximately 1.8 cm less water holding capacity in the upper 30 cm of the tank trafficked soils. The trend shifts at pressures above 1.0 bar wherein the moisture retention capacity of the tank trafficked samples is significantly greater than the non-trafficked control samples. This suggests that compaction is achieved by a relative collapse of the pores of all sizes within the range of pressures investigated with a relative increase in the number of small pores at the 20 cm depth interval with a corresponding increase in bulk density from 1.65 g/cm^3 to 1.76 g/cm^3.

In samples taken from a depth of 50 cm, volumetric moisture retention in the control samples were slightly higher than the trafficked samples by 0.014 cm^3/cm^3 at pressures ≤ 0.01 bar, however this difference was not statistically significant (Figure 3.16). At all pressures ≥0.1 bar, the tank trafficked samples exhibited greater water retention capacity than the control samples though the differences were not significant at pressures between 0.1 and 0.5 bars where the curve slopes cross. However, at pressures ≥ 1.0 bar the differences were significant and increased as pressure increased. The average moisture retention values with standard deviations and the average moisture content difference between control and tank trafficked samples for both the 20 cm and 50 cm depth intervals, are presented in tabular form in Table 3.13.

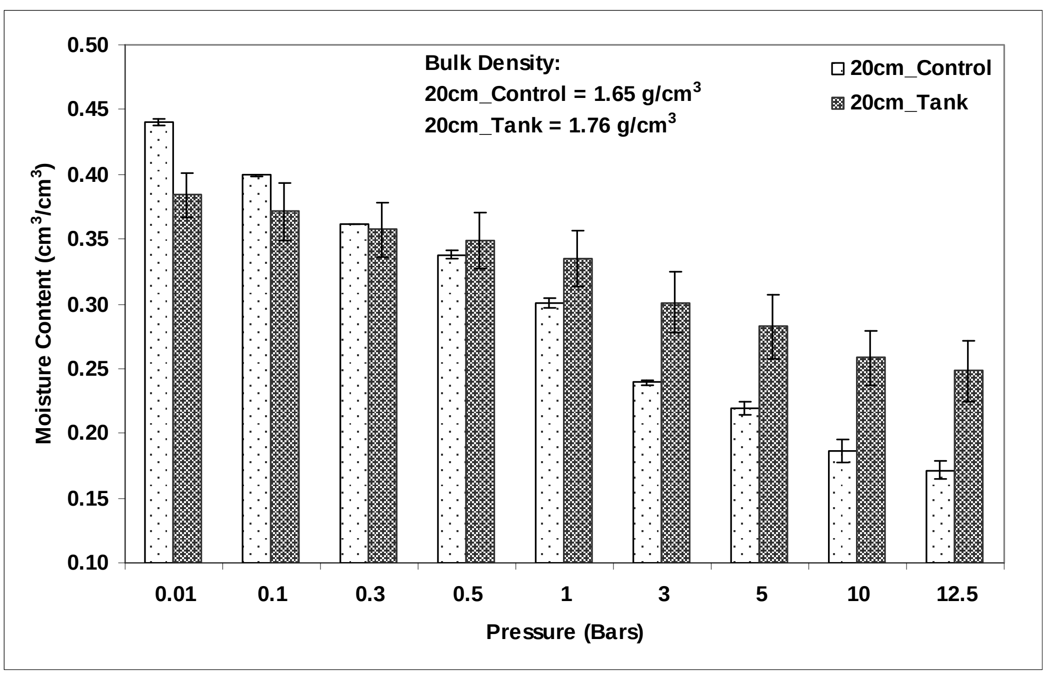


Figure 3.15. 20 cm depth interval soil moisture retention curve. Error bars represent standard deviation.

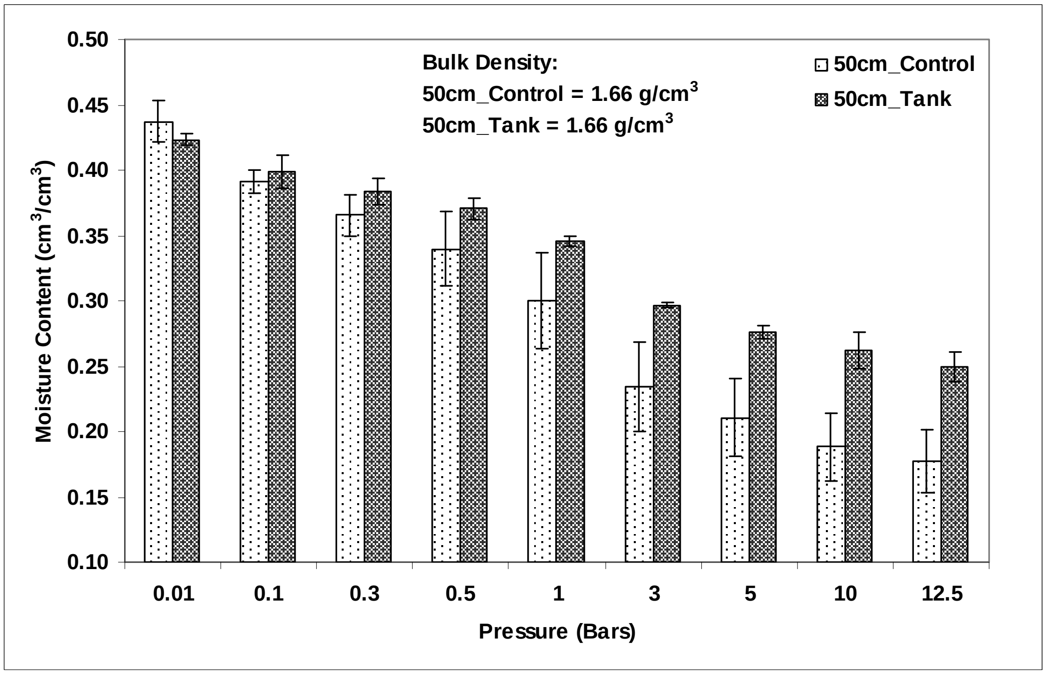


Figure 3.16. 50 cm depth interval soil moisture retention curve. Error bars represent standard deviation.

Table 3.13. Moisture retention curve statistics.

Statistic	Sample ID	Moisture Content (cm³/cm³) @ Pressures - Height - Pore diameter								
	Press. Bars	0.01	0.1	0.3	0.5	1	3	5	10	12.5
	Height - h (cm)	10.2	102	306	510	1020	3060	5100	10200	12750
	Pore dia. (μM)	150	15	5	3	1.5	0.5	0.3	0.15	0.12
Mean	20cm_Control	0.440	0.399	0.362	0.338	0.300	0.239	0.220	0.186	0.171
SD	20cm_Control	0.002	0.001	0.000	0.003	0.004	0.002	0.005	0.009	0.007
Mean	20cm_Tank	0.384	0.371	0.357	0.349	0.335	0.301	0.282	0.258	0.248
SD	20cm_Tank	0.017	0.022	0.021	0.021	0.022	0.024	0.024	0.021	0.023
Mean	50cm_Control	0.437	0.391	0.365	0.340	0.300	0.235	0.211	0.188	0.177
SD	50cm_Control	0.016	0.009	0.016	0.028	0.036	0.034	0.029	0.026	0.024
Mean	50cm_Tank	0.423	0.398	0.384	0.370	0.345	0.297	0.276	0.262	0.249
SD	50cm_Tank	0.005	0.013	0.010	0.008	0.003	0.002	0.005	0.014	0.012
Difference	20cm_Control	0.056	0.028	0.004	-0.011	-0.034	-0.062	-0.063	-0.072	-0.077
Difference	50cm_Control	0.014	-0.007	-0.018	-0.030	-0.045	-0.062	-0.065	-0.074	-0.072

The average moisture content difference was calculated as: (control moisture content (cm^3/cm^3)) – (tank trafficked moisture content (cm^3/cm^3)), at each pressure (bars) and height or pressure head (cm). Positive values indicate greater volumetric water content for control samples, whereas negative values indicate greater volumetric water content for tank trafficked samples at a specific pressure value. Additionally, the table displays the average pore size diameter associated with the different pressure ranges investigated. The substantial increase in moisture retention capacity of the tank trafficked samples at the higher pressure ranges in the 50 cm interval data suggest that there is an increase in the relative number of smaller intermediate and micro pores at that depth. Additionally, there does appear to be a significant corresponding volumetric reduction in the larger interaggregate macro pores associated with pressures between 0.3 and 0.1 bars as compared to the 20 cm interval in spite of the fact that there is no appreciable increase in bulk density at the 50 cm depth.

A point of particular interest is the fact that average bulk density increased in the 20 cm depth interval samples from 1.65 to 1.76 g/cm^3, whereas average bulk density in the 50 cm interval only increased from 1.65 to 1.66 g/cm^3. The increase in bulk density at the 20 cm interval is expected due to what appears to be the progressive collapse of the larger interaggregate pores, through the smaller intermediate and micropores in the 1.0 to 12.5 bar pressure ranges. The relative shift of pores size distribution toward the predominance of smaller pores in the 50 cm depth interval, as indicated by the higher moisture retention values at the higher pressures, would suggest that some significant degree of compaction could be expected. However, there appears to be a shift in pore size distribution without a corresponding increase in bulk density at that depth interval. Other researchers have made similar observations, and Horn (1995) states that retarded water fluxes at high water content, in conjunction with loading at high dynamic forces, can result in a completely homogenized soil characterized by a low bulk density and a predominance of fine pores. Shroff and Shah (2003) suggest that, at high water content at or near saturation, with additional compaction effort, soil particles may simply be realigned with a more orderly arrangement of particles and no substantial increase in bulk density. Gresser (2008) states that, at very high water content (e.g., ≥ 90% of pore volume), energy has little effect on compacted density of a fine textured soil, because water is incompressible and takes the applied energy without further compacting the soil. Assouline (2006) states that bulk density change, due to compaction, is an integrative variable that reflects the total change in the voids volume of the soil. While citing Lenhard (1986), he also states that subtle changes in the voids volume, distribution, tortuosity, or connectivity could still occur during compaction, especially during elastic deformation, while no corresponding changes in bulk density are noticed. To reiterate, the soil cores utilized in the moisture retention curves were sampled from the Hi moisture, 9 and 6 pass treatment combinations. Several of the Hi moisture plots did exhibit ‘pumping’ as the tanks made traffic passes which is indicative of moisture contents above the liquid limit and the idealized ‘optimum’. It should also be noted that plots meeting the Hi moisture criteria for trafficking had average profile water contents in excess of 0.30 cm^3/cm^3 and subsoil water contents were always greater than that of the upper profile. As such, it is likely that these soils were at or near satiation when trafficked and would meet the suggested criteria referenced previously. The relatively minor bulk density increase and the corresponding increase in moisture retention across the range of pressures ≥ 0.1 bar would suggest that, at the high water content, at or near saturation, tank trafficking caused soil particles to be realigned resulting in a more orderly arrangement of particles with no substantial increase in bulk density. It is suggested that the confined subsoils were subjected to wet soil deformation and homogenization with some possible interruption of pore continuity due to the inability of water to move out of the soil.

3.4.4 Soil-Moisture Retention Curve Fitting

Known particle size parameters and experimentally determined moisture retention values were utilized as input data for the pedotransfer function based Rosetta model (Schaap, 1999). The Rosetta model offers five hierarchical pedotransfer functions that allow the prediction of hydraulic properties with limited to more extensive input data. We utilized the highest order model which required sand, silt, clay, bulk density, and water retention points at 330 and 15000 cm (0.3 and 15 bar) respectively. As stated earlier, the model generates van Genuchten water retention parameters: Θ_r and Θ_s (cm^3/cm^3) which represent residual and saturated water contents, respectively; and α (1/cm) and *n*, which are curve shape parameters. These parameters were subsequently used to graph the van Genuchten water retention function, where Θ (*h*) represents the water retention curve defining water content Θ (cm^3/cm^3) for a given soil water pressure head *h* (cm). The Rosetta program output tables are illustrated in Figures A3.1 thru A3.4 in the appendix section as a reference. Figures 3.17 and 3.18 illustrate Rosetta parameter estimate water retention function curves plotted against the measured retention data for the 20 cm and 50 cm depth intervals respectively. The Rosetta parameter estimate curves underestimated the moisture retention values of the experimentally determined data at both the 20 and 50 cm intervals. The model did a better job of predicting moisture retention values and slopes for the 50 cm depth interval than the 20 cm interval. However, the line fit was less accurate at the higher pressures than in the lower pressure ranges. At the beginning of the tank study in 2006, a soil characterization pit was opened and samples were sent to the USDA-Soil Characterization Lab in Lincoln, Nebraska.

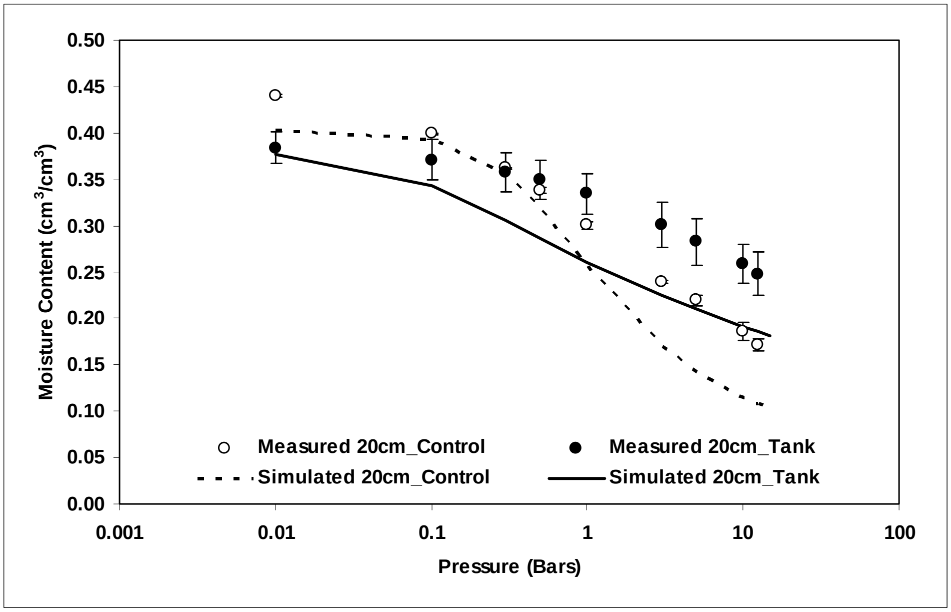


Figure 3.17. 20 cm depth interval Rosetta model generated van Genuchten parameter moisture retention curves (VGM) as plotted against measured data. Error bars on measured data represent standard deviation.

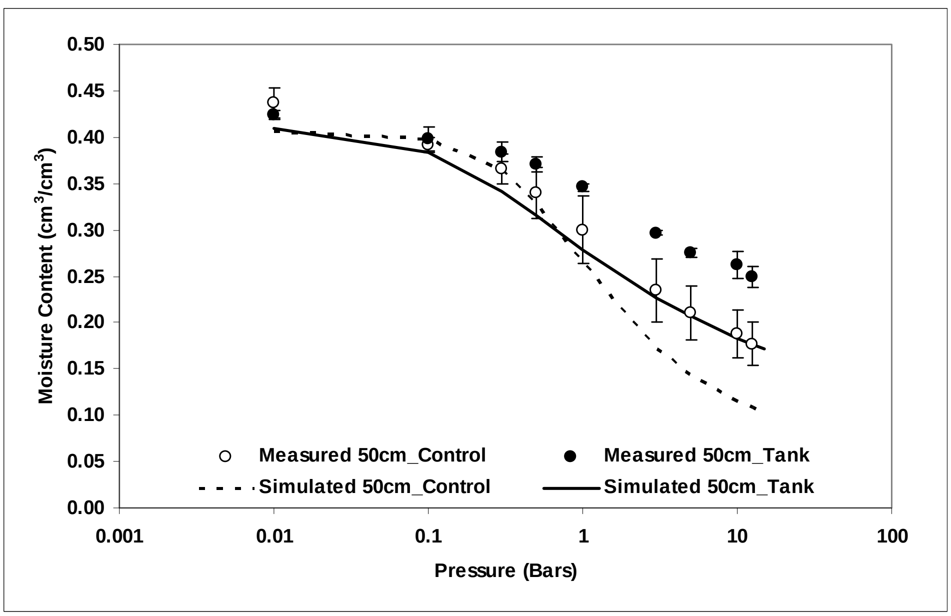


Figure 3.18. 50 cm depth interval Rosetta model generated van Genuchten parameter moisture retention curves (VGM) as plotted against measured data. Error bars on measured data represent standard deviation.

A full suite of physical and chemical analysis was conducted on the samples. Additionally, the Lincoln laboratory produced a set of moisture retention curves for the characterization pit samples using the Rosetta Model estimated van Genuchten parameters. The curves for the horizons corresponding with the 20 cm and 50 cm depth intervals are shown in Figures A3.5 and A3.6 of the appendix section, respectively, as a comparative reference. The Rosetta program estimates did a slightly better job at predicting the moisture retention curve for the 20 cm interval of the characterization pit data than it did with the study site Control or Tank samples though the model did underestimate the theta 1500 (15 bar) moisture retention value at the higher pressure. It also underestimated the moisture retention volume at the 0.3 and 15 bar range in the 50 cm depth interval, as it did with the study site samples. The most obvious difference between the soils modeled is the higher relative silt and lower relative clay content in the 20 cm interval USDA laboratory samples. Though not presented, the generated moisture retention curve of another Wrightsville soil for nearby Bossier Parish Louisiana, accessed on the USDA-Soil Characterization website, indicate that the Rosetta model generated van Genuchten parameters also tended to underestimate the higher pressure water retention values, as reflected in the model slope curves. In a personal communication with Mr. Thomas Reinsch, Acting National Leader for Soil Survey Investigations, he stated that the Rosetta model does a better job at predicting the van Genuchten parameters in some soils than others; due, in part, to the fact that the model was developed and calibrated with a limited range of soils. Of primary importance is the fact that the USDA laboratory curves and the curves that we generated are very similar and supports the assumption that our methods and procedures were sound.

In addition to plotting the Rosetta parameter estimates, we utilized Microsoft Excel Solver, an add-in analysis tool incorporated into Microsoft Excel (2007) for Windows, to obtain best-fit estimates of the van Genuchten parameters (Table 3.14). Using Solver, an iterative, non-linear least square optimization procedure was used to obtain best-fit parameter estimates for two soil-moisture retention data sets and for two different depths.

Table 3.14. Solver curve fitting parameter estimates.

	20cm_VGM_Control	20cm_VGM_Tank	50cm_VGM_Control	50cm_VGM_Tank
θ_s	0.454	0.391	0.443	0.440
Log α	-3.207	-4.324	-3.123	-4.008
log n	0.210	0.180	0.236	0.165
θ_r	0.100	0.063	0.126	0.071

As readily seen in Figures 3.19 and 3.20, the Solver program did a much better job of determining the parameter estimates for the Camp Minden study site soils than did the Rosetta Model. The r^2 value for all four moisture retention curves was ≥ 0.9946. The experimental data is represented by the open (Control) and closed (Tank trafficked) circles. It can be seen that the Solver program did a superior job of fitting the line to the averaged moisture retention values at both the 20 cm and the 50 cm depth intervals. The graphs illustrate the reduction in water holding capacity of the larger pores having average pore size diameters ≥ 15 μM in the tank trafficked soils. Pores in this larger size range tend to comprise the interaggregate pores spaces in well structured soils and are responsible for the more readily transmissible water. The graphs also show a strong apparent trend of increasing moisture retention capacity in the smaller micro pore size range having average diameters ≤ 1.5 μM, which are typically considered to have

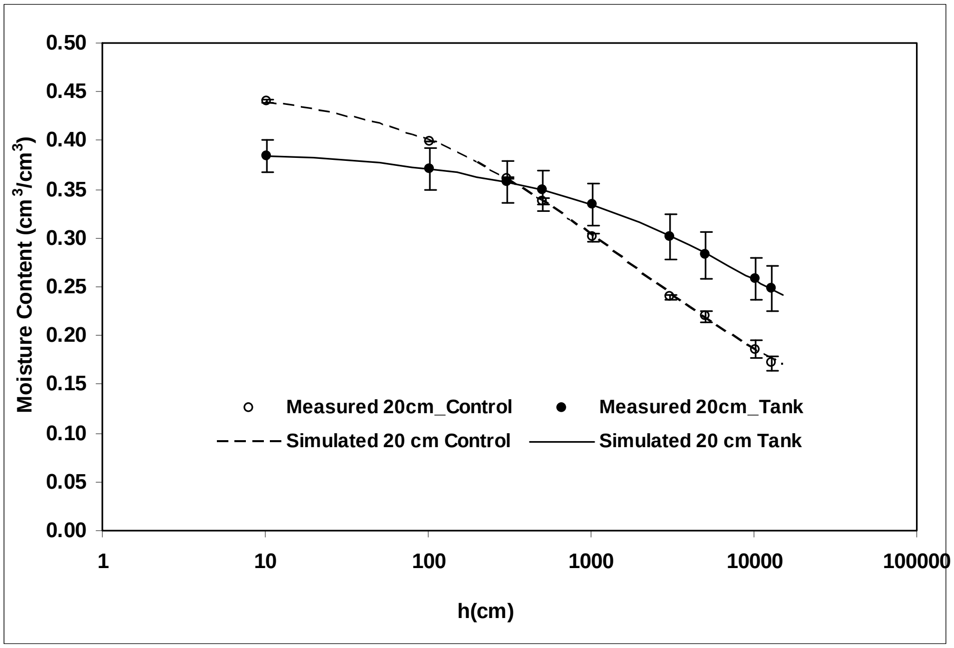


Figure 3.19. 20 cm depth interval Solver generated van Genuchten parameter moisture retention curves (VGM) plotted against measured data. Error bars = standard deviation.

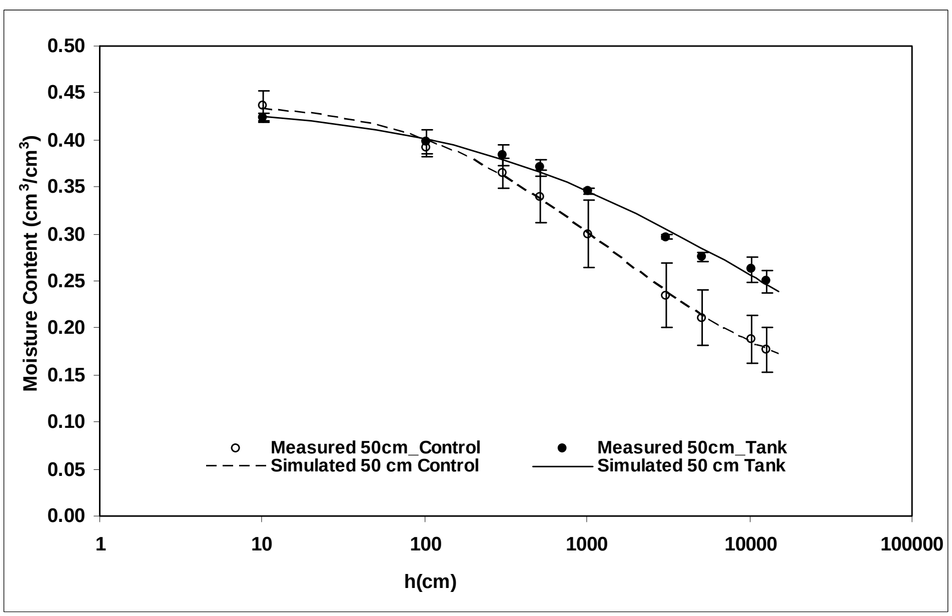


Figure 3.20. 50 cm depth interval Solver generated van Genuchten parameter moisture retention curves (VGM) plotted against measured data. Error bars = standard deviation.

relatively thin water layers associated with the soil fabric. As observed in the previous graphs, there appears to be less collapse of the largest pores with diameters ≥ 15 μM in the tank trafficked soils at the 50 cm depth interval. However, there is a trend of increasing moisture retention capacity in all pores ≤ 5 μM at this depth interval.

3.5 CONCLUSIONS

No statistically significant differences in relative bulk density change were observed at an alpha level of 0.05 at the 20 or 50 cm depth (Tables 3.11 – 3.12), which is due to the variability of the data. Additionally, neither ANOVA nor the Tukey-Kramer HSD revealed statistically significant trends that could be attributed to treatment combinations. However, evaluation of the post trafficked bulk densities at the 20 cm depth interval shows that 'moisture' treatment effect followed the trend Hi > Mid > Lo, with 1.65, 1.61, and 1.57 g/cm^3 respectively. Additionally, the Hi moisture treatment post trafficked bulk densities all approached the 1.65 g/cm^3 root limiting threshold (National Soil Survey Handbook, 2007) in the 20 cm depth interval. When evaluating 'traffic' rate at the 20 cm depth interval, the 3 and 9 pass treatments were nearly identical at 1.60 g/cm^3, with the greatest resulting bulk density in the 6 pass treatment level with 1.63 g/cm^3. When considering individual treatment factor only, moisture was a stronger determinant of final bulk density than was traffic rate. This was supported by evaluation of leverage plots produced in the Fit Model routine in JMP statistical software using standard least squares (data not shown). The leverage plots indicated that, at the 20 cm depth interval, moisture treatment was significant at a confidence level of 0.05; whereas traffic rate level and the interaction between moisture treatment and traffic rate were not significant.

At the 50 cm depth interval, the ‘moisture’ treatment effect followed the trend Mid > Hi > Lo; with values of 1.61, 1.60, and 1.56 g/cm^3 respectively. The Hi and Mid moisture treatment levels were essentially equal, with the Lo moisture treatment level being less, when using standard deviation as the significance criteria. When considering ‘traffic’ rate at the 50 cm depth interval, the 3 and 6 pass treatments were nearly identical at 1.61 g/cm^3, with the lowest resulting bulk density in the 9 pass treatment level at 1.56 g/cm^3. The leverage plots indicated that moisture treatment, traffic rate, and their interactions were all borderline significant at a confidence level of 0.05, as indicated by confidence interval curves.

The moisture retention curves indicate that there is an overall reduction in total porosity, as a result of tank traffic induced compaction, with corresponding reduction in water holding capacity in the 20 cm depth interval. There is also a significant reduction in average pore size, with an increase in smaller pores associated with higher pressures. These changes affect numerous soil physical properties and processes to varying degrees. Included are reduced infiltration, water retention and hydraulic conductivity; air capacity and gaseous exchange; increased runoff and erosion, soil strength and mechanical impedance to root growth. In turn, these changes indirectly affect numerous chemical and biological processes (Assouline, 2004; Johnson and Bailey, 2002; Glinski and Lipiec, 1990; Hakansson et al, 1988). There is a high probability of decreases in redox potential during the wet season, due to reduced air permeability of the more numerous smaller pores. The result of compaction was a decrease in the air-filled porosity of pores drained of water at pressures ≤ 0.3 bars, which will result in reduced aeration (Startev, 2001). The significant shift in pore size distribution toward smaller pore sizes also support the observation that compaction, particularly in the 20 cm depth interval, will impede natural regeneration of vegetation of soils trafficked under conditions where soil moisture content is at or near the plastic limit (19% gravimetric water content ≈ 29% volumetric content) of these soils.

The combined bulk density and soil-moisture retention data suggest that tank trafficking maneuvers on the study site soils, results in compaction levels in excess of the root restriction initiation level of 1.54 g/cm^3 can be anticipated during periods when soil moisture volumetric content exceeds 20%, (levels corresponding to the Mid and Hi moisture treatment levels). Additionally, tank trafficking maneuvers on these soils at the volumetric water contents in excess of 30% (levels corresponding to the Hi moisture treatment level) can be expected to result in bulk density values very near, or in excess of the recognized root limiting value of 1.65 g/cm^3, with as few as 3 traffic passes.

Ideally, a range management plan would monitor soil volumetric moisture content and, whenever practical, consider avoiding training activities with the M1A1 tank when soil moisture levels exceed volumetric water content of 20%. This is a value less than the average plastic limit (19% gravimetric water content ≈ 29% volumetric content) of the CMTS study site soils. Additionally, M1A1 training activities would be avoided when soil moisture levels exceed a volumetric water fraction of 30% to avoid soil compaction levels very near, or in excess of the recognized root limiting value of 1.65 g/cm^3. However, the intermound Wrightsville soils at the CMTS can be expected to have near saturated soil moisture contents, in excess of field capacity (36% volumetric), for significant periods during the months of December through April as indicated by the USDA official series description (Soil Data Mart-USDA, 2007). Since it would be impractical to suspend training maneuvers for the duration of this ‘wet season’, it is anticipated that root limiting soil compaction levels will develop in tank trafficked areas of this soil type. As such, it is suggested that range management plans include the contingency for disking operations to loosen compacted soil areas to maximize vegetative growth.

These conclusions are in agreement with other researches that found optimal conditions for soil compaction often occur at water content near field capacity, particularly as water content approaches the soils liquid limit (Porsinsky et l, 2006; Akram and Kemper, 1979; Soane et al, 1981; Gent and Morris, 1986; Startsev and McNabb, 2001).

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CHAPTER 4

INFLUENCE OF TRAFFIC RATE AND SOIL MOISTURE CONTENT ON SOIL PENETRATION RESISTANCE

4.1 INTRODUCTION

Military training exercises, using heavy tracked vehicles, is an intensive land use activity that results in vegetation disturbance and soil compaction, which can have long lasting environmental effects (Althoff and Thien, 2005; Palazzo et al., 2003, 2005; Fehmi et al., 2001; Diersing and Severinghaus, 1988). Mobile tracked vehicles crush and shear woody and herbaceous vegetation during maneuvers, with potentially long-lasting damage, depending on use intensity. Additionally, the resulting soil compaction can alter soil physical, chemical, biological and hydrologic properties to the extent that vegetation regeneration is impaired and can ultimately lead to a shift in plant community composition and productivity (Althoff and Thien, 2005; Halvorson et al, 2003; Prosser et al, 2000; Johnson and Bailey, 2002; Prose and Wilshire, 2000; Diersing and Severinghaus, 1984).

Preliminary evaluation of the “soil factors” that affect plant growth and natural vegetation regeneration at Camp Minden Louisiana led investigators to conclude that soil compaction would be the primary factor of investigation. A brief listing of effects of soil compaction is as follows:

- ✓ Increased soil strength and bulk density,
- ✓ Increased mechanical impedance,
- ✓ Alteration and/or destruction of soil aggregate structure,
- ✓ Decreased total pore volume,
- ✓ Changes in pore size distribution percentage,
- ✓ Reduced water infiltration, drainage, and aeration,
- ✓ Potential increased frequency and duration of anaerobic conditions

Impaired soil and soil-plant processes resulting from soil compaction include, but are not limited to:

- ✓ Reduction or prevention of root penetration and root elongation,
- ✓ Limited water, aeration and nutrient availability for plants and microbes,
- ✓ Potential redox implications due to modified hydrology,
- ✓ Potential alteration of organic matter decomposition rate and release of plant nutrients.

The objectives of this research were to study the effects of M1A1 tank traffic on soil compaction as influenced by soil moisture and traffic rate. We utilized soil penetration resistance measurements taken immediately prior to and following tank traffic passes as one of the indicators of soil compaction. We took additional penetration resistance measurements 15 months after initial traffic passes to assess relative compaction levels and soil resilience.

4.2 REVIEW - SOIL COMPACTION AND ITS RELATION TO OTHER FACTORS

Soil compaction is generally defined as the process by which a mass of soil consisting of solid soil particles, air, and water is reduced in volume by mechanical means thereby increasing dry density or bulk density (Shroff and Shah, 2003). As bulk density increases, there is frequently a corresponding increase in soil mechanical strength, resulting from the closer packing orders of the soil particles. Soil compaction is a more or less rapid process of volume reduction resulting from dynamic loading, usually resulting in substantial rearrangement of soil particles and the expulsion of air from the soil voids. Soil consolidation is similar to soil compaction; however, it is a gradual process of volume reduction and densification under sustained static loading, with little rearrangement of soil particles typically accompanied by the expulsion of air and water (USDA-SCS-NEDS, 1988).

Three primary variables that interact and determine the dry unit weight or bulk density of a compacted soil mass are: 1) moisture content at which the soil is compacted, 2) type of soil being compacted, and 3) the amount and type of energy applied (USDA-SCS-NEDS, 1988). In the following discussion, the focus is on characteristics of fine-grained soils comparable to those encountered at the site selected for the present study.

A soil's resistance to compaction is a function of soil strength. Soil strength can generally be defined as the minimum stress required that will cause a soil body to fail by means of fragmentation, rupture or flow. Soil strength can be difficult to measure due to the high variability of the property which can change during the process of measurement. During measurement, the deformed soil body may increase or decrease its resistance to further deformation, depending on other conditions. Illustration of this point can be made by considering that the strength of an unsaturated soil may increase as the soil becomes compacted; while a saturated soil may experience loss of cohesion and possibly liquefaction (Hillel, 1998). As such, the moisture content at which a soil is compacted is particularly important. At any given compaction effort, the resulting bulk density is dependent upon the soil moisture content or wetness. Starting from a dry condition, the attainable bulk density initially increases with soil wetness and then reaches a maximum at a wetness referred to as 'optimum' moisture content. Beyond this 'optimum' moisture, additional water decreases the resulting attainable density. This typical soil moisture to compaction trend can be explained by the fact that dry soils are typically resistant to compaction because of their stiff matrix and high degree of particle to particle bonding, interlocking, and frictional resistance to deformation (Hillel, 1998). As soil moisture increases, the thicker films of water weaken the interparticle bonds in low charge particles by means of expansion of the diffuse double-layer. This results in a corresponding reduction in attractive forces between particles, or an increased interparticle repulsion, which permit the particles to slide past one another into a more uniformly oriented, or denser, packing state. Additionally, initial increments of water tend to reduce interparticle friction between coarser, less electro-chemically active particles, thus serving as a lubricant. However, beyond the previously mentioned optimum soil moisture content, the incremental fractional volume of expelled air is reduced and the addition of water may actually start to increase, thus reducing soil bulk density and apparent soil strength (Shroff and Shah, 2003).

The second primary variable in soil compaction, 'type of soil', is characterized by the particle size distribution, size and distribution of void spaces, and the electro-chemical properties of soil particle surfaces. The soils of our study site are considered fine-grained soils and consist of various percentages of silt and clay fines with small percentages of sand sized particles. Classification of soils under the Unified Soil Classification System (USCS) uses a combination of letters to describe soil properties that primarily affect engineering properties. The abbreviation for a soil group in the USCS consists of two or more letters. The soils at the Camp Minden study site are classified as ML, CL, and CL-ML under the USCS. These soils are dominated by CL and to a lesser degree ML soils. The two-letter abbreviations for the classification groups encountered at the Camp Minden site are modifiers used to describe the plasticity characteristics and liquid limit values. A summary of the meaning of each letter is as follows: C = fines with plastic characteristics; M = fines with non-plastic to slightly plastic characteristics; and L = fine-grained soils with low liquid limit values less than 50. The USCS classification and Atterberg limits of the Camp Minden soils are found in Table 4.1 and graphically displayed in Figure 4.1a and b.

Coarse-grained soils derive their strength, or resistance, to compaction primarily from internal friction resistance as coarser particles tend to interlock as they slide past

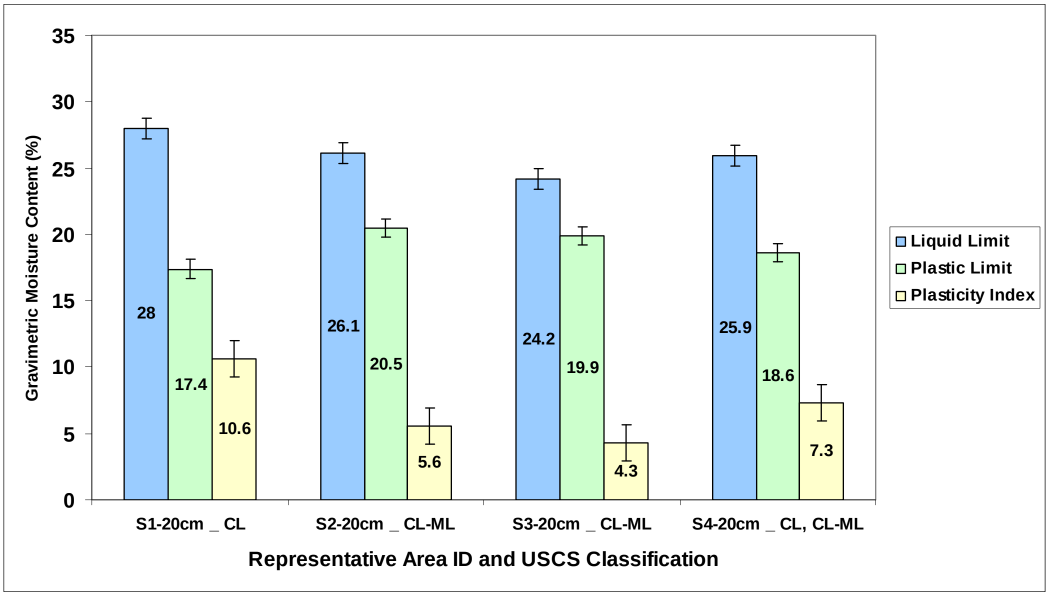
Table 4.1. Atterberg limits (LL, PL, and PI) and Unified Soil Classification System (USCS) class for shallow (20cm) and deep (50cm) horizons by site area.

Site Area ID†	Liquid Limit	Plastic Limit	Plasticity Index	USCS Class
S1-20cm	28	17.4	10.6	CL
S2-20cm	26.1	20.5	5.6	CL-ML
S3-20cm	24.2	19.9	4.3	CL-ML
S4-20cm	25.9	18.6	7.3	CL, CL-ML
S1-50cm	29.1	18.5	10.6	CL
S2-50cm	30.7	17.7	13	CL
S3-50cm	29.6	18.4	11.2	CL
S4-50cm	29.5	18.7	10.8	CL

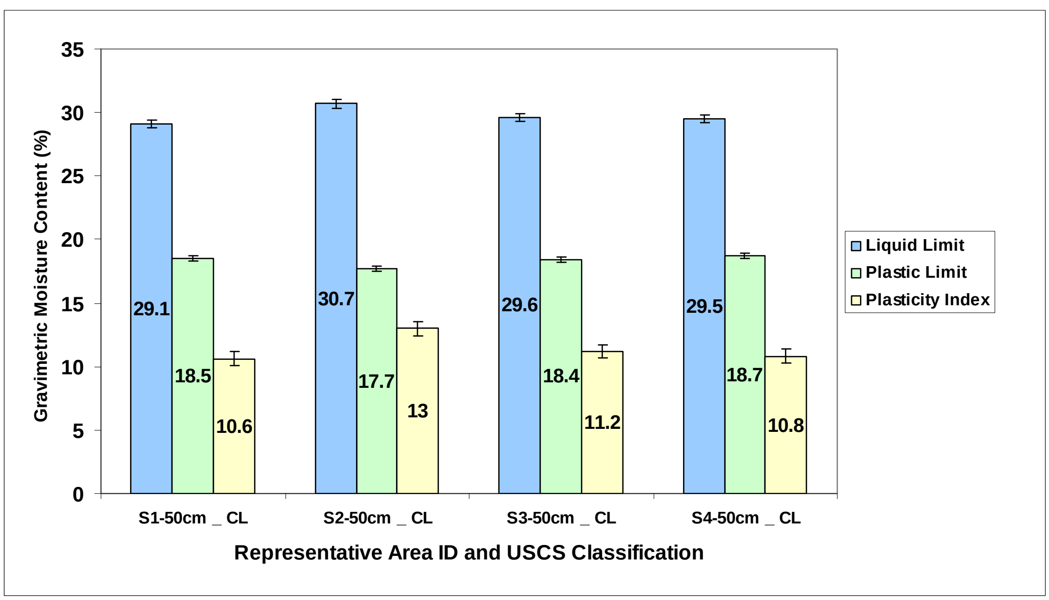
† Site Area ID denotes plots associated with data loggers S-(1-4) and depth (cm).

each other. Fine-grained soils derive their strength primarily from cohesion, due to electro-chemical properties of the fine fraction. Soils having high percentages of clay sized particles are typically classified as CL or CH and tend to be strongly influenced by the high electrical charge to surface area ratio. The cohesive strength of clays with finer structure and higher electrical charge such as montmorillonite are most affected; whereas clays with coarser lattice structure and less electrical charge, such as kaolinite, are somewhat less affected. The silt size particles, however, are relatively inert; and the soils classified as ML and CL-ML, which are dominated by silt, exhibit little internal friction or cohesion (USDA-SCS-NEDS, 1988).

Clay size particles have a high attraction to water and to each other. They can only be readily compacted over a very narrow range of water content. At very low water content there is insufficient water for lubrication and to generate interparticle attraction. Compaction is made more difficult, at very high water content in clayey soils, due to their inherent low permeability, resulting from small soil pore or void sizes, making expulsion of water difficult (USDA-SCS-NEDS, 1988). In general, the higher the liquid limit and the higher the plasticity index, the more difficult a fine-grained soil is to compact and the more important water content is to effective compaction.



a)



b)

Figure 4.1. Atterberg Limits and USCS Classification for a) EBg horizon and b) Btg/E1 horizon. Error bars represent standard error.

As seen in Table 4.1, the soils at the study site are dominated by soils classified as CL and to a lesser degree ML. These soils are relatively easy to compact, particularly when wetted, due to the lack of internal friction, moderate to low cohesion, low liquid limit and low plasticity.

The amount and type of mechanical energy applied is the third primary variable of importance in the final compaction density of a soil. The primary types of mechanical energy application are grouped as follows: 1) static load application or live weight, 2) kneading action, 3) vibratory action, 4) impact load application, or 5) a combination of two or more of the above. The A1 tank weighs 63 tons (57 mt) and has a ground pressure of 15.0 psi (1.05 kg/cm^2). The amount and type of mechanical energy produced by the A1 is similar to that of a heavy crawler tractor (bulldozer). It imparts a combination of static live load, vibratory action and some degree of kneading as a result of the track grousers (USDA-SCS-NEDS, 1988). For most soils, and with all methods of compaction, an increase in compaction effort results in an increased bulk density, with a corresponding reduction in optimal water content. However, at high water content, at or near saturation, soil particles may simply be realigned without significantly altering particle spacing; and no substantial increase in bulk density will result from additional compaction effort.

The primary objective of this study was to determine the relative degrees of compaction induced by varying tank traffic rates on these soils under varying moisture conditions. Specifically, the goal was to determine the critical soil moisture content and number of passes with the M1A1 tank required to induce maximum compaction. It was hypothesized that the relative amount of applied external forces exerted by the M1A1 tank, in conjunction with the relative moisture content of the soil at the time the force is applied and the soil particle size distribution, will determine the degree to which the soil is compacted. With this knowledge, training officers can avoid these conditions during training maneuvers. As such, the relative degree of soil compaction induced by tank traffic on soils of this study site needs to be determined using similar field plot methods as that described below.

4.3 MATERIALS AND METHODS

4.3.1 Study Area

The location selected for the study was the Camp Minden Training Site (CMTS), which is the Louisiana Army National Guard's (LAARNG) second largest training site. The CMTS is located approximately 16 miles east of Bossier City, Louisiana on the Bossier/Webster Parish line and covers approximately 13,682 acres (Figure 4.2). The CMTS was selected because it had been designated as an A-1 tank training facility and was to have approximately 50, A-1 tanks available for detailed training and maneuvers. Camp Minden is located in the Western Coastal Plain Major Land Resource Area (MLRA 133B) and in the Coastal Plain Province physiographic region. Camp Minden is situated on Quaternary geologic sediments. These sediments were the braided stream terrace deposits of ancient river systems. The sediments were subdivided according to different interglacial periods. Camp Minden is on two of the five divisions, the Montgomery and Prairie Terraces. The surface landscape is comprised of nearly level to rolling topography with relatively broad, nearly level to gently sloping ridge tops and gently to moderately sloping sideslopes. The area is dissected by several drainageways. Elevation ranges from about 184 feet on the eastern boundary along Bayou Dorcheat to about 225 feet near the geographic center of the facility. Air temperature averages from 7 to 28 degrees C (44 to 82 degrees F) and precipitation averages about 120 centimeters (48 inches) annually. The frost-free season is about 233 days.

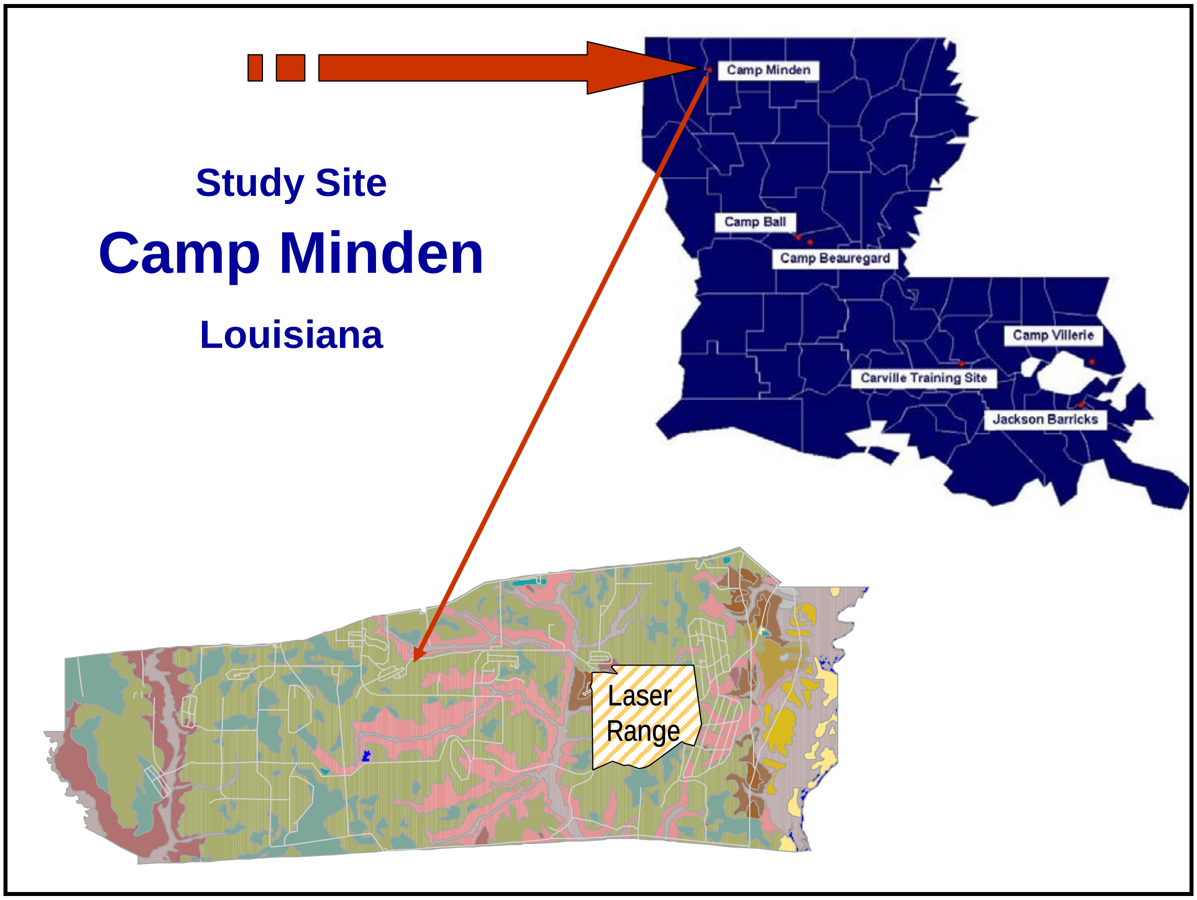


Figure 4.2. Map of Louisiana Army National Guard facilities and the Camp Minden Tank Trafficability and Soil Resilience Study Site.

4.3.2 Soil Type

The soils at the experimental test site at the CMTS are mapped Kolin silt loam (Fine-silty, siliceous, active, thermic Oxyaquic Glossudalfs) (Soil Data Mart-USDA, 2007). These soils are on uplands and terraces of Pleistocene Age. The Kolin soil series consists of very deep, moderately well drained, very slowly permeable soils that formed in loamy sediments overlying clayey sediments. A perched water table exists above the argillic horizon (45 to 90 cm) from December through April in most years.

Most of the areas of this soil are in mixed hardwood and pine woodland. A small acreage is used for pasture and cultivated crops. The soils at the study site have a complex landscape micro-topography of mounds and inter-mounds, with the mounds having better drainage (Web Soil Survey-USDA, 2007). During the initial phases of this study, the dominant proportion of inter-mound area was identified as inclusions of Wrightsville (Fine, mixed, active, thermic Typic Glossaqualfs) that is less well drained. The Wrightsville series consists of very deep, poorly drained, very slowly permeable soils, with slow runoff, that formed in old silty and clayey alluvium. Slopes are less than 1 percent. These soils are on level to depressional areas on old stream terraces. As a result, the soil is wet in the layers below a depth of 15 to 45 cm (6 to 18 inches) and above the Btg horizon, during December through April, in normal years (Web Soil Survey-USDA, 2007).

The Wrightsville soil is in land capability subclass IIIw and, as such, has severe limitations due to wetness. These limitationst reduce the choice of plants or that require special conservation practices, or both. The soil is used mainly as woodland and is moderately well suited as pine woodland. The main concerns in producing and harvesting timber are severe equipment use limitations and severe seedling mortality, caused by wetness. When the soil is moist, methods of harvesting timber that use standard wheeled and tracked vehicles causes rutting and soil compaction (Soil Data Mart-USDA, 2007). Because of this high susceptibility to wetness and the associated negative affects of soil compaction that would result from heavy mechanized maneuvers, the study plots were established in the inter-mound Wrightsville soils.

A soil characterization pit was excavated (Figure 4.3) in the spring of 2006 to facilitate detailed soil profile description and soil sample collection and analysis. The soil pit was in a wooded area adjacent to the study site and located at Lat: 32° 33' 55.50" north, Long: 93° 24' 24.60" west, NAD 83, MLRA 133B. Soil samples were extracted from each horizon of the soil pit profile and shipped to the USDA-NRCS National Soil Survey Center - Soil Survey Laboratory in Lincoln NE for detailed physical and chemical analysis. The Site ID and Pedon No. on record are 06LA119001 and 06N0859 respectively. The soil was taxonomically identified as Wrightsville Fine, mixed, active, thermic Typic Glossaqualf. Detailed USDA soil lab characterization data can be accessed via the internet from the National Cooperative Soil Survey Soil Characterization Database (http://ssldata.nrcs.usda.gov/querypage.asp).

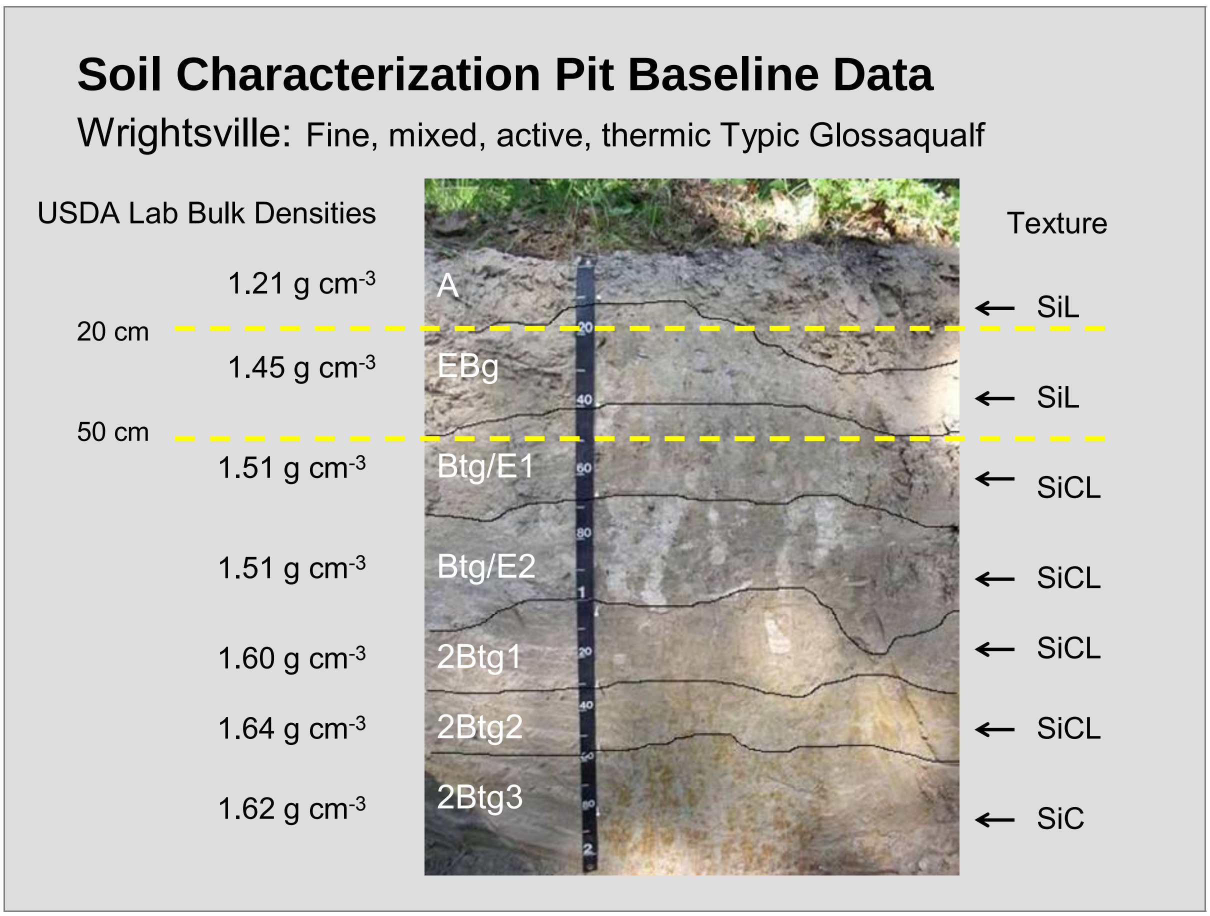


Figure 4.3. Wrightsville characterization pit photograph with horizon designations, USDA lab bulk densities, horizon textures, and critical investigation depths.

Of potential relevance to this study was the identification of soil textures in the A, EBg, and Btg/E horizons. Soil particle size distribution was determined by hydrometer method (Gee and Bauder, 1986). Generalized USDA soil textures were as follows: (i) A horizon – silt loam; (ii) EBg horizon – silt loam and silty clay loam; and (iii) Btg/E horizon – silty clay loam and silt loam. The EBg horizon textures tend toward the upper clay threshold of silt loam while the Btg/E horizon textures tend toward the lower clay threshold of silty clay loam. The less than 2 mm fine earth fractions, particle densities, and USDA textural classes are illustrated in Table 4.2. Plot textures were grouped and averaged by 'Site Area' (1-4), which corresponds to centralized data loggers around which individual plots are distributed.

Table 4.2. Mean particle-size fractions, particle density and USDA class.

Site Area ID†	Clay	Silt	Sand	Particle Density	USDA Texture
	(< 2μm)‡	(2-50μm)‡	(>50μm)‡		
	--------------------	%	--------------------	g cm^{-3}	
A-8cm	15±3	71±6	14±5	2.71	SiL
S1-20cm	28±3	66±5	6±2	2.69	SiL, SiCL
S2-20cm	24±3	68±3	8±2	2.69	SiL
S3-20cm	23±2	62±3	15±3	2.69	SiL
S4-20cm	24±3	61±4	15±4	2.69	SiL
S1-50cm	28±7	62±2	10±8	2.69	SiCL, SiL
S2-50cm	26±3	66±4	8±5	2.69	SiL, SiCL
S3-50cm	27±4	57±4	16±6	2.69	SiCL, SiL
S4-50cm	27±6	56±2	17±6	2.69	SiCL, SiL

† Site Area ID denotes plots associated with data loggers S-(1-4) and depth (cm).
‡ Values following ± represent standard deviation.

4.3.3 Site Preparation and Plot Establishment

In March of 2003, 48 plots measuring 5 meters by 5 meters square were established in the intermound areas of the selected study site, which was in a managed pine forest stand. The plots were distributed over an area of approximately 2.6 hectares (6.4 acres) and were permanently located by driving 1.5 meter long by 1.6 centimeter diameter steel rebar rods into the ground at the plot corners. A numerically stamped metal identification tag was affixed to one corner rod of each plot and a GPS reading was taken at the center point. The trees were subsequently removed from the study site between March and July of 2003. Special instructions were issued to the harvesting personnel to avoid driving equipment on, or allowing harvested trees to fall on, the individual plots to minimize compaction or other disturbance. The site remained undisturbed for four years (June 2007) to allow establishment of early succession vegetation.

4.3.4 Experimental Design

The experimental design was a completely randomized factorial design that attempted to evaluate the effects of soil moisture content (Factor 1) and tank traffic rates (Factor 2) on soil compaction and soil strength. Factor 1 was split into three levels as determined by volumetric water fraction (wfv): (i) Dry or ‘Lo’ (0.05 to 0.20 wfv); (ii) Intermediate or ‘Mid’ (0.20 to 0.30 wfv); and (iii) Wet or ‘Hi’ (>0.30 wfv). Factor 2 was split into three levels: (i) 3; (ii) 6; and (iii) 9 passes with the M1A1 battle tank in crisscross configuration to achieve complete coverage of each plot. Each treatment combination was replicated 3 times resulting in a total of 27 experimental plots. A single representative replicate is illustrated in Table 4.3. Treatment combinations were randomly assigned to 27 plots with the remaining 21 plots available as control checks in follow-up evaluations (Figure 4.4). Tank runs were conducted between August and October 2007. Specific dates of individual runs are presented in Table A.3.1 in the appendix. Average monthly temperature and precipitation data are presented in Table A.3.2 of the appendix.

Table 4.3. Single replicate of soil moisture and traffic rate treatment combinations. Soil moisture = volumetric water fraction (wfv), Passes = passes with Abrams tank in crisscross configuration.

Soil Moisture†	Passes	Passes	Passes
Lo = Dry (< 0.20 wfv)	3	6	9
Mid = Intermediate (0.20 to 0.30 wfv)	3	6	9
Hi = Wet (> 0.30 wfv)	3	6	9
Control = Not applicable	0	0	0

†wfv - Volumetric water fraction.

4.3.5 Site Instrumentation

In June 2007, a Campbell Scientific, Inc. (Logan, UT), CR-10X datalogger with CSI AM16/32 multiplexer (Figure 4.5) was installed at each of four site station locations distributed across the larger study area. The dataloggers were linked by means of radio telemetry and satellite uplink equipment to facilitate daily soil moisture and temperature monitoring via internet website. A tipping bucket rain gauge and Campbell Scientific Inc., Model# 107 air temperature sensor were wired into the datalogger at site 1 for atmospheric environmental monitoring purposes. Dataloggers were powered by 12 volt batteries charged by solar panels.

In May and June 2007, Stevens ‘Hydra Probe II’ soil moisture, temperature and salinity sensor probes (Stevens Water Monitoring Systems, Beaverton, OR) were modified to facilitate long cable runs up to 150 feet from the experimental plots to the centralized Campbell dataloggers. Each Hydra Probe II sensor had a seven wire cable which was extended to accommodate plot distances of up to 150 feet. Individual wires within the cable were spliced, soldered, and sealed with heat shrink tubing. In addition, each cable was then water-tight sealed with heat shrink tubing and silicone and

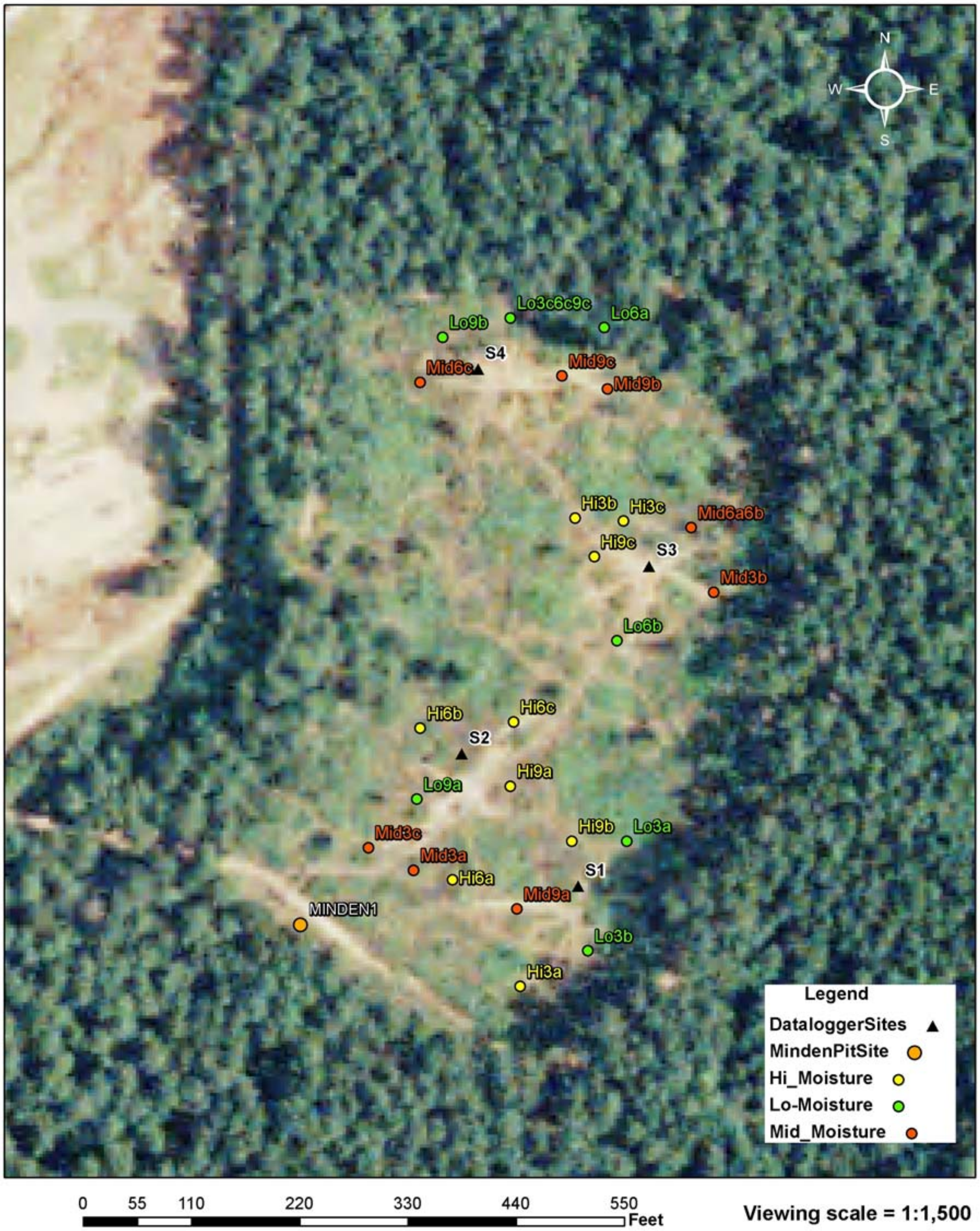


Figure 4.4. Map of Camp Minden tank study site.

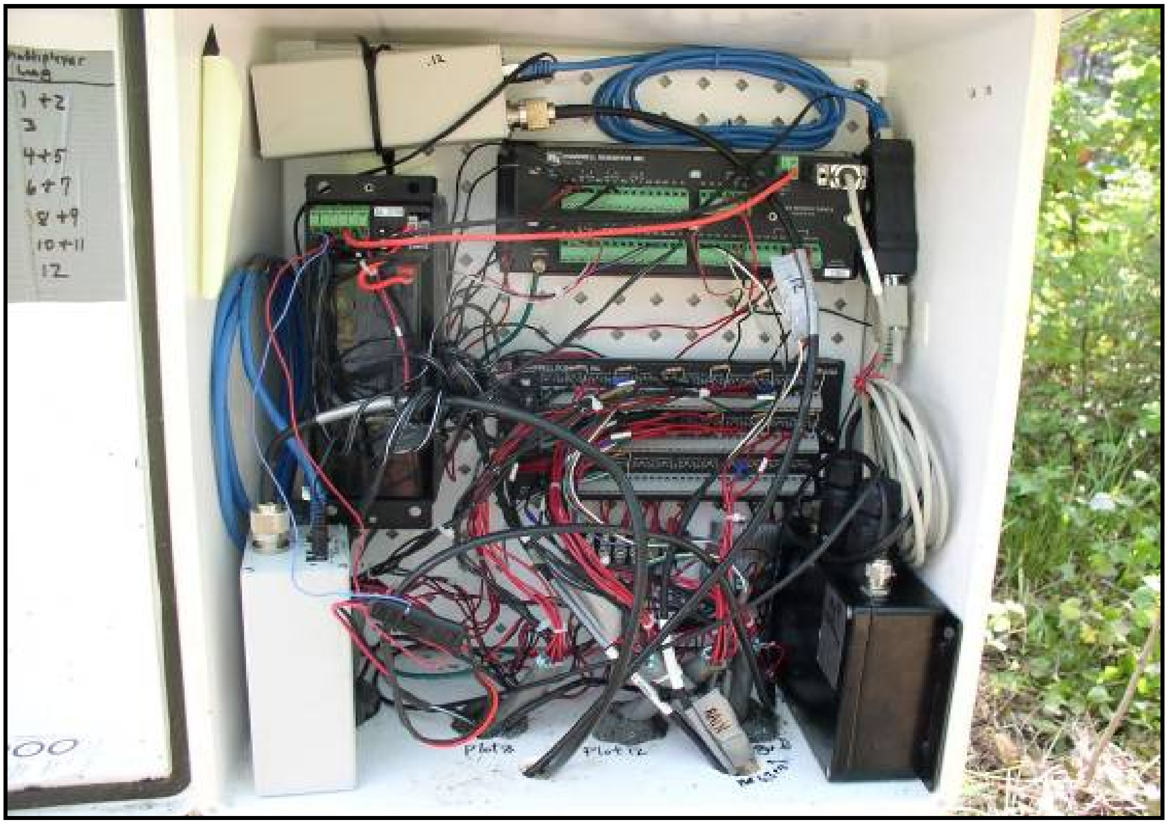


Figure 4.5. Primary site data logging station with Campbell Scientific CR-10X® datalogger, CSI AM16/32 multiplexer, radio telemetry, satellite uplink, and atmospheric environmental monitoring equipment.

wrapped with duct tape. Each sensor was tested before and after splicing, in open air and in tap water, to insure acceptable operation across wide moisture ranges.

In June, July, and August 2007, the modified Hydra Probe II sensors were installed at depths of 20 and 50 cm within 18 of the 30 plots (Figure 4.4). Sensors were installed at 50 cm only in the remaining 12 plots. Installation depths of 20 and 50 cm were chosen to yield information on soil moisture content of the epipedon (A and EBg horizons) and the argillic subsoil (Btg/E horizons). Sensor installation was facilitated by excavating a 30 cm diameter hole to a depth of approximately 60 cm deep. The sensor tongs were inserted into the soil bore wall (Figure 4.6) and the sensors were connected to Campbell dataloggers.

Sensors were allowed to “equilibrate” for 5 to 7 days in the soil environment and test readings were taken for each sensor to insure proper operation. Sensor cables were buried in 60 cm deep trenches to protect them from being damaged by tank traffic. The soil bore holes were then backfilled with soil material to approximate original soil density. Hydra Probe II moisture and temperature readings were to be taken hourly and averaged daily.

Figure 4.6. Stevens Vital soil moisture, temperature, and salinity sensor with depiction of typical installation in excavation wall at 20 cm and 50 cm depths. Cables were buried in trenches.

The dataloggers were equipped with satellite remote download capabilities so that soil moisture levels could be remotely monitored on a daily basis to determine appropriate timing for tank runs. The location of the site characterization pit, the four datalogger stations, and the study plots with treatment combination identification is illustrated in the map shown in Figure 4.6. The map base is 2007 ortho imagery.

Soil moisture was initially to be determined by averaging moisture content of the upper 50 cm of the plot soil profile as indicated by soil moisture sensor readings, as described above, and verified by soil core extraction to a depth of 50 cm and microwave drying to a stable soil weight. However, soil moisture sensor readings became erratic and unreliable following thunderstorm activity in early September 2007 and soil moisture content was subsequently determined by microwave drying extracted soil cores to a depth of 50 cm. A soil core with a volume of 142 cm^3, measuring 1.9 cm diameter by 50 cm deep, was taken from the center of each plot prior to tank runs with an Oakfield tube sampler. The bulk sample was microwave dried to a constant weight to determine volumetric moisture content. Treatment level average moisture contents with standard deviations and ranges are presented in Table 4.4.

Table 4.4. Measured pre-traffic soil moisture levels.

Moisture Treatment Level	**Volumetric Moisture Content** Mean ± Std. Dev.	**Moisture Range**
Hi	0.38 ± 0.02	0.34 - 0.41
Mid	0.27 ± 0.02	0.24 - 0.30
Lo	0.18 ± 0.01	0.17 - 0.21

4.3.6 Soil Compaction Measurements – Initial Pre and Post Tank Cone Penetration Resistance and Follow-Up Penetration Resistance

Initial cone penetration resistance (PR) measurements were taken at 5 cm depth intervals to a depth of 45 cm using a Spectrum Technologies, Inc. (Plainfield, IL) Field Scout SC-900 cone penetrometer. The PR measurements were taken in August, September, and October of 2007, when tank traffic was applied to individual plots. A total of 18 PR measurements were taken in each of the 27 experimental treatment plots. Nine measurements were taken immediately preceding (Pre) and 9 were taken immediately after (Post) tank passage to minimize possible temporal effects related to soil moisture change and possible disturbances. Pre and post PR measurements were taken along a diagonal transect in predetermined 1 meter grid sections within each plot

(Figure 4.7). The pre and post PR measurements were taken under variable soil moisture levels as outlined in section 4.3.4.

In addition, follow-up PR measurements were taken at 1 cm depth intervals to a total depth of 60 cm using an Eijkelkamp Agrisearch Equipment (Giesbeek, Netherlands) Penetrologger cone penetrometer. The follow-up measurements we taken in January 2009, when all plots had relatively uniform volumetric soil moisture contents at levels near saturation (0.40 +/- 0.05 wfv). Note: This moisture content is above the ideal 'field capacity' moisture content for soil penetration resistance measurements. Seven PR measurements were taken from all experimental plots and from 8 randomly selected control plots in an attempt to compare residual soil compaction effects on trafficked plots relative to undisturbed control plots. The PR measurements were taken along two diagonal transects in predetermined 1 meter grid sections within each plot (Figure 4.7). A total of 224 PR measurements were taken for a total of 13,440 data points.

4.3.7 Statistical Analysis of Penetration Resistance Measures

Statistical analysis of pre and post tank traffic penetration resistance measurements was accomplished using JMP Statistical Software, Version 5.0.1.2. JMP was developed by SAS Institute Inc., Cary NC. JMP is a business unit of SAS. Exploratory statistical analysis of all penetration resistance data was conducted to screen for extreme outliers that could lead to false interpretation of data results. Possible outliers were identified, as observations on generated box and whisker plots, that fell below and above the first and third quartiles by a magnitude of 1.5 times the interquartile range (McClave and Dietrich, 1992).

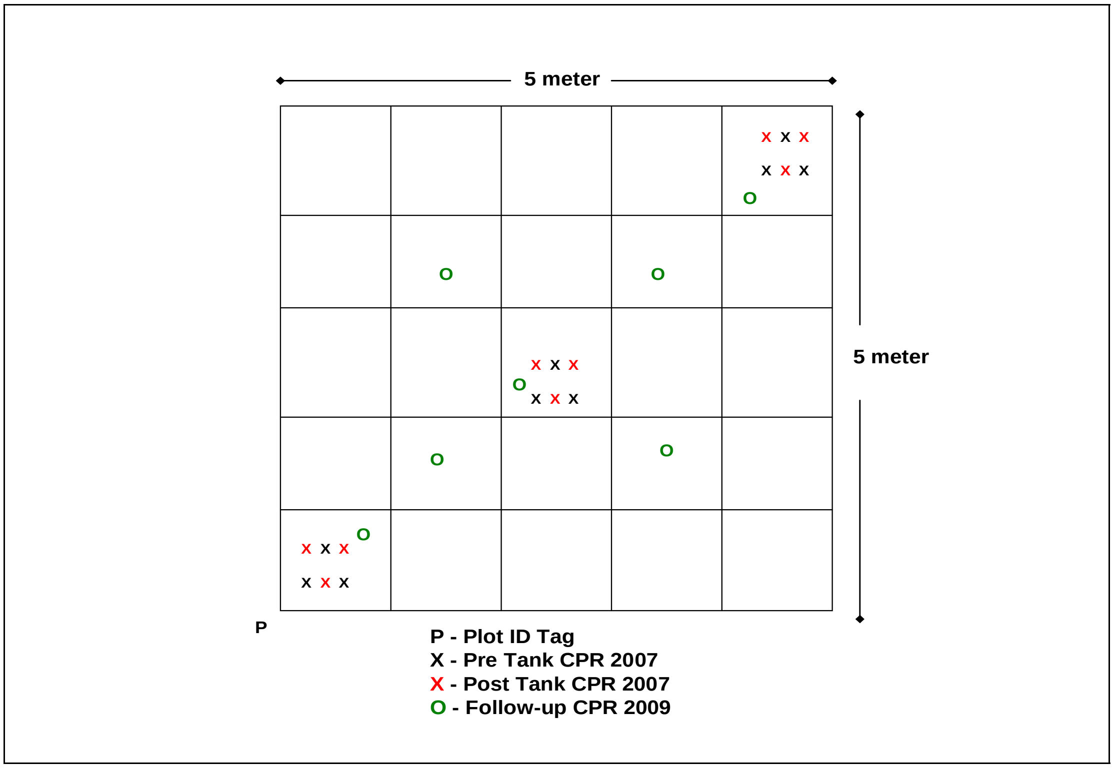


Figure 4.7. Plot grid diagram of cone penetration sampling locations.

Of the 13,440 data points originally collected in the 2009 follow-up penetrations, 126 points (0.9%) were removed due to high likelihood that they were outliers not representative of soil conditions. These extreme data points can be readily explained by the fact that the experimental plots were located in a recently cleared pine forest area. Numerous roots of varying sizes were encountered during trenching and excavation operations. Frequently, large roots were encountered that the penetrometer could not bore through, requiring the operator to move some distance and restart the penetration.

ANOVA and Tukey-Kramer HSD means comparisons were used to determine statistical significance between treatment combinations. Comparisons of treatment variability and means are presented graphically as box and whisker plots and Tukey means comparison circles. There is an accompanying data table for each graph. The

2009 follow-up data, presented in the statistical evaluation, are penetrometer cone index values, which have been averaged over 10 cm depth intervals, from the surface to a depth of 60 cm. Cone index is defined as the insertion force required to insert the penetrometer cone into the soil, divided by the cross-sectional area of the base of the cone (CEMML, 2004). The accompanying data tables give analysis of variance statistics and means comparisons for all pairs using an alpha level of 0.05. The F-probability, mean, standard error, 95% confidence intervals, error sources, and means comparisons by letter are produced.

4.4 RESULTS AND DISCUSSION

The initial 2007 pre and post PR measurements provide overall information on the relative increase in soil strength resulting from tank induced compaction when comparing within plot and within moisture treatment levels. However, due to extensive soil heterogeneities and the sensitivity of the cone penetrometer to soil moisture they did not provide a direct measure for between moisture treatment comparisons. As an illustration of this point, compare the range of the ‘pre’ tank passage PR values for the Hi, Mid and Lo moisture plots that are presented in Figures A.4.1a – A.4.9a in the Appendix at the end of the document. The 5 cm depth PR values range from 2 to 2.5 MPa in Hi, 2.8 to 2.9 MPa in Mid, and 3.25 to 4.25 MPa in Lo moisture treatments. This demonstrates a near doubling in the baseline penetrometer readings across the untreated plots as a result of initial moisture content only and is not atypical (Busscher, 1997). Comparison of the pre and post readings, depicted as blue and orange lines respectively, do give some indication of the variability in compaction within treatment groups, as indicated by the error bars which represent standard error of the means at each depth interval. It can also be observed that all treatment combinations resulted in increased penetration resistance measurements, as compared to the Control plots indicating an increase in soil compaction levels for all treatments. Figures A.4.1b – A.4.9b show the relative change between pre and post treatments in MPa. While the relative change in the Lo and Hi moisture treatments follow similar trends between numbers of passes, the Mid moisture trend lines appear much more erratic throughout the profile. This observation could be due to non-uniformity of soil moisture contents throughout the profile in these plots at the time the tanks were run and the PR readings were taken. To further illustrate the effect of soil moisture on penetration readings, each figure A, with the pre and post comparisons, has the 2009 follow-up PR readings that were taken in the corresponding plots while soil moisture was relatively uniform and above field capacity, e.g., L9 FC in Figure A.4.1a. These readings were much less erratic than the 2007 pre and post treatment PR measures and were more indicative of the residual relative differences in soil compaction levels due to tank traffic at varying moisture and traffic levels. As such, the 2009 follow-up data were used to make statistical inferences about soil compaction levels, as indicated by cone penetrometer readings.

As mentioned in the materials and methods section, the follow-up PR measurements of January 2009 were taken at uniform soil moisture levels using an Eijkelkamp Penetrologger, which gives readings at one centimeter intervals as opposed to the 5 cm interval readings produced by the SC900 penetrometer used in the initial 2007 data collection. As a result, the Eijkelkamp Penetrologger yields much more detailed profile measurements. While it is impractical to make comparisons at each one centimeter interval among all treatment combinations, the detailed readings produced by the Eijkelkamp make it possible to identify a maximum cone index interval, or averaged depth interval, with which to analyze the data without losing precision. Averaging and grouping the data into 10 cm intervals retained the general slope shape and inflection points when compared to graphs using the full 1 centimeter interval data set. Cone Index values represent averaged (10 cm interval) penetration resistance measurements of all plots at soil moisture contents greater than field capacity and near saturation levels. The exception to the 10 centimeter 'grouping' interval used was the surface CI, which was the reading for the surface one centimeter. This reading gives an indication of surface or crust strength. Figure 4.8 illustrates the averaged 10 cm interval PR profiles for each treatment combination and the averaged untreated control profiles as a comparative reference for pre-experimental field conditions. A number of inferences can be made from this graphic. The first inference being that there was little relative difference in PR between any of the treatment combinations at the surface as compared to the subsurface intervals. Additionally, maximum relative rate of change or increase in PR occurs between the surface and the 10 cm depth for the Lo and Mid moisture treatments, and between the surface and the 20 cm depth for the Hi moisture treatments. This observation is indicated by the slope of the lines and their inflection points. It can also be observed that the 'general trend' in PR values throughout the profile follows moisture class such that Hi = Mid > Lo > Control treatments for all depth intervals except the 20 and 30 cm intervals where trends were Hi > Mid > Lo > Control treatments. Less obvious from the graph was the effect of traffic rate, or number of passes. While the general trend was such that 9 > 6 > 3 > 0, there was less consistency among 'number of passes' at each depth interval than there was among 'moisture' treatments.

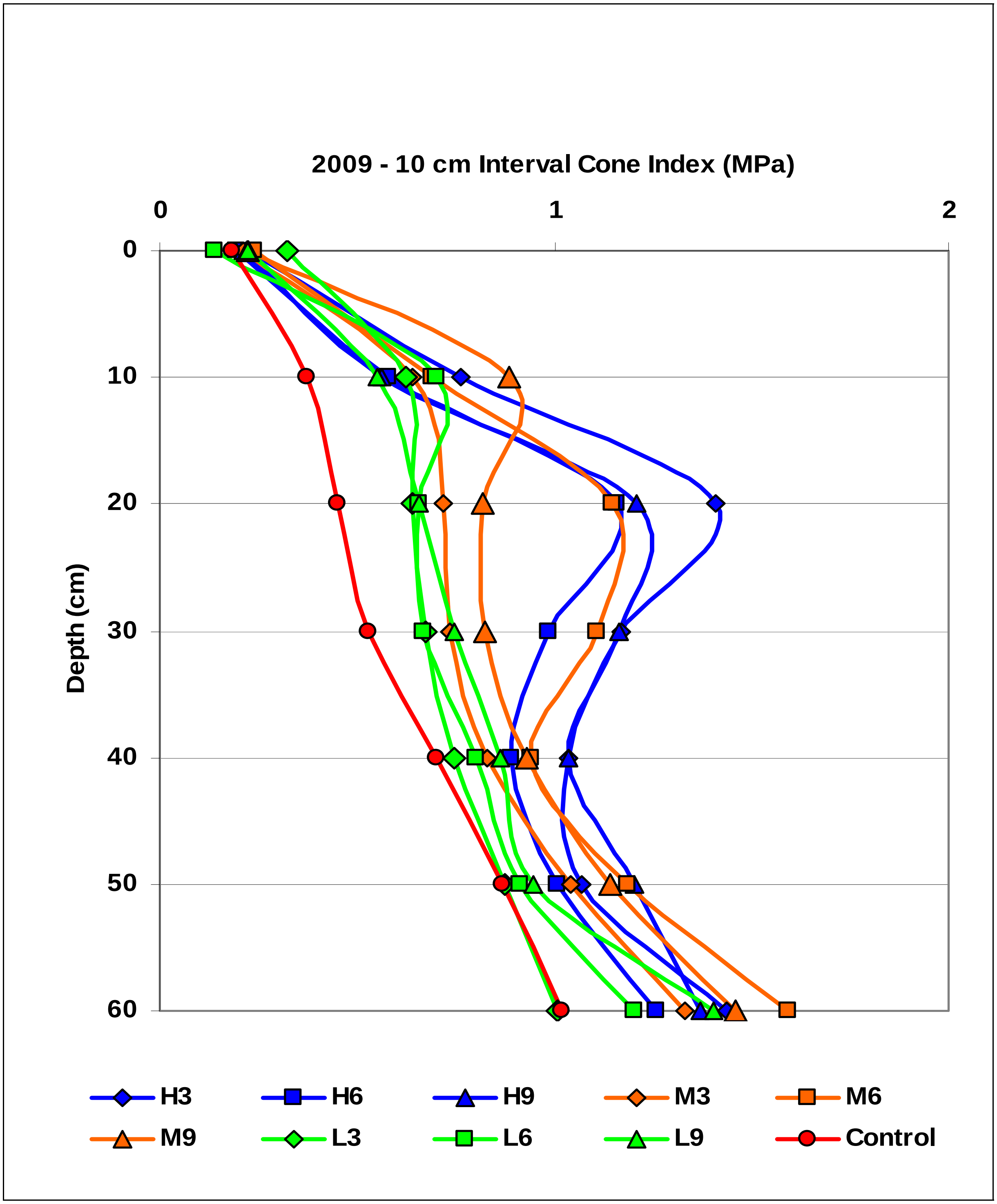


Figure 4.8. 10 cm Interval Cone Index (CI) profiles of 2009 follow up penetration resistance measurements for all treatment combinations.

To determine statistical significance of these observations and other possible variables, analysis of variance, Tukey- Kramer HSD comparison of means, and factorial analysis were employed. While soil moisture levels and number of passes were the primary ‘controllable’ variables in the experimental design of the study, the potential contribution of soil texture could not be ignored. Particle size distribution (PSD) for each plot was determined from samples collected for bulk density cores at 20 and 50 cm depths within each plot. These data were averaged by site area and the results can be reviewed in Table 4.1 in the materials and methods section. Factorial analysis indicated that clay, silt, and silt:clay ratio did not contribute a significant interaction. The F-probabilities for each textural factor was well above the 0.05 significance threshold and were typically ± 0.45. This is not unexpected as a review of the PSD data indicates that there is little texture variation among site areas at the respective depths. As per the initial assumptions, soil moisture and number of passes were evaluated as the primary factors controlling relative soil compaction levels due to tank traffic.

As illustrated in the previously discussed graphs, a significant amount of variability existed at the site prior to tank trafficking experiments. This observation is not unexpected in a recently cleared forest area. The pre-existing variability can make trend analysis less robust than observations taken from an area that has been in long-term agricultural production or pasture. In spite of the inherent variability at the site, a number of consistent trends were present in the data, as indicated by analysis of variance and means comparisons. These analyses are presented in Figures 4.9a and b through 4.16a and b and Tables 4.5 through 4.12. The graphs were generated using the JMP Statistical Software.

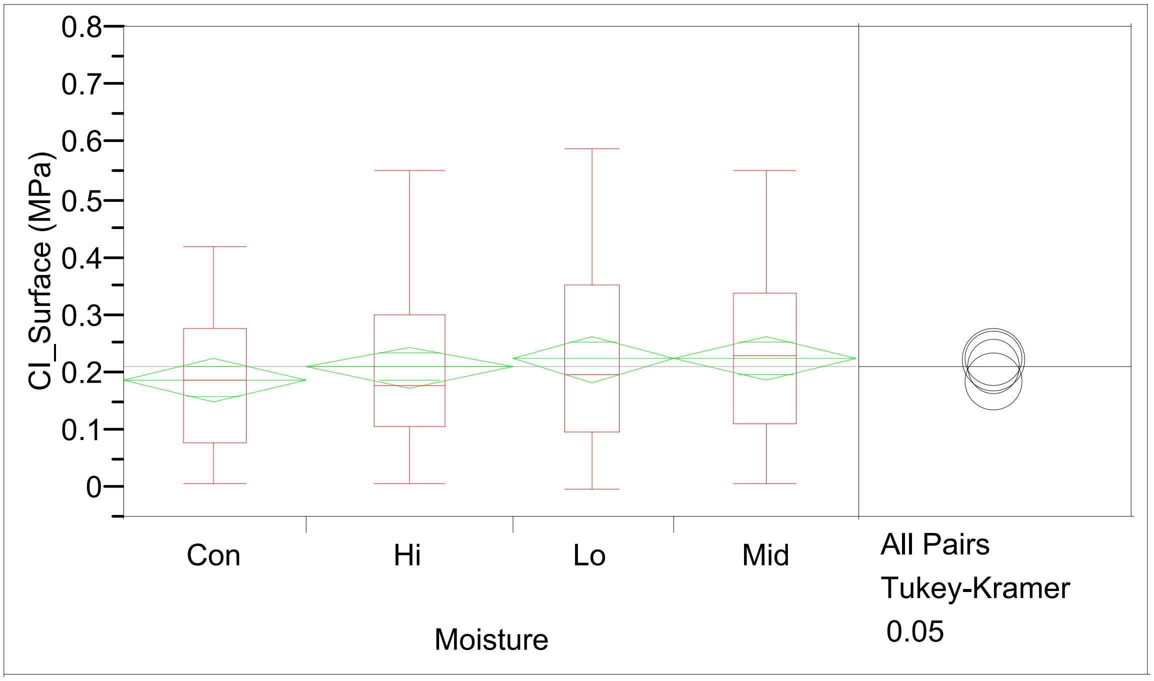
A brief description of the graph properties will aid in the interpretation of the analysis. Interpretation of the box and whisker plots is such that the ends of the box are the 25th and 75th percentiles, also called quartiles. The difference between the 25th and 75th percentiles is the interquartile range. The line across the middle of the box identifies the median sample value and the means diamond indicates the samples mean and 95% confidence interval. The whiskers extend from the ends of the box to the outer-most data point that falls within a distance computed to be equal to the upper or lower quartile +/- 1.5 times the interquartile range. The Tukey-Kramer HSD (honestly significant difference) test means comparison circles that do not overlap graphically illustrate significant differences between means.

There were no statistical differences in CI values for the soil surface between any of the treatment combinations or factors (Figure 4.9a and b, Table 4.5). Mean Control CI for the surface interval was 0.19 MPa. While PR values of >2 MPa have been associated with restricted root elongation (USDA-NRCS, National Soil Survey Handbook. 2007) in soils at field capacity moisture content. The follow-up PR measurements were taken when the soils were at an average moisture content of 0.40 wfv, which is at or near saturation. As such, these values were less than would be expected at field capacity and care should be taken not to underestimate root limiting potentials based upon these CI values. Numerous researchers have attempted to make moisture corrections for PR values with varying success (Busscher, 1997; and Christensen, 1989). Where PR values exceed 2 MPa, these data can be used to make qualitative inferences about root restricting compaction levels. With more certainty, they can be used to make inferences about relative degrees of compaction between treatment levels and give very good indications of the effect of tank traffic on soil compaction levels throughout the soil profile.

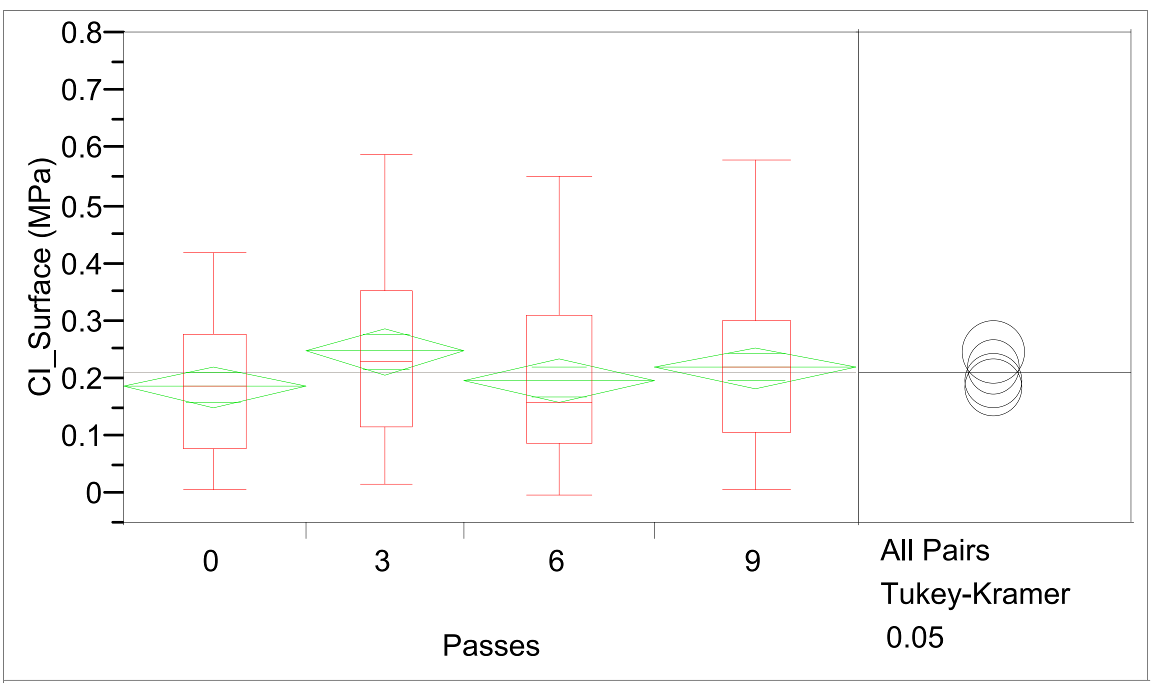
In the 0 – 10 cm interval, no treatment moisture levels or pass levels were significantly different from each other but all treatment levels were significantly different than the Controls, with an F-probability of 0.0001 (Figure 4.10a and b, Table 4.6). The average increase in CI over this interval above controls was 75%, with a mean value of 0.67 MPa. Though not an indication of root restricting PR levels, it should also be noted that several data points exceed the 2 MPa threshold in the high moisture plots with 3, 6 and 9 passes. This indicates that moisture is a more important factor than number of passes at this depth interval. Mean Control CI for the 0 – 10 cm interval was 0.38 MPa.

In the 10 – 20 cm interval (Figure 4.11a and b, Table 4.7), the 3, 6, and 9 pass treatment levels were not different from each other, but were different from the Controls with an average increase of ±200% (F-probability 0.0001). While the Lo moisture level did not differ from the Controls, the Mid and Hi moisture levels were significantly different, with the Hi moisture level being different from all other levels. Again, soil moisture level appears to be a greater factor in resulting soil compaction than number of passes. Mean Control CI for the 10 – 20 cm interval was 0.45 MPa.

In the 20 – 30 cm interval (Figure 4.12 a and b, Table 4.8), the 3, 6, and 9 pass treatment levels were not different from each other; but were different from the controls with an average increase of 175%. All moisture treatment levels were different from each other following the order Hi > Mid > Lo > Control. None of the data points exceeded the 2 MPa threshold in this interval. Mean Control CI for the 20 - 30 cm interval was 0.53 MPa.



a)



b)

Figure 4.9. Surface interval CI ANOVA box plots and Tukey-Kramer HSD means comparisons by a) moisture and b) number of passes.

Table 4.5. Surface interval CI ANOVA and Tukey-Kramer HSD means comparisons by moisture and number of passes.

Oneway Analysis of CI_Surface By Moisture

Rsquare 0.013

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture	3	0.05	0.02	0.9218	0.4312
Error	207	3.95	0.02		
C. Total	210	4.00			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Con	53	0.19	0.02	0.1492	0.22401
Hi	59	0.21	0.02	0.17625	0.24714
Lo	46	0.22	0.02	0.18442	0.26471
Mid	53	0.23	0.02	0.1892	0.26401

Comparisons for all pairs using Tukey-Kramer HSD

Level		Mean
Mid	A	0.23
Lo	A	0.22
Hi	A	0.21
Con	A	0.19

Levels not connected by same letter are significantly different

Oneway Analysis of CI_Surface By Passes

Rsquare 0.03

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Passes	3	0.11	0.04	1.9158	0.1281
Error	207	3.89	0.02		
C. Total	210	4.00			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	53	0.19	0.02	0.14946	0.22374
3	45	0.25	0.02	0.20725	0.28786
6	55	0.20	0.02	0.16081	0.23373
9	58	0.22	0.02	0.18588	0.25688

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
3	A	0.25
9	A	0.22
6	A	0.20
0	A	0.19

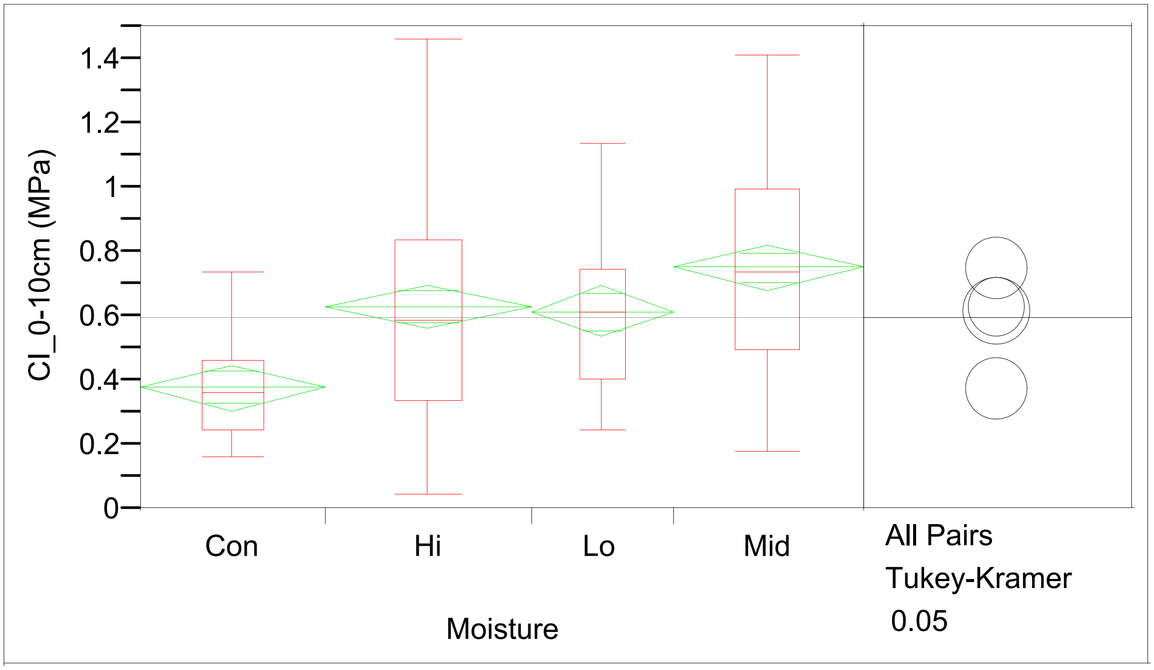
Levels not connected by same letter are significantly different

In the 30 – 40 cm interval (Figure 4.13a and b, Table 4.9), the 3, 6, and 9 pass treatment levels were not different from each other; but were different from the Controls, with an average increase of ±28% (F-probability 0.0001). The Hi and Mid moisture treatments were different than the Controls whereas the Lo moisture treatment was not. The moisture trend is such that CI increases with increase in moisture level, though with less distinct significant difference between levels than in the 20-30 cm interval. Interpretation could be that moisture variability is somewhat less pronounced at these greater depths. The mean Control CI for the 30 – 40 cm interval was 0.70 MPa.

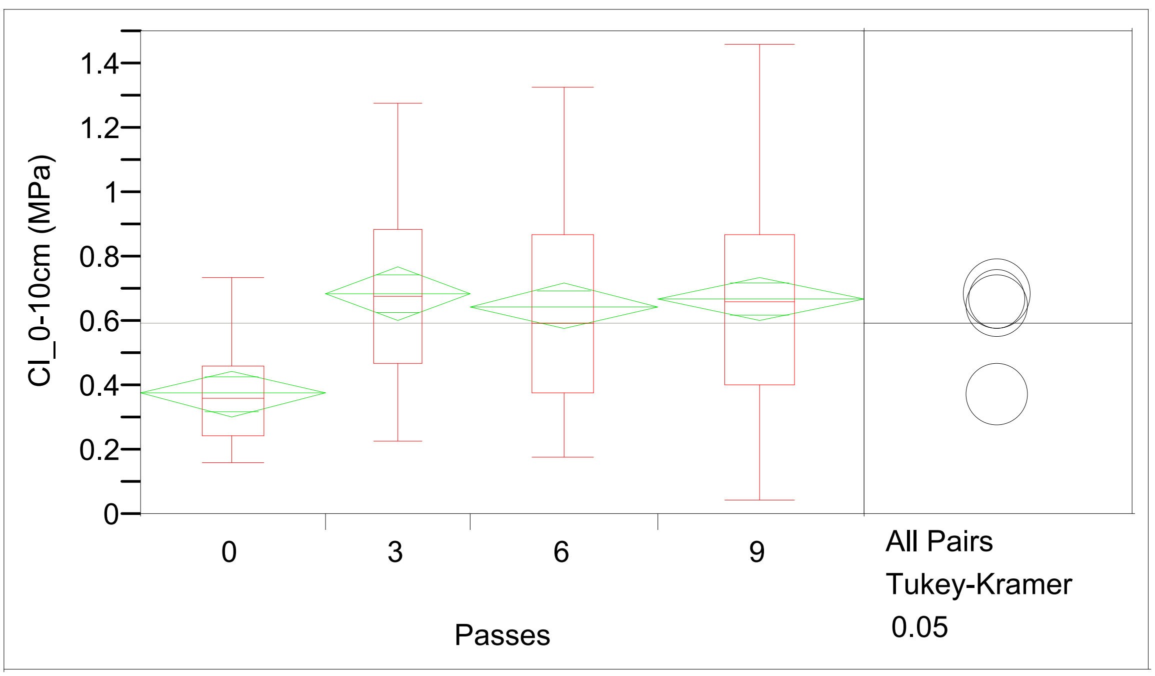
In the 40 – 50 cm interval (Figure 4.14a and b, Table 4.10), only the 9 pass treatment is significantly different from the Control plots. The Lo moisture levels are not significantly different from the Controls. Moisture trends are similar to the 30 – 40 cm interval but the Mid moisture level had the highest overall effect, but was not significantly different than the Hi moisture level. Mean Control CI for the 40 – 50 cm interval was 0.87 MPa.

In the 50 – 60 cm interval (Figure 4.15a and b, Table 4.11), 9 and 6 pass treatment levels are significantly greater than the Controls. The 3 pass treatment is not. The moisture level trends are the same as in the 40 – 50 cm interval with Mid and Hi moisture levels being significantly greater than the Controls. The mean Control CO for the 50 – 60 cm interval was 1.02.

The final analysis of CI was an attempt to determine differences in treatment response by using an average of the full profile CI. In the 0 – 60 cm full profile interval (Figure 4.16a and b, Table 4.12), all pass treatment levels were significant as compared to the Control plots; though none of the experimental treatment levels differ significantly



a)



b)

Figure 4.10. 0-10 cm interval CI ANOVA box plots and Tukey-Kramer HSD means comparisons by a) moisture and b) number of passes.

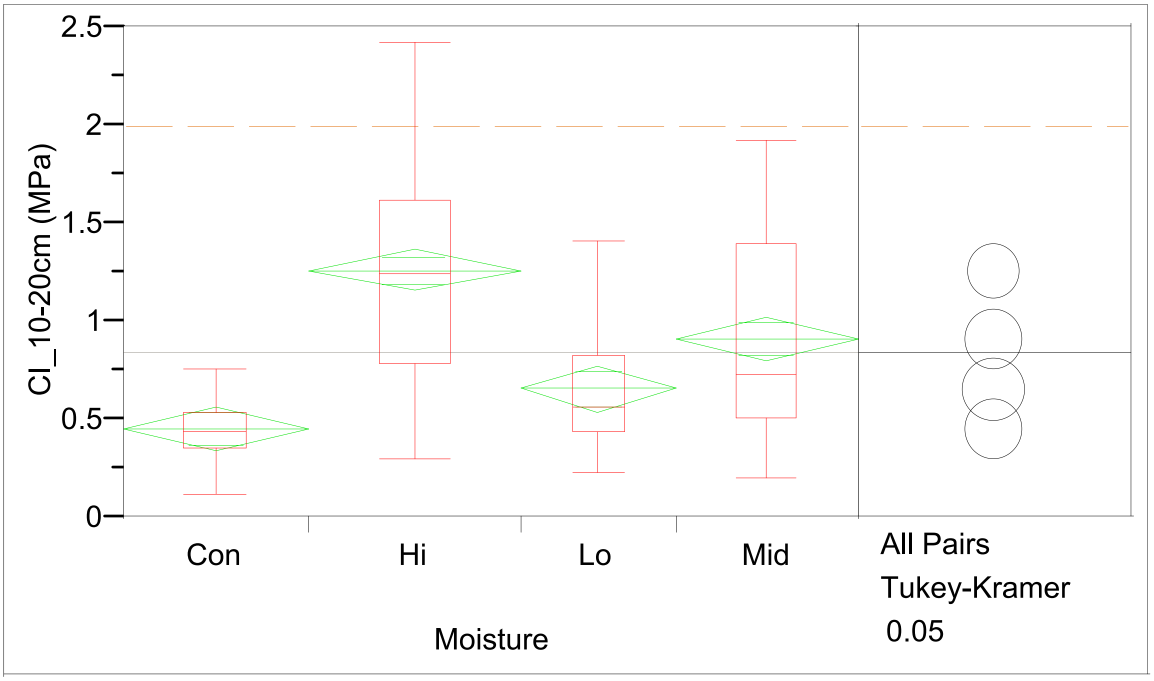
Table 4.6. 0-10 cm interval CI ANOVA and Tukey-Kramer HSD means comparisons by moisture and number of passes.

<u>Oneway Analysis of CI_0-10cm By Moisture</u>

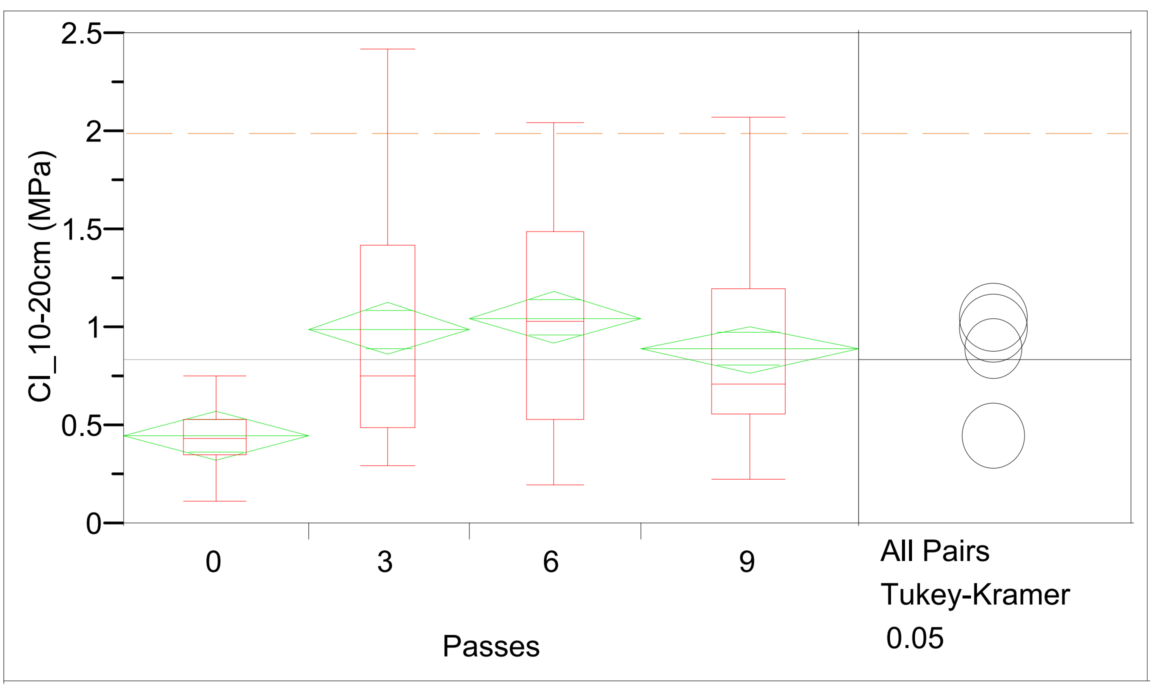
Rsquare	0.22				
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture	3	4.09	1.36	19.2352	<.0001
Error	210	14.88	0.07		
C. Total	213	18.97			
Means for Oneway Anova					
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Con	55	0.38	0.04	0.30451	0.44604
Hi	61	0.63	0.03	0.56166	0.69604
Lo	42	0.62	0.04	0.53402	0.69598
Mid	56	0.75	0.04	0.68005	0.82031
Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05					
Level		Mean			
Mid	A	0.75			
Hi	A	0.63			
Lo	A	0.62			
Con	B	0.38			
Levels not connected by same letter are significantly different					

<u>Oneway Analysis of CI_0-10cm By Passes</u>

Rsquare	0.19				
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Passes	3	3.54	1.18	16.0601	<.0001
Error	210	15.43	0.07		
C. Total	213	18.97			
Means for Oneway Anova					
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	55	0.38	0.04	0.30322	0.44733
3	43	0.69	0.04	0.60828	0.77126
6	55	0.65	0.04	0.57685	0.72097
9	61	0.67	0.03	0.60125	0.73809
Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05					
Level		Mean			
3	A	0.69			
9	A	0.67			
6	A	0.65			
0	B	0.38			
Levels not connected by same letter are significantly different					



a)



b)

Figure 4.11. 10-20 cm interval CI ANOVA box plots and Tukey-Kramer HSD means comparisons by a) moisture and b) number of passes.

Table 4.7. 10-20 cm interval CI ANOVA and Tukey-Kramer HSD means comparisons by moisture and number of passes.

Oneway Analysis of CI_10-20cm By Moisture

Rsquare 0.37

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture	3	20.53	6.84	40.0467	<.0001
Error	206	35.21	0.17		
C. Total	209	55.74			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Con	53	0.45	0.06	0.3382	0.5621
Hi	61	1.26	0.05	1.1543	1.363
Lo	44	0.65	0.06	0.5301	0.7758
Mid	52	0.91	0.06	0.796	1.0221

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
Hi	A	1.26
Mid	B	0.91
Lo	C	0.65
Con	C	0.45

Levels not connected by same letter are significantly different

Oneway Analysis of CI_10-20cm By Passes

Rsquare 0.21

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Passes	3	11.58	3.86	18.0096	<.0001
Error	206	44.16	0.21		
C. Total	209	55.74			

Means for Oneway Anova

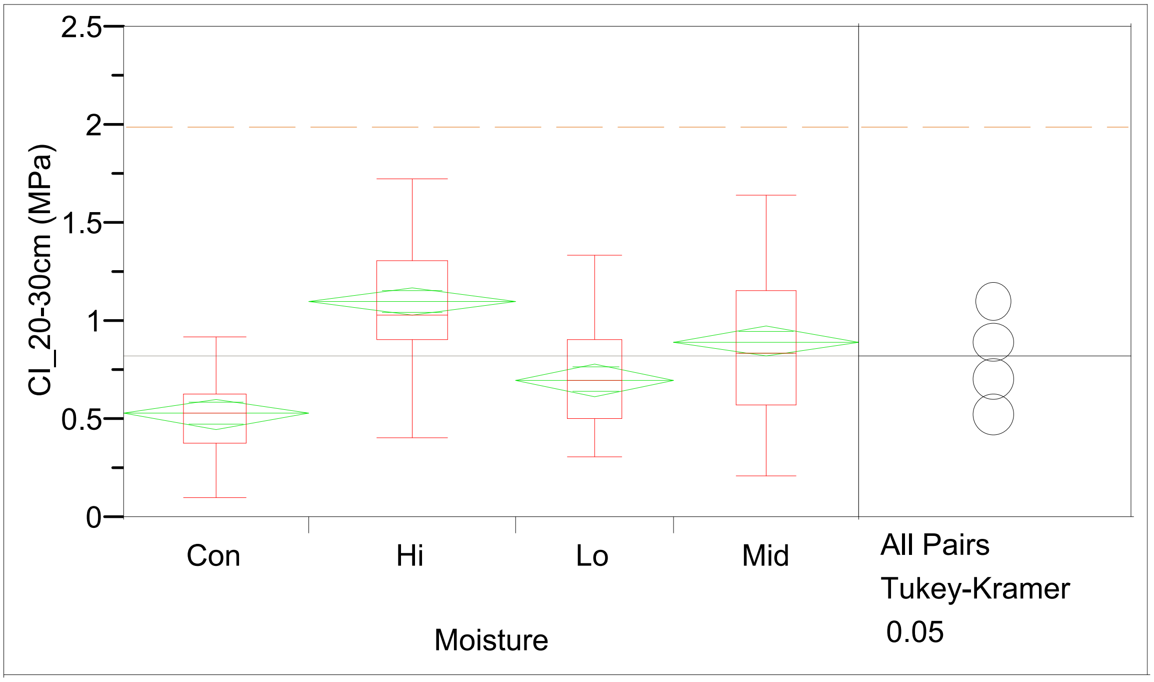
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	53	0.45	0.06	0.3248	0.5756
3	46	1.00	0.07	0.86324	1.1324
6	49	1.05	0.07	0.92225	1.1831
9	62	0.89	0.06	0.77601	1.0079

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
6	A	1.05
3	A	1.00
9	A	0.89
0	B	0.45

Levels not connected by same letter are significantly different

a)



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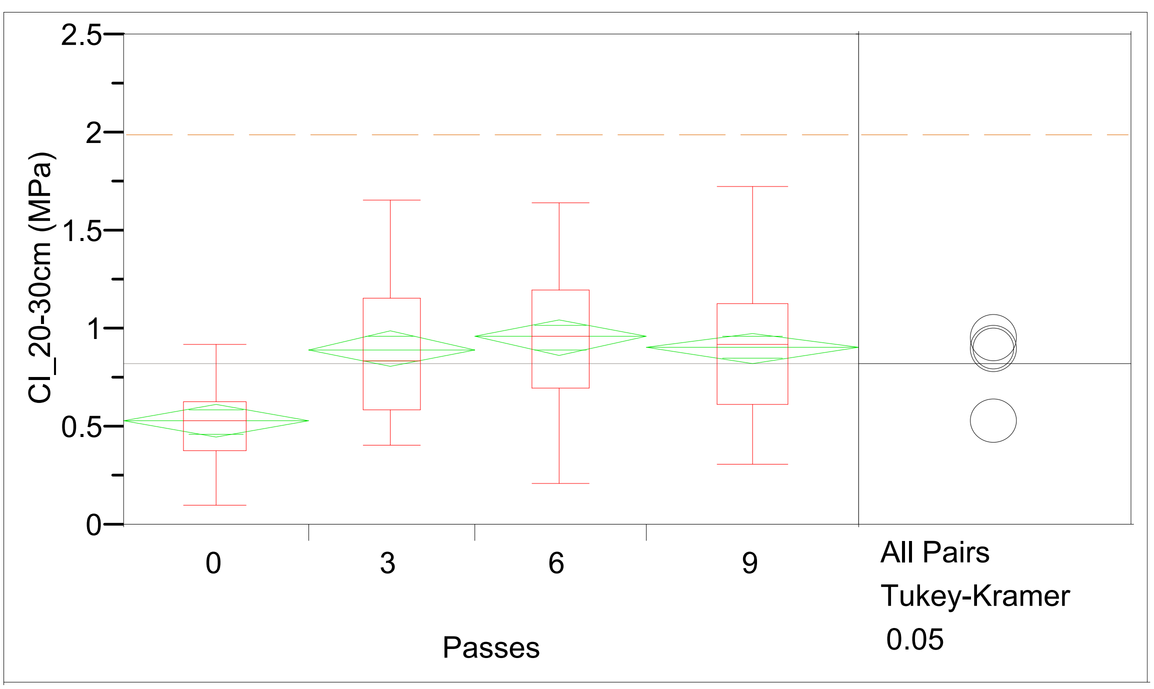


Figure 4.12. 20-30 cm interval CI ANOVA box plots and Tukey-Kramer HSD means comparisons by a) moisture and b) number of passes.

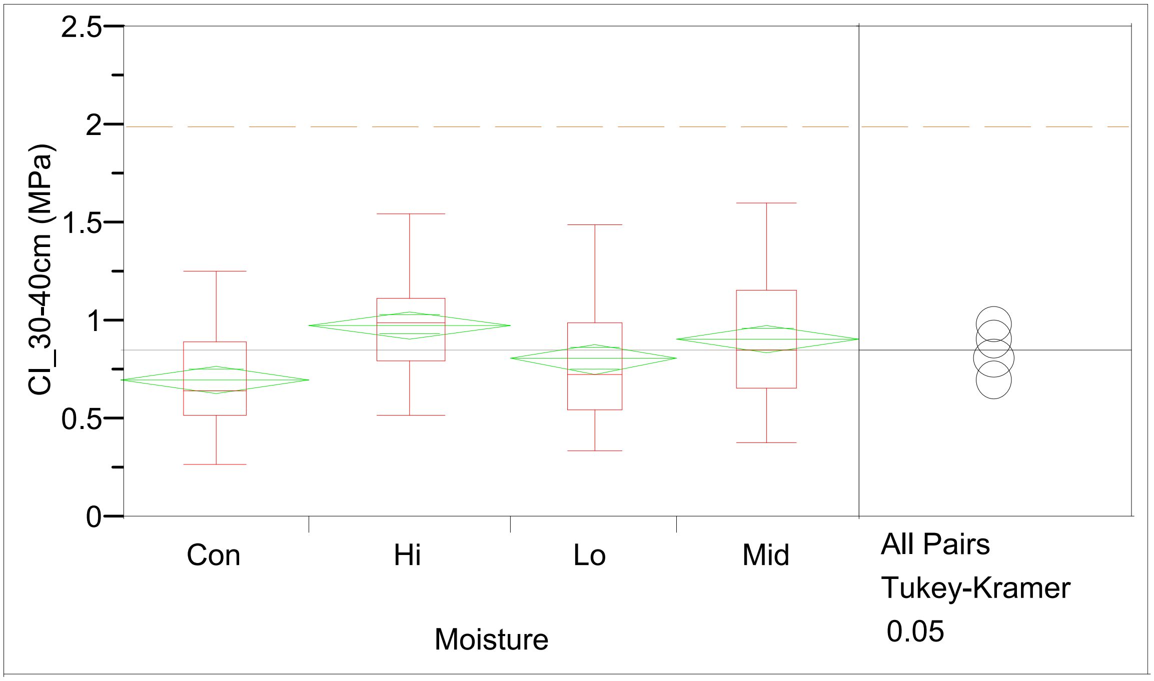
Table 4.8. 20-30 cm interval CI ANOVA and Tukey-Kramer HSD means comparisons by moisture and number of passes.

Oneway Analysis of CI_20-30cm By Moisture

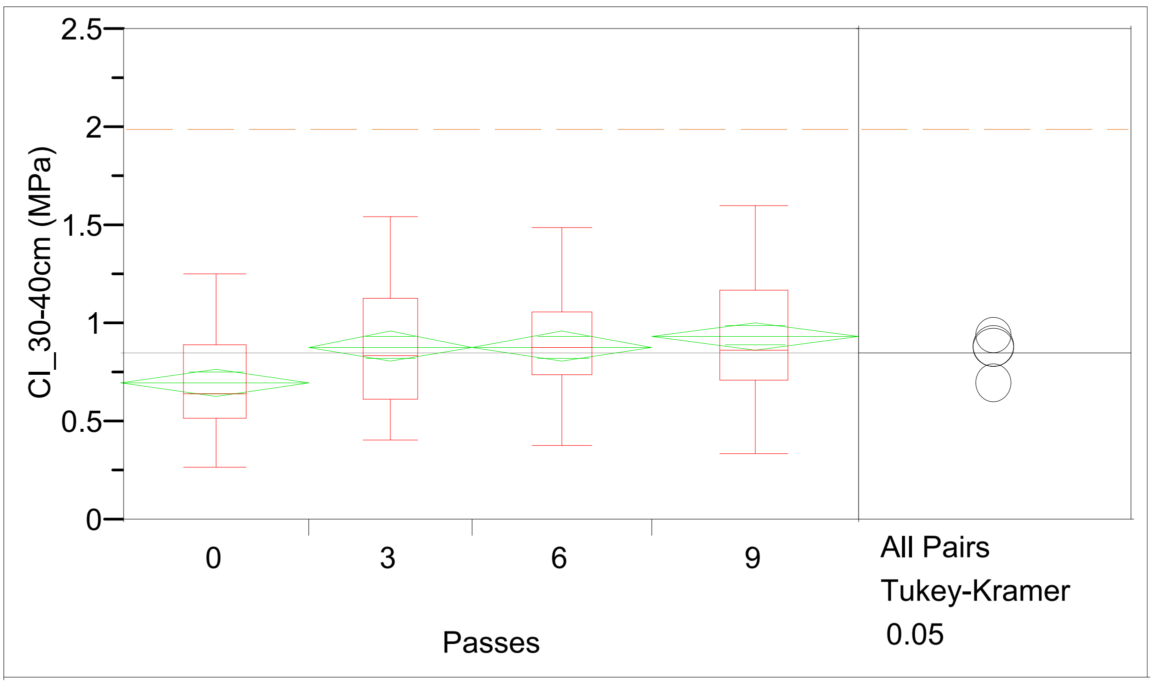
Rsquare	0.38				
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture	3	10.26	3.42	42.5414	<.0001
Error	209	16.81	0.08		
C. Total	212	27.07			
Means for Oneway Anova					
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Con	54	0.53	0.04	0.4536	0.6057
Hi	60	1.10	0.04	1.031	1.1753
Lo	46	0.71	0.04	0.6248	0.7896
Mid	53	0.90	0.04	0.82	0.9736
Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05					
Level		Mean			
Hi	A	1.10			
Mid	B	0.90			
Lo	C	0.71			
Con	D	0.53			
Levels not connected by same letter are significantly different					

Oneway Analysis of CI_20-30cm By Passes

Rsquare	0.23				
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Passes	3	6.25	2.08	20.9254	<.0001
Error	209	20.82	0.10		
C. Total	212	27.07			
Means for Oneway Anova					
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	54	0.53	0.04	0.44497	0.6143
3	48	0.90	0.05	0.80854	0.9881
6	50	0.96	0.04	0.87142	1.0474
9	61	0.90	0.04	0.82461	0.9839
Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05					
Level		Mean			
6	A	0.96			
9	A	0.90			
3	A	0.90			
0	B	0.53			
Levels not connected by same letter are significantly different					



a)



b)

Figure 4.13. 30-40 cm interval CI ANOVA box plots and Tukey-Kramer HSD means comparisons by a) moisture and b) number of passes.

Table 4.9. 30-40 cm interval CI ANOVA and Tukey-Kramer HSD means comparisons by moisture and number of passes.

Oneway Analysis of CI_30-40cm By Moisture

Rsquare 0.14

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture	3	2.55	0.85	11.3381	<.0001
Error	209	15.64	0.07		
C. Total	212	18.19			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Con	54	0.70	0.04	0.62975	0.7765
Hi	58	0.99	0.04	0.91418	1.0558
Lo	48	0.81	0.04	0.73402	0.8897
Mid	53	0.92	0.04	0.84742	0.9956

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
Hi	A	0.99
Mid	AB	0.92
Lo	BC	0.81
Con	C	0.70

Levels not connected by same letter are significantly different

Oneway Analysis of CI_30-40cm By Passes

Rsquare 0.10

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Passes	3	1.84	0.61	7.8386	<.0001
Error	209	16.35	0.08		
C. Total	212	18.19			

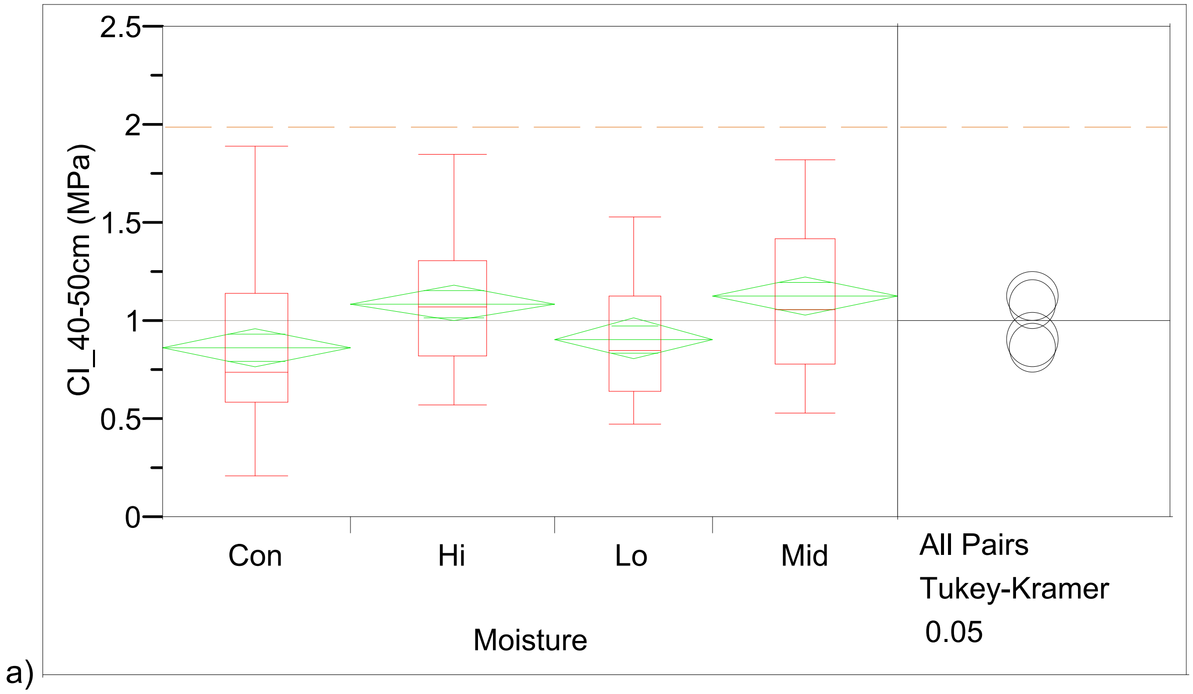
Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	54	0.70	0.04	0.62811	0.7782
3	47	0.89	0.04	0.80787	0.9687
6	53	0.90	0.04	0.82275	0.9742
9	59	0.94	0.04	0.87008	1.0137

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
9	A	0.94
6	A	0.90
3	A	0.89
0	B	0.70

Levels not connected by same letter are significantly different



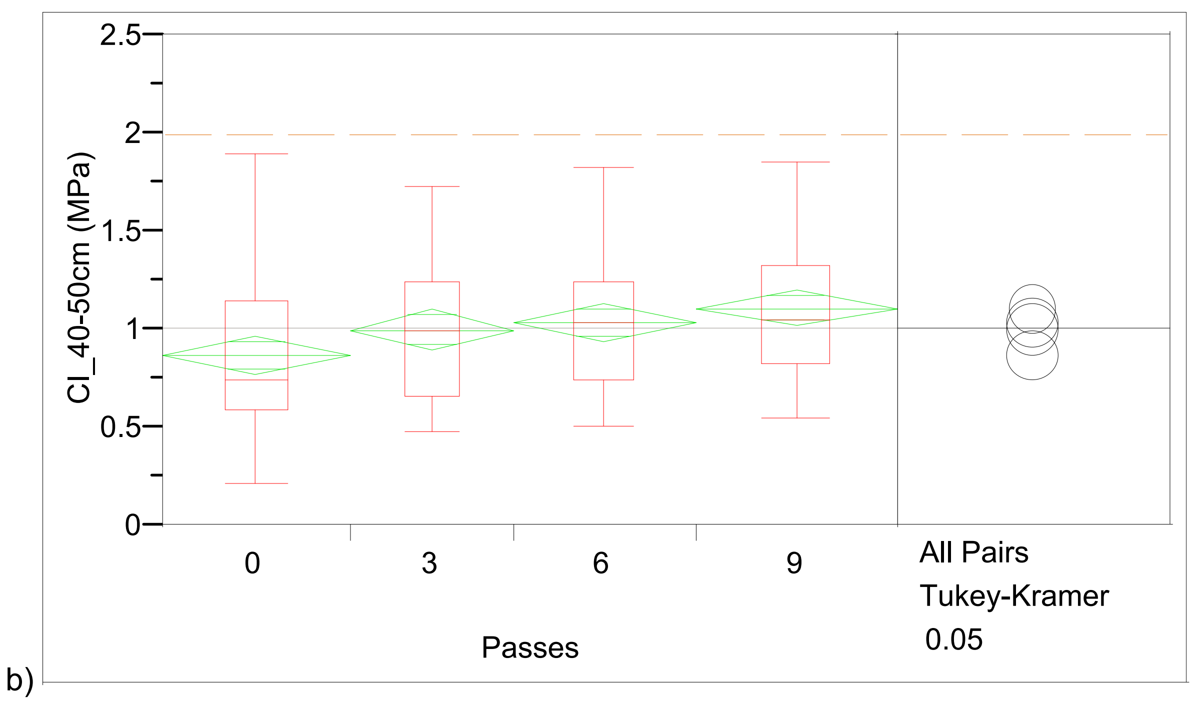


Figure 4.14. 40-50 cm interval CI ANOVA box plots and Tukey-Kramer HSD means comparisons by a) moisture and b) number of passes.

Table 4.10. 40-50 cm interval CI ANOVA and Tukey-Kramer HSD means comparisons by moisture and number of passes.

<u>Oneway Analysis of CI_40-50cm By Moisture</u>

Rsquare 0.09

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture	3	2.60	0.87	7.137	0.0001
Error	201	24.40	0.12		
C. Total	204	27.00			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Con	53	0.87	0.05	0.773	0.9617
Hi	57	1.09	0.05	1.0006	1.1826
Lo	44	0.91	0.05	0.8087	1.0158
Mid	51	1.13	0.05	1.0332	1.2256

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
Mid	A	1.13
Hi	AB	1.09
Lo	BC	0.91
Con	C	0.87

Levels not connected by same letter are significantly different

<u>Oneway Analysis of CI_40-50cm By Passes</u>

Rsquare 0.06

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Passes	3	1.65	0.55	4.3709	0.0052
Error	201	25.34	0.13		
C. Total	204	27.00			

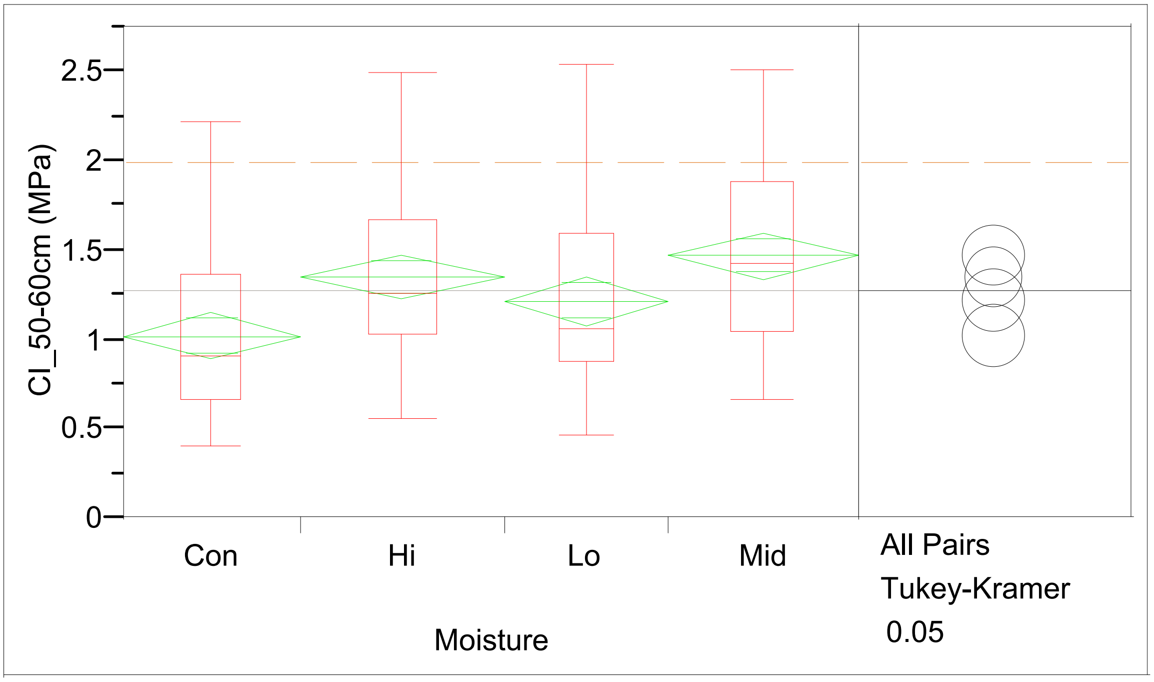
Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	53	0.87	0.05	0.7712	0.9635
3	45	1.00	0.05	0.8956	1.1044
6	51	1.04	0.05	0.9394	1.1355
9	56	1.11	0.05	1.0145	1.2016

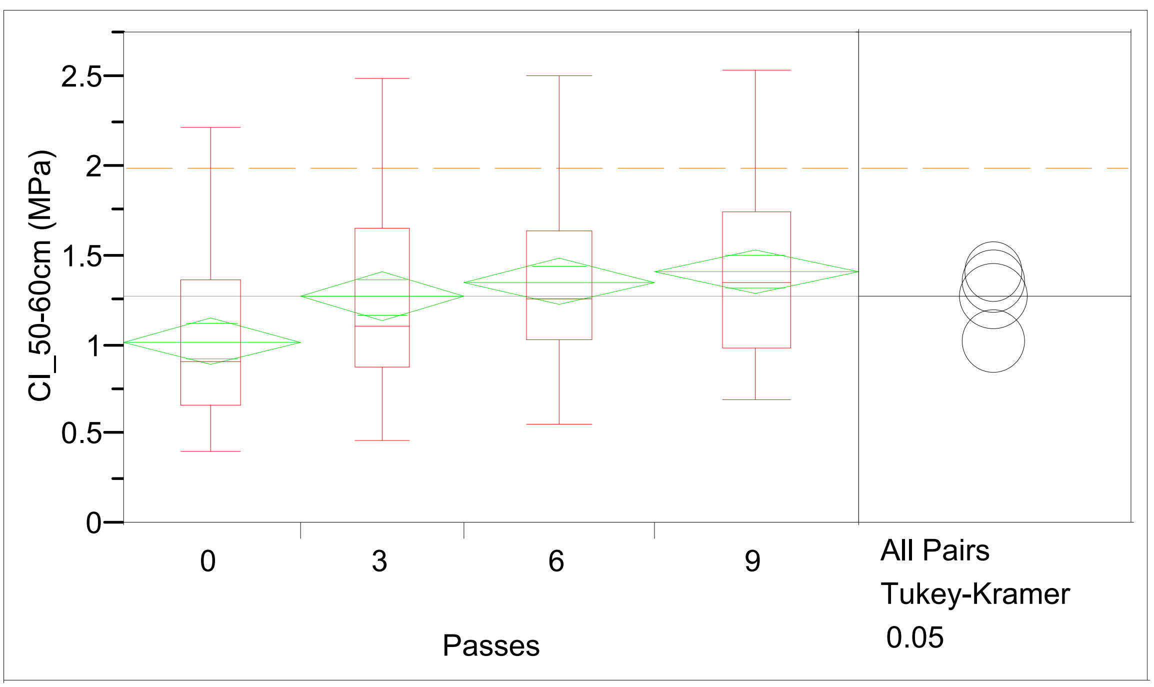
Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
9	A	1.11
6	AB	1.04
3	AB	1.00
0	B	0.87

Levels not connected by same letter are significantly different



a)



b)

Figure 4.15. 40-50 cm interval CI ANOVA box plots and Tukey-Kramer HSD means comparisons by a) moisture and b) number of passes.

Table 4.11. 50-60 cm interval CI ANOVA and Tukey-Kramer HSD means comparisons by moisture and number of passes.

<u>Oneway Analysis of CI_50-60cm By Moisture</u>

Rsquare 0.11

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture	3	5.74	1.91	8.4405	<.0001
Error	202	45.80	0.23		
C. Total	205	51.54			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Con	50	1.02	0.07	0.8886	1.1542
Hi	57	1.35	0.06	1.2262	1.4749
Lo	46	1.22	0.07	1.0824	1.3593
Mid	53	1.47	0.07	1.3435	1.6014

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
Mid	A	1.47
Hi	AB	1.35
Lo	BC	1.22
Con	C	1.02

Levels not connected by same letter are significantly different

<u>Oneway Analysis of CI_50-60cm By Passes</u>

Rsquare 0.09

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Passes	3	4.68	1.56	6.7257	0.0002
Error	202	46.86	0.23		
C. Total	205	51.54			

Means for Oneway Anova

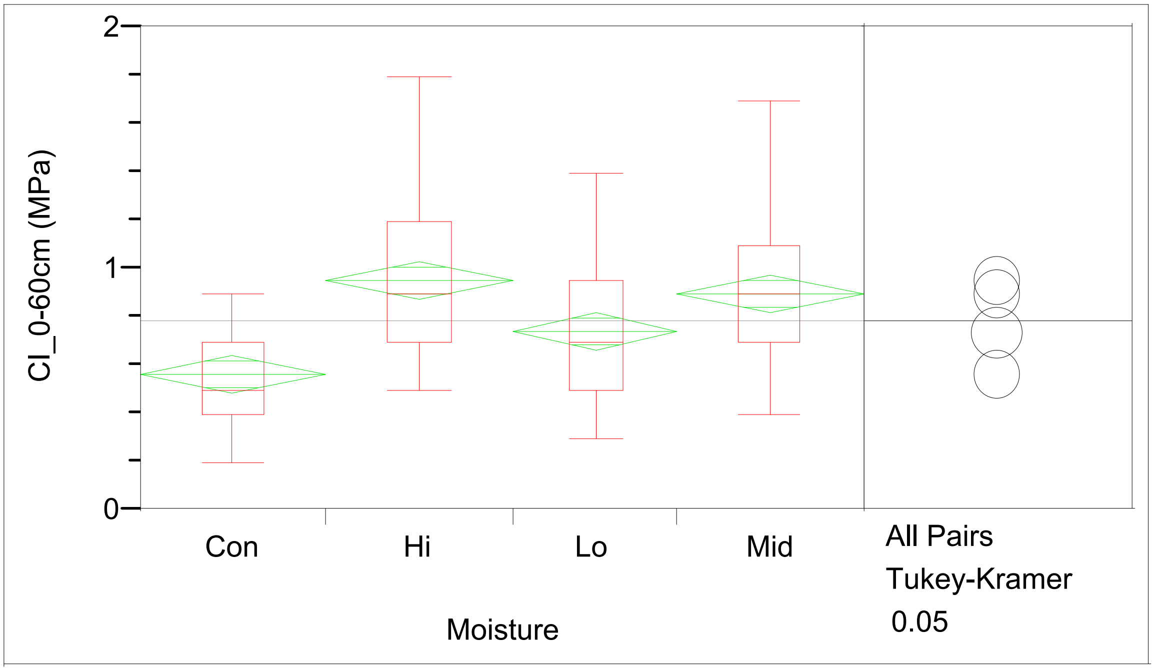
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	50	1.02	0.07	0.8871	1.1557
3	46	1.27	0.07	1.1339	1.4139
6	53	1.36	0.07	1.228	1.4889
9	57	1.41	0.06	1.2879	1.5395

Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05

Level		Mean
9	A	1.41
6	A	1.36
3	AB	1.27
0	B	1.02

Levels not connected by same letter are significantly different

a)



b)

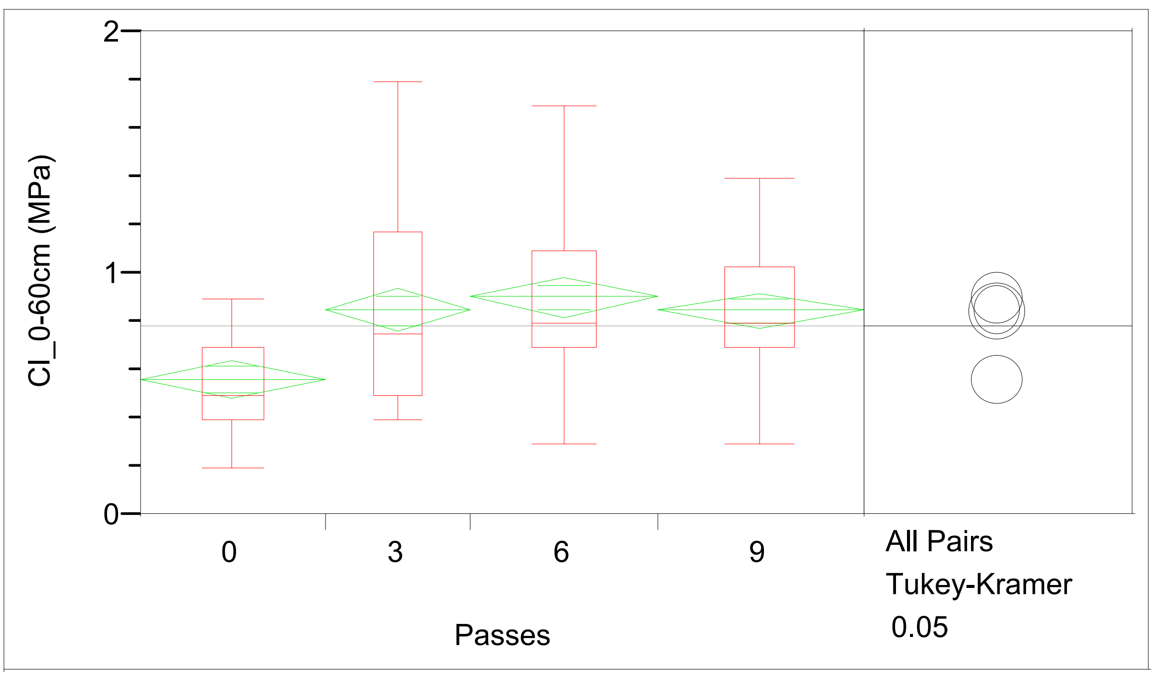


Figure 4.16. 0-60 cm (full profile) interval CI ANOVA box plots and Tukey-Kramer HSD means comparisons by a) moisture and b) number of passes.

Table 4.12. Full profile (0-60 cm) interval CI ANOVA and Tukey-Kramer HSD means comparisons by moisture and number of passes.

Oneway Analysis of CI 0-60cm by Moisture

Rsquare	0.26				
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Moisture	3	5.90	1.97	26.5177	<.0001
Error	220	16.31	0.07		
C. Total	223	22.21			
Means for Oneway Anova					
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Con	56	0.66	0.04	0.589	0.7324
Hi	63	1.07	0.03	1.0006	1.1359
Lo	49	0.85	0.04	0.7703	0.9236
Mid	56	1.02	0.04	0.9461	1.0896
Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05					
Level		Mean			
Hi	A	1.07			
Mid	A	1.02			
Lo	B	0.85			
Con	C	0.66			
Levels not connected by same letter are significantly different.					

Oneway Analysis of CI 0-60cm by Passes

Rsquare	0.20				
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Passes	3	4.48	1.49	18.5264	<.0001
Error	220	17.73	0.08		
C. Total	223	22.21			
Means for Oneway Anova					
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	56	0.66	0.04	0.58594	0.7355
3	49	0.98	0.04	0.90374	1.0636
6	56	1.00	0.04	0.92344	1.073
9	63	0.98	0.04	0.90887	1.0499
Comparisons for all pairs using Tukey-Kramer HSD Alpha = 0.05					
Level		Mean			
6	A	1.00			
3	A	0.98			
9	A	0.98			
0	B	0.66			
Levels not connected by same letter are significantly different					

from each other. There was a difference of 2% between treatment pass levels. The experimental moisture treatments were all significantly greater than the Control plots, with Hi and Mid moistures being greater than the Lo moisture level but not significantly different from each other. These trends do not conflict with the initial observations when interpreting the 10 centimeter interval data.

4.5 CONCLUSIONS

While the 'number of passes' treatments were consistently different from the Controls, there was no difference among treatment pass levels. This is consistent with the findings of a number of researchers who indicate that as much as 80 percent of the potential compaction occurs during the first pass with subsequent passes causing additional, but progressively less, compaction (Daum, 1996; Horn et al, 1995; Lenhard, 1986; and Taylor et al, 1982). However, the cone penetration data suggested that soil moisture content did have a significant and variable effect on soil compaction levels, and was the dominant variable of concern with respect to compaction potential in the soils at Camp Minden. The general trend was such that PR values throughout the profile follows moisture class such that Hi = Mid > Lo > Control treatments for all depth intervals except the 20 and 30 cm intervals, where trends were Hi > Mid > Lo > Control treatments. Additionally, because the Hi and Mid soil moisture treatment levels consistently produced PR values significantly greater than the Controls, efforts should be made to limit tank exercises when soil moisture contents are greater than 0.20 on a volumetric water fraction basis. As such, it is anticipated that these soils readily deform and compact when wetted to moisture contents less than the plastic limit (19% gravimetric ≈ 29% volumetric), with certain deformation and compaction at moisture contents greater than the plastic limit (29% volumetric) under compaction energy of the M1A1 tank. This conclusion is in agreement with other researches that found optimal conditions for soil compaction often occur at water content near field capacity, particularly as water content approaches the soils liquid limit (Porsinsky etal, 2006; Akram and Kemper, 1979; Soane et al, 1981; Gent and Morris, 1986; Startsev and McNabb, 2001).

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CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 STUDY SUMMARY AND CONCLUSIONS

Intensive, realistic military training activities frequently result in land degradation which can negatively affect long term training use capability of the land, in addition to a broad range of deleterious environmental and ecosystem impacts. In response, the U.S. Army Construction Engineering Research Laboratories (CERL) developed the Integrated Training Area Management (ITAM) program as a comprehensive approach to land management on all military installations. The Louisiana Army National Guard (LAARNG) Camp Minden Training Site (CMTS) was chosen to serve as an M1A1 battle tank training facility. Soil compaction, or densification, and the resulting associated negative effects on other soil physical, chemical, biological and hydrologic properties is widely recognized as the primary factor in reduced soil quality and function where tank training activities occur.

In response to this environmental issue, a research project was initiated in 2006 to ascertain the soils resilience to compaction with respect to tank maneuvers at the Camp Minden training facility. The general objectives of the tank study were to (1) establish soil compaction thresholds for the M1A1 battle tank for soil resilience, and (2) develop guidelines based upon the above referenced thresholds that will allow Army Range Managers to determine appropriate timing and intensity levels for tank training maneuvers at the facility that will allow for maximum utilization of the land resource with minimal degradation. Specific objectives to establish soil compaction thresholds were to determine the effects of tank training maneuvers on the soils bulk density, moisture retention, and penetration resistance characteristics as a function of traffic rates and soil moisture conditions. The experimental design was a completely randomized factorial design that attempted to evaluate the effects of soil moisture content (Factor 1) and tank traffic rates (Factor 2) on soil compaction and soil strength.

Pre and post tank trafficed measurement of soil bulk density and cone penetration resistance were assessed to determine relative soil resilience to compaction. Field extracted soil cores from 20 cm and 50 cm depth intervals were used for soil bulk density measurements and to develop soil moisture retention curves. Together, these methods allow interpretation of soil density and volume changes, and alteration in pore size distribution resulting from compaction. Cone penetrometer measurements were used to determine changes in soil strength throughout the upper 50 cm of the soil profile.

No statistically significant differences in relative bulk density change were observed at an alpha level of 0.05 at the 20 or 50 cm depth. Additionally, neither ANOVA nor the Tukey-Kramer HSD revealed 'statistically' significant trends that could be attributed to moisture or traffic pass treatment levels. However, post trafficked bulk densities and standard deviations at the 20 cm depth interval show that 'moisture' treatment effect followed the trend Hi > Mid > Lo, with 1.65 (±0.07), 1.61 (±0.09), and 1.57 (±0.09) g/cm^3 respectively. Additionally, the Hi moisture treatment post trafficked bulk densities all approached the 1.65 g/cm^3 root restricting threshold (National Soil Survey Handbook, 2007) in the 20 cm depth interval. When evaluating 'traffic' rate at the 20 cm depth interval, the 3 and 9 pass treatments were nearly identical at 1.60 (±0.08) g/cm^3 with the greatest resulting bulk density in the 6 pass treatment level, with 1.63 (±0.08) g/cm^3. When considering individual treatment factor only, moisture was a stronger determinant of final bulk density than was traffic rate. At the 50 cm depth interval, the 'moisture' treatment effect followed the trend Mid > Hi > Lo with values of 1.61 (±0.05), 1.60 (±0.05), and 1.56 (±0.06) g/cm^3 respectively. The Hi and Mid moisture treatment levels were essentially equal, with the Lo moisture treatment level being less, when using standard deviation as the significance criteria. When considering 'traffic' rate at the 50 cm depth interval, the 3 and 6 pass treatments were nearly identical at 1.61 (±0.05) g/cm^3. While these differences were not statistically different at an alpha level of 0.05 because of the inherent site variability, the trends were consistent and cannot be ignored.

The moisture retention curves indicate that there is an overall reduction in total porosity with corresponding reduction water holding capacity in the 20 cm depth interval as a result of tank traffic induced compaction. There is also a significant reduction in average pore size with an increase in smaller pores associated with higher pressures. These changes affect numerous soil physical properties and processes to varying degrees. Included are reduced infiltration, water retention and hydraulic conductivity; air capacity and gaseous exchange; increased runoff and erosion, soil strength and mechanical impedance to root growth. In turn, these changes indirectly affect numerous chemical and biological processes (Assouline, 2004; Johnson and Bailey, 2002; Glinski and Lipiec, 1990; Hakansson et al, 1988). There is a high probability of increases in redox potential during the wet season due to reduced air permeability of the more numerous smaller pores. The result of compaction was a decrease in the air-filled porosity of pores drained of water at pressures ≤ 0.3 bars, which will result in reduced aeration (Startev, 2001). The significant shift in pore size distribution toward smaller pore sizes also support the observation that compaction, particularly in the 20 cm depth interval, will impede natural regeneration of vegetation of soils trafficked under conditions where soil moisture content is at or near the liquid limit (27 to 30% volumetric water content) of these soils.

Penetration resistance (PR) data suggest that while the 'number of passes' treatments were consistently different from the Controls, there was no difference between treatment pass levels. This is consistent with the findings of a number of researchers who indicate that as much as 80 percent of the potential compaction occurs during the first pass with subsequent passes causing additional, but progressively less, compaction (Daum, 1996; Horn et al, 1995; Lenhard, 1986; and Taylor et al, 1982). However, the cone penetration data do suggest that soil moisture content does have a significant and variable effect on soil compaction levels and was the dominant variable of concern with respect to compaction potential in the soils at Camp Minden. The general trend was such that PR values, throughout the profile, follows moisture class such that Hi = Mid > Lo > Control treatments for all depth intervals, except the 20 and 30 cm intervals, where trends were Hi > Mid > Lo > Control treatments. Additionally, because the Hi and Mid soil moisture treatment levels consistently produced PR values significantly greater than the Controls, efforts should be made to limit tank exercises when soil moisture contents are greater than 0.20 on a volumetric water fraction basis. As such, you would expect these soils to readily deform and compact when wetted to moisture contents less than the plastic limit, with certain deformation and compaction at moisture contents at and above the plastic limit. This conclusion is in agreement with other researches that found optimal conditions for soil compaction often occur at water content near field capacity, particularly as water content approaches the soils liquid limit (Porsinsky et al, 2006; Akram and Kemper, 1979; Soane et al, 1981; Gent and Morris, 1986; Startsev and McNabb, 2001).

In summary, the combined bulk density, soil moisture retention characteristic curves, and penetration resistance data suggest that tank trafficking maneuvers, on the study site soils, will result in compaction levels in excess of the root restriction initiation level of 1.54 g/cm^3 during periods when soil moisture volumetric content exceeds 20%, (12 – 13% gravimetric). Additionally, tank trafficking maneuvers on these soils at the volumetric water contents in excess of 30% (18 – 19% gravimetric) can be expected to result in bulk density values very near, or in excess of the recognized root limiting value of 1.65 g/cm^3, with as few as 3 traffic passes.

Ideally, a range management plan would monitor soil volumetric moisture content and, whenever practical, consider avoiding training activities with the M1A1 tank when soil moisture levels exceed volumetric water content of 20%. Additionally, M1A1 training activities would be avoided when soil moisture levels exceed a volumetric water content of 30% to avoid soil compaction levels very near, or in excess of the recognized root limiting value of 1.65 g/cm^3. However, the intermound Wrightsville soils at the CMTS can be expected to have near saturated soil moisture contents, in excess of field capacity (36% volumetric), for significant periods during the months of December through April as indicated by the USDA official series description (Soil Data Mart-USDA, 2007). Since it would be impractical to suspend training maneuvers for the duration of this 'wet season', it is anticipated that root limiting soil compaction levels will develop in tank trafficked areas of this soil type during that period. As such, it is our recommendation that range management plans include the contingency for monitoring soil bulk density in the upper 20 cm of the tank trafficked soils and implement disking operations to loosen compacted soil areas with bulk density greater than 1.65 g/cm^3 to maximize vegetative growth.

These conclusions are in agreement with other researches that found optimal conditions for soil compaction often occur at water content near field capacity, particularly as water content approaches the soils liquid limit (Porsinsky et al, 2006; Akram and Kemper, 1979; Soane et al, 1981; Gent and Morris, 1986; Startsev and McNabb, 2001).

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APPENDIX A

MONTHLY CLIMATE DATA

Table A.1 Monthly climate data 2007 – 2009.

	-----------Temperature-----------			Precipitation
Mo/Year	**Max**	**Min**	**Avg**	**Inches**
Jan-07	56	38.3	47.1	7.6
Feb-07	61.2	38.9	50	3.32
Mar-07	75.9	52.4	64.2	1.75
Apr-07	74	51.8	62.9	1.64
May-07	84.7	65.4	75.1	4.26
Jun-07	90.6	71.8	81.2	6
Jul-07	89.6	73.3	81.4	10.27
Aug-07	96.6	76.1	86.3	0.61
Sep-07	90.9	69.8	80.3	1.32
Oct-07	81.9	57.9	69.9	2.36
Nov-07	69.3	48	58.6	3.06
Dec-07	63.2	40.4	51.8	4.58
Jan-08	55	35.9	45.5	2.07
Feb-08	65.8	39.2	52.5	4.71
Mar-08	71.2	46.6	58.9	2.13
Apr-08	76	53.6	64.8	2.62
May-08	83.4	62.5	73	11.56
Jun-08	91.3	71.3	81.3	3.85
Jul-08	95.6	72.5	84	1.08
Aug-08	91.8	73.5	82.7	5.73
Sep-08	83.7	65.7	74.7	3.84
Oct-08	77.5	52.8	65.2	1.41
Nov-08	67	43.4	55.2	4.98
Dec-08	59.6	37.7	48.7	3.14
Jan-09	59.5	36.3	47.9	2.14
Feb-09	66.1	43.3	54.7	1.63
Mar-09	69.1	47.1	58.1	6.35
Apr-09	74.9	52.9	63.9	3.97
May-09	82.2	63.7	73	7.44
Jun-09	91.9	70.7	81.3	1.22
Jul-09	94.7	73.4	84.1	6.49
Aug-09	91.4	71.8	81.6	1.69

APPENDIX B

TANK RUN DATES

Table A.2 Tank run dates.

Treatment	Plot	Moisture	Passes	Date
P14-H9	14	Hi	9	21-Aug-09
P07-H6	7	Hi	6	21-Aug-09
P01-H3	1	Hi	3	21-Aug-09
P13-H9	13	Hi	9	22-Aug-09
P33-H9	33	Hi	9	22-Aug-09
P16-H6	16	Hi	6	22-Aug-09
P17-H6	17	Hi	6	22-Aug-09
P32-H3	32	Hi	3	22-Aug-09
P34-H3	34	Hi	3	22-Aug-09
P35-M6	35	Mid	6	29-Aug-09
P41-M9	41	Mid	9	19-Sep-09
P48-L6	48	Lo	6	20-Sep-09
P08-M9	8	Mid	9	20-Sep-09
P06-M3	6	Mid	3	20-Sep-09
P15-L9	15	Lo	9	11-Oct-09
P46-L9	46	Lo	9	11-Oct-09
P47-L9	47	Lo	9	11-Oct-09
P23-L6	23	Lo	6	11-Oct-09
P47-L6	47	Lo	6	11-Oct-09
P12-L3	12	Lo	3	11-Oct-09
P09-L3	9	Lo	3	11-Oct-09
P47-L3	47	Lo	3	11-Oct-09
P40-M9	40	Mid	9	11-Oct-09
P21-M6	21	Mid	6	11-Oct-09
P44-M6	44	Mid	6	11-Oct-09
P21-M3	21	Mid	3	11-Oct-09
P05-M3	5	Mid	3	11-Oct-09

APPENDIX C

ROSETTA MOISTURE RETENTION PARAMETERS

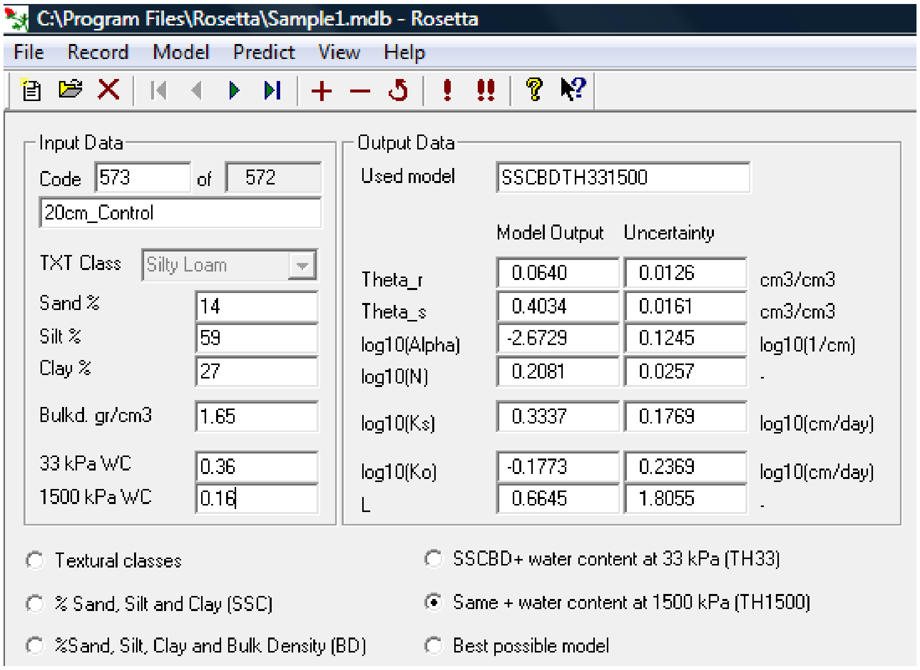


Figure A.3.1. 20 cm ‘Control’ Rosetta model van Genuchten retention parameters.

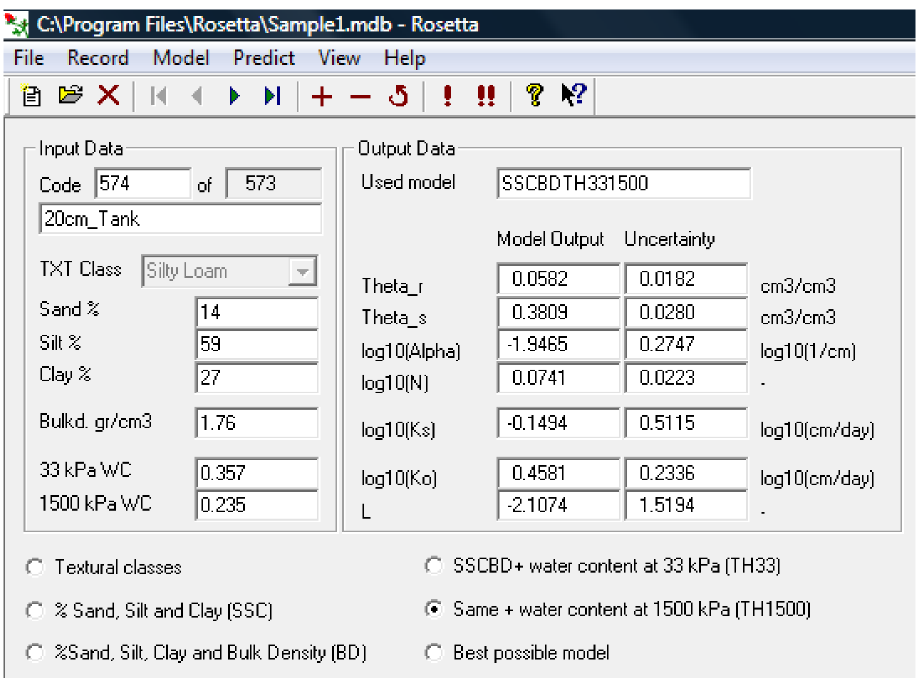


Figure A.3.2. 20 cm ‘Tank’ Rosetta model van Genuchten retention parameters.

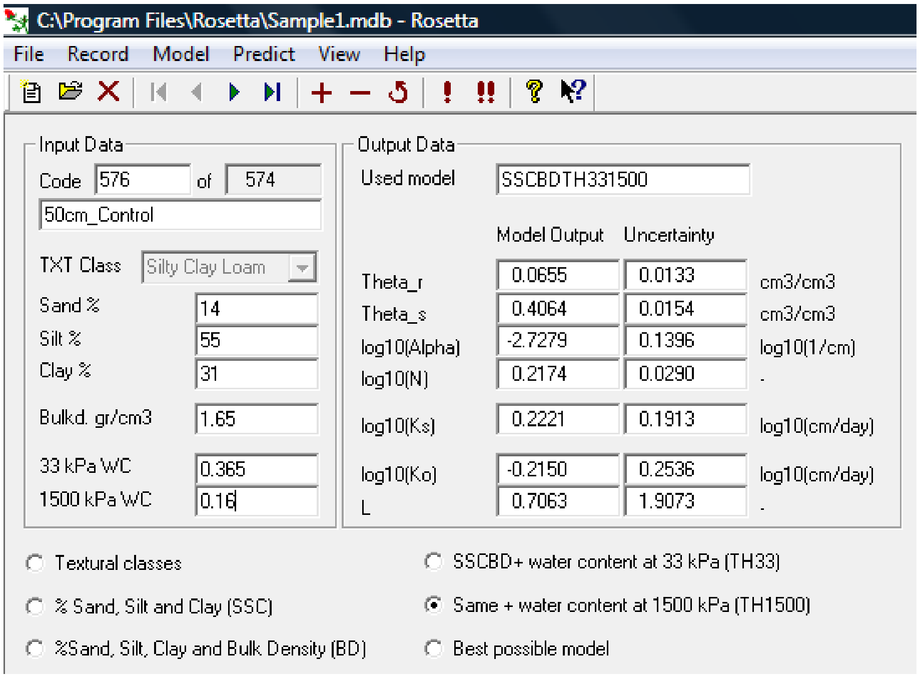


Figure A.3.3. 50 cm 'Control' Rosetta model van Genuchten retention parameters.

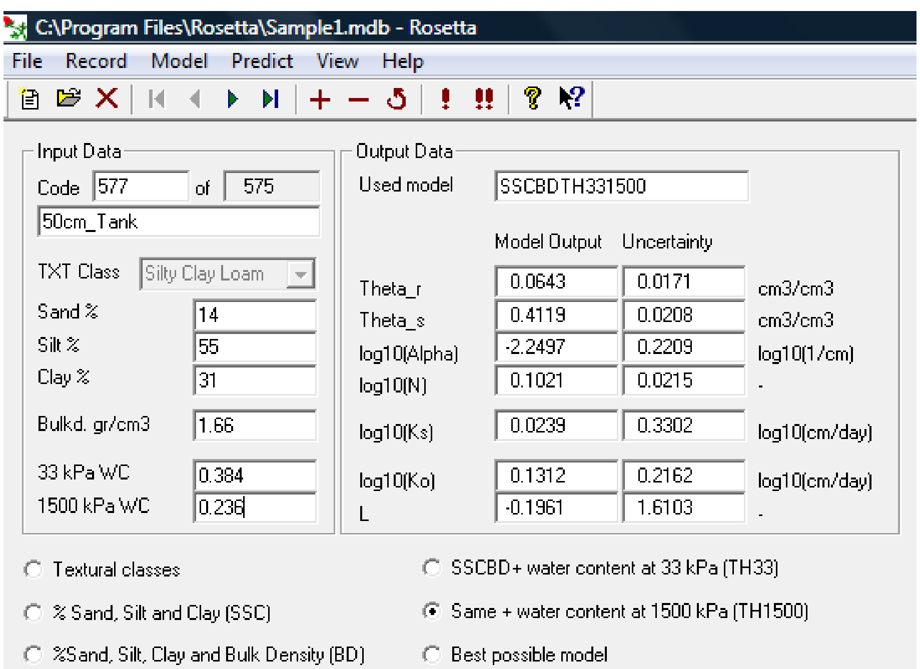


Figure A.3.4. 50 cm 'Tank' Rosetta model van Genuchten retention parameters.

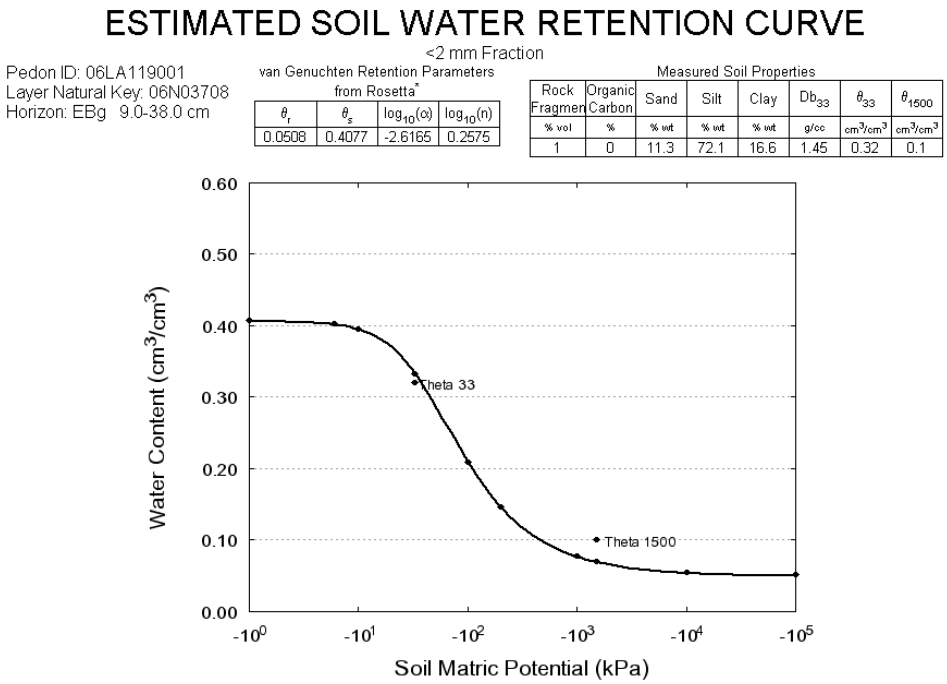


Figure A.3.5. 20 cm interval estimated soil water retention curve USDA lab.

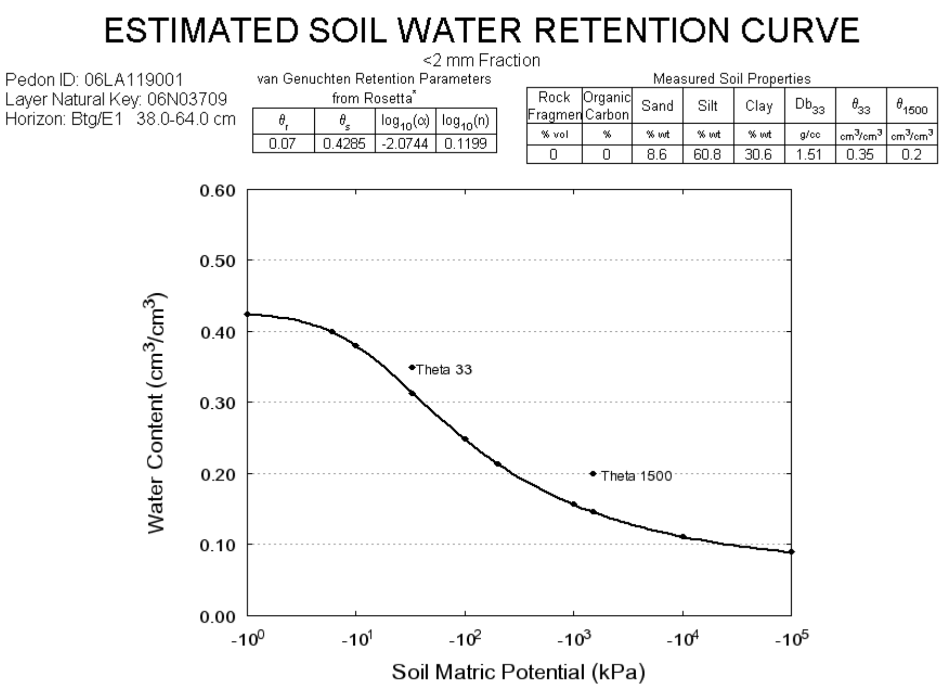


Figure A.3.6. 50 cm interval estimated soil water retention curve USDA lab.

APPENDIX D

COMPARATIVE PENETRATION RESISTANCE GRAPHS

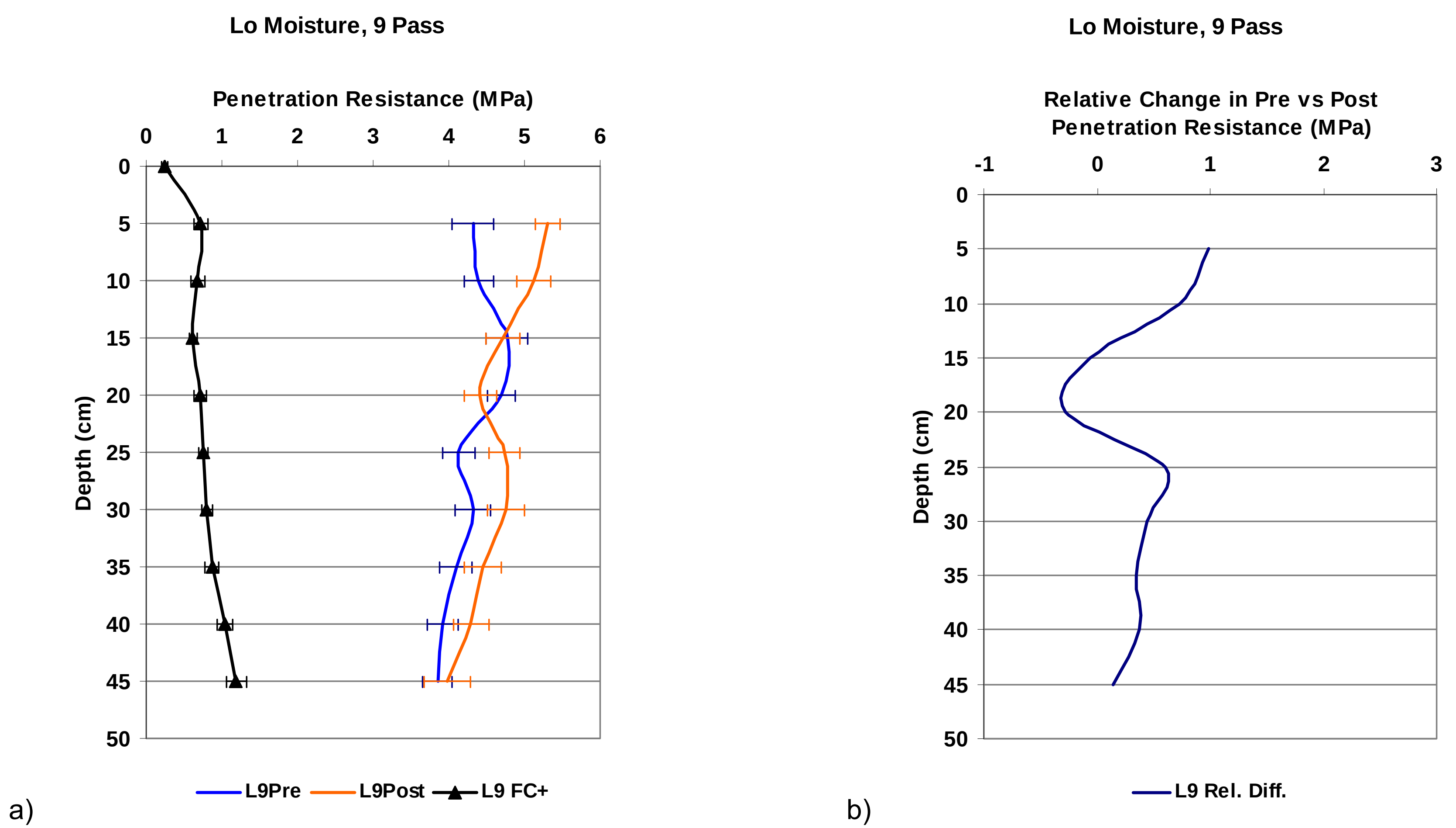


Figure A.4.1. Comparative Penetration Resistance Low Moisture – 9 Pass. a). Average penetration resistance (MPa) measurements of Low Moisture 9 Pass plots immediately preceding (L9Pre) and following (L9Post) tank passage in 2007 and follow up measurements taken at Field Capacity+ (L9 FC+) in 2009. Error bars represent ± standard error of the mean. b). Relative penetration resistance (MPa) change between L9Pre and L9Post measurements.

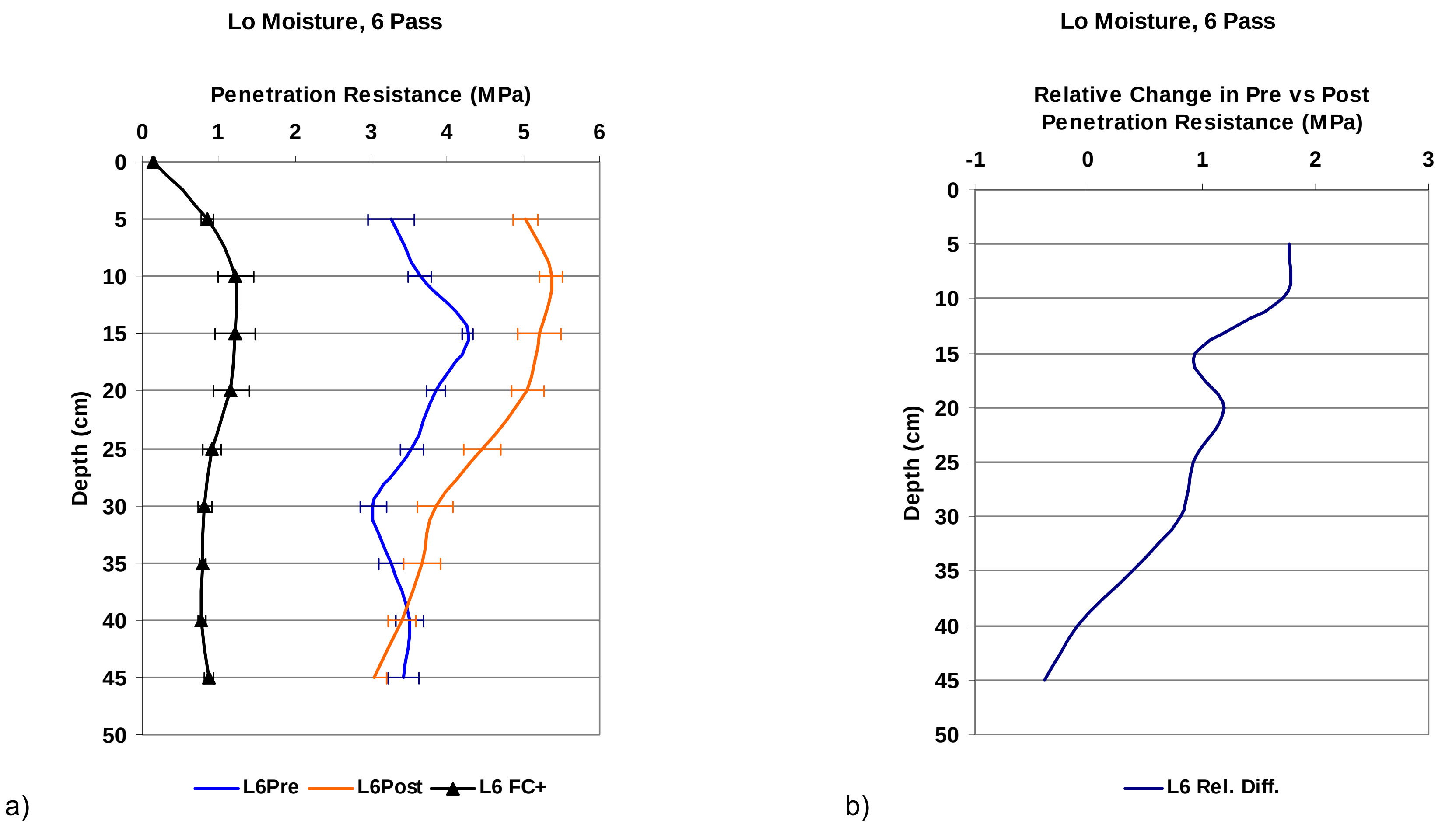
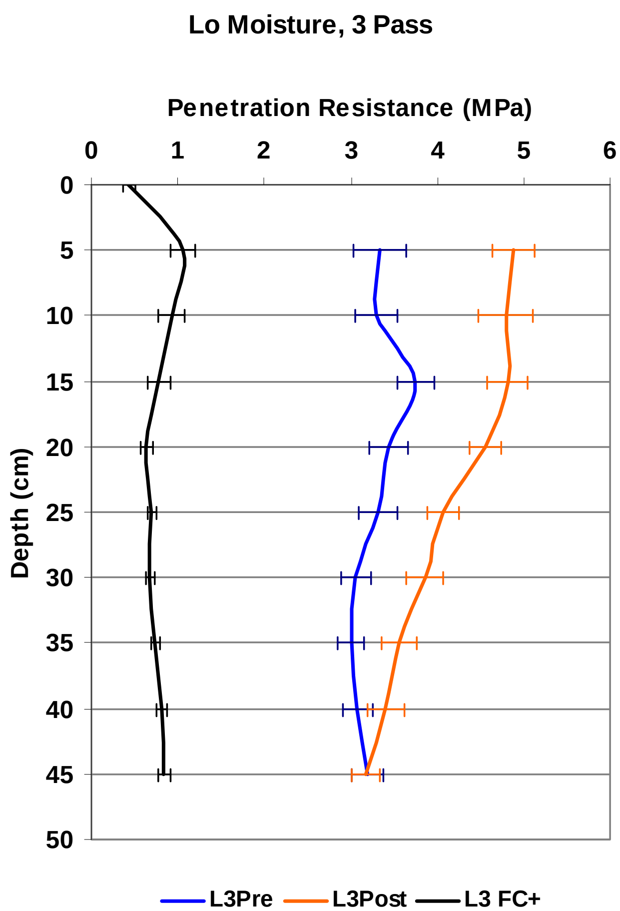
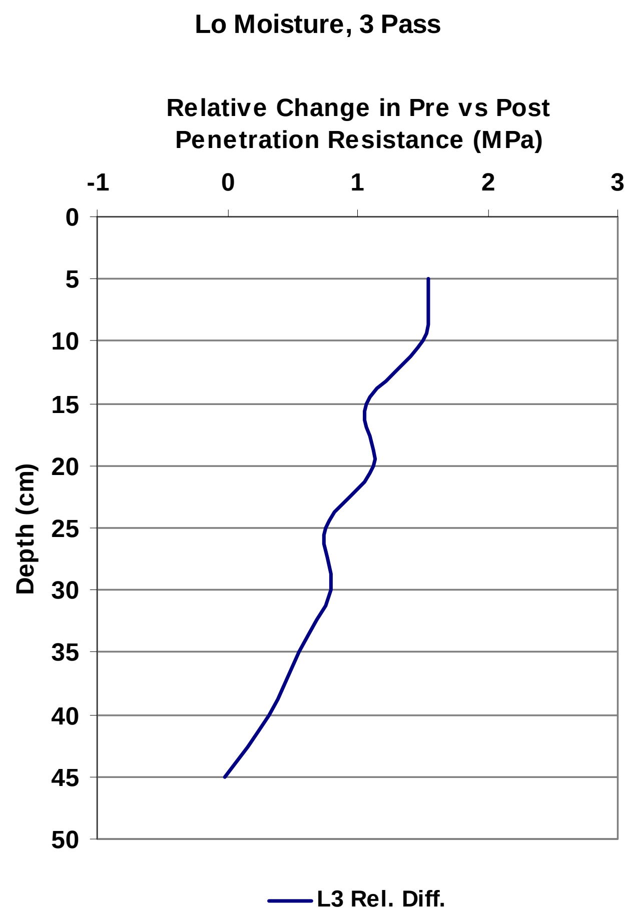


Figure A.4.2. Comparative Penetration Resistance Low Moisture – 6 Pass. a). Average penetration resistance (MPa) measurements of Low Moisture 6 Pass plots immediately preceding (L6Pre) and following (L6Post) tank passage in 2007 and follow up measurements taken at Field Capacity+ (L6 FC+) in 2009. Error bars represent ± standard error of the mean. b). Relative penetration resistance (MPa) change between L6Pre and L6Post measurements.



a)



b)

Figure A.4.3. Comparative Penetration Resistance Low Moisture – 3 Pass. a). Average penetration resistance (MPa) measurements of Low Moisture 3 Pass plots immediately preceding (L3Pre) and following (L3Post) tank passage in 2007 and follow up measurements taken at Field Capacity+ (L3 FC+) in 2009. Error bars represent ± standard error of the mean. b). Relative penetration resistance (MPa) change between L3Pre and L3Post measurements.

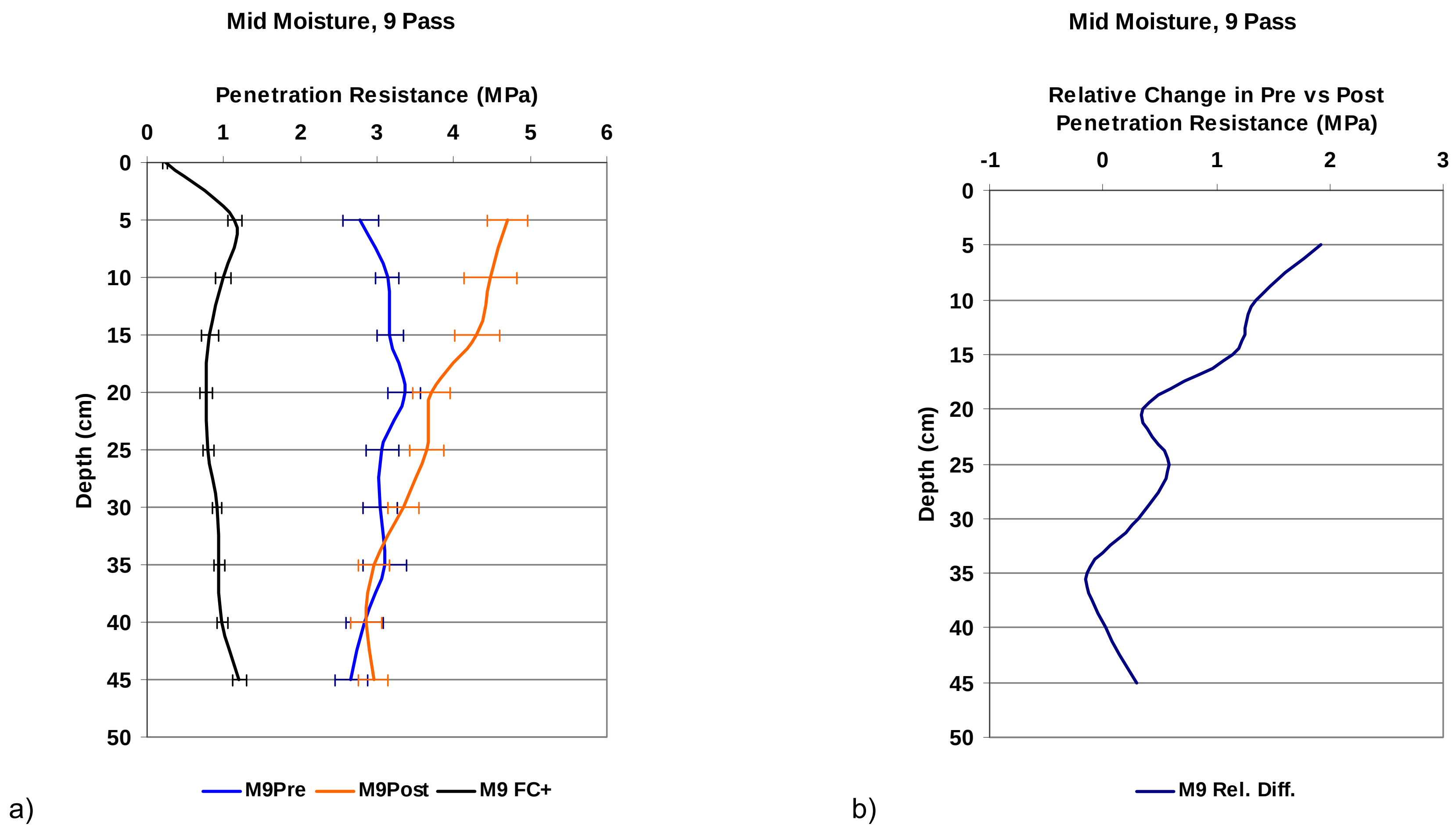


Figure A.4.4. Comparative Penetration Resistance Mid Moisture – 9 Pass. a). Average penetration resistance (MPa) measurements of Mid Moisture 9 Pass plots immediately preceding (M9Pre) and following (M9Post) tank passage in 2007 and follow up measurements taken at Field Capacity+ (M9 FC+) in 2009. Error bars represent ± standard error of the mean. b). Relative penetration resistance (MPa) change between M9Pre and M9Post measurements.

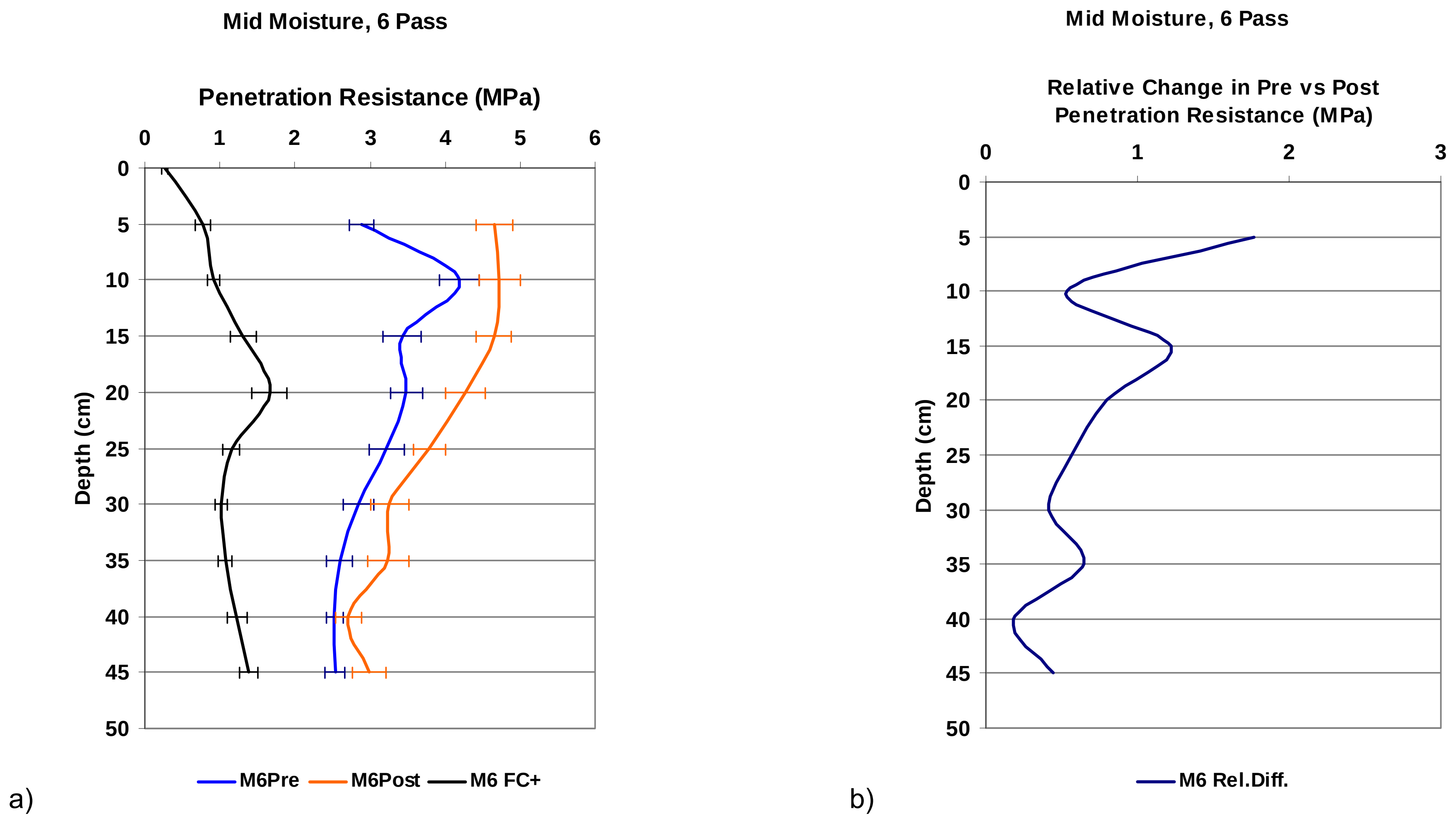
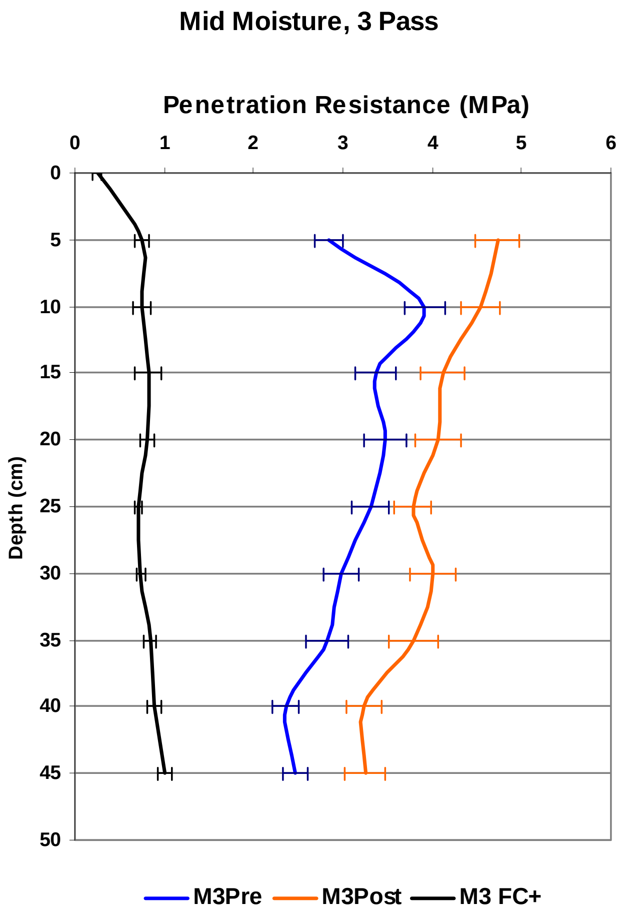
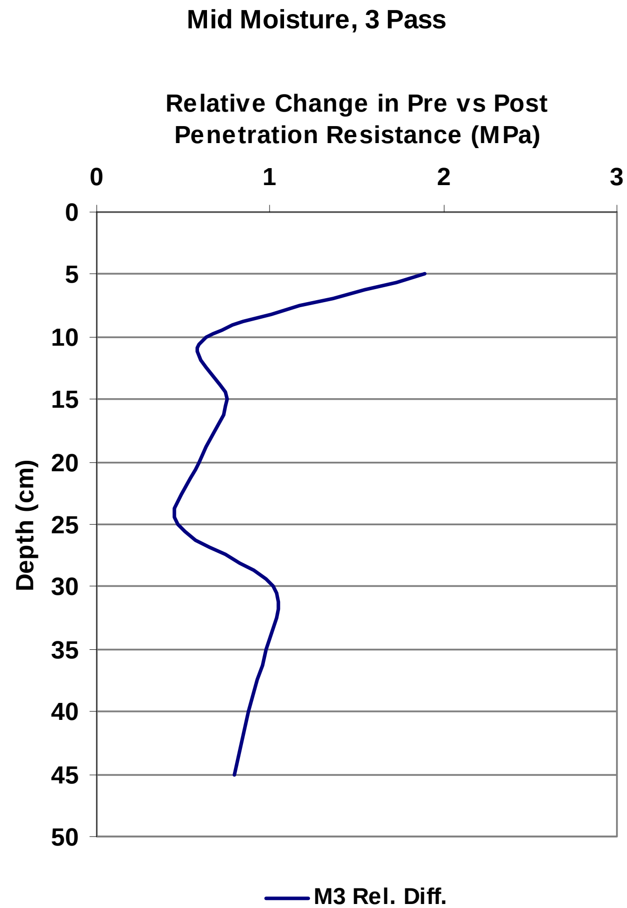


Figure A.4.5. Comparative Penetration Resistance Mid Moisture – 6 Pass. a). Average penetration resistance (MPa) measurements of Mid Moisture 6 Pass plots immediately preceding (M6Pre) and following (M6Post) tank passage in 2007 and follow up measurements taken at Field Capacity+ (M6 FC+) in 2009. Error bars represent ± standard error of the mean. b). Relative penetration resistance (MPa) change between M6Pre and M6Post measurements.

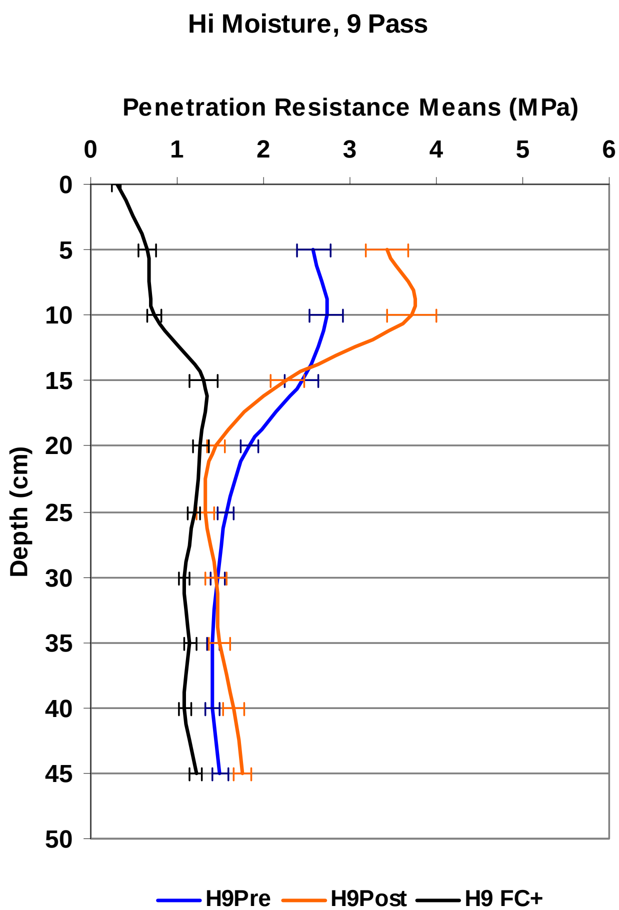


a)

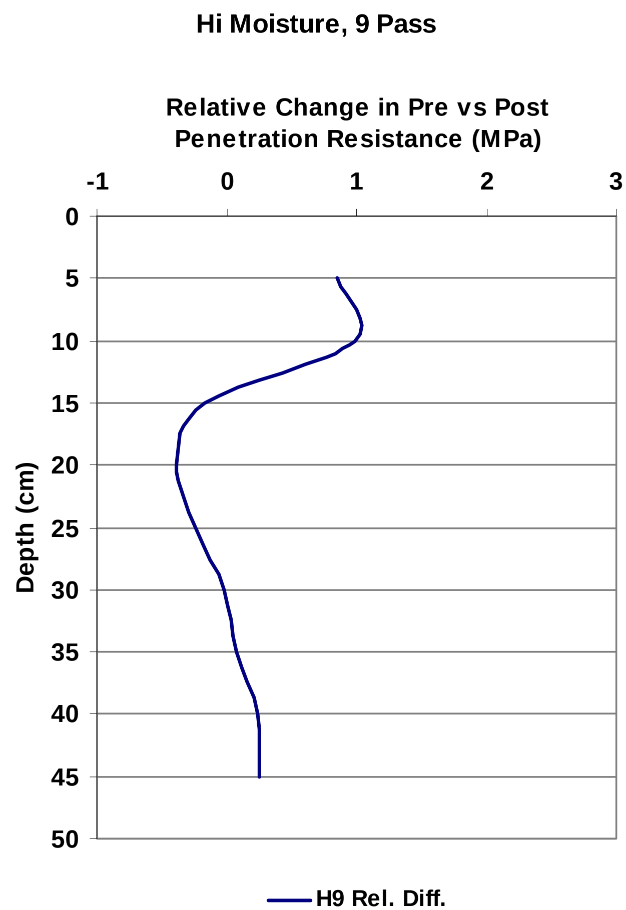


b)

Figure A.4.6. Comparative Penetration Resistance Mid Moisture – 3 Pass. a). Average penetration resistance (MPa) measurements of Mid Moisture 3 Pass plots immediately preceding (M3Pre) and following (M3Post) tank passage in 2007 and follow up measurements taken at Field Capacity+ (M3 FC+) in 2009. Error bars represent ± standard error of the mean. b). Relative penetration resistance (MPa) change between M3Pre and M3Post measurements.

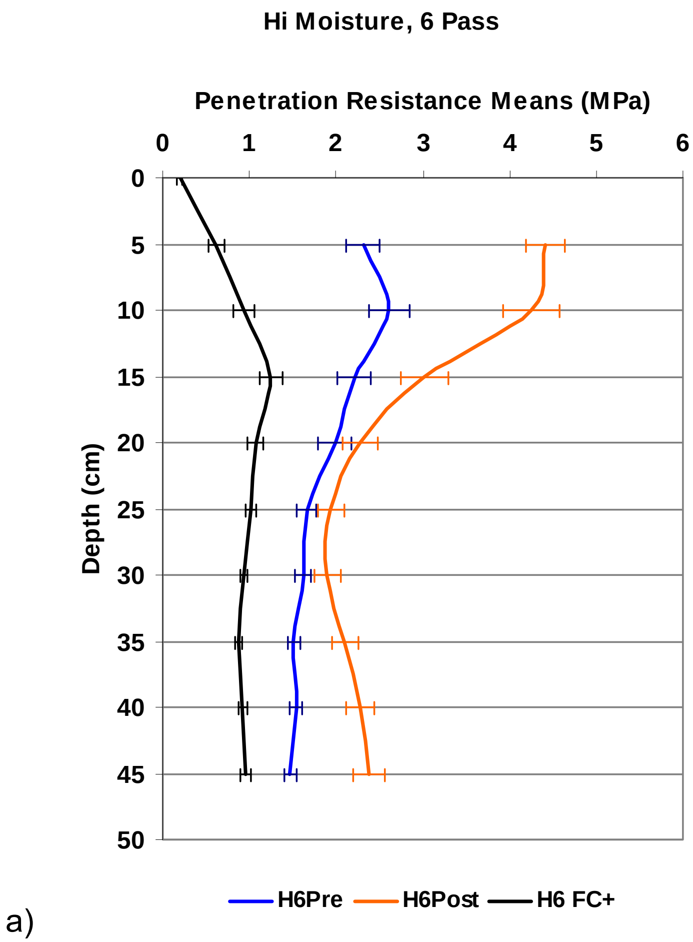


a)



b)

Figure A.4.7. Comparative Penetration Resistance Hi Moisture – 9 Pass. a). Average penetration resistance (MPa) measurements of Hi Moisture 9 Pass plots immediately preceding (H9Pre) and following (H9Post) tank passage in 2007 and follow up measurements taken at Field Capacity+ (H9 FC+) in 2009. Error bars represent ± standard error of the mean. b). Relative penetration resistance (MPa) change between H9Pre and H9Post measurements.



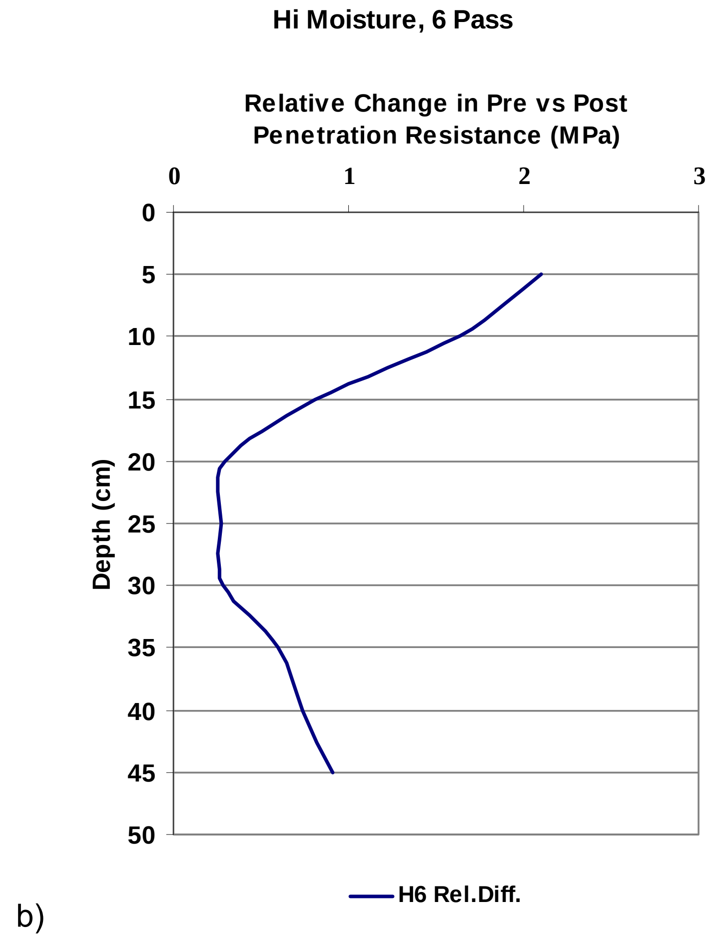


Figure A.4.8. Comparative Penetration Resistance Hi Moisture – 9 Pass. a). Average penetration resistance (MPa) measurements of Hi Moisture 9 Pass plots immediately preceding (H9Pre) and following (H9Post) tank passage in 2007 and follow up measurements taken at Field Capacity+ (H9 FC+) in 2009. Error bars represent ± standard error of the mean. b). Relative penetration resistance (MPa) change between H9Pre and H9Post measurements.

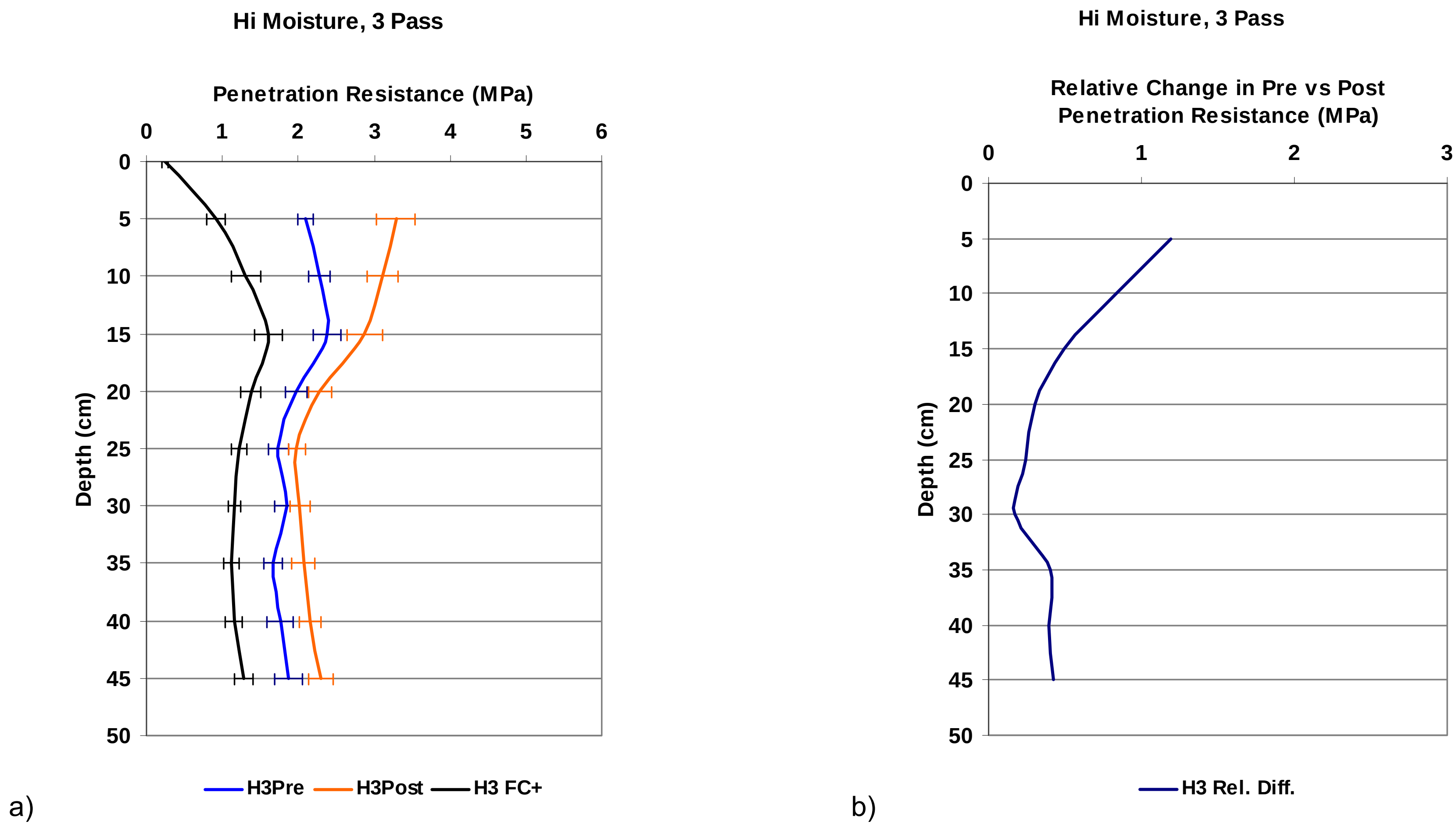


Figure A.4.9. Comparative Penetration Resistance Hi Moisture – 3 Pass. a). Average penetration resistance (MPa) measurements of Hi Moisture 3 Pass plots immediately preceding (H3Pre) and following (H3Post) tank passage in 2007 and follow up measurements taken at Field Capacity+ (H3 FC+) in 2009. Error bars represent ± standard error of the mean. b). Relative penetration resistance (MPa) change between H3Pre and H3Post measurements.

VITA

Michael R. Lindsey was born February 1956, in Shreveport, Louisiana. He attended the University of Southwestern Louisiana (USL) briefly then began a career in commercial construction. He became construction superintendent for a Lafayette area construction firm where he worked until 1991 when he started a small construction business upon re-entering USL. He earned a Bachelor of Science degree in environmental and sustainable resources in December 1995. In June 1996 he began work toward a Master of Science degree in agronomy at Louisiana State University (LSU). Prior to graduation in December 1998 he was offered a 70/30 teaching-student advising/research instructor's position in the Agronomy Department at LSU. While at LSU he taught the undergraduate soil conservation and the soils in the environment courses and a one-time graduate credit level non-point source pollution control course designed for AgCenter personnel needs. While in the employ of LSU he took coursework toward a doctoral degree. He remained in that position until January of 2004 when he began work as a field soil scientist with the USDA-NRCS Soil Survey Division in the Carencro Soil Survey Office. It was his good fortune that the opportunity arose to work on an NRCS tank trafficability study which he utilized as his doctoral research project. He expects to graduate in December 2009.

He has been married to the former Charlotte DuCote' for twenty-eight years. Together they raised three children, Michael East, Holly East, and Aja Lindsey. They now enjoy an extended family with six grandchildren.