A WETLAND TRAFFICABILITY HAZARD INDEX BASED ON SOIL PHYSICAL PROPERTIES AND SITE HYDROLOGY EVALUATIONS

by

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
in
Forestry

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July 1994

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(ABSTRACT)

Harvesting of forested wetlands in the Atlantic and Gulf lower coastal plains has the potential to cause intense site disturbance. Often, as a result of poor pre-harvest planning, silvicultural activities are performed on wetland soils highly susceptible to rutting and puddling. Potential decreases in pine productivity have been connected with increased soil strength and decreased aeration that are commonly remnants of site disturbances associated with wet-weather harvesting. A simple and economical rating system is needed to identify soils susceptible to disturbance by various types of equipment. The use of such a system could lower the impact on wetland soils and lower the cost of extensive site preparation methods. Logging efficiency and operational productivity could also be increased by identifying equipment types compatible with site conditions.

The purpose of this study was to characterize and model soil strength as a function of soil physical properties and site characteristics. The soil strength model was subsequently used to develop a trafficability hazard index. Forested wetland sites in the

South Carolina coastal plain were characterized to develop the trafficability hazard index. The study site consisted of three blocks located on poorly drained loblolly pine plantations. Five sequences of measurements were taken consisting of soil moisture, water table depth, and soil strength. The five sequences of measurements were taken over a wide range of soil moisture contents and water table depths to characterize the effects on soil strength. Bulk density, porosity, texture, organic matter, and hydraulic conductivity were also determined to characterize the blocks and identify effects on soil strength.

Evaluating the effects of these properties on soil strength identified two relatively easily determined soil properties that could be used for the trafficability index. Volumetric moisture content and penetration resistance of the A horizon were used due to their relationships with trafficability and ease of determination. Estimates of pressure applied to the soil by harvesting equipment were used to find the limits of the sandy loam A horizon to support various types of equipment. Equipment pressures were compared to soil penetration resistance pressures estimated by soil moisture. The trafficability hazard index presented used general ground pressures for various harvesting equipment, but use of specific equipment pressures would provide the best results. Using the trafficability hazard index, sites with less than optimal conditions for traffic can be avoided or special harvesting equipment can be identified to limit site disturbance.

ACKNOWLEDGMENTS

I would like to thank all my committee members, Drs. W.M. Aust, J.L. Smith, and N. Persaud for their advice and assistance with my master's program. A special thanks goes to my advisor, Dr. W.M. Aust, for his guidance and input. Other persons deserving recognition are Steve Patterson and Denis Joliet of Westvaco, for their assistance in data collection and establishing this project.

I would also like to recognize my fellow graduate students, too numerous to list (but you know who you are) for their help with field work. I would also like to thank the secretaries, Nancy Chapman, Kathy Hollandsworth, Sue Snow, and Peggy Quarterman who were always helpful. Credit should also be given to Westvaco Corporation and the U.S. Forest Service for the financial support which made this research possible.

Most importantly, I would like to thank my wife to be, Denice Renkenberger for her love and support through my field work and writing.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTENSIVE MANAGEMENT OF FORESTED WETLANDS

Wet-Weather Harvesting in Forested Wetlands

Wet pine flats are the low-lying, somewhat-poorly- to poorly-drained areas common along the Atlantic and Gulf Coastal Plains. Many of these areas are currently classified as jurisdictional wetlands. Within the Atlantic Coastal Plain, large acreages of wet pine flats are currently under intensive management for pine production. Forest management of wet pine flats represents some of the most intensive silvicultural operations in the world (Allen and Campbell 1988).

These areas originally had relatively low productivity as forest land. Various site preparation techniques such as drainage, bedding, and fertilization have been used on these areas to greatly enhance the commercial production of pine, particularly of Pinus taeda. Large acreages of wet pine flats have been under such intensive management regimes for the past 25-35 years. When intensive forestry operations began, pine plantations only produced 4 percent of the pine harvested. After fourteen years, plantation forests were producing 18 percent of harvested pine. Plantations are expected to produce 54 percent of harvested pine by the year 2000 (Earley 1991a).

Despite their enhanced productivity, Wet pine flats are difficult to harvest due to wet soil conditions. Water tables are frequently near the soil surface throughout the winter and spring months, and wet growing seasons are common. On non-drained sites, operation of harvesting equipment without soil rutting problems is limited to a 3 to 6 month period (Allen and Campbell 1988). The limited window of operability makes it necessary to conduct harvesting operations during wet conditions. The effect of such operations may cause soil rutting and puddling.

The impact of rutting and puddling on site productivity has not been determined, but site disturbance can alter hydrology (Trousdell and Hoover 1955), reduce soil aeration and modify other soil physical properties (Childs et al. 1989). Soil strength, the ability of the soil to bear a traffic load, is strongly correlated to soil moisture (Greacen and Sands 1980). If soils are trafficked under wet conditions they may fail to support a load as a result of reduced soil strength. At this point, rutting and puddling can occur. As a result of rutting and puddling during wet weather operations, soil strength is increased and large soil voids are collapsed, thus reducing total soil porosity (Greacen and Sands 1980). Increased soil strength and reduced porosity may negatively affect the development of root systems in soil (Letey 1985). Thus, it has been suggested that rutting and puddling may decrease site productivity.

In recent years, the effect of site disturbance on productivity and wetland functions has been of increasing interest to a variety of groups. Related concerns include sustainable forest productivity, wetland carbon storage, water quality, wetland ecosystem processes, wetland production of greenhouse gases, landscape disturbance effects, and federal and state forestry Best Management Practices (BMP's)for wetlands.

Many states have developed Best Management Practices in order to avoid, minimize, or ameliorate site disturbances incurred during intensive management operations (Golden et al. 1984, Ice 1989). The use of high-flotation, wide-tired skidders has been advocated as a BMP for reducing impacts from wet weather harvesting (Figure 1.1). The applicability and benefits of such equipment has been overestimated. Aust et al. (1990) concluded that use of wide-tired skidders can reduce site impacts as compared to conventionally-tired skidders, but wide-tired skidders can have negative site impacts if they are used to extend the area of operations onto wetter sites.

Historically, timber industries have been able to use intensive management practices in wetlands with little regard to the effects (Earley 1991b). As second and third rotation pine plantations are being harvested, the concern over long-term consequences of rutting on site productivity is increasing among forest managers. Forest managers not only have to be concerned with possible productivity decline, but also with increased opposition to pine plantations in wetlands (Early 1991a).

Figure 1.1. A skidder equipped with experimental ultra-wide tires (dual 43-inch wide-tires).

Perhaps the best method of avoiding the rutting and puddling problem is through better planning combined with an improved understanding of soil and site characteristics. It has been concluded in many studies that better pre-harvest planning could have avoided or reduced soil disturbance on wet sites (Aust et al. 1990, Gent et al. 1983). A relatively simple technique of evaluating soil and site characteristics would aid land managers in making informed, on-site decisions concerning site operability and potential site damage.

This study was developed in order to resolve some of the site disturbance problems associated with forestry operations in wetlands. The overall objectives of this study are:

1. to characterize and model soil strength as a function of soil physical properties and site characteristics, and
2. to use the soil strength model to develop a trafficability hazard rating that can be used on similar soils and sites.

Wetland Definition

The term wetland includes a wide range of inland, coastal, and marine habitats which exhibit many of the same features (Dugan 1990). Forested wetlands of the southeastern coastal plain region are commonly referred to as muck swamps, peat swamps, wet flats, red river bottoms, black river bottoms, branch bottoms, bay forests, head water forests, and cypress stringers and domes (Kellison et al. 1981). Approximately ten percent of the forested wetlands are wet pine flats (1 million ha) (Cubbage and Flather 1993). All of these forested wetland types are classified as paustrine forested wetlands by the federal regulatory agencies.

The federal Clean Water Act of 1977 (and amendments) and the Food Security Act of 1985 provided the majority of federal jurisdiction over wetlands to four federal agencies: U.S. Army Corps of Engineers (COE), U.S. Environmental Protection Agency (EPA), U.S.D.A. Fish and Wildlife Service, and the U.S.D.A. Soil Conservation Service (SCS). The COE and EPA have permitting and regulatory authority, while the Fish and Wildlife service has the ability to comment on wetland permit applications. The Fish and Wildlife Service is also responsible for wetland inventories. The SCS has the responsibility of determining the criteria for hydric soils. Prior to 1989, the federal agencies had different criteria for identifying forested wetlands subject to permitting requirements under section 404 of the Clean Water Act. Conceptually all of the wetland delineation methods were similar and used the same three basic identifying characteristics: hydrophytic vegetation, hydric soils, and wetland hydrology. In 1989 the 4 agencies made an attempt to develop a consistent methodology for the identification of wetlands. However, the 1989 manual resulted in over expansion of wetlands jurisdiction (Dubensky et al. 1993). Tremendous increases in wetland acreage occurred as a result of the 1989 manual. In 1991 the 1989 manual was withdrawn and the 1987 COE delineation method was identified as the official wetland identification methodology (Toliver 1993). Section 404 of the Clean Water Act enacted a legal definition of wetlands stated as: "...areas that are inundated or saturated by surface ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs and similar areas." (Anonymous 1987). The Corps 1987 manual also used hydrology, hydric soils, and hydrophytic vegetation as a basis for wetland identification; however the requirements are different from the 1989 manual. The following is a definition of each parameter used in the 1987 manual.

Vegetation. Wetland vegetation consists typically of plants adapted to areas having hydrologic and soil conditions described in the wetlands definition. Hydrophytic species must not only be present, but compete effectively, reproduce, and persist in anaerobic soil conditions (Toliver 1993). Wetland plants are categorized into three groups: hydrophyte wetland species (greater than 99% chance of occurring in wetlands), facultative wetland species (67% to 99% chance), and facultative species (33% to 67% chance) (Cowardin et al. 1979).

Soils. Hydric soils are saturated, flooded, or ponded for a duration during the growing season necessary to develop anaerobic conditions. However, a drained hydric soil that no longer supports hydrophytic vegetation is not a wetland soil. The soil must also have indicators of wetland hydrology before it is considered a wetland soil (Toliver 1993).

Hydrology. Area is inundated permanently or periodically at mean water depths less than or equal to 2 meters (Toliver 1993). The 1987 manual does not identify a specific duration of inundation required. However, the 1989 manual did require soils to be saturated for a period of 7 days. A proposed revision in 1991 suggested wetland hydrology should be defined as 15 consecutive days of inundation or 21 consecutive days of saturation during the growing season (Dubensky et al. 1993). Many other proposals have been suggested to aid in defining wetlands. The forest industry suggested the most scientifically credible way to identify a wetland is to use a combination of the three criteria along with identification of specific wetland ecosystem types (Dubensky et al. 1993). Dubensky et al. (1993) suggested "regional wetland manuals should be developed based on the presence and geographic extent of specific wetland ecosystems and land forms within regions."

In 1986 the Office of Wetland Protection was developed by the EPA for the purpose of dealing with wetland regulation authorized under the 1972 Act and the Clean Water Act Amendments of 1977 (Cubbage et al. 1990). The EPA's objective was to prevent any net loss of wetlands in the U.S. Any activities which altered wetlands were subject to permits. However, the 1977 Clean Water Act Amendments exempted normal silvicultural activities from permit regulations (Cubbage et al. 1990), allowing the forest industry to continue intensive management of pine plantations in wetlands. However, the issue of wetland delineation is still a major concern to the forest industry. If large increases in wetland acreage occurs as a result of new delineation standards, current forest operations falling within the new delineation may not be exempt from permitting. This could add to management costs and possibly result in limited harvesting.

Wetland functions

The hydrology, soils, and vegetation which define a wetland ecosystem may also result in ecological processes (functions) that may provide societal values (Table 1.1)

(Walbridge 1993). All functions will not occur to the same degree within every wetland, thus all wetlands will not have equal value.

Table 1.1. Wetland social values stemming from wetland functions, adapted from Walbridge (1993).

Function	Societal value
Plant and Animal Habitat	Animal pelts Commercial fishing Recreational hunting and fishing Timber Production
Hydrology	Flood mitigation Storm abatement* Groundwater recharge
Biogeochemistry	
Sediment deposition Denitrification Sulfate reduction* Phosphorus sorption Nutrient uptake Decomposition of waste organics Sorption of heavy metals Retention of toxins	Improved water quality
Carbon storage* Methane production	Global change mitigation

*Functions and values not commonly attributed to forested wetlands in the southern United States.

The National Wetlands Policy Forum's final report in 1988 specifically identified silviculture as a compatible use of wetlands without causing significant loss of valuable functions (Conservation Foundation 1988). Research supported by the National Council of the Paper Industry for Air and Stream Improvement (NCASI) has been measuring the effects of forest management practices on wetland functions. According to many studies, timber harvesting generally has little effect on wetland water quality (Mader 1991, McCarthy and Skaggs 1992). The effects of forest management on wildlife habitat are still being researched; however, preliminary results concerning the compatibility of forest management and wildlife habitat in wetlands are encouraging (Shepard et al. 1993).

Intensive Management of wetland forests

Pine productivity in the coastal plain is maximized by intensive forest operations. The most widespread forest type in the South, Pinus taeda - Pinus echinata (Mann 1973) has been intensively managed for pine production for the past 25-35 years. In order to achieve optimal growing conditions, extensive site manipulation is required. Such site manipulations influence several principal features of the soil profile that contribute to site quality. Site preparation is a deliberate attempt to increase site productivity by manipulation of depth of the surface soil (A horizon), depth to the least permeable layer, depth to mottling, physical nature of the surface soil, aeration and mechanical hindrance to root growth, organic matter, chemical characteristics, relative topographic position, and distance from the soil surface to the water table (Coile 1952).

Drainage is necessary for the production of pine on poorly drained soils (Figure 1.2). The drainage of large areas is accomplished by extensive ditch networks (Earley 1990a). Drainage is often used to provide greater site access and to enable silvicultural equipment operations (Allen and Campbell 1988), secondary ditching has also been used to increase tree growth on wet sites (Ralston 1965). Drainage increases pine productivity because drained soils have a greater depth to mottling and depth to the water table. If the sites are not drained, forest operations should be limited to a shorter time span. However, mill wood shortages occur during wet weather and consequently sites may be harvested under less than optimal conditions.

Three primary site disturbances can occur during wet weather harvesting: rutting, puddling, and compaction. Site disturbance often alters soil physical properties reducing site productivity, and limits future silvicultural treatments to the stand (Terry and Campbell 1981).

The alteration of the soil properties may be ameliorated by natural or artificial methods (Voorhees 1983). Natural agents may restore the site to its original soil conditions. Annual freezing and thawing is one such natural amelioration. However, in the Southeast, the absence of this event allows the condition to persist (Gill 1971). Site preparation is an artificial mechanism for amelioration.

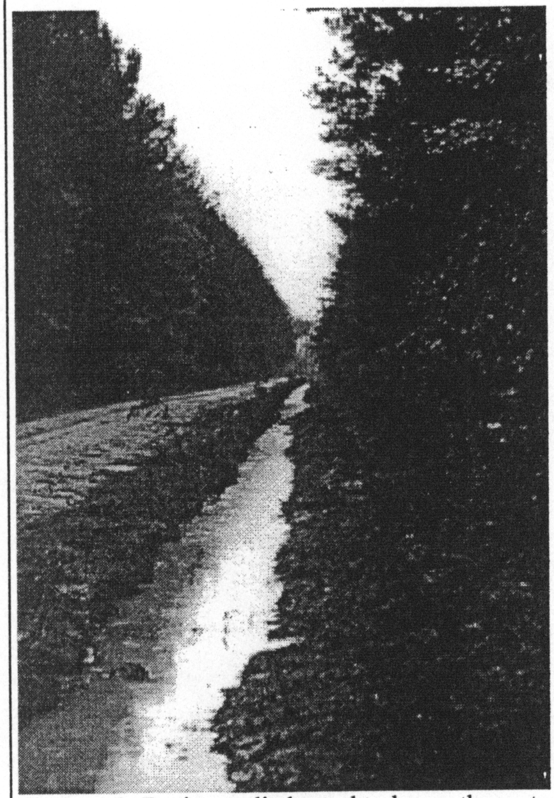


Figure 1.2. Drainage ditch used to lower the water table in order to increase productivity.

In order to create optimal conditions for seedling growth, logging debris is commonly chopped, harrowed, and sometimes burned. This eliminates debris which was left after harvest. On wet sites, bedding is often the last site preparation operation. The beds are raised mounds of soil on which seedlings will be planted. The bedding increases the seedling survival and growth rate by increasing the depth of the surface soil, improving soil physical properties by increasing aeration and decreasing mechanical hindrance. The beds also serve to elevate the seedlings above the water table and concentrate organic matter. Once all of the site preparation is completed, regeneration is accomplished by planting or direct seeding (Toliver and Jackson 1988). The strongly acid soils commonly found on poorly-drained coastal plain sites have low levels of available phosphorus (Terry and Hughes 1975). The application of both nitrogen and phosphorus have been found to increase pine seedling growth (Moehring, 1966; Langdon 1976). As a result pine plantations are often fertilized.

Effects of site disturbance on soil physical properties

The physical nature of a soil directly affects the management which can be imposed without causing significant site disturbances. The degree of soil disturbance can be evaluated by an examination of various soil physical properties, such as: soil strength, bulk density, porosity, moisture content, hydraulic conductivity, and water table levels (Aust et al. 1990).

An understanding of the relationships between soil physical properties, site disturbance, and resultant site productivity can help the land manager avoid and minimize site disturbance. Due to the close proximity of the water tables to the surface of many sites in the Southeastern coastal plain, harvesting under wet conditions is common. When sites are harvested under wet conditions two major site disturbances can occur, rutting and puddling.

Shear strength refers to the ability of a soil to be trafficked or bear a load. When a soil is near saturation, it's shear strength is very low. If a load is applied, shear failure may occur. Subsequently, when the soil moisture approaches the liquid limit the soil flows when trafficked and this phenomena is referred to as puddling and rutting (Figure 1.3). The kneading action of machinery and logs obliterates the soil structure (Froehlich and McNabb 1984), producing a soil with unfavorable physical conditions for plant growth. Soil puddling alters soil structure by destroying soil aggregates and peds and churning the soil into a liquid paste (Beacher and Strickling 1955, Swanson et al. 1955, Buehrer and Rose 1943). Rutting and puddling is at a maximum when a soil is greater than field capacity, approaching saturation (Bodman and Rubin 1948, Koenigs 1963, Akram and Kemper 1979). The mass flow of soil at the liquid limit is due to moisture films around the soil particles becoming so thick that cohesion is decreased. The increased water content decreases the cohesive forces and acts as a lubricant between soil particles to allow them to align and slide past one another. The effects of rutting and puddling are somewhat similar to soil compaction. After a study comparing the effects of compaction and rutting and puddling on soil physical properties and hydrologic characteristics of a South Carolina coastal plain wetland, Aust et al. (1992) concluded that "Visually, the rutted areas appeared to be more highly disturbed than the compacted areas, and measurements of soil physical and hydrologic properties verified this."

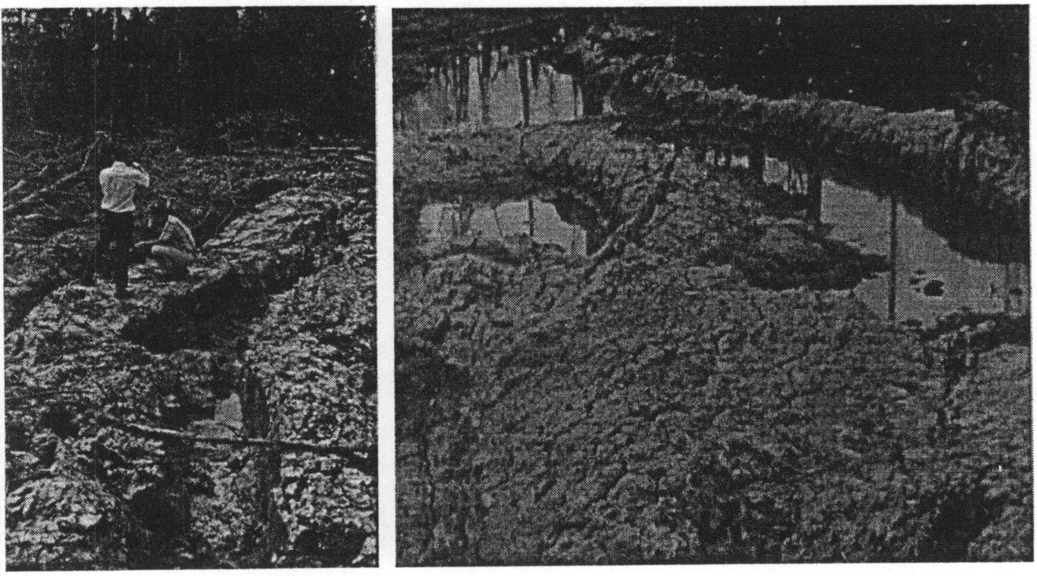


Figure 1.3. Soil puddling and rutting as a result of wet-weather harvesting.

Once a site has been rutted or compacted, the disturbance can have drastic effects on other soil physical properties, sometimes resulting in a potential site productivity decline (Figure 1.4). Figure 1.4 is similar to the model presented by Greacen and Sands (1980); however, an attempt has been made to re-categorize interactions to describe various effects of compaction and rutting or puddling on tree growth. The evaluation of bulk density, soil strength, porosity, moisture content, hydraulic conductivity, and water table heights can be used to evaluate the extent of site disturbance created by rutting and compaction.

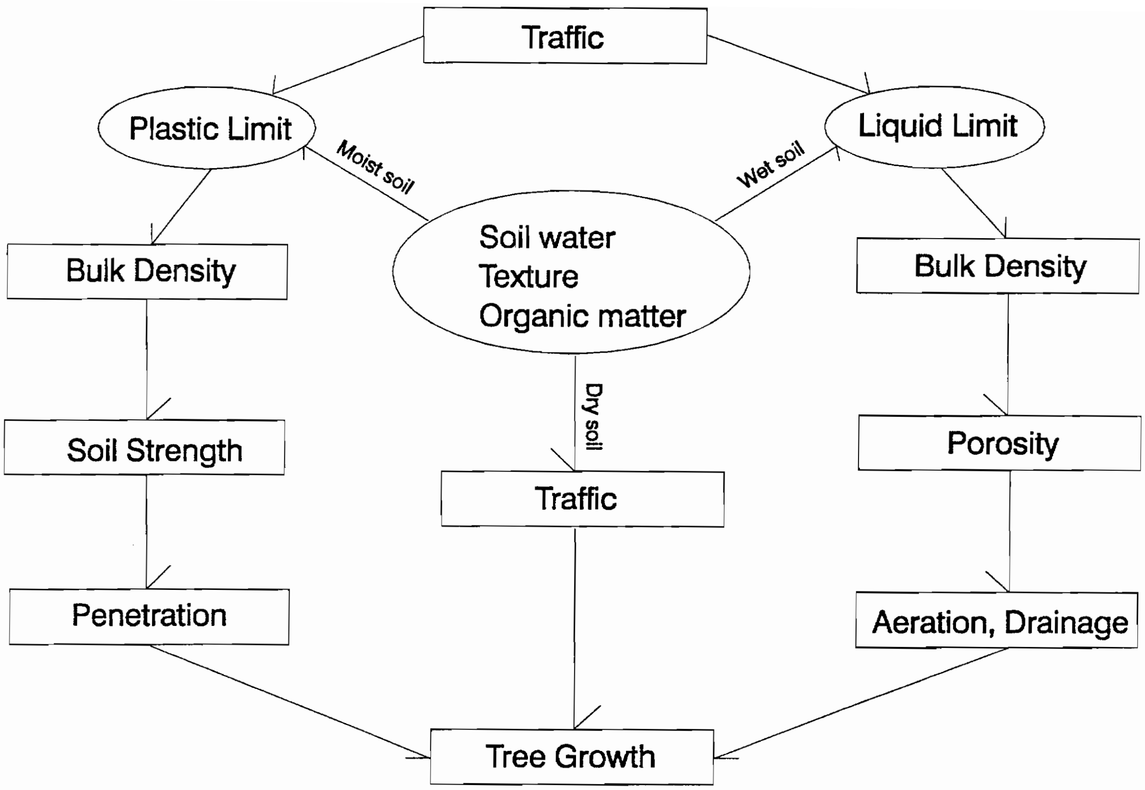


Figure 1.4. Conceptual model illustrating possible disturbance paths effecting tree growth.

Rutting / Puddling

Bulk density is defined as the mass of a given soil per unit volume (Blake and Hartge 1986). When a soil is rutted or puddled the effects on bulk density are not always predictable. The changes in bulk density after puddling depend on the soil aggregation status prior to the disturbance. If a soil is well aggregated before disturbance and a closely packed structure exists after disturbance the bulk density will increase; however, puddling of a closely packed soil structure will not drastically change the bulk density from the original value (Aylmore and Quirk 1962). As a result, a porous soil is more subject to traffic induced bulk density increases than is a less porous soil. When bulk density increases as the result of rutting or puddling, the distribution of micro- and macro-pores is affected. The total porosity of the soil may not decrease significantly, but the distribution of micro- and macro-pores is altered. Macro-pores are the larger pores (r = 0.06mm) that are responsible for rapid draining of water from a soil and allowing adequate aeration. The porosity of a soil refers to the non-solid phase which is in two forms, gaseous and liquid phases per unit volume of soil. When a soil is puddled the soil gaseous phase is eliminated, leaving only the solid and liquid phases (Buehrer and Rose 1943). In a comparison between compaction and rutting, it was concluded that the total pore space (micro-pores and macro-pores) was reduced by both types of disturbance (Aust et al. 1992). As a soil is puddled, large voids and macro-pores are lost and the amount of micro-pores increases. This decrease in macro-pores is a result of large voids collapsing under shearing forces. Aust et al. (1992) found that the total porosity and macro-porosity were decreased significantly, but micro-porosity was not affected. When macro-porosity decreases as a result of puddling, the ability of soil to transmit water also decreases because the macro-pores are responsible for the mass movement of water. Thus, a soil with a higher macro-pore volume will generally have faster rates of hydraulic conductivity than a soil with a lower macro-pore volume. The decrease in hydraulic conductivity slows water movement and potentially decreases the site drainage. Decreased drainage increases soil moisture, therefore the site is more susceptible to puddling during future forest operations. Gent et al. (1983) found that there was not a significant decrease in hydraulic conductivity after harvest, but when the site had additional forest operations (site preparation) the hydraulic conductivity of the soil was significantly lower than the pre-harvest values. As a result of decreased hydraulic conductivity, soil moisture and depth to the water table can increase. Aust et al. (1992) found that decreased hydraulic conductivity resulted in decreased water table depths, producing sites which remained wet for longer periods of time. It was also found that disturbance in a moderately well-drained site increased depth to the water table to a greater degree than somewhat poorly and poorly-drained sites. Thus, the rutting and puddling of a site with an inherently low hydraulic conductivity will result in less of an impact than the disturbance of a soil with a higher conductivity. This can be explained by the relationship between hydraulic conductivity and porosity. When large voids are eliminated by parallel orientation and close packing of soil particles the hydraulic conductivity is decreased. (Sharma and De Datta 1986). This effect causes water table depths to increase and limit workability. The decrease in water table depth can also cause low soil oxygen levels which have been shown to decrease tree growth if conditions persist (Kozlowski 1986).

Compaction

Soil compaction results when moist sites are trafficked. Soil compaction causes decreased porosity, hydraulic conductivity and increased bulk density and strength (Gent et al. 1983; Gameda et al. 1987). Although, effects of compaction and puddling are somewhat similar, the disturbances occur under different conditions of soil moisture. Soil puddling generally occurs on very wet poorly-drained sites when soils are near the liquid limit. Soil compaction generally occurs on drier sites where soils are near the plastic limit. Two kinds of stresses affect soil during puddling: (1) normal stress associated with compression and (2) tangential stress which causes shear (Bodman and Rubin 1948). The normal stress associated with compression results in compaction and tangential stress has a greater affect on puddling. Due to the continuous change in the direction of shear planes caused by rotary motion, a better puddling effect is expected from rotary implements than by plows for rice production (Sharma and De Datta 1986). The forces imposed on the soil by rotary motion are similar to the forces applied to the soil by spinning tires of forest equipment. This suggests that the forces applied to the soil by forest equipment is that which is conducive to puddling. As a result, the increase in soil strength generally caused by increased bulk density and decreased porosity is not found on puddled sites due to the over abundance of water. However, once the site dries out there is a potential for increased soil strength. Tippett (1992) found soil strength was not measurably different as a result of rutting disturbance. This effect was explained by high soil moisture contents possibly resulting in soil strengths never reaching root restricting levels. The increased moisture content appears to eliminate root restrictions due to soil strength; however, the high moisture contents may result in decreased oxygen causing additional root growth restrictions (Figure 1.4.). Conversely, high moisture contents are generally not present on sites affected by soil compaction, eliminating aeration problems, but manifesting soil strength root restrictions. The increased soil strength as a result of compaction has the potential to decrease root growth causing decreased tree growth. However, it must also be understood that soil compaction can occur on sites where soil puddling has caused soil disturbance. The two disturbances have been separated to illustrat the effects of increased soil strength and decreased aeration on tree growth.

Soil Strength Modeling and Traffic Hazard Models

Timber managers are realizing that rutting and puddling have the potential to reduce site productivity. Currently, site preparation methods have been suggested for amelioration of the disturbance caused by harvest operations. However, site preparation used to ameliorate soil disturbances has the potential to cause greater soil disturbance than the initial harvest operation or may not ameliorate disturbances (Gent et al. 1983). If a land manager could make informed decisions regarding the potential for site disturbance, alternate sites could be harvested which did not have a high risk of damage. Pre-harvest planning could be used to determine sites having a high or low potential for damage and harvest of high risk sites could be postponed until the conditions are appropriate for harvest. This would decrease site disturbance and reduce site preparation.

The lack of information about the relationship between water content and other factors limits the usefulness of strength measurements (Greacen 1960). A conceptual model can be used to summarize knowledge of major processes which are known to influence soil strength (Figure 1.5). This model represents a greatly simplified attempt to characterize a very complex system. The model does not include all of the interactions between the parameters involved in the determination of a soil's strength. The trafficability of a site can be determined by interactions of soil physical properties as can the effect of traffic on soil physical properties. Understanding the relationship between soil physical properties and soil strength can give land managers detailed trafficability information for individual forest tracts on a day to day basis.

The use of penetration resistance has been used on a wide scale to describe the soil physical status (Canarache 1990). Canarache cites the uses of penetration resistance in a number of soil applications, soil management (Mitscherlich 1913), soil dynamics (Gill and Vanden Berg, 1968; Koolen and Kuipers 1983), resistance to ploughing or cutting (Bakhtin 1954; Zelenin 1959), soil compaction (Barnes et al. 1971), and soil tillage (Cassel 1982). Many researchers such as Wells and Treesuwan (1978), Busscher et al. (1987), Ayers and Perumpral (1982), Henderson et al. (1988), Canarache (1990), Mirreh and Ketcheson (1972), and Rounsevell and Jones (1993) have attempted to

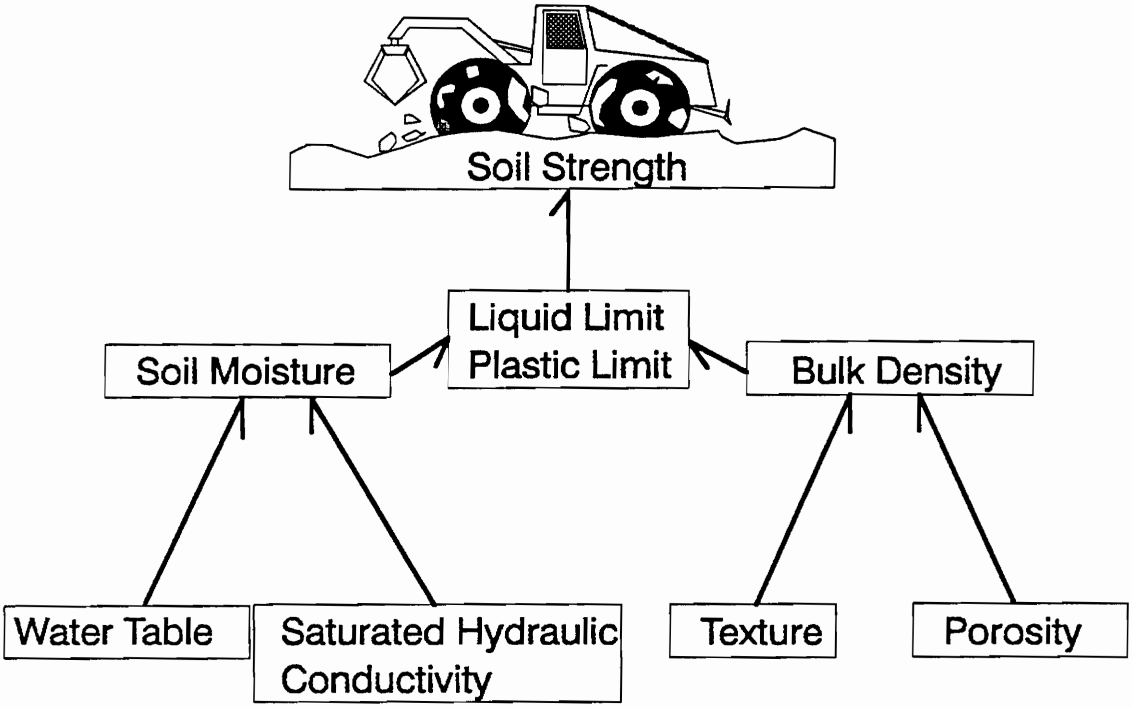


Figure 1.5. Conceptual model of soil parameters affecting soil strength.

indirectly estimate resistance to penetration or trafficability by using various soil parameters.

Many of the soil physical properties affected by rutting and puddling also affect the soils susceptibility to these disturbances. The strength of the soil depends on a number of physical properties including bulk density, texture, moisture content, and pore space. However, soil water content is the most important parameter influencing soil strength (Kay 1986). Other reports also discuss the significant effect of moisture on penetration resistance (Busscher 1990; Ayers and Perumpral 1982; Henderson et al. 1988). The influence of water content on soil strength can be derived by the relationships of many soil physical properties and the interactions between these properties which affect the trafficability of a soil. Soil strength, as defined above, has many physical attributes affecting its limits. Soil strength decreases as bulk density decreases and water content increases. Ayers and Perumpral (1982) found that the cone index or soil strength increased exponentially with dry bulk density at low moisture contents (2.6%, 4.4%, and 6.7%). An increase in moisture content (8.8% and 11.8%) resulted in a more linear relationship between soil strength and dry bulk density. As the moisture content increased the rate of increasing strength with bulk density decreases. A similar relationship was observed by Mulqueen et al. (1977).

Spivey et al. (1986) suggests that soil strength may be related to the texture of single grained or massive soils of the Southeastern coastal plain soils. This suggestion is made from textural relationships with both moisture and bulk density (Gupta and Larson 1979; Byrd and Cassel 1980; Stitt et al. 1982). Spivey et al. (1986) found that probe resistance of samples with comparable forces of consolidation was correlated with particle size class. This also enforces the importance of bulk density to soil strength. There have been many studies that have reported the importance of particle size distribution on the compactibility or bulk density of soil (Bodman and Constaintin 1965; Gupta and Larson 1979). Henderson et al. (1988) reviewed several studies and concluded that particle size distribution had a strong influence on soil density. A soil with a wide range of particle sizes is more easily compacted, because the smaller particles fit between larger grains in the soil (Panayiotopoulos and Mullins 1985).

The porosity or void ratio of a soil at saturation is directly related the amount of water present in soil. Hvorslev (1937) as cited by Greacen (1960) used frictional shear strength and void ratio to determine shear strength in a saturated clay. The void ratio was used to determine the cohesion component of shear strength. Croney and Coleman (1954) also used void ratio as a determinate of soil strength. Roscoe, Schofield, and Wroth (1958) as cited by Greacen (1960) found and demonstrated a critical voids ratio

(CVR) which added to the concepts of Croney and Coleman (1954). Gerard, Sexton and Shaw (1982) used a number of soil physical properties to model soil strength, including voids. They found that voids were negatively related to soil strength.

Organic matter has also been used as a predictor of soil strength. Typically, organic matter increases are associated with decreases in soil strength. Increases in organic matter also decrease bulk density, suggesting a complex set of interactions attributing to soil strength. Sands et al. (1979) reported that organic matter was important for the maintaince of favorable soil conditions in Australian radiata pine (Pinus radiata) forests. Spivey et al. (1986) found an unusual correlation between organic matter and soil resistance. As organic matter increased there was a significant increase in soil strength. Spivey attempted to explain the relationship by the type of packing and the low bulk density of the organic matter. When soil with a high organic matter content is compressed into the same volume as a soil with a lower organic matter content the mineral fraction of the soil is compacted more in the soil containing the greatest amount of organic matter. However, the findings suggest organic matter is a parameter with effects soil strength.

Henderson et al. (1988) looked at the effects of water content and bulk density on the soil penetration resistance of some sandy Western Australian soils. Henderson compacted a known weight of dry soil to a designated density in PVC cylinders. The cylinders were then wetted to a desired water content. Penetration resistance (PR) was measured for different combinations of bulk density (BD) and moisture (MC).

The best prediction equation of penetration resistance was found to be:

$$PR = (BD/1000)^{a}/(bMC+c)$$

Where PR = penetration resistance

BD = dry bulk density

MC = moisture content

a,b,c = constants

Ayers and Perumpral (1982) also used dry bulk density and moisture content to develop a mathematical relationship. Again soil cylinders were used in a laboratory environment. Cylinders were filled with varying amounts of clay and sand. The following equation was reported:

$$PR = (a*BD^{d})/[b+(MC-c)^{2}]$$

Where PR = penetration resistance

BD = dry bulk density

MC = moisture content

a,b,c = constants

Ayers and Perumpral (1982) examined a soil with 50 percent sand and 50 percent clay and determined that the cone index increased exponentially with density and moisture contents between 2.6 and 6.7 percent. Increases in moisture content caused a more linear relationship between cone index and density. The rate of increase in cone index with density decreased as the moisture content increased.

Spivey et al. (1986) examined the effects of soil texture on soil strength of Southeastern coastal plain soils. They evaluated soils with comparable densities, and found a correlation between texture and probe resistance. Types of regression equations used by various authors to make indirect estimations of penetration resistance are listed in Table 1.2. Every equation used some expression of soil moisture to predict soil penetration resistance and most equations included a bulk density component.

Table 1.2. Types of regression equations used to estimate penetration resistance.

Reference	Regression Equation
Bennie and Botha (1986)	$\log PR = \log a + b1 \log MC + b1 \log BD$
Jakobsen and Dexter (1987)	$PR = \exp(a + b1MC + b2BD$
Wells and Treesuwan (1978)	$PR = a + b \ln MC$
Henderson et al. (1988)	$PR = (BD/1000)^{a}/(bMC+c)$
Ayers and Perumpral (1982)	$PR = (a^{*}BD^{d})/[b+(MC-c)^{2}]$

Where PR = penetration resistance

BD = dry bulk density

MC = moisture content

a,b,c = constants

PENETR is a generalized semi-empirical model that is used to estimate soil resistance to penetration (Canarache 1990). The basic relationships used to show resistance to penetration were effects of texture (expressed as clay content), bulk density, and moisture content. The model uses a series of regression equations which characterizes the affects of each attribute. The PENETR model was validated using data from the literature and from Canarache's own studies. When comparing determined resistance values, to the model calculated values they fit into a linear regression which was statistically significant.

Henderson et al. (1988) suggested that there is no reliable method of predicting either laboratory of field response of penetration resistance to changes in density and moisture content for Western Australia's candlepin soils. Other soil factors not used in the study are suggested to have an effect on the penetration resistance and only direct field measurements would accurately determine effects on soil resistance. Other research supports the necessity of field measurements of penetration resistance. Busscher (1990) reported better penetration resistance predictions using equations developed from field observations. Rounsevell and Jones (1993) discussed a model first introduced by Thomasson (1982) which was later modified by Thomasson and Jones (1989). The model determines the number of days that a soil is workable or trafficable over a large geographic area by incorporating meteorological and soil survey data. Their model utilized field measurements of static soil characteristics obtained from soil survey data. Precipitation and evaporation data were taken from meterological records. The model incorporates a number of the soil factors which have been discussed and have an effect on soil strength: texture, density, hydrology, and organic matter (Figure 1.6). The model has been validated by Reeve and Earl (1989) and Carter et al. (1990) against a range of soils in the field. Field observations compared well with values obtained by the model.

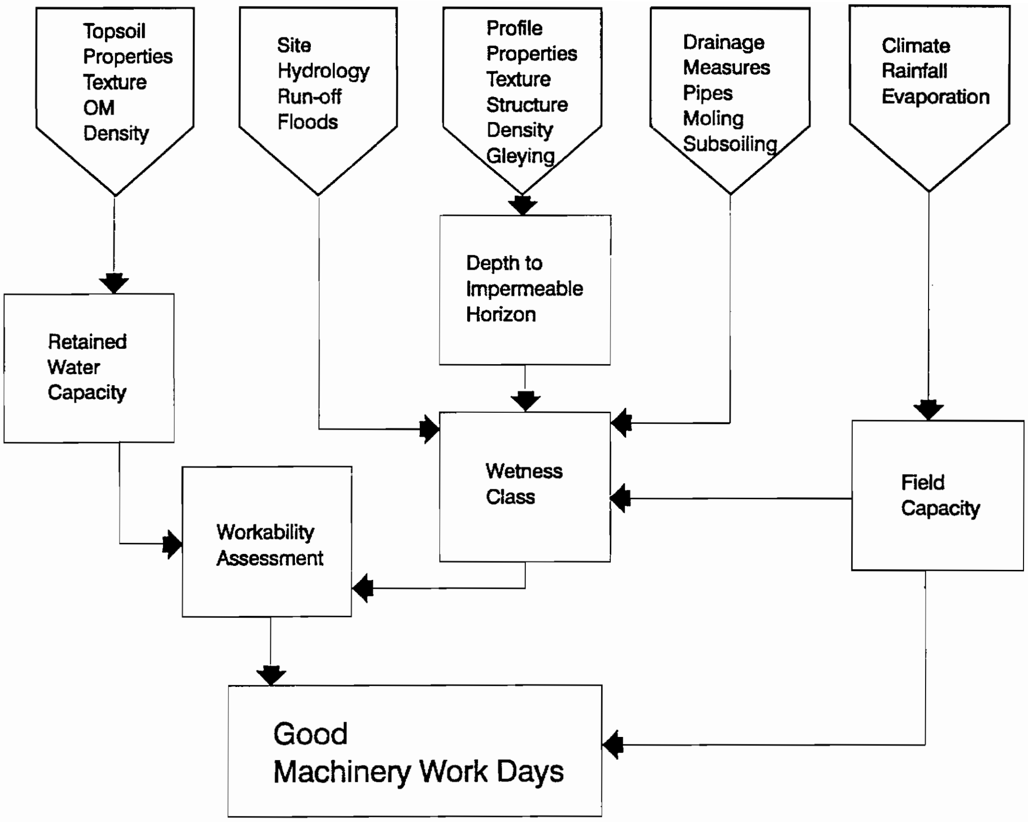


Figure 1.6 Information flow chart for machinery work day model as presented by Rounsevell and Jones (1993).

Soil survey reports are a large source of data which can be used in the interpretation of soil strength. USDA Soil Survey Reports, GIS soil mapping and other spatial soils data bases present a wide range of soil physical and chemical properties which could be and have been used in soil strength estimations. Mckee et al. (1985) suggested the use of county soil surveys to give insight into how and when equipment may be used without serious impact. Soil survey interpretations are also recommended to avoid logging damage on the most productive soils; however, this method also could be used to identify soils with low strength. Mckee et al.(1985) also presented a guide to be used in selecting types of equipment which can be used under certain conditions (Figure 1.7). In order to determine water table depths during the wet season it is suggested to use a soil auger for a quick and easy way of determination. Depth to gray mottles are also suggested as a way to indirectly estimate water table depth during the wet season, again utilizing soil survey data. Both of the above models only provide management information over a long time frame. In order to achieve a more site specific and time specific model the dynamic soil strength factor, moisture must be quickly and early attainable. The use of time domain reflectometry has been suggest by many researches as a quick and accurate way of determining soil water content (Topp and Davis 1985, Dasberg and Dalton 1985, and Drungil et al. 1989).

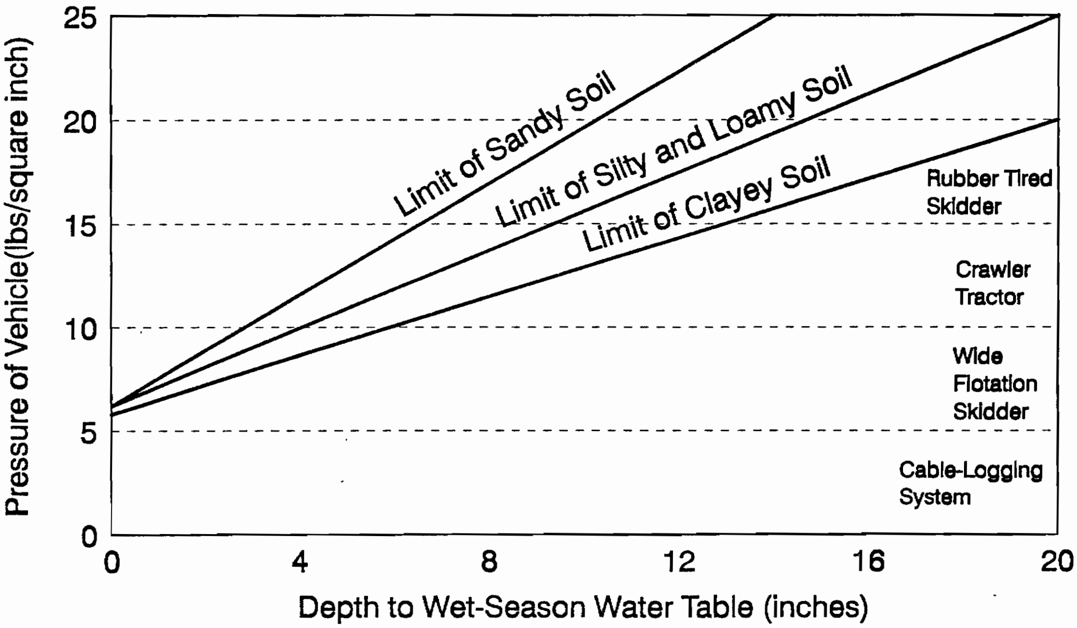


Figure 1.7. Wet-weather harvesting guide developed by McKee et al. (1985).

CHAPTER II

PROJECT HISTORY AND DESIGN

Project History

A long-term sustainable forestry-site impact project was started in 1992 as a cooperative effort among the USDA Forest Service, Westvaco Corporation, and Virginia Polytechnic Institute and State University. This project was designed to achieve Phase I of the larger, long-term study. The objectives of the larger, long-term study are:

Phase I - determine and describe soil, hydrologic, and site properties that may influence wet-weather logging disturbance

Phase II - determine the impact on site productivity as a result of site disturbance

Phase III - determine mitigation treatments needed to restore productivity.

In order to achieve these objectives, 3 similar blocks of loblolly pine (Pinus taeda) were located on Westvaco land near Cottageville, SC., latitude 32°55', longitude 80°30' (Figure 2.1). Each of the 3 study blocks were divided into six, 3.2 ha (8 acre) treatment plots. Three plots in each block will be harvested under wet conditions and two will be harvested during the summer under dry conditions. The sixth plot in each block will remain as an non-harvested control. Each treatment will be imposed to satisfy Phases II, and III. Phase I (this study) deals with the modeling of soil strength as a function of forest soil, hydrology, and site properties and uses a soil strength model to develop a trafficability hazard rating index.

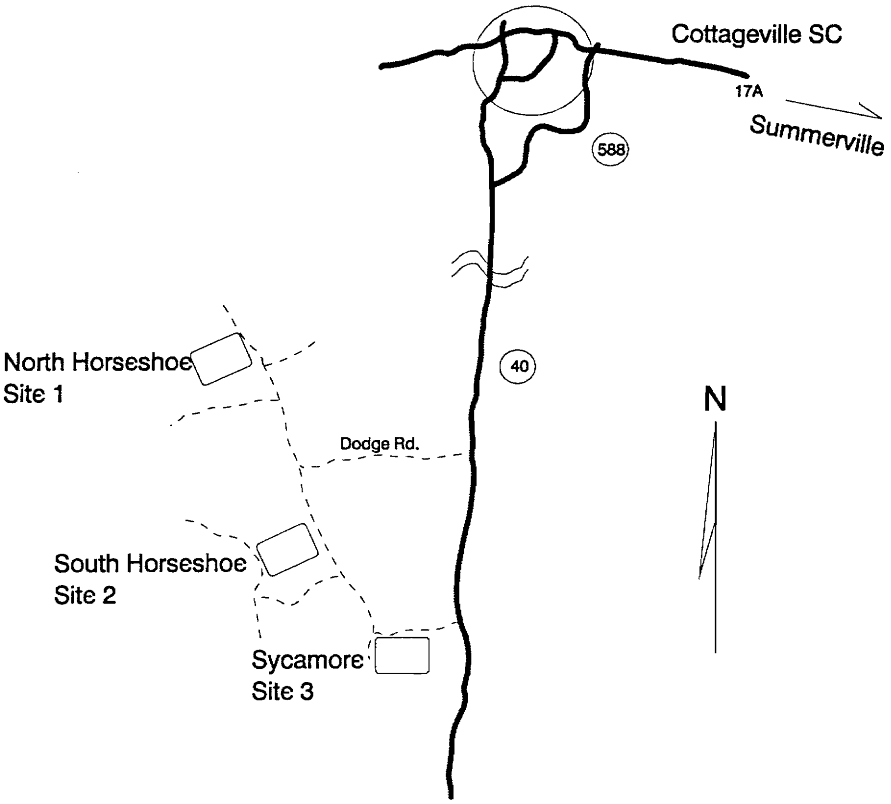


Figure 2.1. Location for wet-weather trafficability index study (not to scale).

Site Characteristics

The three study areas (North Horseshoe, South Horseshoe, and Sycamore) are located on wet pine flats within Westvaco's Sycamore and Horseshoe Management Units (Figures 2.1, 2.2, 2.3, and 2.4). The three sites were similar in stand age, soil type, drainage, and surface water. Each block contains 20 ha (48 acres) of loblolly pine (Pinus taeda) plantations that are 19-21 years old. The pre-treatment stands were established following a clear-cut harvest of a first rotation pine plantation. After harvesting, the sites were raked, windrowed and burned. The sites were then bedded and planted. Common mid story vegetation includes red maple (Acer rubrum), black gum (Nyssa sylvatica), water oak (Quercus nigra), green ash (Fraxinus pennsylvanica), laurel oak (Quercus laurifolia), and elm (Ulmus spp.). The shrub and ground layers consist of switch cane (Arundinaria gigantea), Easter baccharis (Baccharis balimifolia), and southern bayberry (Myrica cerifera). These species are most common in windrows and very wet areas where loblolly pine was not established.

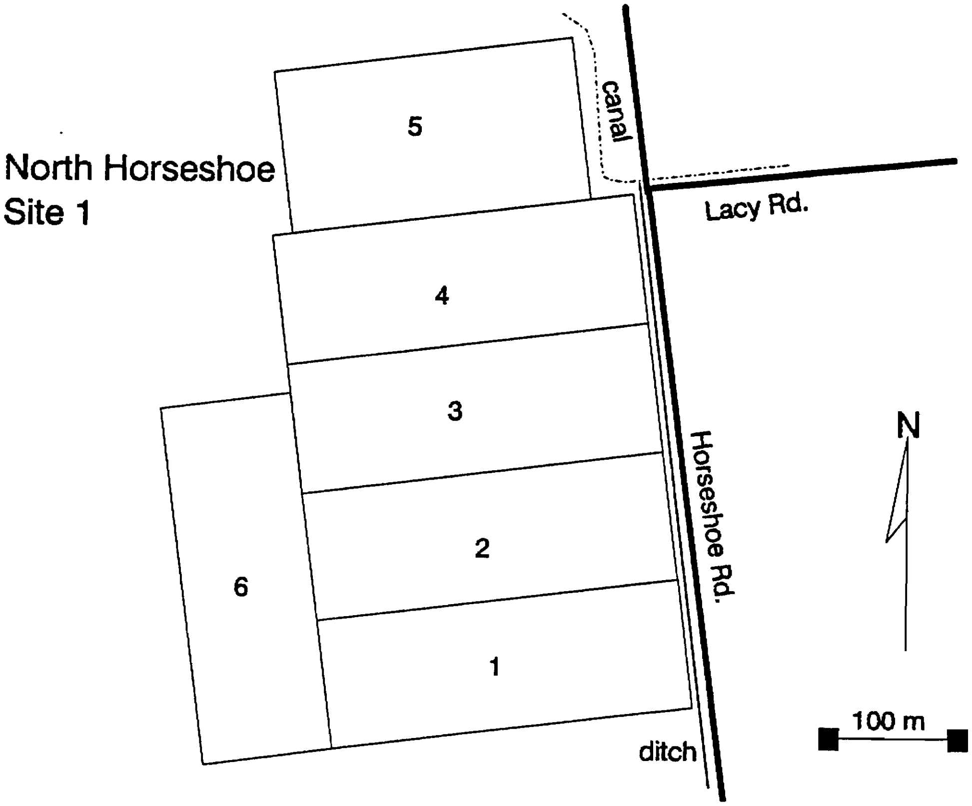


Figure 2.2. Layout for North Horseshoe study site.

1,2,3 = Wet harvest treatments

4,5 = Dry harvest treatments

6 = Non-harvested control

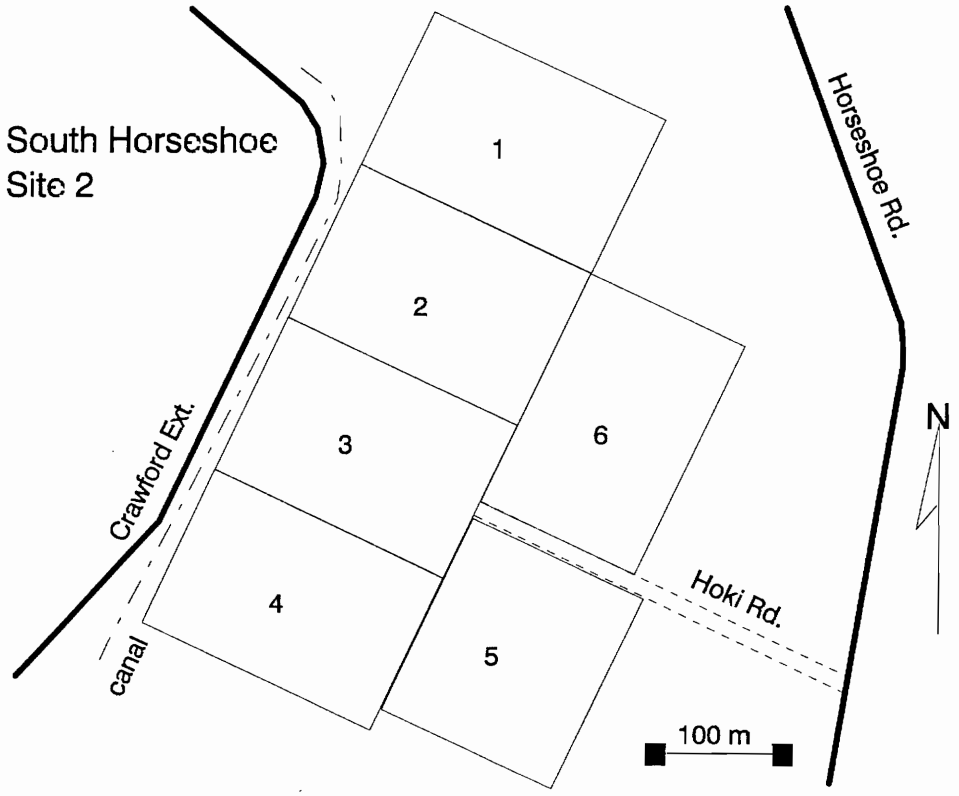


Figure 2.3. Layout for South Horseshoe study site.

1,2 = Dry harvest treatments

3,5,6 = Wet harvest treatments

4 = Non-harvested control

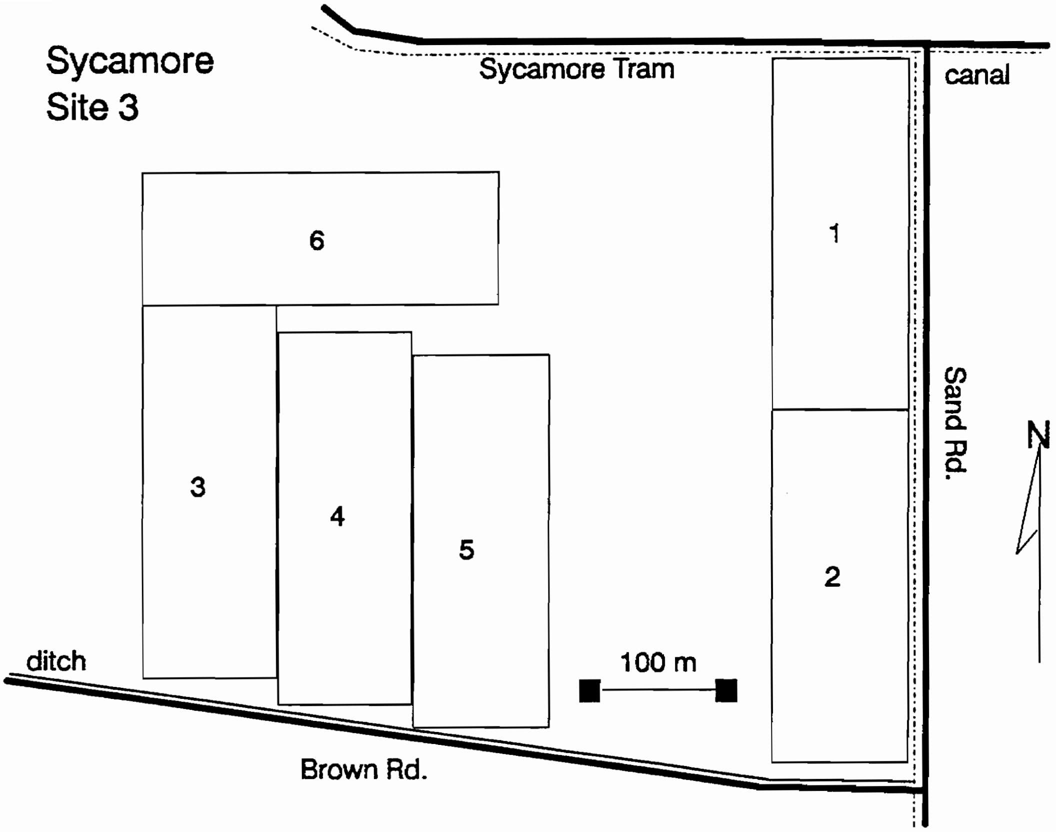


Figure 2.4. Layout for Sycamore study site.

1,4 = Dry harvest treatments

2,3,5 = Wet harvest treatments

6 = Non-harvested control

Average annual rainfall is 133 cm (52 in), with 82 cm (39 in) falling between March and October. Average summer temperature between March and October is 83^{o}F, and the average winter temperature between November and February is 63^{o}F (Stuck, 1980).

The soils within the study sites are all poorly drained, deep, acidic soils. The poorly drained character of the soil profile is due to the nearly level landscape (0-2% slope) and deposits of fine clays. The soils were formed on unconsolidated marine sediments. The three blocks range between 4.6 m (15 feet) to 7.6 m (25 feet) above sea level. Water tables remain within one foot of the surface for most of the year leaving only a narrow window for management operations. As a result of the poor drainage and the overabundance of water, ditching has been used to improve seedling survival and provide surface drainage for greater site access. Within the North Horseshoe and Sycamore units there are two soil series: Argent loam and Santee loam (Stuck 1980). Within the South Horseshoe unit, three soil series exist: Hobcaw, Nemours, and Yemassee (Stuck 1980). According to Soil Survey Staff (1992), and the National Technical Committee for Hydric Soils (1987), all of the soils within the three study sites are described as hydric. During the growing season, water tables are within 60 cm (24 in) of the surface for 21 consecutive days, and the vegetation is predominantly species adapted to surviving in saturated conditions.

The Argent loam and Santee loam in the North Horseshoe and Sycamore units are classified as fine, mixed, thermic Typic Ochraqualfs and fine, mixed, thermic Typic Argiaquolls respectively. The Argent series is poorly drained with slowly permeable soils that are nearly level with a slope of 0-2 percent (Stuck 1980). The soils are commonly found on narrow to broad flat areas adjacent to drainage ways having been formed in deposits of clay sediment. A typical profile contains a very dark gray surface horizon with a loam texture 0-5 inches in depth. The A horizon also has a moderate medium granular structure, friable consistency and many fine roots. The subsurface consists of a grayish brown to gray clay with brownish yellow and olive brown mottles. The solum thickness ranges from 54 to more than 80 inches with an extremely acid to medium acid pH in the upper 50 inches. The Santee profile is very similar to the Argent except for the presence of a mollic epipedon. Santee soils are located on similar landscapes as the Argent, but slopes are dominantly less than 1 percent (Stock 1980). Both soils have a low nutrient availability and are low in organic matter (1-5%).

The Hobcaw, Nemours, and Yemassee soils in the South Horseshoe unit are classified as Fine-loamy, siliceous, thermic Typic Umbraquults, Clayey, mixed, thermic Aquic Hapludults, and Fine-loamy, siliceous, thermic Aeric Ochraquults, respectively. All three of the soils found in this unit are of similar character. The Hobcaw is formed from a thick loamy sediment on the lower marine terraces. The Nemours and Yemassee are both formed from clayey marine sediments. Both the Hobcaw and the Yemassee are poorly drained with slopes ranging from 0 to 2%. The Nemours is moderately well drained with 0 to 6% slopes. All three soils have a similar dark grayish brown fine sandy loam surface horizon ranging for 9 - 16 inches in depth. The better drainage of Nemours is evident by the lack of a gleyed horizon to a depth of 25 inches. The other two soils have gleying within 15 inches of the surface. The subsurface of the Hobcow and Yemassee is characterized by a sandy clay loam gray matrix with brownish yellow and dark gray mottles. The Nemours has a red clay subsurface with brownish gray and strong brown mottles.

Field Methods

Water Table

Harvesting operations on soils with water tables in close proximity to the surface have the potential to reduce site productivity (Aust et al. 1990). The puddling of a site may reduce site productivity, but actual prediction of the extent of reduction is difficult. In order to make any predictions about the extent of damage, the complex interactions of wetland soils, hydrology and vegetation must be understood. One important factor to be considered in this complex system are the effects of the soil water regime (Greacen and Sands 1980). Aust et al. (1993) found that the hydrology of a wet pine flat was significantly influenced by harvesting with rubber tired skidders. The increase in depth to the water table was a function of a reduction in the hydraulic conductivity and not a result of increased precipitation or reduced evapotransporation.

Data collection stations where located on a 20 m X 20 m grid across all 18 treatment plots. All data points where located at least 10 m in from each side of the plots. Water table wells at each sampling station were established with a gasoline power head auger which was equipped with a 3.8 cm diameter auger bit. At every sampling point (20 m X 20 m spacing) a well was established to a depth of 0.9 m. On every other sampling line and at every other sampling point (spacing 40 m X 40 m) a second well was established to a depth of 2 m (Figure 2.5). Each well was lined with a 3.8 cm diameter PVC pipe. Before installation, the pipe was perforated with 0.5 cm slits in order to allow water to enter. Water tables were measured monthly and in conjunction with soil strength and soil moisture determinations. A total of 1409 shallow wells and 421 deep wells were installed over the study area. The elevation of each well was established with a transit. This information was used to adjust water table readings and create three dimensional maps.

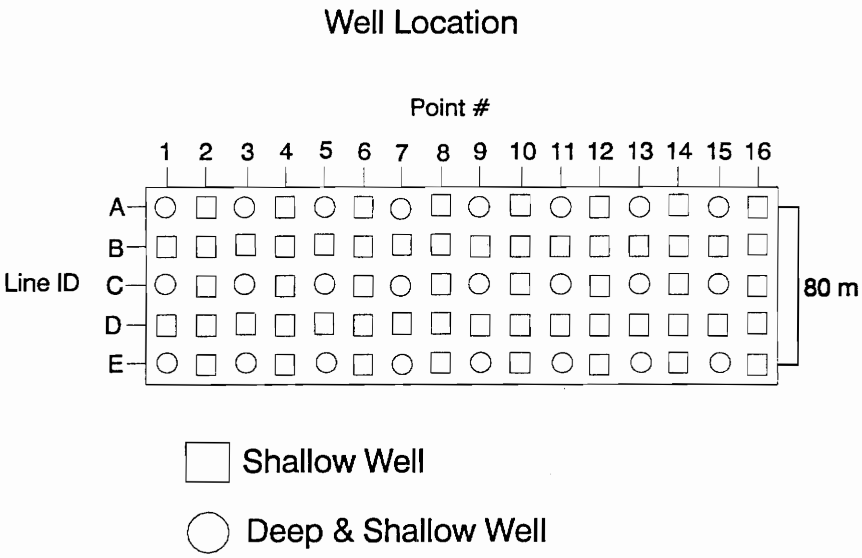


Figure 2.5. Idealized layout for well location in one treatment plot.

Soil Moisture

In practically every type of soil study, a measure of soil water content is needed (Gardner 1986). Due to the water table being at or near the soil surface for the majority of the year, the soil has a high water content. When soils have a high water content they are susceptible to compaction and deformation. When soils are saturated not only is compaction a potential source of decreased productivity, but puddling can also have ill effects on soil physical properties. When drastic sinkage as a result of shear failure occurs, soil structure is destroyed along degradation of other soil physical properties degradation (Greacen and Sands 1980). The soil moisture was measured using Time Domain Reflectometry (TDR). The TDR system measures the volumetric water content of soil using a microwave pulse of electricity (Soilmoisture Equipment Corp. 1989). The application of time-domain reflectometry (TDR) to measure soil moisture has shown considerable progress with few limitations (Topp and Davis 1985; Drungil et al. 1988). Soil moisture was taken at every other deep well location (80 m X 40 m grid). At each sampling location 2 sets of 3 mm diameter stainless steel rods were inserted in the soil. One set was inserted to a depth of 15 cm and the second set was inserted to a depth of 45 cm. Five sequences of measurements were taken at each station in order to capture soil moisture values at or near saturation and below field capacity beginning in January of 1993. The stainless steel rods where located approximately 2 m from the shallow well on the same type of micro site.

Soil Strength

The measure of the ease with which an object can be pushed through a soil is a measure of penetrability. The two principal types of penetrometers are the dynamic and the static. A static penetrometer was used to measure the cone resistance of the soil (Bradford 1986) The mechanical resistance or strength of a soil determines its ability to resist compaction (Greacen and Sands 1980). Cone penetrometers have been widely used for a rapid and accurate method of determining soil strength (Soane et al. 1981) A standard cone penetrometer (ASAE 1990) was used to measure the soil strength within a 0.25 m radius of the soil moisture station. After the soil strength was determined the hole was closed to prevent drying of the soil around the moisture rods. The soil strength was measured to a depth of 0.5 m in 5 cm intervals. Specifications of the penetrometer include: 0.95 cm graduated driving shaft, 1.3 cm^2 cone area, 1.28 cm cone diameter, and a 30^o included cone angle (ASAE 1990).

Water table, soil moisture, and soil strength measurements were taken simultaneously at every other deep well location. This set of dynamic measurements were taken at 5 different times throughout the wetting and drying cycle of the sites. This was done in order to obtain soil strength measurements over a wide range of soil moisture contnet. The following static soil characterization data was also collected in conjunction with these three measurements, but was only measured once during the study.

Bulk Density

Soil bulk density is the mass of an oven-dried soil per total volume, where total volume includes all solids and pore space (Blake and Hartge 1986). Bulk density is commonly used as a measure of the degree of compaction in a soil. Core samples were collected to characterize bulk density and its effect on soil strength. Bulk density cores were obtained using a hammer-driven double-cylinder sampler (Blake and Hartge 1986). A relatively undisturbed 5.08 cm by 5.08 cm cylindrical soil core was collected for the A, E, and B horizons. A 10 cm diameter soil auger was used to remove soil from surface horizons enabling samples to be taken from the surface of each horizon. The samples were taken from the same type of micro site where the water table well was located, but approximately 2 m away from the well to avoid sampling soil altered by the installation of the well. The core samples were retained for laboratory analyses.

Composite Soil Samples

Loose soil samples were taken with a soil auger from the identical hole that the soil cores were removed. These samples were used for laboratory analysis of particle size distribution, organic matter, liquid limit, and plastic limit.

Depth of Horizons

The depth of each horizon was determined using a 1.9 cm push tube. The depth of each horizon was determined in the same location as soil strength measurements were taken.

Laboratory Methods

Particle Size Analysis

Due to the effects of particle size distribution on soil strength, the soil texture was determined. Soil texture refers to the percentages of sand, silt, and clay present in soil. Soil texture also influences soil aeration, bulk density, drainage, and other soil properties that have the potential to alter soil strength (Pritchett and Fisher 1987; Jury et al. 1991). The U.S. Department of Agriculture (USDA) particle size classifications were used to identify sand, silt, and clay. The USDA classifications are as follows: sands (2.00-.05 mm), silts(.05-.002 mm), and clay (<.002 mm) (Gee and Bauder 1986). The Bouyoucos (1962) hydrometer method was used to measure the amount of each particle size in the sample. The sand fraction was run through a nest of sieves to determine the distribution sand size classes as outlined by Gee and Bauder (1986).

Bulk Density

Oven-dried bulk density was determined using intact soil cores. The samples were oven dried at 105°C for 24 hours and weighed to determine the oven dry weight. The bulk density was calculated using the following equation: bulk density = oven dry weight. / cylinder volume (Blake and Hartge 1986).

Porosity

The non-solid, proportion of a soil sample which is occupied by air or water is referred to as porosity (Danielson and Sutherland 1986). As with bulk density, when soil particles are rearranged by puddling soil porosity can be negatively impacted (Greacen and Sands 1980). There are two types of pore space, micro- and macro-pore space. Macro-pores are larger than micro-pores and allow for the easy flow of water and gas through the soil. Micro-pores are pores which are less than 0.06 mm in diameter, larger pores are considered to be macro (Brady 1984).

Total porosity, macro-porosity, and micro-porosity (Danielson and Sutherland 1986) were determined using the aforementioned bulk density cores. Soil cores were saturated and weighed to the nearest 0.1g (saturated weight). Cores were placed on a tension table with 50 cm of tension (Danielson and Sutherland 1986). After 24 hours samples reached equilibrium and were removed from the tension table and weighed to the nearest 0.1 g (equilibrium weight). The samples were then oven-dried for 24 hours and weighed. The following equations were used to determine total porosity, macro porosity and micro porosity, assuming one gram of water equaled 1cm^3.

$$\text{Macro-porosity (\%)} = \frac{\text{saturated weight - equilibrium weight}}{\text{cylinder volume}} \times 100$$

$$\text{Micro-porosity (\%)} = \frac{\text{equilibrium weight - oven-dried weight}}{\text{cylinder volume}} \times 100$$

$$\text{Total Porosity (\%)} = \text{macro-porosity (\%)} + \text{micro-porosity (\%)}$$

Hydraulic Conductivity

The rate at which a soil can transmit water is referred to as hydraulic conductivity (Klute and Dirksen 1986). When a soil is puddled, a reduction in large pores occurs, reducing soil porosity. When the number of large pores are decreased, water infiltration and hydraulic conductivity are decreased (Greacen and Sands 1980). As the infiltration rate decreases, surface runoff may increase resulting in limited management opportunities and reductions in site productivity may accrue (Greacen and Sands 1980). Using intact soil cores the saturated hydraulic conductivity was determined using the constant head method (Klute and Dirksen 1986). The volume of water that flowed through each sample per unit time was used to calculate saturated hydraulic conductivity (Ks) of the soil. The following equation was used.

$$Ks = (Q/At)\,(L/H)$$

Where Ks = hydraulic conductivity

Q = volume of water passing through sample (cm3)

A = cross sectional area of cylinder (cm2)

t = time (sec)

H = hydraulic head (cm)

L = length of cylinder (cm)

Liquid Limit / Plastic Limit

The plastic limit of a soil is often defined as the moisture content at which a soil can be easily deformed. The liquid limit is often referred to as the upper plastic limit. When a soil is rutted and puddled it has reached the liquid limit. At this point the moisture content within the soil has reduced cohesive forces between soil particles to the degree that the soil flows. The liquid and plastic limit for each of the soil textures found with in each plot were determined using methods outlined by Sowers (1965) for measuring Atterberg limits.

Organic Matter Analysis

The solid, non-mineral portion of the soil, originating from plant and animal residues is referred to as organic matter. Organic matter has been found to affect such soil properties as strength and aeration (Sands et al. 1979; Rawls 1983). Due to documented importance that organic matter has on the strength of soil it was determined for each horizon from composite samples. A LECO carbon analyzer was used to determine percent carbon. Organic matter is commonly determined by multiplying the percent carbon by 1.72. This conversion factor has been suggested to be too low for many soils (Broadbent 1953; Howard 1965; Ranney 1969). A conversion factor of (2.00) is suggested as the most universally accepted by Nelson and Sommers (1982). Therefore, a conversion of (2.00) was used to convert percent carbon to percent organic matter.

Statistical Analysis

Dynamic soil properties were measured at 5 different periods, representing a range of wet to dry conditions. At each measurement location, penetrometer readings were taken every 5 cm to a depth of 50 cm. As a result 10900 penetrometer measurements were taken each with dynamic and static soil properties associated with it. Scatter plots of soil strength vs. soil and site properties were used to determine if relationships were linear or non-linear. When a soil property had a non-linear relationship with soil strength a transformation was made to produce a linear relationship. A stepwise backwards elimination procedure (Belsley et al. 1980) was used to determine the soil and site characteristics which had the greatest influence on soil strength for the A, E, and Bt horizons. Multiple linear regression was used to describe soil strength as a function of dynamic and static properties. Stepwise and Multiple linear regression calculations were done using Minitab (Minitab Reference Manual 1993).

Due to the obvious relationship between water and soil strength, penetrometer reading were adjusted for moisture to evaluate the effects of static properties on soil strength (Busscher, 1990; Towner 1974; Clark and Clark 1979) . Covariate analysis (adjustment of treatment means) was used to adjust soil strength linearly upward or downward relative to it's covariate (soil moisture) (Gomez and Gomez, 1984). Often missing penetrometer measurements during dry time periods were the result of excessively hard soil layers which could not be penetrated. The soil strength measurements below these layers were not obtained and resulted in large gaps in dry soil strength data sets. These missing data points needed to be estimated before soil strength could be adjusted. The iterative procedure for more than one missing observation was used to estimate the missing data (Gomez and Gomez, 1984).

CHAPTER III

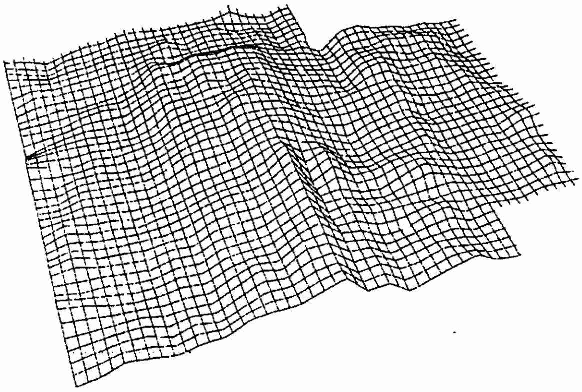
SOIL and SITE CHARACTERISTICS

RESULTS and DISCUSSION

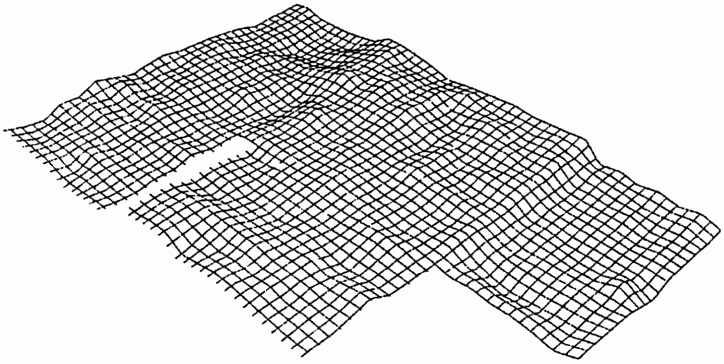
Soil and Site Characteristics

Surface Elevations

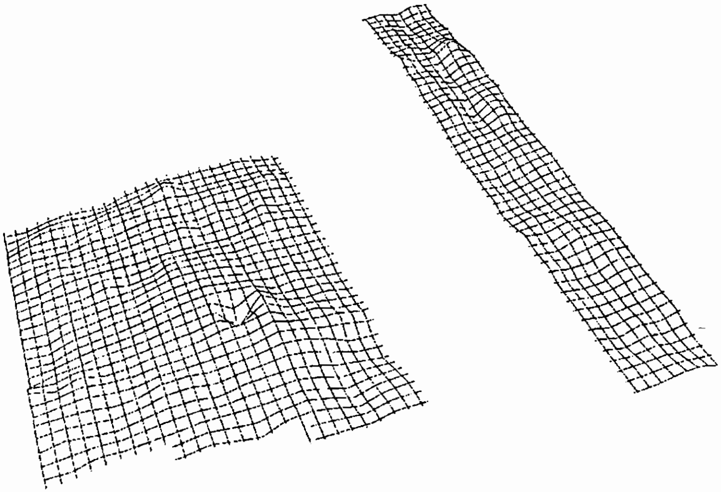
Three dimensional elevation maps provide information pertinent to pre-harvest planning. Three dimensional maps were created for each of the study site (Figure 3.1). Elevational differences are obvious and emphasize micro-topographic differences across the site. As expected water table levels corresponded to micro-topography. Water tables were closer to the soil surface in low lying elevations than in high elevations. Therefore, these low lying areas can be expected to have lower soil strength values and are expected to have less frequent periods suitable for logging without excessive rutting. Currently, topographic maps do not provide sufficient elevational resolution to identify higher soils for road, decks, or specialized harvesting machinery. It is impractical from an operational viewpoint to survey elevational differences to the resolution used in this study. However, it is operationally feasible to use soil moisture and soil strength data to make management decisions.



North Horseshoe, Site #1



South Horseshoe, Site #2



Sycamore, Site #3

Figure 3.1. Three Dimensional elevation maps for each study site (30:1 vertical exaggeration).

WATER TABLE

" It is generally accepted that natural wetland functions are closely linked to hydrology " (Sather and Smith 1984). Water table fluctuations for each study site reflect the effects of precipitation and evapotransporation. Two distinct water tables were identified on the sites, deep (seasonal) and a perched water table. Deep and perched water tables followed two trends across all three sites (Figure 3.2). During the fall and winter months the perched and deep water tables tended to correspond more closely to one another. During this period, evapotransporation and precipitation rates are minimized (Table 3.1). However, as the transpiration rates increased in the early spring, the deep and perched water tables tended to separate. During this period of time, the transpiration rates are increased and the trees are actively taking up larger quantities of water than precipitate. Frequent thunderstorms during the growing season partially recharged the perched water table, but rapid recharge of the deep water table is prevented because of the slow internal water movement of the Bt horizon. Daily fluctuations in perched water table levels have the potential to decrease the trafficability of a site complicating long term harvest planning. The adverse effects of seasonal water table levels can be avoided easier than the rapid changes in perched water levels.

Table 3.1. Estimated average monthly precipitation for Colleton County (Stuck 1980).

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
------	------	------	------	------	------	(cm)	------	------	------	------	------
8.6	10.1	10.8	7.6	11.1	15.4	19.5	15.0	13.1	7.9	5.4	8.0

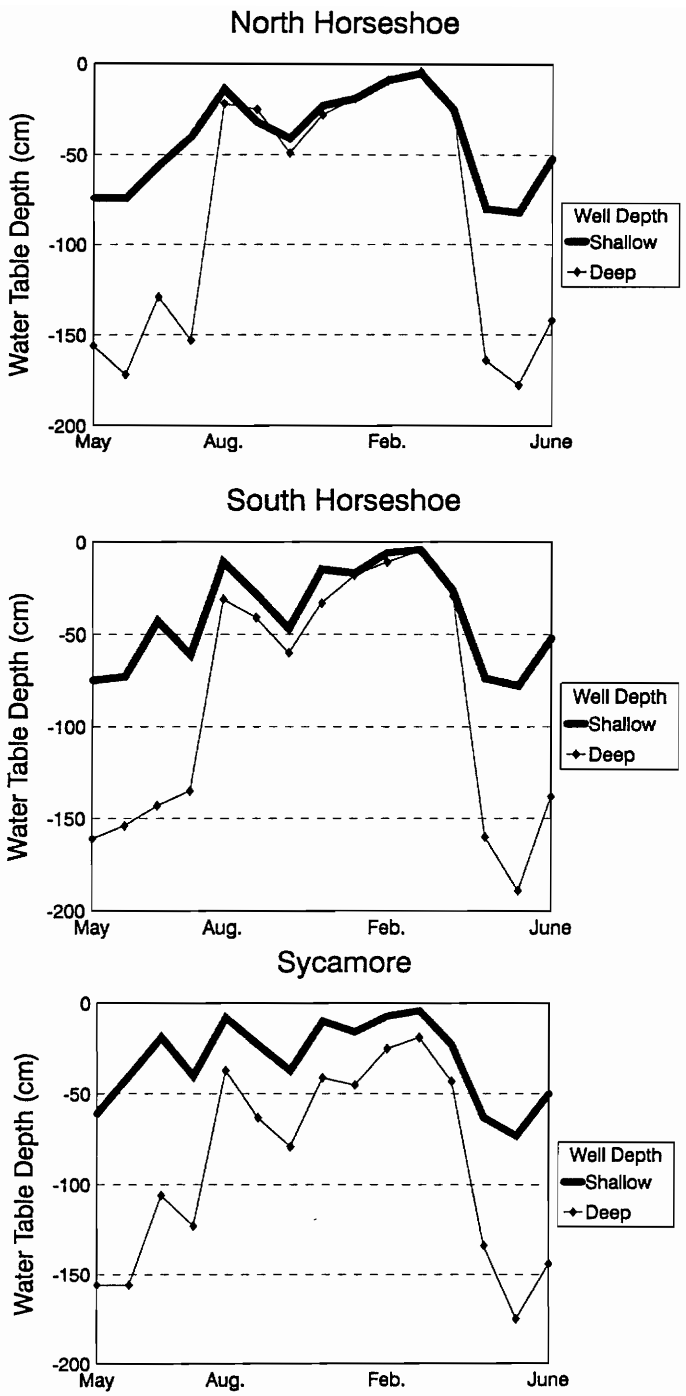


Figure 3.2. Monthly water table fluctuations for the each study site. May 1992 - June 1993

SOIL MOISTURE

As expected, average soil moisture values for the 0 - 15 cm and 15 - 50 cm soil depths followed a pattern similar to the water table levels. However, the relationship between the two soil depths varied with season (Figure 3.3). The first two soil moisture measurements periods were during the wet season. During the wet period, the surface (0-15cm) volumetric soil moisture was greater than the subsurface volumetric soil moisture. During the last 3 measurement periods (dry season) the volumetric water content was greater for the lower soil depth (15-50cm) Volumetric water content is the volume of soil water per unit soil volume. The surface 15 cm is predominantly the A horizon which has a much higher porosity (total porosity and macro-porosity) than the E and Bt horizons which comprise the lower 35 cm. During the wet season, water tables are near the soil surface and soils were saturated. Saturation of the more porous A horizon resulted in higher volumetric water contents than the E and Bt horizons. However, when the soil is not saturated during the other 3 measurement periods the surface 15 cm has a lower volumetric water content than the lower 35 cm. During these measurements water table levels were well below the soil surface. It can also be seen that the moisture content of the lower 35 cm remains relatively constant over time even when the water table level is near the lower limit of the moisture reading, except for the driest measurement. This phenomena is the result of the capillary fringe, which is the moist soil extending above the ground water level (Gerla, 1992). In this zone all soil pores are saturated due to a slightly negative pressure head which can extend up to 0.01 m for medium sand and greater than 1.0 m for clay (Gillham 1984).

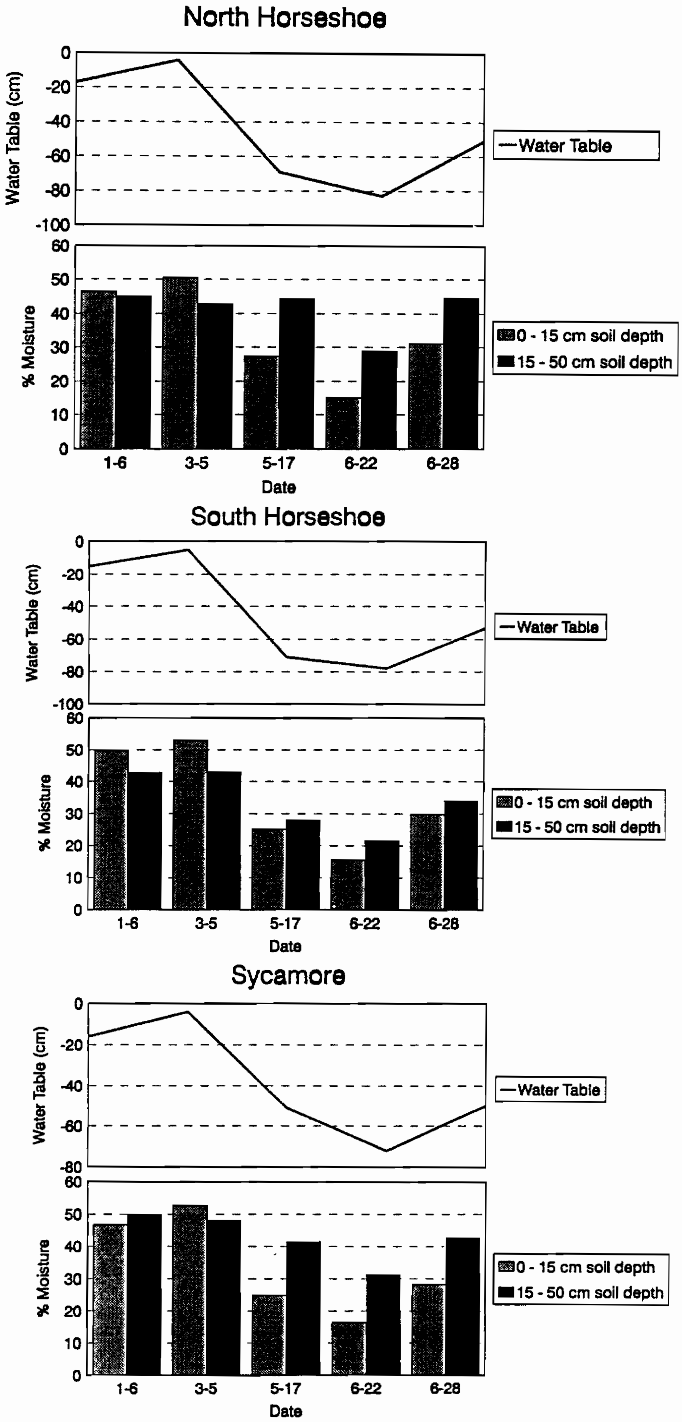


Figure 3.3. Characteristics of volumetric soil moisture changes in the upper 15 cm and lower 35cm of the surface 50 cm of soil with water table fluctuation.

TEXTURE

All three sites were relatively uniform in soil texture. The A and E horizons were sandy loams (Table 3.2). In general, the E horizon sandy loam contained more sand and less silt than the A horizon. The Bt horizon of the North and South Horseshoe units had a sandy clay loam texture, while the sycamore site had a Bt horizon composed of clay loam.

Table 3.2. Average sand, silt, and clay content for each horizon in each site including soil texture class.

Site	Horizon	Clay	Silt	Sand	Texture
		-----------	(%)	-----------	
North Horseshoe	A	8.3	29.8	61.9	Sandy loam
	E	7.4	20.4	72.2	Sandy loam
	Bt	28.3	20.7	51.1	Sandy clay loam
South Horseshoe	A	4.7	28.4	66.8	Sandy loam
	E	7.8	23.7	68.4	Sandy loam
	Bt	28.4	24.7	46.9	Sandy clay loam
Sycamore	A	11.4	29.5	59.1	Sandy loam
	E	10.4	24.6	65.0	Sandy loam
	Bt	36.9	22.4	40.8	Clay loam

Table 3.3. Sand fraction classes by site and horizon.

Site	Horizon	1 mm	0.5 mm	0.25 mm	0.106mm	0.053mm
		--------	---------	(%)	---------	---------
North Horseshoe	A	3.22	14.53	24.84	49.20	8.22
	E	3.95	17.65	25.85	41.59	10.97
	Bt	4.69	17.27	23.21	42.82	12.01
South Horseshoe	A	2.9	15.34	26.97	46.32	8.47
	E	4.23	17.97	29.28	40.00	8.52
	Bt	4.33	16.39	26.35	42.86	10.06
Sycamore	A	5.38	17.57	25.25	45.52	6.27
	E	7.43	21.19	20.87	43.90	6.61
	Bt	7.18	19.36	22.51	43.54	7.42

Sand fraction sizes: 2mm > X < 1mm, 1mm < X > 0.5mm, 0.5mm < X > 0.25, 0.25mm < X > 0.106mm, and 0.106mm < X > 0.053mm

ORGANIC MATTER

The amount of organic matter found in soil is dominantly influenced by temperature and rainfall (Brady 1984). As a result of the abundant precipitation and warm climate, soil organic matter levels were low (Table 3.4). More organic matter was in the A horizon because organic residue is deposited directly on the soil surface. Due to the rapid turnover rate, soil organic matter is rarely translocated by water to lower horizons resulting in rapid decreases in organic matter with depth (Figure 3.4). Again there is little significant variation between sites, but horizons differ markedly (Table 3.4).

Organic matter levels in the A horizon in the North Horseshoe site were significantly higher than values found on the South Horseshoe and Sycamore sites ($P < 0.5$). This variation allows for soil strength characteristics caused by naturally occurring organic matter contents to be evaluated.

Table 3.4. Average organic matter content for each horizon in each site.

Site	Horizon	Organic Matter (%)	Standard Deviation
North Horseshoe	A	5.26	2.45
Site #1	E	1.60	0.75
	Bt	1.39	0.60
South Horseshoe	A	4.48	2.26
Site #2	E	1.19	0.74
	Bt	1.31	0.49
Sycamore	A	4.40	2.21
Site #3	E	1.74	0.78
	Bt	1.48	0.56
Average across all sites	A	4.71	
	E	1.51	
	Bt	1.39	

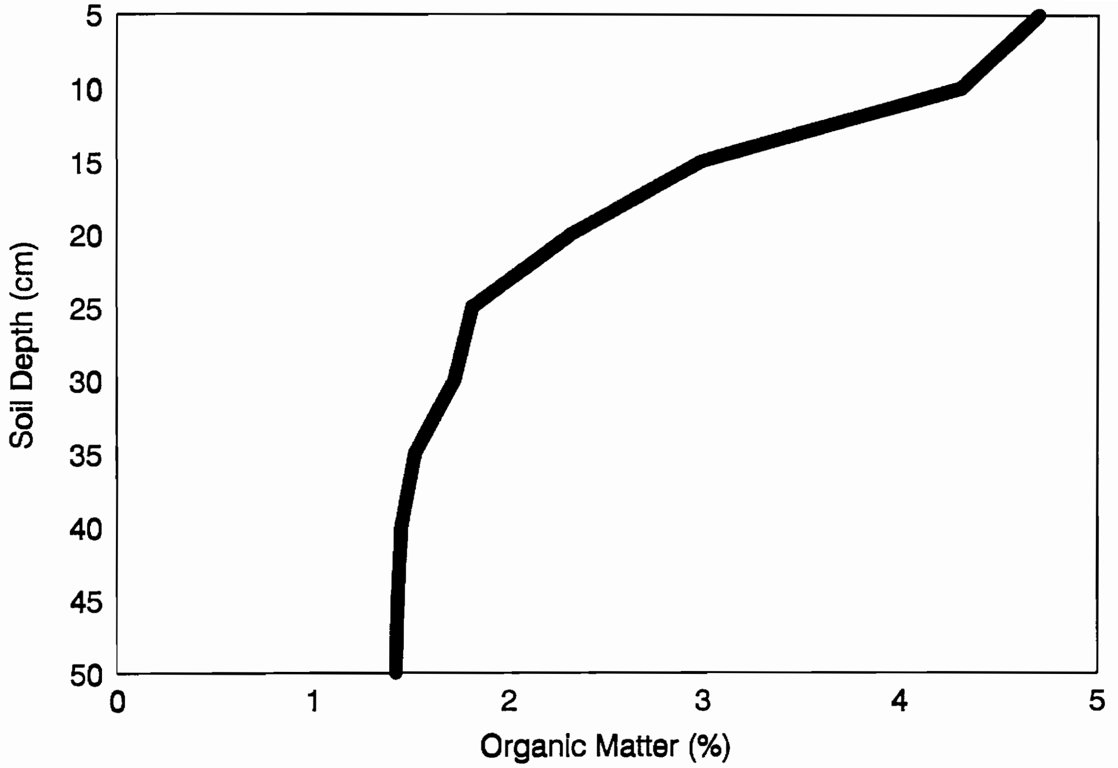


Figure 3.4. Average organic matter decreasing with increasing soil depth.

BULK DENSITY

Bulk density was relatively uniform between sites; however, dramatic differences occurred between horizons. Overall, the bulk density values of the A horizons averaged 1.17 Mg/m^3. The E and Bt horizons had less organic matter and less pore space and had higher bulk density values, averaging 1.62 and 1.52 Mg/m^3, respectively (Table 3.5). The E and Bt horizons have similar amounts of organic matter; however, the Bt horizon has much less sand and more clay producing a finer textured soil with a lower bulk density (Table 3.5). The A and E horizons are significantly similar between sites ($P > 0.1$) except for the A horizon between North Horseshoe site and the South Horseshoe and Sycamore sites ($P < 0.1$).

Table 3.5. Average bulk density values for each horizon in each site.

Site	Horizon	Bulk Density Mg/m^3	Standard Deviation
North Horseshoe	A	1.13	0.216
	E	1.66	0.134
	Bt	1.51	0.157
South Horseshoe	A	1.15	0.168
	E	1.57	0.415
	Bt	1.52	0.130
Sycamore	A	1.23	0.199
	E	1.64	0.175
	Bt	1.52	0.128
Average	A	1.17	
	E	1.62	
	Bt	1.52	

SOIL POROSITY AND SATURATED HYDRAULIC CONDUCTIVITY

The volume of air and water with in a soil volume is termed pore space. The pore space is determined largely impart by the arrangement of solid particles. As a result the porosity of a soil is closely related to bulk density. The aggregating effect of organic matter increases porosity were as discussed before causes decreases in bulk density. Soils which have high bulk density values generally have low total porosity and vice versa.

Total pore space is conveniently divided into macro- and micro-pores. The high organic matter content and coarse texture in the A horizon suggests a soil with a high total porosity dominated by micro pores, but with substantial macro pores for high infiltration rates as was determined. Low organic matter and coarse texture resulted in a low total porosity with few macro pores and a low hydraulic conductivity. As the decrease in macro pores and increase in micro pores continued in the Bt horizon, total porosity increased slightly more that in the E horizon. However, the increased total porosity in the Bt horizon was the result of abundant micro pores, contributing to a very low hydraulic conductivity rate. (Table 3.6) Similar results were reported by Meek et al. (1992) and Akram and Kemper (1979). Capillary pore are much smaller diameter than non capillary pores, soils with high proportions of such pores have slow infiltration rates. The larger non-capillary pores cause soils to have lower bulk densities and rapid infiltration rates. As a result saturated hydraulic conductivity decreases as the portion of non-capillary pores decreases with depth (Figure 3.5).

Table 3.6. Average total, macro-, and micro-porosity, and saturated hydraulic conductivity values for each horizon in each site. Values in parentheses are standard deviations.

Site	Horizon	Total Porosity ----------	Micro Porosity % (STDEV)	Macro Porosity -----------	Sat. Hydraulic Conductivity cm/hr (STDEV)
North Horseshoe	A	53.8	38.0	15.8	17.06
		(9.56)	(7.34)	(10.6)	(25.5)
	E	33.9	22.0	11.9	1.62
		(6.41)	(6.83)	(7.49)	(4.86)
	Bt	44.8	41.1	3.7	0.20
		(8.35)	(10.10)	(5.75)	(1.01)
South Horseshoe	A	53.5	37.9	15.6	15.24
		(6.71)	(7.91)	(10.4)	(25.0)
	E	34.3	23.2	11.2	0.43
		(4.93)	(5.58)	(7.12)	(1.25)
	Bt	43.8	39.4	4.4	0.10
		(4.56)	(6.79)	(6.22)	(0.59)
Sycamore	A	52.8	41.0	11.6	5.20
		(7.42)	(8.64)	(7.89)	(9.75)
	E	37.9	29.1	8.7	0.50
		(11.20)	(13.50)	(6.20)	(1.37)
	Bt	45.4	41.7	3.7	0.01
		(5.21)	(7.56)	(5.08)	(0.13)
All Sites	A	53.4	39.0	14.4	12.50
	E	35.4	24.8	10.6	0.85
	Bt	44.7	40.7	4.0	0.10

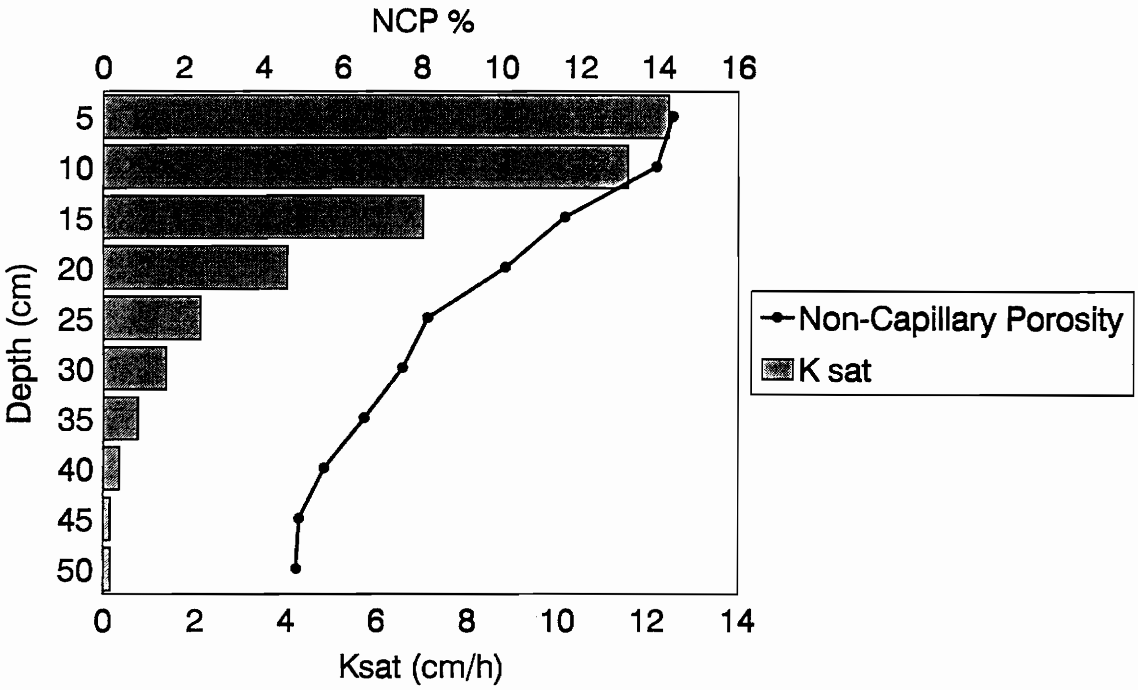


Figure 3.5. The effects of decreasing non-capillary porosity (NCP) with increasing depth on saturated hydraulic conductivity.

LIQUID LIMIT AND PLASTIC LIMIT

Consistency limits are used as an index of soil workability or firmness as affected by soil water content (Sowers 1965). The plastic limit is the soil moisture content at which a soil can be deformed and molded by a force without breaking apart. Soils, such as sands with low organic matter levels, are non plastic and will lose the molded shape when they dry (Baver et al. 1972). Fine textured soils have greater cohesion forces between soil and water, therefore, they are more subject to deformation and retention of molded shapes (Baver et al. 1972). Therefore, only finer textured soils have plastic limits. The liquid limit is the soil moisture content at which the soil becomes semi-fluid and begins to flow under applied force. Finer textured soils have higher liquid limits due to their greater particle surface area. The greater particle surface area allows the soil to have a much higher moisture content before water films become sufficiently thick for particle slip to occur. Organic matter levels act as modifiers of consistency limits. The A horizon has higher organic matter levels that the similarly textured E horizon, but the higher organic matter level of the A horizon increase the liquid limit (Table 3.7). As the clay content increase or the texture becomes finer, liquid limit values will also increase (Figure 3.6.). Soils having low liquid limits are more susceptible to puddling due to trafficking. Soils which maintain their firmness at high water contents are favorable for wet weather harvesting.

Table 3.7. Average liquid and plastic limits for each horizon in each site. Values in parentheses are standard deviations.

Site	Horizon	Liquid Limit % (STDEV)	Plastic Limit % (STDEV)
North Horseshoe	A	32 (14.50)	23 (9.74)
	E	15 (0.00)	non plastic
	Bt	33 (4.89)	18 (1.45)
South Horseshoe	A	26 (3.80)	22 (1.65)
	E	13 # (2.25)	18 * (0.00)
	Bt	34 (1.93)	18 (0.90)
Sycamore	A	29 (3.17)	22 (1.04)
	E	13 # (3.63)	14 * (4.31)
	Bt	37 (6.89)	17 (2.44)
All Sites	A	29	22
	E	13 #	16 *
	Bt	35	18

* Across all sites the E horizon contained three texture classes, loamy sand, sandy loam, and loam. Due to the coarse texture of the loamy sand, only sandy loam and loam liquid limits could be obtained and reported.

As for the liquid limit, only the loam texture class of the E horizon was plastic; all other texture classes were non-plastic.

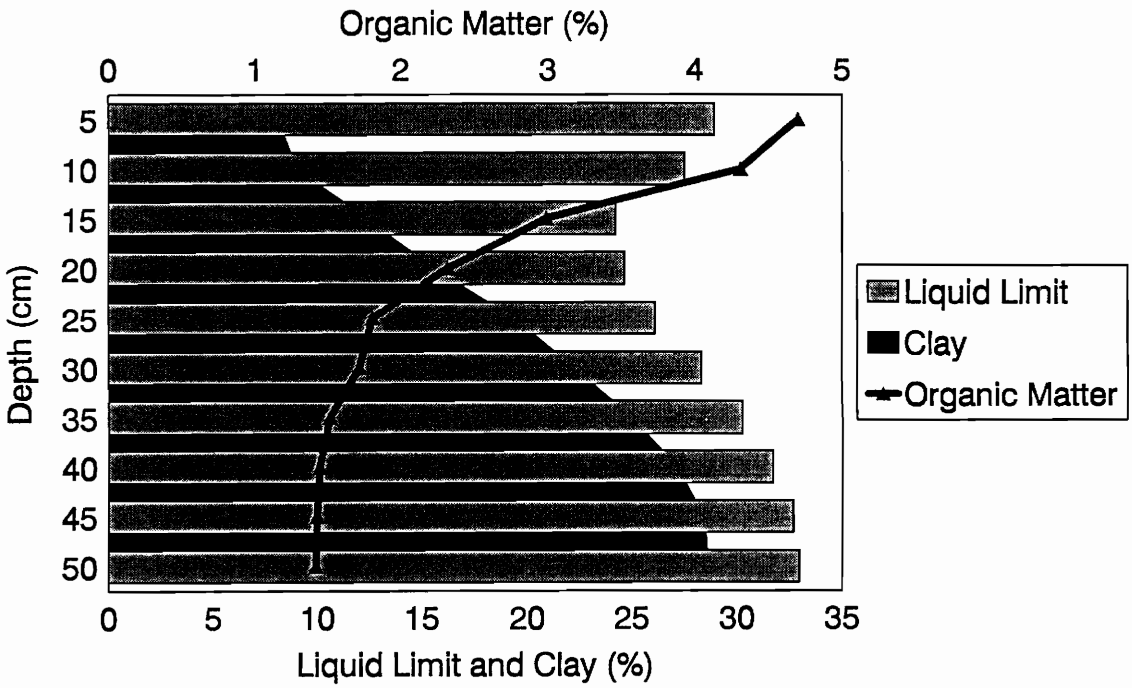


Figure 3.6. Effects of clay and organic matter content on soil liquid limit.

CHAPTER IV

SOIL STRENGTH MODELING

RESULTS and DISCUSSION

Effects of Static and Dynamic Soil Physical Properties and Site Characteristics on Soil Strength

Soil strength, as measured by penetration resistance varies with a number of semi-static soil physical properties. Soil bulk density (Taylor and Gardner, 1963; Camp and Lund, 1968;), soil texture and organic matter (Sands et al.,1979; Gupta and Larson, 1982; Spivey et al., 1986), soil void volume (Gibbs and Reid, 1988; Roscoe et al., 1958; Capper and Cassie 1963), and soil consistency (Muller et al., 1990) have been reported to significantly affect soil strength. Invariably, soil moisture is reported to be the major dynamic soil property that influences soil strength (Busscher 1990; Braunack and Malafant, 1988).

Soils resist deformation by forces such as trafficking due to frictional forces, cohesion forces, and soil moisture bonds. Frictional forces resist sliding of soil particles while cohesive forces and soil moisture bonds act as cementing and bonding agents (Capper and Cassie 1963, Yong and Warkentin 1966, Mirreh and Ketcheson 1972, Aitchison 1961). Mirreh and Ketcheson (1972) concluded that soil moisture bonds were more subject to change within a given soil. Therefore, soil penetration resistance can change rapidly, as a result of soil moisture effects on soil particle water bonds (Busscher 1990).

Dynamic Properties Effecting Soil Strength

Soil Moisture

As a result of changing moisture contents cohesion forces can vary between and within different soils (Camp and Gill, 1969; Greacen et al. 1968). As moisture content increases, cohesive forces resulting from moisture bonds decreases. As water film thickness increases, frictional forces between soil particles decrease and soil particles flow pass one another.

Most attempts to quantify soil strength incorporate some measure of soil moisture. Canarache (1989) reviewed soil strength regression equations used by various researchers to estimate penetration resistance. All equations used some form of moisture content to predict variation in soil strength. Busscher (1990) reported that soil moisture had such significant effects on penetration resistance that it was often difficult to determine if water content or treatments effects were causing differences in soil strength. A soil mechanical behavior model revealed the importance of soil moisture in the aggregation of soils during tillage (Gupta and Larson 1982). Gupta and Larson (1982) reported that more energy was required to break a unit mass of dry soil into the same number of aggregates as a unit mass of wet soil. Many researchers reported that when a soil is saturated it is subject to severe rutting. Bodman and Rubin (1948) and Koenigs (1963) determined that soils with a moisture content approaching saturation may have maximum susceptibility for puddling.

Soil volumetric water content had significant effects on soil strength in all three horizons. Field-sampled soil strength and moisture content relationships were similar to results reported from laboratory determinations by Busscher (1990), and Braunack and

Malafant (1988). The following regression equations were used to describe penetration resistance across a wide range of natural soil moisture contents for the A, E, and Bt horizons:

A horizon: $\log(\text{kPa}) = 5.09 - 1.39 \log(\text{MC})$ (P value < 0.01, $R^2 = 43.1$)
(Appendix, Tables 1a, 1b)

E horizon: $\log(\text{kPa}) = 5.37 - 1.32 \log(\text{MC})$ (P value < 0.01, $R^2 = 28.9$)
(Appendix, Tables 2a, 2b)

Bt horizon: $\log(\text{kPa}) = 4.11 - 0.496 \log(\text{MC})$ (P value < 0.01, $R^2 = 8.1$)
(Appendix, Tables 3a, 3b)

Where kPa = soil strength
MC = % volumetric moisture content

There was also a significant relationship between strength and moisture content for the soil as a profile: $\log(\text{kPa}) = 4.58 - 0.849 \log(\text{MC})$ (P value < 0.01, $R^2 = 16.5$) (Appendix, Tables 4a, 4b). Scatter plots of soil strength vs. volumetric moisture content illustrate the effects of soil moisture on soil strength (Figure 4.1). A scatter plot of each regression equation can be seen in figure 4.2. The unusual distribution of data points is the result of soil strength measurements having been taken in increments of 5 psi. The use of a log-log transformation results in wide differences between measured values. Wells and Treesuwan (1978) cited Collins (1971) reporting cone index values decreasing with increasing moisture contents from analysis of field determinations. The use of field determinations allowed the study of cone index values across a natural range of field moisture contents. Bennie and Botha (1986) developed a regression equation to estimate soil strength using moisture content and bulk density. A log (base 10) transformation was used between soil strength and moisture content. A similar transformation was used for the equations presented in this study.

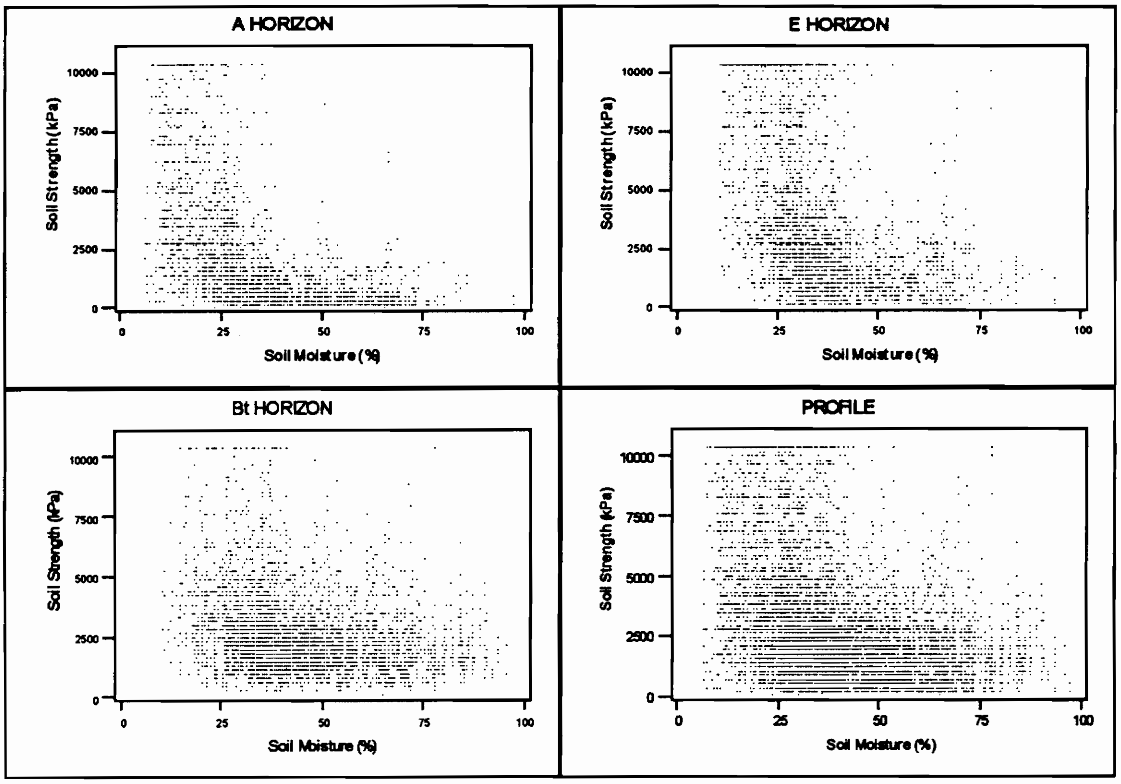


Figure 4.1. Soil strength vs. volumetric moisture content scatter plots for each horizon and the entire soil profile. Individual scatter plots illustrate variations between hoirzons and location within the profile plot.

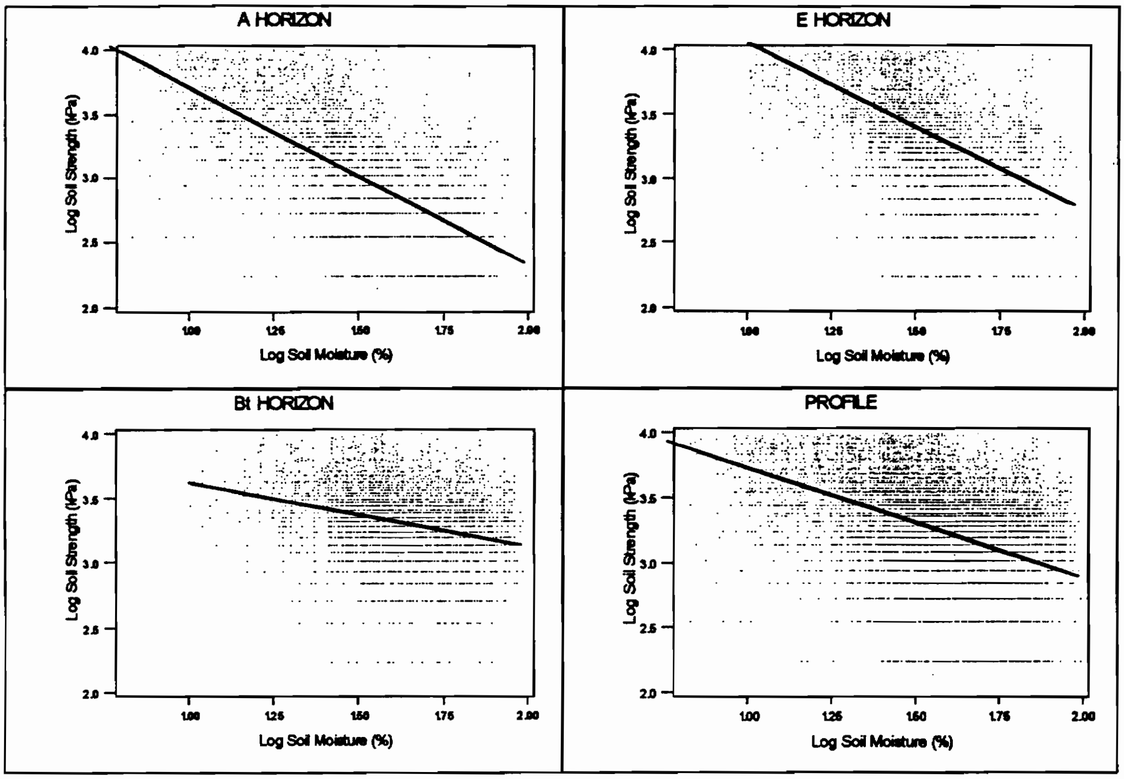


Figure 4.2. Soil strength vs. volumetric soil moisture regression equation plots for each horizon and the entire soil profile. Individual plots illustrates variations between horizons and location within the profile plot.

A horizon: log(kPa) = 5.09 - 1.39 log(MC) (P value < .01, $R^2 = 43.1$)
E horizon: log(kPa) = 5.37 - 1.32 log(MC) (P value < .01, $R^2 = 28.9$)
Bt horizon: log(kPa) = 4.11 - 0.496 log(MC) (P value < .01, $R^2 = 8.1$)
Profile: log(kPa) = 4.58 - 0.849 log(MC) (P value < .01, $R^2 = 16.5$)

Where kPa = soil strength
MC = volumetric moisture content (%)

Site Hydrology

The hydrology of forested wetlands along the Atlantic coastal plain is the most important factor controlling wetland functions and structure (Day et al. 1988). Due to the naturally high water tables which inundate much of forested wetlands, intensive drainage systems have been installed to lower water tables creating larger windows for management operations. Sites that have not been drained are subject to soil disturbance caused by rutting, 6 to 9 months of the year (Allen and Campbell, 1988). Site operability and pine productivity are increased by site drainage. Loblolly (Pinus taeda)and slash (Pinus echinata) pine growth has been reported to increase as a result of drainage (Langdon and Mckee, 1981; Walker et al. 1962).

Decreases in soil strength as a result of decreased water table depths below the soil surface have been reported by many researchers (Greacen and Sands 1980; Bradford, 1986). Muller et al. (1990) used depth of soil layers above the water table to aid in the determination of trafficability and workability of alluvial clay soils (Eutric Gleysols and Fluvisols). Muller et al. (1990) found that soils with shallow perched water tables (less than 55 cm below soil surface) had fewer workable days than soils with greater water table depths. Soil consistency of the Ap and subsoil horizons was determined each time water table levels were measured. As depth of water tables below the soil surface decreased, soil consistency also decreased producing a very soft, plastic soil. In a report by Mckee et al. (1985) sites with water tables close to the surface should not be trafficked because soil strengths are insufficient to support a load. The depth of wet-season water tables are suggested as a variable for determining rutting hazard. In a study of helicopter and rubber-tired skidder harvesting methods on a tidal palustrine swamp in southwestern Alabama, water table depth influenced site disturbance. As a result of saturated soil conditions, skidder tires sank into the soil causing it to flow like a liquid (Aust et al.

1989). Similar result were found as a result of water table depth. Water table levels close to the surface caused increased moisture contents resulting in decreased soil strength.(Figure 4.3) Each horizon had a significant relationship between soil strength and water table depth. Regression equation scatter plots can be seen in Figure 4.4. Similar non-linear regression equations were used for each horizon:

A horizon: $\log(kPa) = 2.60 - 0.0101(WT)$ (P value < 0.01, $R^2 = 44.6$)

(Appendix, Tables 5a, 5b)

E horizon: $\log(kPa) = 3.06 - 0.00805(WT)$ (P value < 0.01, $R^2 = 33.1$)

(Appendix, Tables 6a, 6b)

Bt horizon: $\log(kPa) = 3.21 - 0.00282(WT)$ (P value < 0.01, $R^2 = 9.9$)

(Appendix, Tables 7a, 7b)

Where kPa = soil strength

WT = water table depth below the surface (cm)

The following equation described the relationship between the water table depth and soil strength for the A, E, and Bt horizons as a profile:

$\log(kPa) = 3.03 - 0.006(WT)$ (P value < 0.01, $R^2 = 21.2\%$)

(Appendix, Tables 8a, 8b)

For the A horizon, the water table explains 45 % of the variation in soil strength. However, the relationships between strength and water table depth for the E and Bt horizons are not as strong. The Bt horizon equation had a very low R^2 value suggesting that little variation can be explained by the equation; however the equation was still significant. There is less change in soil strength with changes in water table depth in the Bt horizon than the A and E horizons (Figure 4.3). This could be explained by the effects of the capillary fringe (Gillham 1984). The capillary fringe can cause soils to be saturated well above the water table level, causing the Bt horizon to have a similar water content regardless of water table depth. 21% of the variation was explained by the profile equation, indicating some other soil properties are effecting soil strength.

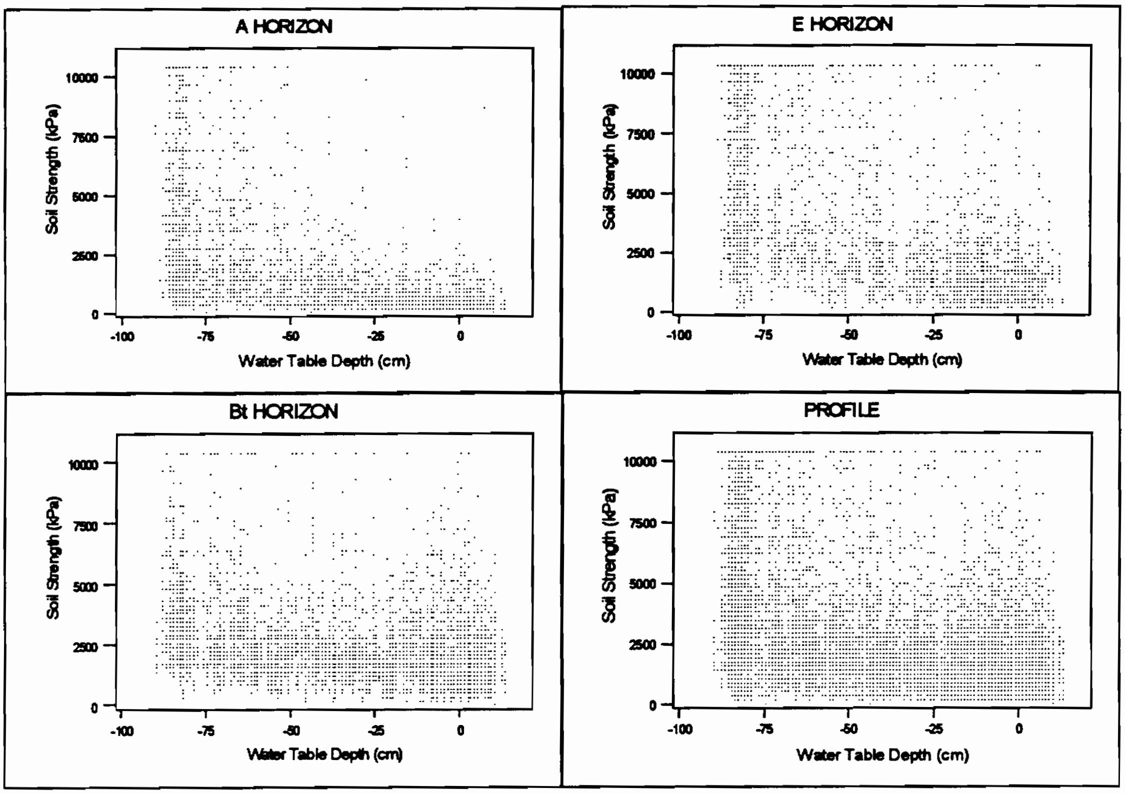


Figure 4.3. Soil strength vs. water table depth scatter plots for each horizon and the entire soil profile. Individual scatter plots illustrates variations between horizons and location within the profile plot.

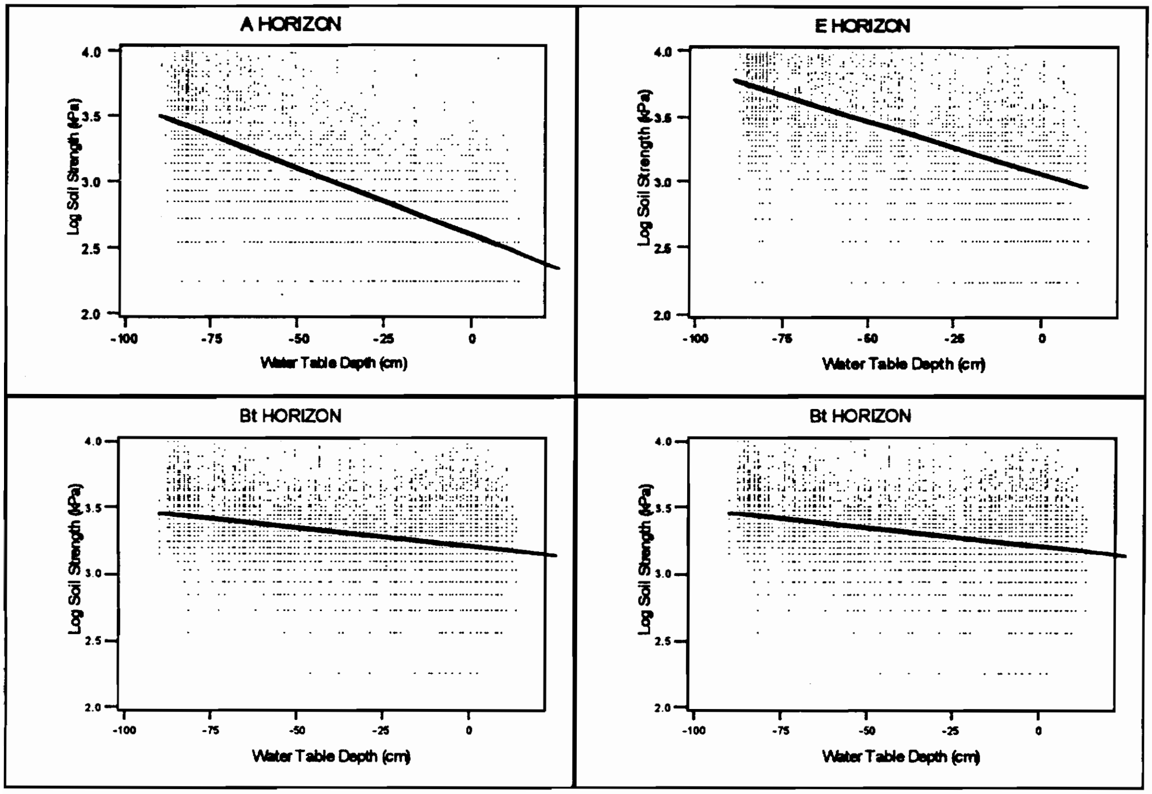


Figure 4.4. Soil strength vs. water table depth regression equation plots for each horizon and the entire soil profile. Individual plots illustrates variations between horizons and location within the profile plot.

A horizon: log(kPa) = 2.60 - 0.0101(WT) (P value < .01, $R^2 = 44.6$)
E horizon: log(kPa) = 3.06 - 0.00805(WT) (P value < .01, $R^2 = 33.1$)
Bt horizon: log(kPa) = 3.21 - 0.00282(WT) (P value < .01, $R^2 = 9.9$)
Profile: log(kPa) = 3.03 - 0.006(WT) (P value < .01, $R^2 = 21.2$)

Where kPa = soil strength
WT = water table depth (cm)

Static Properties

The effects of changes in soil moisture are often so great that other soil factors do not receive adequate attention. In order to evaluate effects of static soil physical properties on soil strength, soil strength values were adjusted to a common soil moisture content so that the effects of soil moisture were held constant. This adjustment allowed the effects of static soil properties to be determined.

Bulk Density

Soil bulk density is the second most commonly used soil parameter in soil strength models. As bulk density increases the number of soil particles per unit volume increases, increasing the frictional forces between particles and decreases pore space (Mirreh and Ketcheson 1972). Decreased pore space results in greater cohesive forces caused by water films and cementing materials. Bulk density is commonly used as a measure of soil compaction. As soil is compacted, the bulk density increases as a result of large pores collapsing. Penetrometers have been used extensively to evaluate the extent and severity of soil compaction resulting from traffic (Henderson et al. 1988).

Aust et al. (1990) compared pre- and post-harvest bulk density values and found post-harvest values were higher than pre-harvest levels. The study was conducted within the Francis Marion National Forest located on the coastal plain of South Carolina. Mechanical resistance values were also higher following harvest. The highest mechanical resistance values were reported to be on log decks which had intensive traffic by tractor-trailers and front-end loaders. Busscher (1990) reported that soil penetration resistance reading should be taken at similar water contents to in order to identify other soil properties effecting soil strength. Ayers and Perumpral (1982) reported the effects of moisture and density on cone index. Cone index values were measured for combinations of different bulk densities and moisture contents. At lower moisture contents ranging from 2.6 to 6.7, increases in dry density appeared to cause a exponential increase in cone index. Moisture contents in this range generally do not represent natural field levels; however, this relationship reveals the effects of bulk density on penetration resistance.

A similar relationship was found in this study (Figure 4.5). Soil penetration resistance has a significant relationship with bulk density for the soil as a profile. For each horizon in the profile, there was no significant relationship (P value < 0.01) or the equation had a very low R^2 value. Regression equations for each horizon are provided in Appendix, Tables 9a,10a,11a. No significant relationship existed between soil penetration resistance and bulk density for the individual horizons, due to the individual horizons having a narrow range in bulk density values. When bulk densities of the entire profile were used, a wide range of bulk densities could be considered. This relationship provided the following profile equation:

$$\log(\text{kPa}) = 2.83 + 0.400(\text{BD}) \quad (\text{P value} < 0.01, R^2 = 15.9)$$

(Appendix, Table 12a, 12b)

Where kPa = soil strength

BD = dry bulk density (Mg/m^3)

Increasing soil strength with a increase in bulk density is evident by the positive coefficient of 0.400 for bulk density. A regression equation scatter plots can be seen in figure 4.6. Many studies report increases in penetration resistance with increased bulk density values (Ayers and Perumpral 1982, Wells and Treesuwan 1978, Henderson et al. 1988). However, these equations are based on artificially laboratory compacted soils, the equation presented in this study describes the relationship between natural occurring variations in bulk density and penetration resistance.

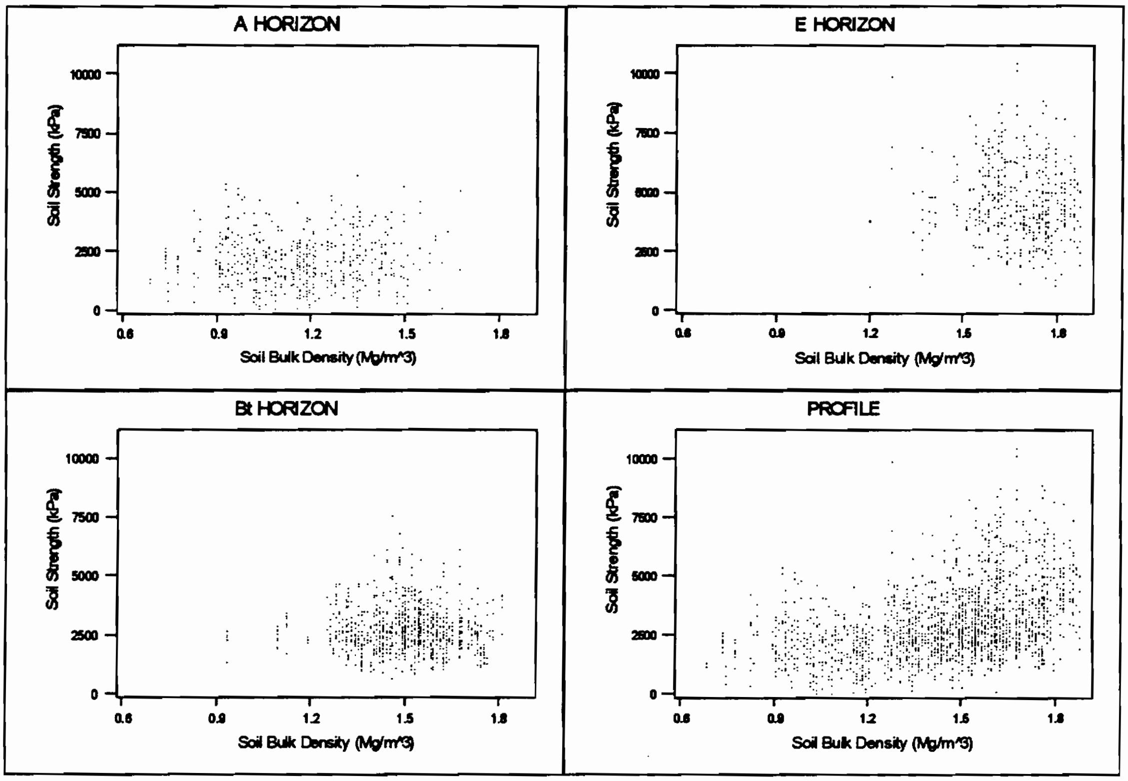


Figure 4.5. Soil strength vs. soil bulk density scatter plots for each horizon and the entire soil profile. Individual scatter plots illustrates variations between horizons and location within the profile plot.

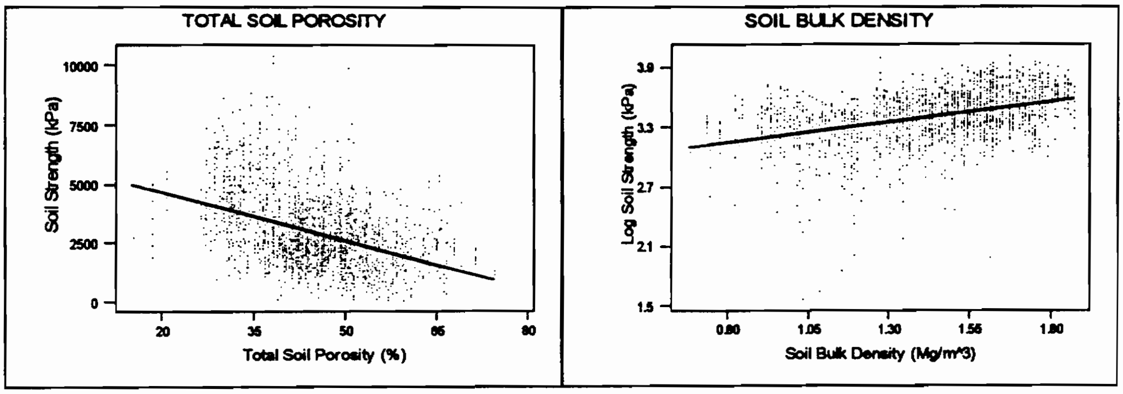


Figure 4.6. Soil strength vs. total soil prosity and soil bulk density regression equation plots for the soil profile.

Porosity: kPa = 6021 - 68.7 (TP) (P value < .01, R^2 = 17.6)

Bulk Density: log(kPa) = 2.83 + 0.4(BD) (P value < .01, R^2 = 15.9)

Where kPa = soil strength
BD = dry bulk density (Mg/m^3)
TP = total soil porosity (%)

Porosity

Total porosity, has also been used by researchers to assist in soil penetration resistance estimation and characterization (Hvorelev 1937 cited by Greacen 1960, Roscoe et al. 1958). Porosity is influenced by bulk density, changes in the latter may produce changes in cohesion resulting from water films. As the void volume decreases, pore diameter decreases resulting in greater moisture films and surface contact between particles. Gerard et al. (1982) reported the effects of voids were negative and decreased soil strength for a fine sandy loam soil. Cultivated soils in the Rolling Plains of Texas were collected and prepared in the laboratory. Soil voids were one of the factors which most influenced the strength of the upper 15 cm of soil. A negative effect of soil voids is presented in Figure 4.7. Significant relationships between total porosity and soil strength were found for the E and Bt horizons; however, the A horizon did not show a significant relationship (Appendix, Tables 13a, 14a, 15a). Again R^2 values for each horizon equations are very low suggesting a limited relationship between soil strength and porosity for each horizon. The over all relationship between soil strength and total porosity for the profile was significant (P value < 0.01):

$$\text{kPa} = 6021 - 68.7(\text{TP}) \quad (\text{P value} < 0.01, R^2 = 17.6)$$

(Appendix, Tables 16a, 16b).

Where kPa = soil strength

TP = total porosity (%)

A scatter plot of the above equation is presented in Figure 4.6. As total porosity decreased soil strength increased as a result of greater frictional and cohesive forces between particles. Similar results were discussed by Hvorelev (1937 as cited by Greacen and Sands 1980) who demonstrated that soil strength was a function of frictional resistance, and void ratio which determined the cohesive component of soil strength. Roscoe et al. (1958) demonstrated the existence of a critical voids ratio. The critical voids ratio was determined for saturated soil yielding under a load. Due to saturated conditions, the critical voids ratio was a determination of a critical volumetric water content.

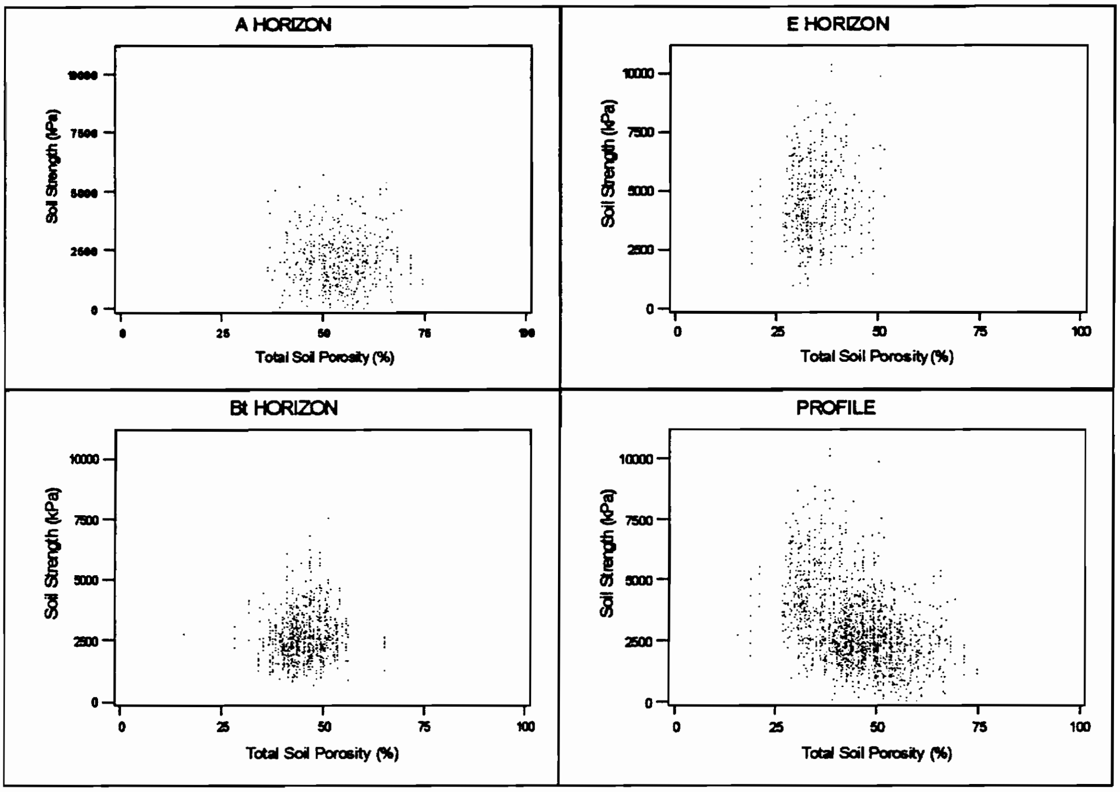


Figure 4.7. Soil strength vs. total soil porosity scatter plots for each horizon and the entire soil profile. Individual scatter plots illustrates variations between horizons and location within the profile plot.

Soil Texture and Soil Organic Matter

Soil texture and organic matter content have both been used to assess soil strength; however, these two soil properties also have large influences on previously discussed soil properties that have influences on soil strength. The influences of texture and organic matter on soil strength are not independent of other factors.

Soil texture is a basic soil property (Brady 1984). Finer textures soils generally have a lower density than coarse textured soils such as sand. This is the result of finer textured soils organizing in granules, especially if adequate organic matter is present (Brady 1984). As would be expected soil texture has a significant effect on the bulk density of a soil. Soils having a wide range of particle sizes have the highest bulk densities. However, organic matter also plays a role in soil particle orientation. Organic matter binds individual soil particles into granules or aggregates, thus, increasing the void space between particles (Brady 1984).

Spivey et al. (1986) studied the effects of texture and organic matter of the A and E horizons of southeastern coastal plain soils on soil strength. They found significant relationships between soil strength and sand, clay and organic matter content. Increases in sand and decreases in clay and organic matter resulted in increased soil strength. The bulk density and water content of the test cores also varied; however, the coefficient of determination of probe resistance vs. texture was larger than probe resistance vs. water content, and bulk density. This implied soil texture had a significant effect on soil strength even though bulk densities and water contents varied. Spivey concluded that there was significant correlation between particle size classes and probe resistance between samples prepared with comparable forces of consolidation, such as water content and bulk density.

Similar correlation's can be seen between soil strength and texture (Figures 4.8, 4.9, 4.10) and organic matter (Figure 4.11). The following equations attempt to estimate soil strength (kPa) as a function of soil particle size classes and organic matter:

$\log(kPa) = 3.35 + 0.0483 \log(clay)$ (P value < 0.01, $R^2 = 0.7$)
(Appendix, Tables 20a, 20b)

$kPa = 3507 - 23.6(silt)$ (P value < 0.01, $R^2 = 1.7$)
(Appendix, Tables 24a, 24b)

$kpa = 2366 + 0.169(sand)^2$ (P value < 0.01, $R^2 = 3.7$)
(Appendix, Tables 28a, 28b)

$\log(kPa) = 3.48 - 0.290 \log(om)$ (P value < 0.01, $R^2 = 11.9$)
(Appendix, Tables 32a, 32b)

Where kPa = soil strength
clay, sand, silt = % of each
OM = organic matter (%)

Regression equations for each of the above relationships were also determined for each horizon; however, the relationships were not significant due to the narrow range of values (Appendix, Tables 17a, 17b-31a, 31b). Scatter graphs of each horizon relationship are presented in Figures 4.13. Increase in both clay and silt resulted in decrease in soil strength; however, increases in sand content resulted in increases in soil strength. Significant relationships between soil texture size classes and soil strength were found, but coefficient of determination values were very low. Apparently the influence of organic matter content on soil strength was sufficient to negate this relationship. The A and E horizons had similar clay and sand contents, but had very different soil strengths. This is the result of the higher organic matter content in the A horizon. The organic matter caused the sandy loam A horizon to have even lower soil strengths than the finer textured Bt horizon. The larger coefficient of determination value for the organic matter equation also indicates that organic matter has a greater effect on soil strength than does texture.

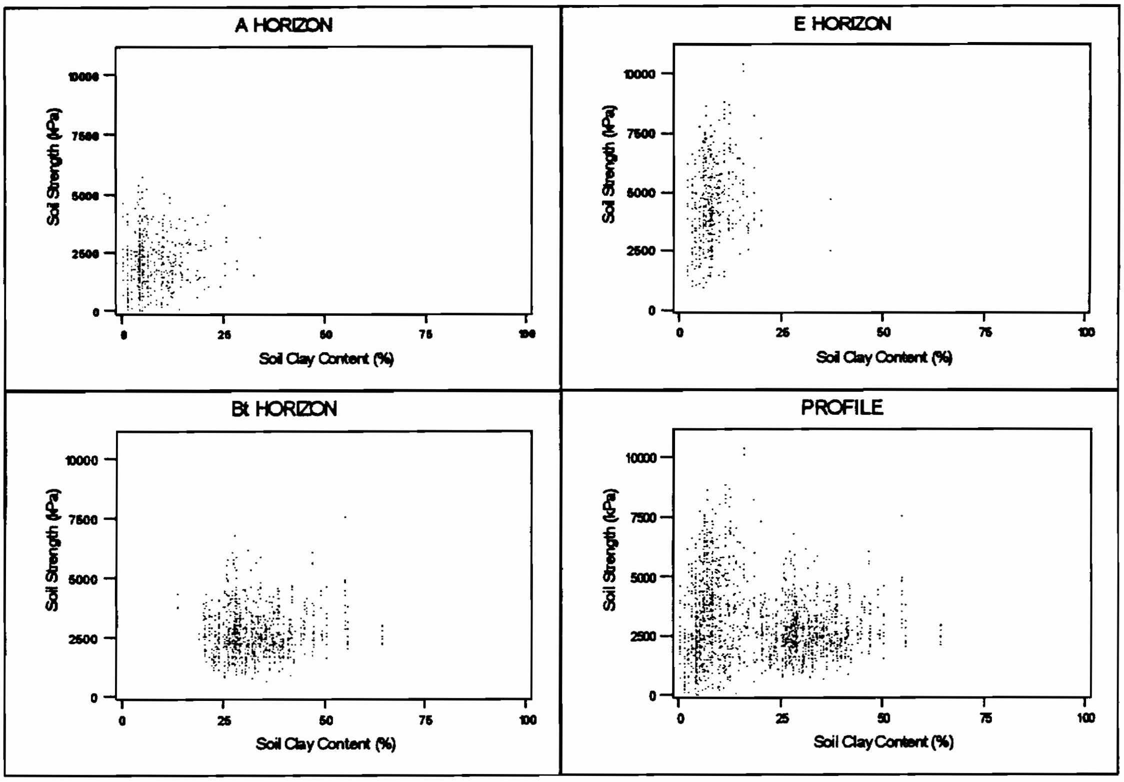


Figure 4.8. Soil strength vs. soil clay content scatter plots for each horizon and the entire soil profile. Individual scatter plots illustrates variations between horizons and location within the profile plot.

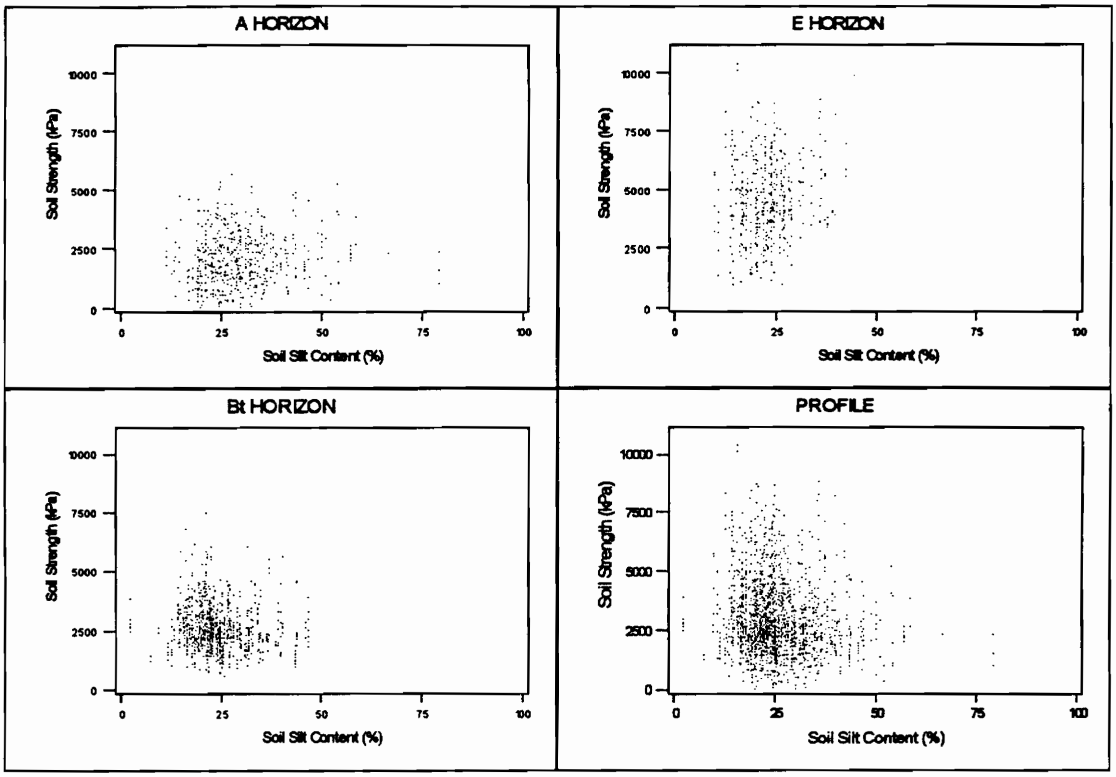


Figure 4.9. Soil strength vs. soil silt content scatter plots for each horizon and the entire soil profile. Individual scatter plots illustrates variations between horizons and location within the profile plot.

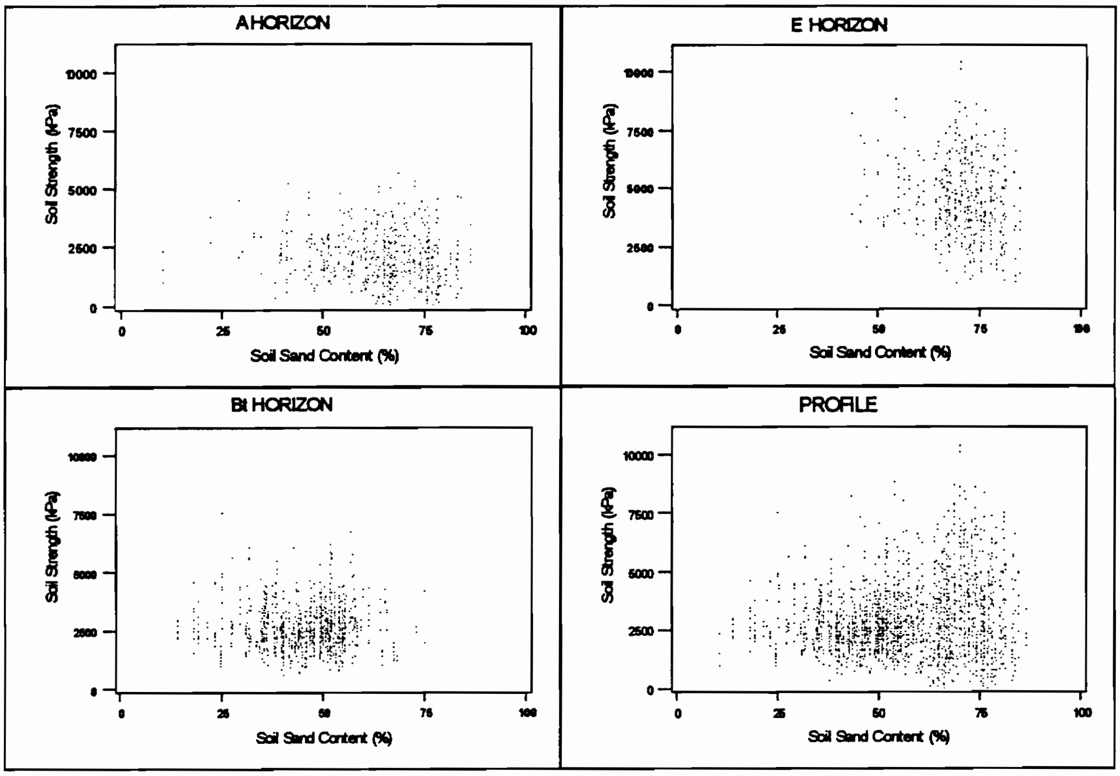


Figure 4.10. Soil strength vs. soil sand content scatter plots for each horizon and the entire soil profile. Individual scatter plots illustrates variations between horizons and location within the profile plot.

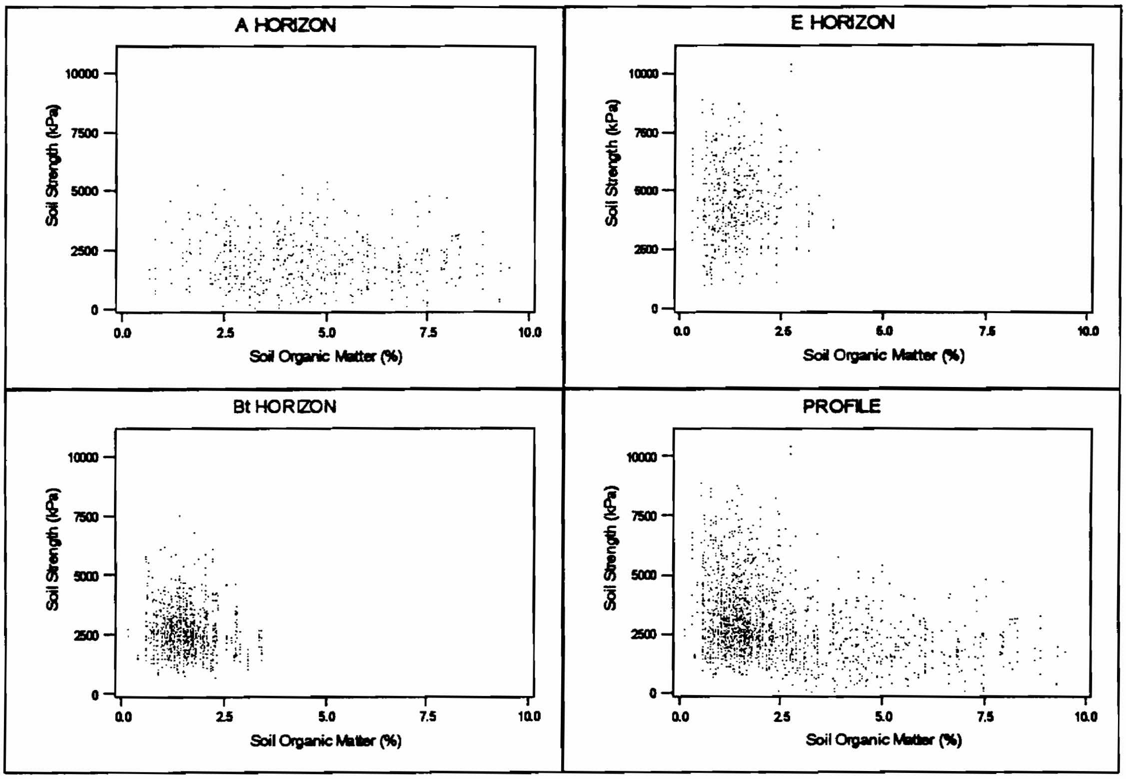


Figure 4.11. Soil strength vs. soil organic matter content scatter plots for each horizon and the entire soil profile. Individual scatter plots illustrates variations between horizons and location within the profile plot.

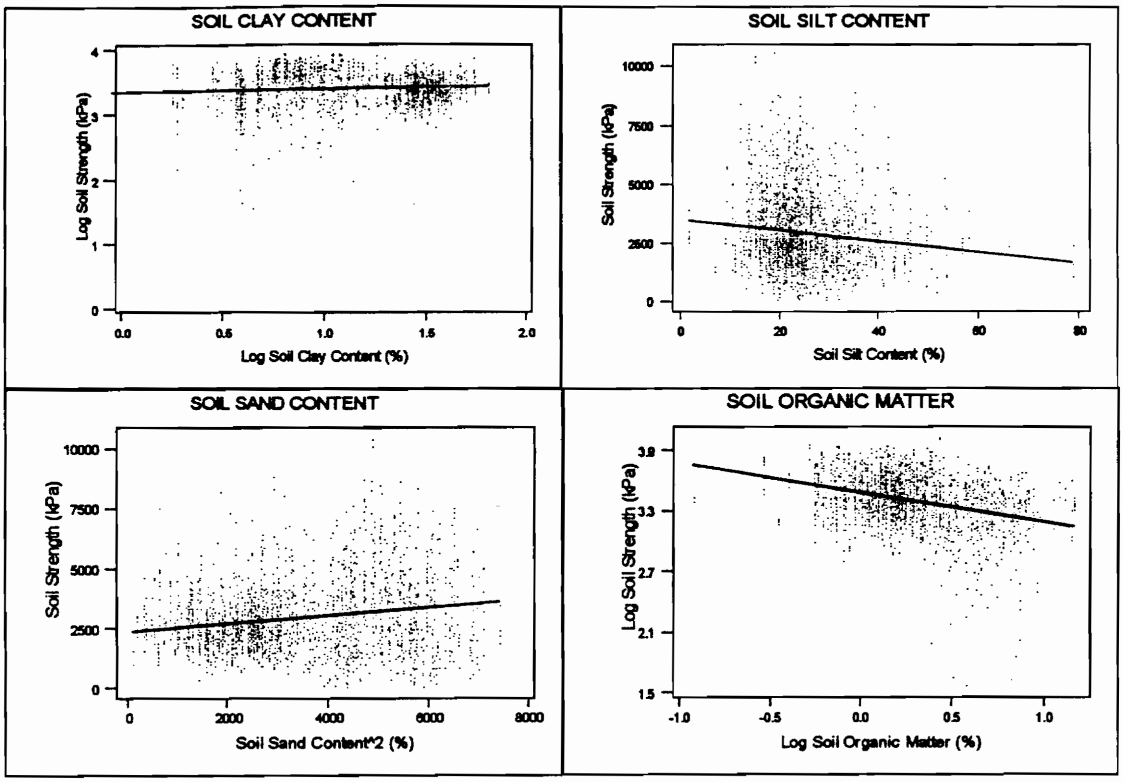


Figure 4.12. Soil strength vs. soil clay, silt, sand, and organic matter content regression equation plots for the soil profile.

Clay: log(kPa) = 3.35 + 0.0483 log(clay) (P value < .01, $R^2 = 0.7$)
Silt: kPa = 3507 - 23.6(silt) (P value < .01, $R^2 = 1.7$)
Sand: kPa = 2366 + 0.169(sand)^2 (P value < .01, $R^2 = 3.7$)
Organic Matter: log(kPa) = 3.48 - 0.2901 log(OM) (P value < .01, $R^2 = 11.9$)

Where kPa = soil strength
OM = organic matter content (%)
clay = soil clay content (%)
silt = soil silt content (%)
sand = soil sand content (%)

Multiple Effects of Soil Properties on Soil Strength

Numerous soil properties influence the penetration resistance of soil. All soil attributes determine it's physical behavior. The two primary forces which hold soil together, friction and cohesion are determined by the interactions of physical forces. The understanding of the relationship between physical properties and soil strength allows the most influential properties to be determined. Wells and Treesuwan (1978), attempted to specify relevant soil strength parameters in terms of physical properties such as bulk density and water content. The effects of vehicular traffic on soil strength parameters (Bernstein's modules of soil deformation, angle of internal soil friction, slip coefficient, cohesion coefficient, and cone index) were measured across a range of bulk densities and water contents. Wells and Treesuwan (1978) found that many soil strength parameters had significant relationships with bulk density and water content; however, cone index was the only parameter which had a clear dependency on both bulk density and moisture content. It was concluded that soil cone index was the most promising methodology for continuously predicting soil trafficability.

After evaluating the independent effects of various soil properties on penetration resistance, the interaction effects of independent properties attributing to soil strength were quantified. Candidate models for the A, E, and Bt horizons were determined using a stepwise regression procedure. The stepwise procedure regressed soil properties which could have a effect on soil strength.

The following candidate models were developed for each horizon:

A horizon: $\log(\text{kPa}) = 3.50 - 0.00642(\text{WT}) - 0.671 \log(\text{MC}) + 0.221(\text{BD})$

(P value < 0.01, $R^2 = 49.9$)

(Appendix, Tables 33a, 33b)

E horizon: $\log(\text{kPa}) = 3.92 - 0.661 \log(\text{MC}) + 0.178(\text{BD}) - 0.00451(\text{WT})$

(P value < 0.01, $R^2 = 32.0$)

(Appendix, Table 34a, 34b)

Bt horizon: $\log(\text{kPa}) = 3.52 - 0.338 \log(\text{MC}) + 0.185 \log(\text{clay}) - 0.144 \log(\text{OM}) - 0.002244(\text{WT})$

(P value < 0.01, $R^2 = 14.5$)

(Appendix, Table 35a, 35b)

Where kPa = soil strength
WT = water table depth (cm)
MC = volumetric moisture content (%)
BD = dry bulk density (Mg/m^3)
clay = clay content (%)
OM = organic matter (%)

When dealing with natural systems such as this, multicollinearity among regressors often results in unstable estimates of parameter coefficients. Soil parameters affecting soil strength can also affect one another. Soil properties such as porosity and organic matter content have been shown to have significant effects on soil bulk density (Federer et al. 1993, Brady 1984). A common step for diagnosing multicollinearity problems among the regressors is to look at correlation matrix between variables (Belsley et al. 1980) (Table 4.1). Regressors that were highly correlated were considered to have potential collinearity problems and were investigated further.

Table 4.1 Correlation matrices for regressor variables in the soil strength multiple regression equation for each horizon.

A horizon	WT	BD
BD	0.065	--------
logMC	0.766	-0.086

E horizon	WT	BD
BD	-0.029	-------
logMC	0.684	-0.067

Bt horizon	WT	logclay	logOM
logclay	0.043	--------	--------
logOM	0.034	0.076	--------
logMC	0.390	0.081	0.180

Where kPa = soil strength

WT = water table depth (cm)

MC = volumetric moisture content (%)

BD = dry bulk density (Mg/m^3)

clay = clay content (%)

OM = organic matter (%)

Within each horizon only moisture content and water table depth were highly correlated. This correlation is simply explained, the water table supplied most of the soil profile moisture.

As a second measure into the investigation of multicollinearity, variance inflation factors (VIFs) were determined and examined (Belsley et al. 1980) (Appendix, Tables 33a, 34a, 35a). The VIFs for water table depth and moisture content were much higher than for bulk density in both the A and E horizon. This suggested that there is a multicollinearity problem between water table depth and moisture content in both of the horizons. The VIFs for the regressors in the Bt horizon were all relatively low indicating no collinearity between regressors. However, the water table regressor was eliminated in order to construct a more usable model.

After the water table depth attribute was eliminated from each horizon model, a final diagnostic method was used to refine the model. DFITS were derived for each observation for the A, E and Bt horizons. DFITS identifies variables having a large leverage or influence on the predicted value (Belsley et al. 1980). Based on the DFITS, an overall measure of how unusual each observation is was made. Observations were considered unusual if DFITS > $2(p/n)^{.5}$ (p = number of coefficients, n = number of observations) (Belsley et al. 1980). Unusual observations were eliminated from the data set and regressor estimated coefficients recalculated to determine the final model for each horizon.

The following is a list of the final regression models for the A, E, and Bt horizons:

A horizon: $\log(\text{kPa}) = 5.21 + 0.0738(\text{BD}) - 1.53 \log(\text{MC})$

(P value < 0.01, $R^2 = 52$)

(Appendix, Tables 36a, 36b)

E horizon: $\log(\text{kPa}) = 4.77 + 0.296(\text{BD}) - 1.21 \log(\text{MC})$

(P value < 0.01, $R^2 = 30.7$)

(Appendix, Tables 37a, 37b)

Bt horizon: $\log(\text{kPa}) = 3.92 + 0.150 \log(\text{clay}) - 0.0737 \log(\text{OM}) - 0.505 \log(\text{MC})$

(P value < 0.01, $R^2 = 11.1$)

(Appendix, Tables 38a, 38b)

Where kPa = soil strength

BD = dry bulk density (Mg/m^3)

MC = volumetric moisture content (%)

clay = clay content (%)

OM = organic matter (%)

When the water table variable (WT) was eliminated from the regression equations because of multicollinearity, the subsequent equations' R^2 decreased. However, the lower R^2 was justified by the time requirements of measuring the water table depth variable vs. the moisture content. Measurements of volumetric water content using a TDR system are easier and more feasible, water table measurements are difficult and less feasible. Drungil et al. (1989) identified the TDR system to give quick results and can be fully automated. As a result of influence diagnostics (DFITS), unusual observations were eliminated from the data set. Elimination of unusual observations increased the R^2

values, and increased the significance of bulk density in the models for the A and E horizon. Before the unusual observations were removed from the data set, bulk density had a decreasing significance with increasing depth in the profile. Bulk density decreased in significance from A to the E horizon and was not even included in the Bt model (Appendix, Tables 33a, 34a, 35a). The absence of bulk density in the Bt horizon model can be explained by the difference in moisture content between the horizons. The average moisture content of the Bt horizon was much larger than the A and E horizons (Figure 4.13). At higher moisture contents bulk density had less of an effect on soil strength than at lower moisture contents. Ayers and Perumpral (1982) found a similar relationship between bulk density and moisture content. They found that bulk density at low moisture contents had an exponential effect on soil strength and as moisture content increased the bulk density relationship became more linear.

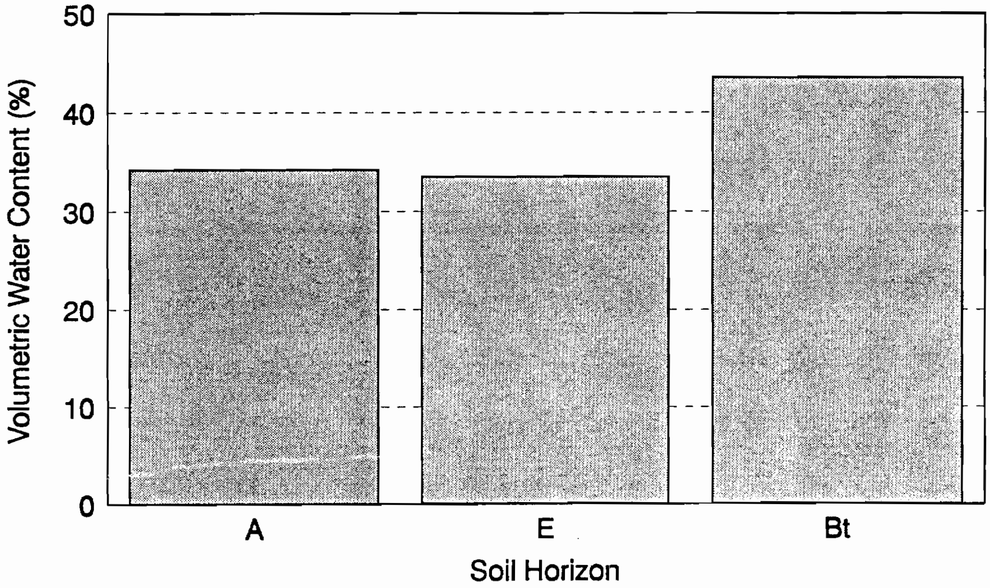


Figure 4.13. Mean volumetric moisture content for each horizon.

In order to characterize soil strength across a wide variation of soil parameter values, a dynamic and static model was developed for the A, E, and Bt horizons as a profile. This eliminated the problem of low R^2 values. In order to characterize soil strength across a wide variation of soil parameter values, dynamic and static models were developed for the entire profile (A, E, Bt horizons). This increased the range of soil parameters sampled and improved the model. The following candidate models were obtained using the same technique used for the horizon models:

Dynamic

$$\log(\mathrm{kPa}) = 3.12 + 0.486(\mathrm{BD}) - 0.00413(\mathrm{WT}) - 0.603 \log(\mathrm{MC}) + 0.191 \log(\mathrm{clay})$$

(P value < 0.01, $R^2 = 37.8$)

(Appendix, Table 39a, 39b)

Static

$$\mathrm{kPa} = 1416(\mathrm{BD}) - 18.8(\mathrm{TP}) - 21.1(\mathrm{clay}) - 88.6(\mathrm{OM})$$

(P value < 0.01, $R^2 = 19.9$)

(Appendix, Table 40a, 40b)

Where kPa = soil strength

BD = dry bulk density ($\mathrm{Mg/m^3}$)

WT = water table depth (cm)

TP = total porosity (%)

clay = clay content (%)

OM = organic matter content (%)

MC = volumetric moisture content (%)

Again multicollinearity was determined between regressors. A correlation matrix (Table 4.2) and variable inflation factors (Appendix, Tables 39a, 40a) were computed to identify variables with high collinearity. As expected, bulk density and total porosity were highly correlated. A high correlation also existed between both bulk density and clay with organic matter content. Therefore, total porosity and organic matter content were eliminated from the static variable equation. Within the equation containing dynamic variables high correlation's were found between water table depth and moisture content, and both bulk density and moisture content had a high correlation with clay content (Table 4.2). The calculation of VIF's reinforced the notion of collinearity between these properties (Appendix, Table 40a). As a product of the multicollinearity investigation, water table depth and clay content were removed from the equation.

Table 4.2. Correlation matrix for regressors in profile dynamic and static equations.

Dynamic regression matrix				Static regression matrix			
	WT	logclay	BD		BD	TP	clay
logclay	0.151	--------	-------	TP	-0.914	-------	-------
BD	0.003	0.260	--------	clay	0.172	0.056	--------
logMC	0.581	0.333	0.007	OM	-0.702	0.610	-0.372

Where kPa = soil strength

BD = dry bulk density (Mg/m^3)

WT = water table depth (cm)

TP = total porosity (%)

clay = clay content (%)

OM = organic matter content (%)

MC = volumetric moisture content (%)

Influence diagnostics were run on each equation using DFITS. Once unusual observations were removed from the data set, the following regression equations were determined:

Dynamic

$\log(\mathrm{kPa}) = 3.75 + 0.569(\mathrm{BD}) - 0.832 \log(\mathrm{MC})$ (P value < 0.01, $R^2 = 31.1$)

(Appendix, Tables 41a, 41b)

Static

$\mathrm{kPa} = -210 + 2260(\mathrm{BD}) - 15.1(\mathrm{clay})$ (P value < 0.01, $R^2 = 20.4$)

(Appendix, Tables 42a, 42b)

Where kPa = soil strength

BD = dry bulk density ($\mathrm{Mg/m^3}$)

MC = volumetric moisture content (%)

clay = clay content (%)

The soil strength models that have been presented incorporate several soil physical properties that many researchers have used in strength estimations and characterizations. The use of multicollinearity determinations also identified the inter-relationship between soil physical properties affecting soil strength. The soil strength equation containing dynamic and static properties uses water content and bulk density, two of the most commonly used soil parameters found in the literature. The effects of various regressor combinations on soil strength are presented in Figure 4.14. The dynamic equation presented here is similar to a penetration resistance equation reported by Bennie and Botha (1986). They used bulk density and water content to estimate penetration resistance using a log relationship. Many scientis have attempted to characterize soil strength as a function of soil physical properties. However, few attempts have been made to do such characterization under field conditions. Ayers and Perumpral (1982) concluded that the model reported in their study must be modified in order to be used under field conditions. Busscher (1990) developed equations to adjust penetrometer resistance data to a common water content. Busscher concluded that an equation developed based on field observations had better fit to the data. The equation's predicted penetration resistance fell closer to a 1:1 ratio line with observed data than other equations did. Henderson et al. (1988) stated that direct field measurements seem to be the only method to accurately determine soil physical properties effects on soil strength.

The static soil property equation also included bulk density. Texture represented by clay content was the second regressor in the equation. This equation has little applicability due to the adjustment of soil strength readings for moisture. Any change in moisture would alter the regression coefficients. This equation should be used primarily to evaluate the effects of the regressors on soil strength. Soil strength measurements estimated using this equations will not represent true soil strength unless soil moisture contents are similar. The effects of various regressor combinations on soil strength are illustrated in Figure 4.15. As expected, bulk density increases resulted in soil strength increases. The negative effect of clay content in the Bt horizon suggests moisture content is affecting soil strength estimates. As has been discussed the Bt horizon also had the greatest moisture content. Due to the use of different horizons to obtain a wide range in characteristics, other soil characteristics are having an indirect effect on soil strength estimations.

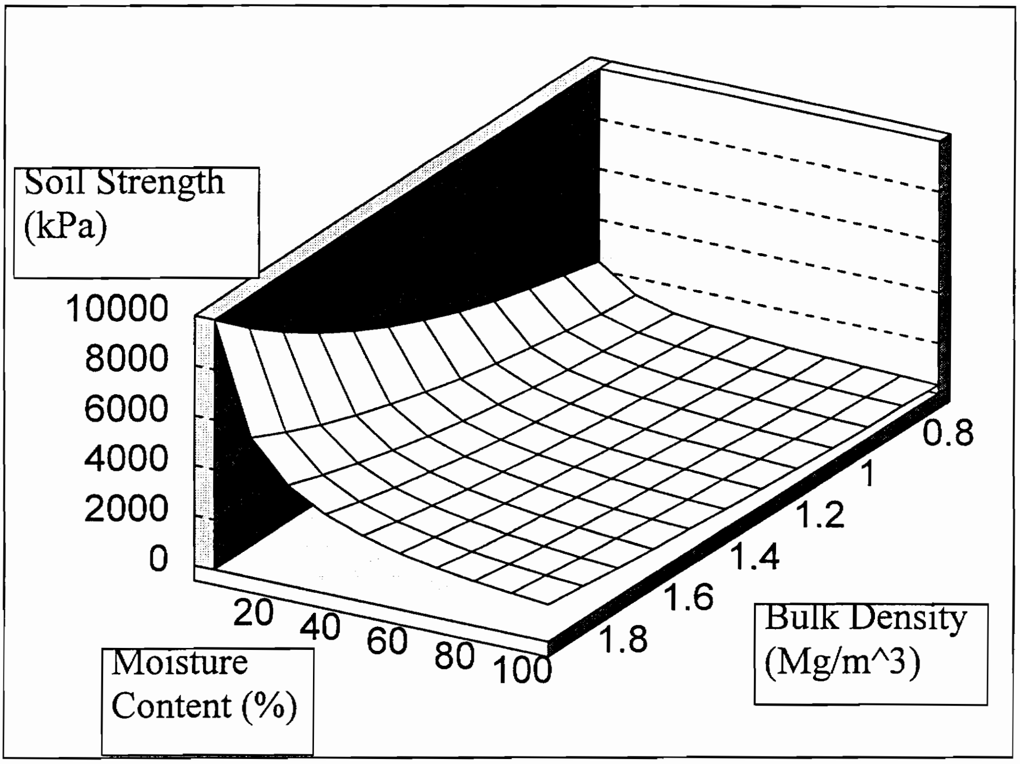


Figure 4.14. Three dimensional graph illustrating effects of bulk density (Mg/m3) and volumetric moisture content (%) on soil strength (kPa).

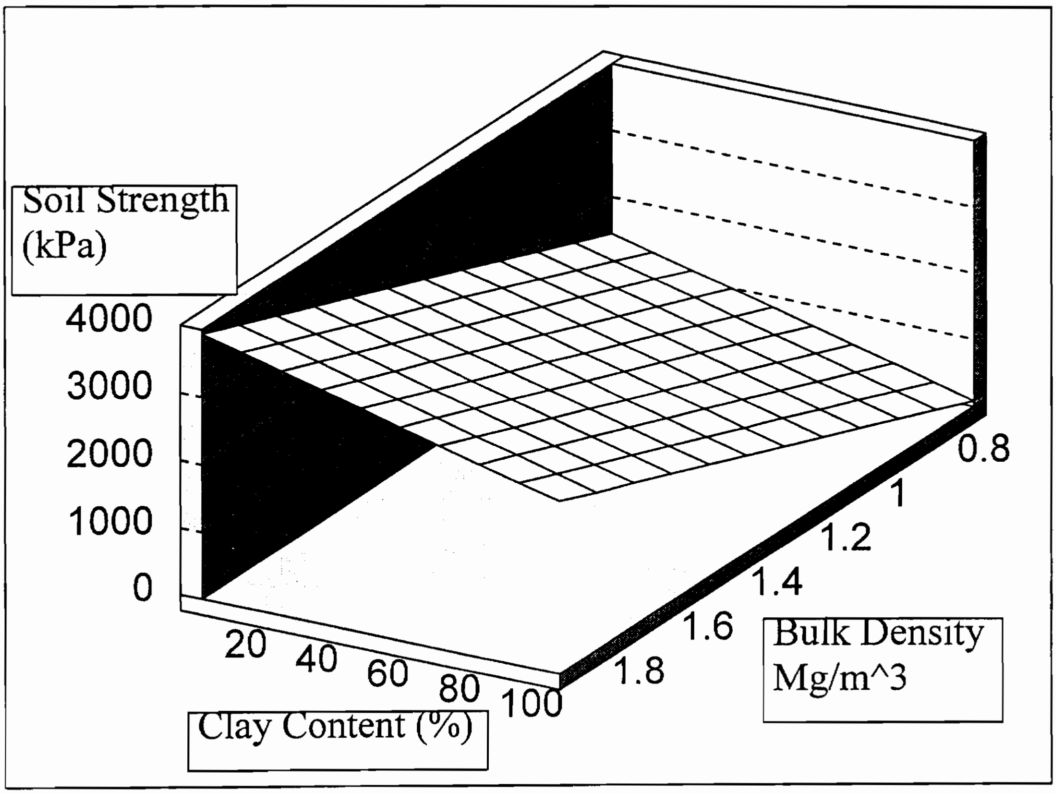


Figure 4.15. Three dimensional graph illustrating effects of clay content (%) and bulk density (Mg/m3) on soil strength (kPa).

TRAFFICABILITY MODEL

Various methods have been developed to predict field workability and trafficability. Models that have been developed include a wide range of soil and site characteristics. Soil moisture is a common component in almost all models. However, characteristics such as drainage (Wind 1976), climate (Rounsevell and Jones 1993), bulk density and texture (Canarache 1990) have been incorporated with soil moisture to determine trafficability and workability. As previously discussed, models developed to predict soil strength or trafficability do not account for all interactions occurring within a given soil. However, if primary interactions resulting in soil strength can be accounted for, a method could be developed to predict trafficability.

In order for soil strength estimations to aid in the management of agricultural or forested land they must be easy to comprehend and economically feasible. Henderson et al. (1988) argued that the field measurements needed to accurately estimate soil strength would require too many resources to be viable as an on-farm diagnostic procedure. Characterizing and estimating soil strength across a range of similar soils could prove to be a feasible method of diagnosing soil strength limitations. Large timber land holdings along the Atlantic coast contain similar soil types that could benefit from such characterization. Soil strength models developed for representative sites could be applied to similar acreages. This type of model could aid land managers in making decisions as to the trafficability of a soil type under dynamic conditions.

A trafficability model has been developed using only the A horizon because the A horizon is unique. Any vehicular traffic across a site will be in direct contact with the surface A horizon. The only case when traffic is not in direct contact with the surface soil would be the result of a O horizon. However, warm temperatures and abundant precipitation common to the coastal plain region results in rapid decomposition and little litter accumulation. If site disturbance is a result of traffic, the A horizon will always be affected. The A horizon also is very important as a nutrient source and, any alteration could result in decrease nutrient availability. Organic matter is the source of nutrients being returned to the soil for plant uptake. The surface horizon had approximately three times the organic matter content than the subsurface horizons. The A horizon also contains the majority of plant roots. Additionally, the location of the A horizon allows for easy sampling.

The original regression equation for the A horizon used soil moisture content and bulk density to estimate soil strength. With in the regression equation, moisture content and bulk density had P values of < 0.001 and 0.034 respectively. The moisture content had a much more significant effect on soil strength. No significant relationship was found between soil strength and bulk density for the A horizon (Figure 3.3, 4.1). Due to the low significance of bulk density the regression equation estimating soil strength as a function of moisture content for the A horizon was used to develop a hazard index. The use of bulk density and water content by many researchers to estimate soil strength has been discussed. However these studies used soils compressed to desired densities. The field measured densities for the A horizon do not have a wide enough range to be of significance. Bulk density is significant in the profile equation and could be used to develop a hazard index; however, another problem eliminates the used of this equation to develop a index. The wide range in bulk density needed to develop a model characterizing it's effects on soil strength is present. However, three different horizons having very different physical properties were used. The effects of bulk density on soil strength for each horizon would be different as moisture content increased and decreased. The use of this equation could only be used to developed a general hazard index for each horizon. The use of such an index would be difficult due to the need for determination of bulk density and moisture content of sub surface horizons as has been discussed. The elimination of bulk density from the equation resulted in a lower R^2, but increased the simplicity of the index and its use. DFITS was run to eliminate any unusual observations from the A horizon data set. The following regression equation was calculated:

$$\log(\text{kPa}) = 5.39 - 1.60 \log(\text{MC}) \qquad (\text{P value} < 0.01, R^2 = 54.5)$$

(Appendix, Tables 43a, 43b)

Where kPa = soil strength

MC = volumetric moisture content (%)

The above equation was used to redefine the limitations of a loamy soil developed by McKee et al. (1985) (Figure 1.7). Figure 4.16 is a graph of the above equation used to develop a trafficability hazard index. The index presented here is based on the effect of volumetric moisture content (%) on soil strength (kPa). By using soil moisture and vehicle ground pressure it can be determined if site disturbance will occur. Vehicle contact ground pressures can be derived by dividing the weight of a machine by the total ground contact area. As a result of various tire inflation amounts and tire sinkage into the soil, ground contact area is often difficult to measure. Wasterlund (1994) used the following formula to calculate ground pressure:

$$\text{Ground Pressure (kPa)} = (\text{load (kg)}/(\text{tire radius(cm)} * \text{tire width(cm)}))*100$$

This is just one example of measuring ground pressure, many other techniques exist. Many factors affect the ground pressure exerted by harvesting equipment, thus specific values for intended equipment should be used in the index. However, this does not take into account pressures generated by movement and uneven axle loads created during log handling (Greacen and Sands 1980). Pressures of up to five times the nominal contact pressures have been measured in the soil under the rear wheels of agricultural tractors (Cohron 1971 cited by Greacen and Sands 1980). Greacen and Sands (1980) cited Farrell and Greacen (1966) identifying soils in equilibrium with a compacting load X, the penetrometer resistance is approximately 10 fold. An example is given of a vehicle applying a ground pressure of 250 kPa will eventually reach a equilibrium state of compaction with a penetrometer resistance of 2500 kPa. Table 4.3 is a list of ground pressures and hazard ratings for various sized skidders with different tire widths. Caterpillar 508, 518, and 528 rubber-tired skidder specifications were used for relative comparisons of light, medium and heavy skidders, respectively. Approximate weights were used for all equipment due to varying equipment attachments. All equipment weights were taken from the Caterpillar performance handbook (1987). Two hazard ratings were derived based on the effects of movement on vehicle ground pressure. Static ground pressure was multiplied by 5 and 10 to estimate dynamic pressure applied by a vehicle. Ground pressures were calculated using the formula reported by Wasterlund (1994). The use of these two multipliers identifies a moisture zone at which machinery-site interactions are unpredictable. No site disturbance would be expected for a moisture content below this zone and intensive site disturbance would be expected for moisture contents above the zone.

The following example demonstrates the use of the model. The soil has a volumetric moisture content of 21% and will be trafficked by a medium sized skidder (23000 lbs) using 23 inch wide tires. The approximate static ground pressure can be found for the intended equipment in table 4.3. The skidder being considered has a ground pressure of 223 kPa. The adjusted equipment ground pressure can be determined by continuing across the table, 2230 and 1115 kPa (with adjustments of 10X and 5X, respectively). Next, these two values are found on the Hazard Index Graph (Figure 4.17). Horizontal lines can be drawn from the adjusted equipment ground pressure value until the horizontal lines intersects the soil strength line. At the intersection, vertical lines can be drawn down to identify critical moisture contents. The moisture content between the two vertical lines represents a unpredictable zone with regards to site disturbance (moisture content between 19 - 28%). This is due to the adjustment of a static measurement to a dynamic measurement. The moisture content of the site falls just within the lower limit of this zone. If the site had a moisture content less than 19%, little site disturbance would be expected. A site with a moisture content greater than 28% would be expected to have intense site disturbance. At a moisture content of 21%, site disturbance would be expected to be limited; however, it would exists. At this point the land manager can use equipment that applies less ground pressure or wait until the site becomes dryer.

Using the index, loggers can choose their equipment that is compatible with a site increasing efficiency, profits and decreasing costs. Land managers can identify sites highly susceptible to disturbance based on the type of logging equipment that is available and choose alternate sites for harvest. Site disturbance having the potential to decrease productivity, water quality, and other wetland functions can be avoided economically by using this index. However, the use of the index presented here is limited to soil similar to that used to develop the index. Large changes in soil properties may result in inaccurate index determinations.

Table 4.3. Estimated equipment ground pressures and adjusted equipment ground pressures.

SYSTEM	TIRE SPECIFICATIONS (IN)	GROUND PRESSURE (kPa)	ADJUSTED EQUIPMENT GROUND PRESSURE (10)	ADJUSTED EQUIPMENT GROUND PRESSURE (5)
Light Skidder 18000 lbs	63-23-26	174	1740	870
	63-28-25	135	1350	675
	67-34-26	111	1110	555
	66-43-25	89	890	445
	73-44-32	79	790	395
	68-50-32	75	750	375
	73-50-32	70	700	350
	68-68-25	55	550	275
	68-72-25	52	520	260
	68-86-25	45	450	225
Medium Skidder 23000 lbs	63-23-26	223	2230	1115
	63-28-25	172	1720	860
	67-34-26	142	1420	710
	66-43-25	114	1140	570
	73-44-32	101	1010	505
	68-50-32	95	950	475
	73-50-32	89	890	445
	68-68-25	70	700	350
	68-72-25	66	660	330
	68-86-25	57	570	285
Heavy Skidder 31000 lbs	63-23-26	300	3000	1500
	63-28-25	232	2320	1160
	67-34-26	192	1920	960
	66-43-25	154	1540	770
	73-44-32	136	1360	680
	68-50-32	128	1280	640
	73-50-32	120	1200	600
	68-68-25	95	950	475
	68-72-25	89	890	445
	68-86-25	77	770	385

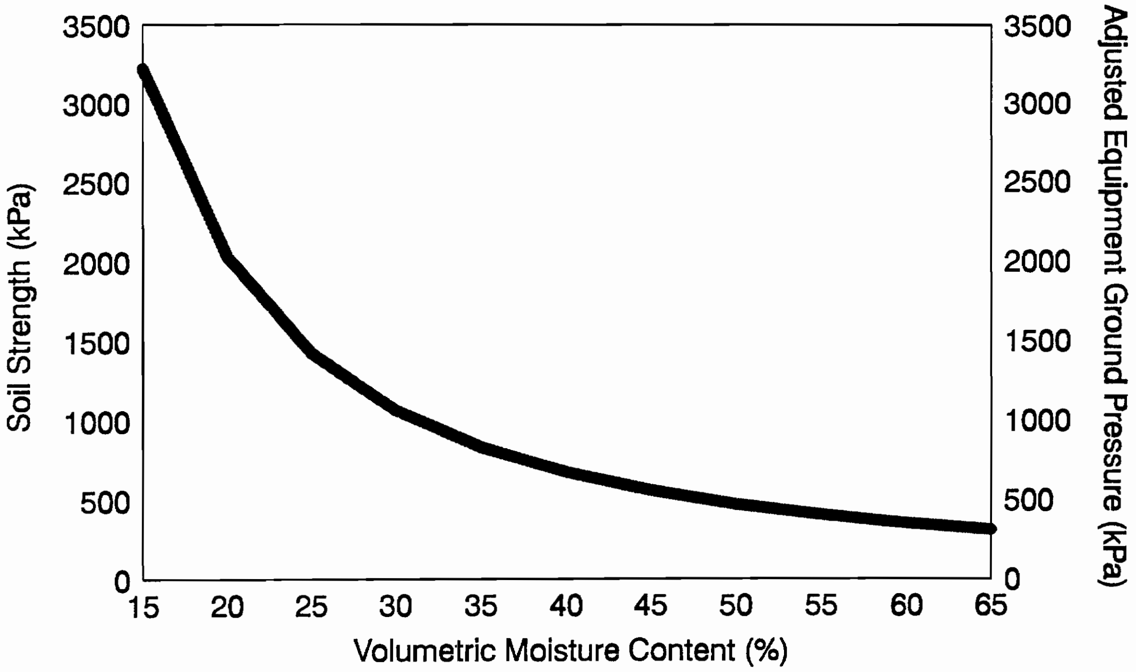


Figure 4.16. Trafficability Hazard Index

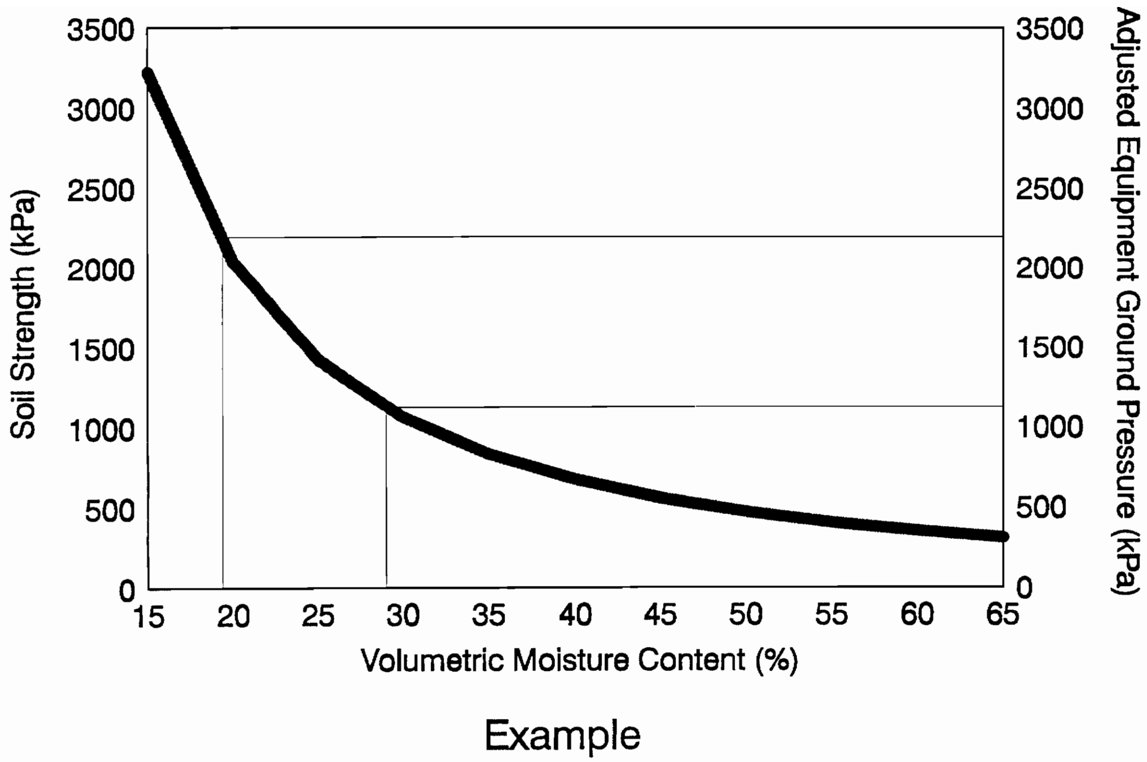


Figure 4.17. How to use the Trafficability Hazard Index.

CHAPTER V.

SUMMARY AND CONCLUSION

The use of harvesting equipment specialized for wet logging conditions have been suggested as a means to minimize site disturbance. When this equipment is used to increase mobility and not used to decrease site impacts, increased site disturbance can be expected. Soil and site characteristics should be examined in order to avoid sites with a high potential for disturbance. Better harvesting planning has also been suggested as a method of limiting site disturbances. Simply by harvesting wetter sites during drier periods and drier sites during wet periods site damage could be minimized. However, land management in the forest industry is often overshadowed by demands for fiber by a mill and harvesting options maybe limited. Sites with high disturbance potentials can be avoided by having an understanding of major soil physical properties and processes that affect soil strength. This understanding can be used to develop a simple and economical way of identifying "trouble" sites. By avoiding extensive site disturbance possible declines in productivity and public opposition to forest management in wetlands can also be avoided by land mangers.

The study revealed very significant relationships between moisture content and site hydrology parameters and soil strength. The effect of moisture would be expected to have a large influence on soil strength simply due to the nature of wetland sites. However, the use of moisture content and water table depth as a base for a identification method vary in applicability. The measurement of water table depth across a large site would be too labor intensive and not economically feasible. However, the measurement of moisture content using time domain reflectometry offers a simple and economically sound alternative for measuring a significance soil strength parameter across large land holdings.

Static soil properties such as bulk density, porosity, particle size distribution, and organic matter content have all been reported to influence soil strength. However, the majority of these reports evaluated the effects of static properties on soil strength on laboratory samples. Variations in property values were often un-natural and did not occur in the field. Static properties were much less significant in explaining variations in soil strength compared to dynamic properties. This was especially true when considering a single horizon that had a narrow range in static property values. When three different horizons were compared together there was a greater significance in explaining the variation in soil strength. This stemmed from the wide variation in property values attained by using different horizons, each having very different properties. Narrow ranges within each horizon limits the use of static properties in a hazard index base on a single horizon. The wide variation in static properties needed to have significant effects on soil strength must be achieved by multiple horizons. However, the use of a static property is also limited due to two reasons. First, each horizon used to achieve the wide variation will not have similar effects on soil strength as other properties change with in the horizon. Secondly, labor intensive sampling would be needed to attain samples from sub surface horizons.

Consequently, to develop a trafficability hazard index based on natural soil and site properties the index must contain attributes that have a significant effect on soil strength and are easily attainable. The use of both moisture content and penetration resistance of the A horizon meet these limitations. Soil strength, estimated by soil moisture can be compared to pressures applied to the soil by equipment to determine if equipment forces are greater than that of the soil. By using only the surface horizon measurements can be made quickly and economically. The moisture content was significant in explaining variations in soil strength; however, penetration resistance was also included in the index to aid in identification of sites susceptible to disturbance. Penetration resistance is also easily attainable by the use of a penetrometer which has been suggested for this purpose in many reports. The use of hazard indices such as the one reported in this study have the potential to limit site disturbance and lower site preparation costs. The use of the trafficability hazard index can give the land manager and logger additional site information. With the ability to identify equipment not suited for a site or identifying sites with limitations for certain equipment, excessive site disturbance can be avoided.

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APPENDIX

Appendix Table 1a. Regression equation between soil strength (kPa) and water table depth (WT) for the A horizon.

log(kPa) = 2.60 - 0.0101(WT)
n = 2646

Predictor	Coefficent	St dev.	T-ratio	P value
Constant	2.59706	0.01200	216.43	0.000
Water Table	-0.0100864	0.0002187	-46.13	0.000
s = 0.3636	R2 = 44.6%	R2(adj) = 44.6%		

Appendix Table 1b. Analysis of variance between soil strength (kPa) and water table depth (WT) for the A horizon.

Source	DF	SS	MS	F	P
Regression	1	281.4	281.40	2127.99	0.000
Error	2644	349.63	0.13		
Total	2645	631.03			

Appendix Table 2a. Regression equation between soil strength (kPa) and water table depth (WT) for the E horizon.

log(kPa) = 3.06 - 0.0085(WT)
n = 2867

Predictor	Coefficnet	St dev.	T-ratio	P value
Constant	3.05527	0.01164	262.39	0.000
Water table	-0.0080488	0.0002139	-37.62	0.000
s = 0.3628	R2 = 33.1%	R2(adj) = 33.0%		

Appendix Table 2b. Analysis of variance between soil strength (kPa) and water table depth (WT) for the E horizon.

Source	DF	SS	MS	F	P
Regression	1	186.30	186.30	1415.59	0.000
Error	2865	377.04	0.13		
Total	2866	563.34			

Appendix Table 3a. Regression equation between soil strength(kPa) and water table depth (WT) for the Bt horizon.

log(kPa) = 3.21 - 0.00282(WT)
n = 4803

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	3.20981	0.00584	549.81	0.000
Water table	-0.0028173	0.0001226	-22.98	0.000
s = 0.2626	R2 = 9.9%	R2(adj) = 9.9%		

Appendix Table 3b. Analysis of variance between soil strength (kPa) and water table depth (WT) for the Bt horizon.

Source	DF	SS	MS	F	P
Regression	1	36.433	36.433	528.3	0.000
Error	4801	331.092	0.069		
Total	4802	367.525			

Appendix Table 4a. Regression equation between soil strength (kPa) and water table depth (WT) for the A, E and Bt horizons as a profile.

log(kPa) = 3.03 - 0.006(water table)
n = 10316

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	3.02786	0.00586	516.72	0.000
Water table	-0.0059958	0.0001138	-52.69	0.000
s = 0.3669	R2 = 21.2%	R2(adj) = 21.2%		

Appendix Table 4b. Analysis of variance between soil strength (kPa) and water table depth (WT) for the A, E and Bt horizons as a profile.

Source	DF	SS	MS	F	P
Regression	1	373.84	373.84	2776.6	0.000
Error	10314	1388.67	0.13		
Total	10315	1762.51			

Appendix Table 5a. Regression equation between soil strength (kPa) and volumetric moisture content (MC) for the A horizon.

$\log(kPa) = 5.09 - 1.39\log(MC)$
n =2633

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	5.09017	0.04640	109.69	0.000
MC	-1.38590	0.03104	-44.65	0.000
s =0.3679	R^2 =43.1%	R^2(adj) =43.1%		

Appendix Table 5b. Analysis of variance between soil strength (kPa) and volumetric moisture content (MC) for the A horizon.

Source	DF	SS	MS	F	P
Regression	1	269.76	269.76	1993.20	0.000
Error	2631	356.08	0.14		
Total	2632	625.83			

Appendix Table 6a. Regression equation between soil strength (kPa) and volumetric moisture content (MC) for the E horizon.

$\log(kPa) = 5.37 - 1.32(MC)$
n =2789

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	5.37178	0.05896	91.11	0.000
MC	-1.31779	0.03912	-33.69	0.000
s =0.3711	R^2 =28.9%	R^2(adj) =28.9%		

Appendix Table 6b. Analysis of variance between soil strength (kPa) and volumetric moisture content (MC) for the E horizon.

Source	DF	SS	MS	F	P
Regression	1	156.26	156.26	1134.90	0.000
Error	2787	383.73	0.14		
Total	2788	539.99			

Appendix Table 7a. Regression equation between soil strength (kPa) and volumetric moisture content (MC) for the Bt horizon.

log(kPa) = 4.11 - 0.496(MC)
n =4731

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	4.11467	0.03952	104.12	0.000
MC	-0.49623	0.02429	-20.43	0.000
s =0.2644	R^2 =8.1%	R^2(adj) =8.1%		

Appendix Table 7b. Analysis of variance between soil strength (kPa) and volumetric moisture content (MC) for the Bt horizon.

Source	DF	SS	MS	F	P
Regression	1	29.194	29.194	417.51	0.000
Error	4729	330.670	0.070		
Total	4730	359.864			

Appendix Table 8a. Regression equation between soil strength (kPa) and volumetric moisture content (MC) for the A, E and Bt horizons as a profile.

log(kPa) = 4.58 - 0.849(MC)
n =10153

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	4.58058	0.02955	155.03	0.000
MC	-0.84884	0.01893	-44.85	0.000
s =0.3756	R^2 =16.5%	R^2(adj) =16.5%		

Appendix Table 8b. Analysis of variance between soil strength (kPa) and volumetric moisture content (MC) for the A, E and Bt horizons as a profile.

Source	DF	SS	MS	F	P
Regression	1	283.77	283.77	2011.76	0.000
Error	10151	1431.87	0.14		
Total	10152	1715.65			

Appendix Table 9a. Regression equation between soil strength (kPa) and bulk density (BD) for the A horizon.

kPa = 1860 + 190(BD)
n =508

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	1860.4	278.6	6.68	0.000
Water table	189.9	237.5	0.80	0.424
s =1068	R^2 =0.1%	R^2(adj) =0.0%		

Appendix Table 9b. Analysis of variance between soil strength (kPa) and bulk density (BD) for the A horizon.

Source	DF	SS	MS	F	P
Regression	1	729390	729390	0.64	0.424
Error	506	577341056	1140990		
Total	507	578070464			

Appendix Table 10a. Regression equation between soil strength (kPa) and bulk density (BD) for the E horizon.

kPa = 6373 - 1064(BD)
n =462

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	6373.1	982.8	6.48	0.000
BD	-1063.7	585.4	-1.82	0.070
s =1585	R^2 =0.7%	R^2(adj) =0.5%		

Appendix Table 10b. Analysis of variance between soil strength (kPa) and bulk density (BD) for the E horizon.

Source	DF	SS	MS	F	P
Regression	1	8291785	8291785	3.30	0.070
Error	460	1155304320	2511531		
Total	461	1163596160			

Appendix Table 11a. Regression equation between soil strength (kPa) and bulk density (BD) for the Bt horizon.

kPa = 2825 - 129(BD)
n =977

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	2825.2	310.4	9.10	0.000
BD	-129.3	205.9	-0.63	0.530
s =920.0	R^2 =0.0%	R^2(adj) =0.0%		

Appendix Table 11b. Analysis of variance between soil strength (kPa) and bulk density (BD) for the Bt horizon.

Source	DF	SS	MS	F	P
Regression	1	333792	333792	0.39	0.530
Error	975	825206080	846365		
Total	976	825539904			

Appendix Table 12a. Regression equation between soil strength (kPa) and bulk density (BD) for the A, E and Bt horizons as a profile.

log(kPa) = 2.83 + 0.400(BD)
n =1947

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	2.83032	0.03073	92.10	0.000
BD	0.40020	0.02087	19.17	0.000
s =0.2260	R^2 =15.9%	R^2(adj) =15.9%		

Appendix Table 12b. Analysis of variance between soil strength (kPa) and bulk density (BD) for the A, E and Bt horizons as a profile.

Source	DF	SS	MS	F	P
Regression	1	18.769	18.769	367.63	0.000
Error	1945	99.303	0.051		
Total	1946	118.072			

Appendix Table 13a. Regression equation between soil strength (kPa) and total porosity (TP) for the A horizon.

kPa = 2016 + 1.08(TP)
n =505

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	2016.3	350.7	5.75	0.000
TP	1.084	6.474	0.17	0.867
s =1070	R^2 =0.0%	R^2(adj) =0.0%		

Appendix Table 13b. Analysis of variance between soil strength (kPa) and total porosity (TP) for the A horizon.

Source	DF	SS	MS	F	P
Regression	1	32085	32085	0.03	0.867
Error	503	575585920	1144306		
Total	504	575617984			

Appendix Table 14a. Regression equation between soil strength (kPa) and total porosity (TP) for the E horizon.

kPa = 3439 + 33.7(TP)
n =462

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	3439.0	444.2	7.74	0.000
TP	33.73	12.81	2.63	0.009
s =1579	R^2 =1.5%	R^2(adj) =1.3%		

Appendix Table 14b. Analysis of variance between soil strength (kPa) and total porosity (TP) for the E horizon.

Source	DF	SS	MS	F	P
Regression	1	17272300	17272300	6.93	0.009
Error	460	1146323840	2492008		
Total	461	1163596160			

Appendix Table 15a. Regression equation between soil strength (kPa) and total porosity (TP) for the Bt horizon.

kPa = 1909 + 16.1(TP)
n =969

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	1909.1	255.4	7.47	0.000
TP	16.123	5.649	2.85	0.004
s =919.3	R^2 =0.8%	R^2(adj) =0.7%		

Appendix Table 15b. Analysis of variance between soil strength (kPa) and total porosity (TP) for the Bt horizon.

Source	DF	SS	MS	F	P
Regression	1	6884572	6884572	8.15	0.004
Error	967	817307776	845199		
Total	968	824192320			

Appendix Table 16a. Regression equation between soil strength (kPa) and total porosity (TP) for the A, E and Bt horizons as a profile.

kPa = 6021 - 68.7(TP)
n =1936

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	6021.1	153.7	39.17	0.000
TP	-68.695	3.374	-20.36	0.000
s =1352	R^2 =17.6%	R^2(adj) =17.6%		

Appendix Table 16b. Analysis of variance between soil strength (kPa) and total porosity (TP) for the A, E and Bt horizons as a profile.

Source	DF	SS	MS	F	P
Regression	1	757779904	757779904	414.44	0.000
Error	1934	3536204288	1828441		
Total	1935	4293984256			

Appendix Table 17a. Regression equation between soil strength (kPa) and clay content (%) for the A horizon.

kPa = 1915 + 22.7(clay)
n =518

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	1915.22	76.79	24.94	0.000
clay	22.686	8.571	2.65	0.008
s =1069	R^2 =1.3%	R^2(adj) =1.1%		

Appendix Table 17b. Analysis of variance between soil strength (kPa) and clay content (%) for the A horizon.

Source	DF	SS	MS	F	P
Regression	1	8013571	8013571	7.01	0.008
Error	516	590190016	1143779		
Total	517	598203584			

Appendix Table 18a. Regression equation between soil strength (kPa) and clay content (%) for the E horizon.

kPa = 3946 + 74.1(clay)
n =461

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	3946.3	166.9	23.65	0.000
clay	74.07	19.15	3.87	0.000
s =1635	R^2 =3.2%	R^2(adj) =2.9%		

Appendix Table 18b. Analysis of variance between soil strength (kPa) and clay content (%) for the E horizon.

Source	DF	SS	MS	F	P
Regression	1	40001796	40001796	14.96	0.000
Error	459	1227397376	2674068		
Total	460	1267399168			

Appendix Table 19a. Regression equation between soil strength (kPa) and clay content (%) for the Bt horizon.

kPa = 2273 + 11.5(clay)
n =1030

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	2272.6	113.6	20.00	0.000
clay	11.514	3.471	3.32	0.001
s =922.3	R^2 =1.1%	R^2(adj) =1.0%		

Appendix Table 19b. Analysis of variance between soil strength (kPa) and clay content (%) for the Bt horizon.

Source	DF	SS	MS	F	P
Regression	1	9362173	9362173	11.01	0.001
Error	1028	874531776	850712		
Total	1029	883893952			

Appendix Table 20a. Regression equation between soil strength (kPa) and clay content (%) for the A, E and Bt horizons as a profile.

log(kPa) = 3.35 + 0.0483 log(clay)
n =1990

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	3.35210	0.01634	205.20	0.000
clay	0.04828	0.01338	3.61	0.000
s =0.2464	R^2 =0.7%	R^2(adj) =0.6%		

Appendix Table 20b. Analysis of variance between soil strength (kPa) and clay content (%) for the A, E and Bt horizons as a profile.

Source	DF	SS	MS	F	P
Regression	1	0.79023	0.79023	13.02	0.000
Error	1988	120.66393	0.06070		
Total	1989	121.45416			

Appendix Table 21a. Regression equation between soil strength (kPa) and silt content (%) for the A horizon.

kPa = 1786 + 9.89(silt)
n =518

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	1786.0	146.3	12.21	0.000
silt	9.888	4.722	2.09	0.037
s =1072	R^2 =0.8%	R^2(adj) =0.7%		

Appendix Table 21b. Analysis of variance between soil strength (kPa) and silt content (%) for the A horizon.

Source	DF	SS	MS	F	P
Regression	1	5042051	5042051	4.39	0.037
Error	516	593161536	1149538		
Total	517	598203584			

Appendix Table 22a. Regression equation between soil strength (kPa) and silt content (%) for the E horizon.

kPa = 3802 + 32.5(silt)
n =461

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	3802.5	293.4	12.96	0.000
silt	32.48	12.81	2.54	0.012
s =1650	R^2 =1.4%	R^2(adj) =1.2%		

Appendix Table 22b. Analysis of variance between soil strength (kPa) and silt content (%) for the E horizon.

Source	DF	SS	MS	F	P
Regression	1	17514558	17514558	6.43	0.012
Error	459	1249884672	2723060		
Total	460	1267399168			

Appendix Table 23a. Regression equation between soil strength (kPa) and silt content (%) for the Bt horizon.

kPa = 2933 - 12.6(silt)
n =1030

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	2933.4	100.7	29.14	0.000
silt	-12.642	4.117	-3.07	0.002
s =923.0	R^2 =0.9%	R^2(adj) =0.8%		

Appendix Table 23b. Analysis of variance between soil strength (kPa) and silt content (%) for the Bt horizon.

Source	DF	SS	MS	F	P
Regression	1	8034593	8034593	9.43	0.002
Error	1028	875859392	852003		
Total	1029	883894016			

Appendix Table 24a. Regression equation between soil strength (kPa) and silt content (%) for the A, E and Bt horizons as a profile.

kPa = 3507 - 23.6(silt)
n =2008

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	3507.0	103.7	33.81	0.000
silt	-23.566	3.995	-5.90	0.000
s =1464	R^2 =1.7%	R^2(adj) =1.7%		

Appendix Table 24b. Analysis of variance between soil strength (kPa) and silt content (%) for the A, E and Bt horizons as a profile.

Source	DF	SS	MS	F	P
Regression	1	74568328	74568328	34.80	0.000
Error	2006	4297946624	2142546		
Total	2007	4372514816			

Appendix Table 25a. Regression equation between soil strength (kPa) and sand content (%) for the A horizon.

kPa = 2748 - 10.6(sand)
n =518

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	2748.2	241.6	11.38	0.000
sand	-10.573	3.727	-2.84	0.005
s =1068	R^2 =1.5%	R^2(adj) =1.3%		

Appendix Table 25b. Analysis of variance between soil strength (kPa) and sand content (%) for the A horizon.

Source	DF	SS	MS	F	P
Regression	1	9185585	9185585	8.05	0.005
Error	516	589017984	1141508		
Total	517	598203584			

Appendix Table 26a. Regression equation between soil strength (kPa) and sand content (%) for the E horizon.

kPa = 6970 - 34.9(sand)
n =461

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	6969.9	656.6	10.62	0.000
sand	-34.919	9.298	-3.76	0.000
s =1637	R^2 =3.0%	R^2(adj) =2.8%		

Appendix Table 26b. Analysis of variance between soil strength (kPa) and sand content (%) for the E horizon.

Source	DF	SS	MS	F	P
Regression	1	37787252	37787252	14.11	0.000
Error	459	1229611904	2678893		
Total	460	1267399168			

Appendix Table 27a. Regression equation between soil strength (kPa) and sand content (%) for the Bt horizon.

kPa = 2708 - 1.59(sand)
n =1030

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	2708.5	134.9	20.07	0.000
sand	-1.586	2.933	-0.54	0.589
s =927.1	R^2 =0.0%	R^2(adj) =0.0%		

Appendix Table 27b. Analysis of variance between soil strength (kPa) and sand content (%) for the Bt horizon.

Source	DF	SS	MS	F	P
Regression	1	251450	251450	0.29	0.589
Error	1028	883642560	859574		
Total	1029	883894016			

Appendix Table 28a. Regression equation between soil strength (kPa) and sand content (%) for the A, E and Bt horizons as a profile.

kPa = 2366 + 0.169$(\text{sand})^2$
n =2008

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	2365.97	71.94	32.89	0.000
sand	0.16915	0.01940	8.72	0.000
s =1449	R^2 =3.7%	R^2(adj) =3.6%		

Appendix Table 28b. Analysis of variance between soil strength (kPa) and sand content (%) for the A, E and Bt horizons as a profile.

Source	DF	SS	MS	F	P
Regression	1	159603872	159603872	76.00	0.000
Error	2006	4212911104	2100155		
Total	2007	4372514816			

Appendix Table 29a. Regression equation between soil strength (kPa) and organic matter (OM) for the A horizon.

kPa = 2100 - 4.9(OM)
n =518

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	2099.8	104.4	20.11	0.000
OM	-4.91	19.15	-0.26	0.798
s =1077	R^2 =0.0%	R^2(adj) =0.0%		

Appendix Table 29b. Analysis of variance between soil strength (kPa0 and organic matter (OM) for the A horizon.

Source	DF	SS	MS	F	P
Regression	1	76238	76238	0.07	0.798
Error	516	598127360	1159162		
Total	517	598203584			

Appendix Table 30a. Regression equation between soil strength (kPa) and organic matter (OM) for the E horizon.

kPa = 4413 + 70(OM)
n =467

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	4412.9	175.8	25.11	0.000
OM	70.1	114.0	0.62	0.539
s =1658	R^2 =0.1%	R^2(adj) =0.0%		

Appendix Table 30b. Analysis of variance between soil strength (kPa) and organic matter (OM) for the E horizon.

Source	DF	SS	MS	F	P
Regression	1	1040418	1040418	0.38	0.539
Error	465	1278360448	2749162		
Total	466	1279400832			

Appendix Table 31a. Regression equation between soil strength (kPa) and organic matter (OM) for the Bt horizon.

kPa = 2950 - 204(OM)
n =1030

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	2949.82	84.04	35.10	0.000
OM	-203.95	51.53	-3.96	0.000
s =920.3	R^2 =1.5%	R^2(adj) =1.4%		

Appendix Table 31b. Analysis of variance between soil strength (kPa) and organic matter (OM) for the Bt horizon.

Source	DF	SS	MS	F	P
Regression	1	13265405	13265405	15.66	0.000
Error	1028	870628544	846915		
Total	1029	883893952			

Appendix Table 32a. Regression equation between soil strength (kPa) and organic matter (OM) for the A, E and Bt horizons as a profile.

log(kPa) = 3.48 - 0.290 log(OM)
n =2014

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	3.48385	0.00693	503.07	0.000
OM	-0.28967	0.01756	-16.49	0.000
s =0.2314	R^2 =11.9%	R^2(adj) =11.9%		

Appendix Table 32b. Analysis of variance between soil strength (kPa) and organic matter (OM) for the A, E and Bt horizons as a profile.

Source	DF	SS	MS	F	P
Regression	1	14.563	14.563	271.99	0.000
Error	2012	107.729	0.054		
Total	2013	122.292			

Appendix Table 33a. Mulitipule regression equation for soil strength (kPa) in the A horizon.

$\log(\text{kPa}) = 3.50 - 0.00642(\text{WT}) - 0.671 \log(\text{MC}) + 0.221(\text{BD})$

n =2580

Predictor	Coefficent	St dev.	T-Ratio	P value	VIF
Constant	3.49585	0.09791	35.70	0.000	
WT	-0.0064	0.000333	-19.27	0.000	2.5
MC	-0.67145	0.04662	-14.40	0.000	2.5
BD	0.22135	0.03479	6.36	0.000	1.0
s =0.3450	R^2 =49.9%	R^2(adj) =49.9%			

Appendix Table 33b. Analysis of variance for soil strength (kPa) in the A horizon.

Source	DF	SS	MS	F	P
Regression	3	305.78	101.93	856.34	0.000
Error	2576	306.61	0.12		
Total	2579	612.39			

Appendix Table 34a. Mulitipule regression equation for soil strength (kPa) in the E horizon.

$\log(\text{kPa}) = 3.92 - 0.661 \log(\text{MC}) + 0.178(\text{BD}) - 0.00451(\text{WT})$

n =2050

Predictor	Coefficent	St dev.	T-Ratio	P value	VIF
Constant	3.9232	0.1485	26.42	0.000	
WT	-0.00451	0.00033	-13.67	0.000	1.8
MC	-0.66074	0.05892	-11.22	0.000	1.8
BD	0.17847	0.06238	2.86	0.004	1.0
s =0.3506	R^2 =32.0%	R^2(adj) =31.9%			

Appendix Table 34b. Analysis of variance for soil strength (kPa) in the E horizon.

Source	DF	SS	MS	F	P
Regression	3	118.354	39.451	320.95	0.000
Error	2046	251.497	0.123		
Total	2049	369.85			

Appendix Table 35a. Mulitipule regression equation for soil strength (kPa) in the Bt horizon.

$\log(\text{kPa}) = 3.52 - 0.338 \log(\text{MC}) + 0.185 \log(\text{clay}) - 0.144 \log(\text{OM}) - 0.00224(\text{WT})$

n =4691

Predictor	Coefficent	St dev.	T-Ratio	P value	VIF
Constant	3.52370	0.06710	52052	0.000	
MC	-0.33758	0.02547	-13.25	0.000	1.2
clay	0.18488	0.03707	4.99	0.000	1.0
OM	-0.14354	0.02255	-6.37	0.000	1.0
WT	-0.002241	0.0001285	-17.44	0.000	1.1
s =0.2550	R^2 =14.5%	R^2(adj) =14.5%			

Appendix Table 35b. Analysis of variance for soil strength (kPa) in the Bt horizon.

Source	DF	SS	MS	F	P
Regression	4	51.858	12.965	199.33	0.000
Error	4686	304.777	0.065		
Total	4690	356.635			

Appendix Table 36a. Mulitipule regression equation after the elimination of unusual observations for soil strength (kPa) in the A horizon.

$\log(\text{kPa}) = 5.21 + 0.0738(\text{BD}) - 1.53 \log(\text{MC})$

n =2456

Predictor	Coefficent	St dev.	T-Ratio	P value	VIF
Constant	5.21158	0.06255	83.31	0.000	
BD	0.07379	0.03467	2.13	0.034	1.0
MC	-1.52522	0.02985	-51.10	0.000	1.0
s =0.3313	R^2 =52.0%	R^2(adj) =52.0%			

Appendix Table 36b. Analysis of variance for soil strength (kPa) in the A horizon.

Source	DF	SS	MS	F	P
Regression	2	291.62	145.81	1328.78	0.000
Error	2453	269.18	0.11		
Total	2455	560.8			

Appendix Table 37a. Mulitipule regression equation after the elimination of unusual observations for soil strength (kPa) in the E horizon.

$\log(\mathrm{kPa}) = 4.77 + 0.296(\mathrm{BD}) - 1.21 \log(\mathrm{MC})$

n =1961

Predictor	Coefficent	St dev.	T-Ratio	P value	VIF
Constant	4.7696	0.1278	37.31	0.000	
BD	0.29567	0.06341	4.66	0.000	1.0
MC	-1.21334	0.04234	-28.66	0.000	1.0
s =0.3279	R^2 =30.7%	R^2(adj) =30.7%			

Appendix Table 37b. Analysis of variance for soil strength (kPa) in the E horizon.

Source	DF	SS	MS	F	P
Regression	2	93.412	46.706	434.51	0.000
Error	1958	210.468	0.107		
Total	1960	303.880			

Appendix Table 38a. Mulitipule regression equation after the elimination of unusual observations for soil strength (kPa) in the Bt horizon.

$\log(\mathrm{kPa}) = 3.92 + 0.150 \log(\mathrm{clay}) - 0.0737 \log(\mathrm{OM}) - 0.505 \log(\mathrm{MC})$

n =4428

Predictor	Coefficent	St dev.	T-Ratio	P value	VIF
Constant	3.91584	0.06099	64.20	0.000	
clay	0.14983	0.03539	4.23	0.000	1.0
OM	-0.07371	0.02211	-3.33	0.001	1.0
MC	-0.5.485	0.02269	-22.25	0.000	1.0
s =0.2272	R^2 =11.1%	R^2(adj) =11.0%			

Appendix Table 38b. Analysis of variance for soil strength (kPa) in the Bt horizon.

Source	DF	SS	MS	F	P
Regression	3	28.3813	9.4604	183.20	0.000
Error	4424	228.4593	0.0516		
Total	4427	256.8406			

Appendix Table 39a. Dynamic mulitipule regression equation for soil strength (kPa) across all horizons as a profile.

log(kPa) = 3.12 + 0.486(BD) - 0.00413(WT) - 0.603 log(MC) + 0.191 log(clay)
n =8865

Predictor	Coefficent	St dev.	T-Ratio	P value	VIF
Constant	3.11508	0.04105	75.88	0.000	
BD	0.48596	0.01443	33.68	0.000	1.1
WT	-0.004132	0.000129	-31.93	0.000	1.5
MC	-0.60278	0.02183	-27.61	0.000	1.6
clay	0.190617	0.009068	21.02	0.000	1.3
s =0.3189	R^2 =37.8%	R^2(adj) =37.8%			

Appendix Table 39b. Analysis of variance for soil strength (kPa) across all horizons as a profile.

Source	DF	SS	MS	F	P
Regression	4	548.61	137.15	1348.83	0.000
Error	8860	900.92	0.10		
Total	8864	1449.53			

Appendix Table 40a. Static mulitipule regression equation for soil strength (kPa) across all horizons as a profile.

kPa = 2340 + 1416(BD) - 18.8(TP) - 21.1(clay) - 88.6(OM)
n =1892

Predictor	Coefficent	St dev.	T-Ratio	P value	VIF
Constant	2340.1	940.6	2.49	0.013	
BD	1416.3	378.5	3.74	0.000	9.2
TP	-18.826	9.762	-1.93	0.054	8.5
clay	-21.073	2.793	-7.54	0.000	1.7
OM	-88.57	22.88	-3.87	0.000	2.3
s =1317	R^2 =19.9%	R^2(adj) =19.7%			

Appendix Table 40b. Analysis of variance for soil strength (kPa) across all horizons as a profile.

Source	DF	SS	MS	F	P
Regression	4	811526592	202881648	116.95	0.000
Error	1887	3273384192	1734703		
Total	1891	4084910848			

Appendix Table 41a. Dynamic mulitipule regression equation after unusual observations have been removed for soil strength (kPa) across all horizons as a profile.

log(kPa) = 3.75 + 0.569(BD) - 0.832 log(MC)
n =8597

Predictor	Coefficent	St dev.	T-Ratio	P value	VIF
Constant	3.75445	0.03275	114.66	0.000	
BD	0.56928	0.01396	40.79	0.000	1.0
MC	-0.83205	0.01701	-48.91	0.000	1.0
s =0.3023	R^2 =31.1%	R^2(adj) =31.1%			

Appendix Table 41b. Analysis of variance for soil strength (kPa) across all horizons as a profile.

Source	DF	SS	MS	F	P
Regression	2	354.88	1.77.44	1942.26	0.000
Error	8594	785.12	0.09		
Total	8596	1140.00			

Appendix Table 42a. Static mulitipule regression equation after unusual observations have been removed for soil strength (kPa) across all horizons as a profile.

kPa = -210 + 2260(BD) - 15.1(clay)
n =1794

Predictor	Coefficent	St dev.	T-Ratio	P value	VIF
Constant	-210.3	154.3	-1.36	0.173	
BD	2260.3	107.3	21.06	0.000	1.0
clay	-15.119	1.874	-8.07	0.000	1.0
s =1075	R^2 =20.4%	R^2(adj) =20.3%			

Appendix Table 42b. Analysis of variance for soil strength (kPa) across all horizons as a prodile.

Source	DF	SS	MS	F	P
Regression	2	530828608	265414304	229.68	0.000
Error	1791	2069658112	1155588		
Total	1793	2600486656			

Appendix Table 43a. Regression equation between soil strength (kPa) and moisture content (MC) after unusual observations had been removed for the A horizon.

log(kPa) = 5.39 - 1.60 log(MC)
n =2458

Predictor	Coefficent	St dev.	T-Ratio	P value
Constant	5.387777	0.04410	122.17	0.000
MC	-1.59566	0.02941	-54.25	0.000
s =0.3198	R^2 =54.5%	R^2(adj) =54.5%		

Appendix Table 43b. Analysis of variance between soil strength (kPa) and moisture content (MC) for the A horizon.

Source	DF	SS	MS	F	P
Regression	1	301.00	301.00	2943.11	0.000
Error	2456	251.18	0.10		
Total	2457	552.17			

VITA

The author was born in Columbus Georgia on November 30, 1969. He grew up in Fairland, Indiana where he graduated from Triton Central High School in May of 1988. He graduated with a B.S. degree in Forestry from Purdue University in May of 1992. In August of 1992, he became a Master of Science in Forestry degree candidate at Virginia Ploytechnic and State University, with an emphasis on soils. He earned his Masters degree in 1994.

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