MITIGATION OF HARVESTING DISTURBANCES ON A FORESTED WETLAND IN THE SOUTH CAROLINA LOWER COASTAL PLAIN

by

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(ABSTRACT)

Wet site timber harvesting often results in rutted and/or compacted soils. These impacts damage inherent site and soil properties and can reduce subsequent pine seedling survival and growth. Site preparation treatments such as bedding, disking, and fertilization are often employed on harvested sites to mitigate these impacts; however, their effectiveness has not been fully documented. Moreover, a distinction between rutting and compaction has not been made in previous research. This study's objectives were to quantify the effects of rutting and compaction on site and soil properties and pine seedling growth and survival, and to quantify the effectiveness of bedding, disking, and fertilization in mitigating these impacts.

Six wet pine flats were salvage logged following Hurricane Hugo in the fall of 1989. High soil moisture conditions during the salvage operations resulted in compaction and rutting damage. Two studies were established to quantify the effects of trafficking on the functions and productivity of wetland sites. One study addressed

soil compaction while the other addressed soil rutting. Each study consisted of three sites, each containing four trafficked and four untrafficked plots.

Four site preparation treatments, one on each disturbance plot, were installed in the fall of 1991. The four treatments were 1) no treatment, 2) bedding, 3) disking, and 4) disking and bedding. The treatment plots were further split with half of each plot receiving 227 kilograms per hectare of 10-10-10 fertilizer. Genetically improved seedlings were hand-planted on the treatment plots in February, 1992.

The site preparation treatments did not completely ameliorate compaction or rutting effects on pine seedling growth and survival. Rutting reduced pine seedling second-year height growth, total volume, and survival by 43, 90, and 9 percent, respectively. Compaction reduced second-year height growth by 31 percent and seedling survival by 14.5 percent. Bedding resulted in 35 and 106 percent greater second-year height growths and 117 and 421 percent greater seedling volumes than disking on the rutted and compacted sites, respectively. Phosphorous fertilization had an additive effect to the site preparation treatments and increased pine seedling height growth by 54 and 65 percent and seedling volume by 125 and 155 percent on the rutted and compacted sites, respectively. The factors that affected pine seedling growth and survival were water supply and movement and phosphorous supply.

Management implications for wetland sites suggested by this study are as follows: 1) avoid rutting and compaction when possible, 2) schedule wet-site harvesting during the driest periods of the year, 3) use specialized wet-site harvesting equipment when needed, and 4) use bedding and fertilization for site preparation.

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INTRODUCTION

The forest products industry, the seventh largest industry in the United States, is facing increased challenges in the management of its woodlands. These challenges include sustaining long-term site productivity and ecosystem function, maintenance of clean and plentiful water from forest lands, preservation of animal species and habitat, carbon storage, increased federal regulations, and development of forestry Best Management Practices (BMP's). These issues are particularly controversial within forested wetlands that are managed for production forestry (pine plantations). Southern pine plantations produced 18 percent of the nation's pine timber harvest in 1984, and experts project this percentage to increase to 54 percent by the year 2000 (Earley, 1991a). However, approximately ten percent of the pine forests in the coastal plain are jurisdictional wetlands, some of which are known as wet pine flats (Society of American Foresters, 1980).

The jurisdictional definition of wetlands has undergone several revisions and is still surrounded by controversy (Olszewski, 1988). The U.S. Army Corps of Engineers currently uses three components to determine wetland status; they are site hydrology, vegetation type, and soil characteristics. Wet pine flats are one type of forested wetland fulfilling these specified requirements. In some eastern coastal counties, an estimated 70 percent of the land area may qualify as wetlands as they are currently defined (Earley, 1991a). Original wetland acreage of the United States is estimated at 221 million acres; however, according to Cashin et al. (1992), only 53 percent of this area remains as wetlands with the greatest recent losses occurring in the Southeast due to pine plantation conversions by the forest industry. In their interpretation, harvests followed by planting represented lost wetland area. Conversely, Moorhead and Cook (1992) reported that agricultural uses account for 63 percent of wetland losses while conversions to pine plantations account for only 17 percent of wetland losses.

Pine stands located on forested wetlands are highly desired for production forestry. Joe Hughes of Weyerhaeuser Company stated "wetlands are the most productive forest lands" (Earley, 1991b). Without intensive management, however, the growth of planted pines is usually slow on these poorly drained sites (Wilhite and Jones, 1981). Therefore, many silvicultural techniques are employed on these sites to improve or maintain their utility for timber production. Unfortunately, many silvicultural operations, especially harvesting, can be detrimental to the site because they involve trafficking by heavy machinery.

The soil disturbances caused by these activities falls into two main categories: compaction and rutting. Soil compaction is defined as the physical compression of the soil mass under excessive pressure (Greacen and Sands, 1980) while soil rutting is the churning of a soil above its liquid limit to the point that it is broken into its ultimate soil particles and flows outward and upward from applied pressure (Karr *et al.*, 1991). These conditions adversely impact site productivity by damaging the inherent properties of the soil. Compacted and rutted soils usually exhibit higher bulk densities, lower porosities, slower water movement, less aeration, and altered organic matter decomposition rates and contents. Each of these conditions can retard the survival and growth of planted seedlings (Reisinger *et al.*, 1988). However, some disturbance is often unavoidable on these wetland sites because wet soils are so susceptible to compaction and rutting (Akram and Kemper, 1979). Hence, in addition to natural processes, there is quite an array of site preparation techniques utilized by the forestry industry to ameliorate these impacts. Natural ameliorative processes for compacted and rutted sites include shrinking and swelling of clays with wetting and drying, freezing and thawing of soil with seasonal changes, fracture and aggregation of soils due to root growth and organic matter, and the burrowing activity of soil organisms such as beetles and earthworms (Bicki and Siemens, 1991; Carter, 1988; and Voorhees, 1983). However, in the South, these processes are not that effective due to the presence of low shrink-swell clays, mild winter temperatures, and fairly acidic forest soils inconducive to earthworm populations; hence, natural soil recovery would require long periods of time. Estimates of time required for natural recovery range from five to sixty years (Dickerson, 1976; Hatchell *et al.*, 1970; and Mitchell *et al.*, 1982). Therefore, mechanical site preparation is usually necessary to help ameliorate the damaged soil properties. Some of the most common site preparation techniques are bedding, disking, ripping, and fertilization (Edwards, 1990; Wilhite and McKee, 1986). However, the actual effectiveness of these treatments in restoring site productivity has not been established for wet pine flats.

RESEARCH PURPOSES

The USDA Forest Service Southeastern Forest Experiment Station and the Virginia Polytechnic Institute and State University Forestry Department entered into a cooperative research agreement in 1990. The overall purposes of the research project were designed to be accomplished in several phases. They are as follows:

Phase I - During Phase I, six sites were identified that had been compacted or rutted during salvage harvest operations associated with Hurricane Hugo. Trafficked and non-trafficked plots were installed on each site and physical and chemical effects of soil rutting and compaction were quantified.

Phase II - Site preparation treatments were installed on the six sites. Phases I and II are described in detail by Tippett (1992).

Phase III - Research activities relating to this thesis were accomplished in Phase III. The two objectives of Phase III were:

1) To determine to what extent rutting and compaction affect soil physical and chemical properties and seedling survival and initial growth;

and,

2) To determine to what extent disking, bedding, and fertilization can mitigate soil problems, both physical and chemical, and enhance seedling growth and survival.

These objectives were achieved by testing the following general null hypotheses:

Ho1: Disking, bedding, and disking and bedding of rutted and compacted sites do not affect soil properties or seedling growth and survival;

and,

Ho2: Fertilization has no additional mitigative value over and above disking, bedding, and disking and bedding.

The overall purpose of this research was to offer a more complete understanding of harvesting impacts on site productivity and the effectiveness of site preparation treatments in ameliorating these impacts.

LITERATURE REVIEW

Silvicultural Operations on Forested Wetlands

The purpose of silvicultural practices is to control forest establishment, composition, structure, and growth (Smith, 1986). Silvicultural treatments commonly used in forested wetlands include draining, bedding, disking, fertilization, and harvesting. These operations have the potential to impact the soil/site relations, hydrology, water quality, temperature, nutrient cycling, and soil properties of wetland sites. Concern about such impacts has caused much controversy concerning the protection of wetlands and whether intensive forest operations can impair their natural wetland ecosystem processes. These functions include excess precipitation absorption and storage, water filtration, and endangered species habitat.

Planted pine seedlings grow slowly on poorly drained sites (wetlands), and biological clearcutting (complete removal of woody stems) followed by intensive site preparation is usually required for adequate growth and survival of these seedlings (Haines and Davey, 1979). Common site preparation techniques employed on wetland sites could include shearing, piling, burning, chopping, bedding, disking, and minor draining (Toliver and Jackson, 1988). Operational prescriptions are site-specific, but caution is required due to the extreme susceptibility of wetlands to long-term site disturbance from silvicultural operations.

Drainage is an expensive and intensive silvicultural operation used to gain access by facilitating road installation, improve establishment and growth of planted pine seedlings, and improve soil trafficability during silvicultural operations (Terry and Hughes, 1978). Drainage is also the most controversial method concerning the conversion of pocosin wetlands into pine plantations. Opponents of ditching argue that this practice destroys the site's ability to perform wetland functions. Drainage lowers the water table on the site thereby improving aeration which is essential to seedling root development and early growth. Waterlogging can kill or seriously impede the growth of trees, especially seedlings, as a result of inhibited gas exchange or completely anaerobic conditions (Kozlowski, 1986). Weyerhaeuser Company is noted for its extensive ditching network in coastal North Carolina which has transformed these poorly drained wet pine flats and pocosins into extremely productive pine timber lands. Drained sites in this region produce up to ten times the amount of wood that undrained sites produce (Earley, 1991b). Pritchett and Fisher (1987) reported that this response may actually be due to increased nutrient supplies rather than increased aeration.

Harvesting on the wet pine flats of the lower coastal plain has been accomplished in many ways. The earliest methods utilized horses or mules to extract logs from the site. More modern operations include rubber-tired and tracked skidders, cabling systems, and even helicopters (Aust *et al.*, 1991; Willingham, 1988). The most economical and common harvesting systems use rubber-tired skidders, which have the greatest potential to cause extensive site disturbance. Recently, skidders have been equipped with dual or wider tires in an attempt to decrease trafficking forces. Theoretically, wider tires minimize site impacts while maximizing wood removal on sites that are too wet for skidders equipped with conventional tires (Reisinger and Aust, 1991). This is only true, however, if the wide-tired skidders are not used to traffic areas inaccessible to conventionally-tired skidders.

Harvesting Impacts on the Soil

Of all the silvicultural operations, harvesting possesses the greatest potential to cause damage to a site. Rubber-tired skidder operations may traffic between 17 and 48 percent of a site during harvest (Aust *et al.*, 1993a, Dickerson, 1976; Hatchell *et al.*, 1970; Willis, 1971). Wet pine flats of the lower coastal plain are exceptionally prone to harvesting disturbance due to the proximity of the water table to the soil surface because wet soils are extremely susceptible to compaction or rutting damage. Steinbrenner and Gessel (1955) reported harvesting impacts to be four times worse on wet soils than on dry soils. Soils are most susceptible to compaction when they are moist, and rutting when they are saturated (Wimme, 1987). Overall, the extent and type of soil damage resulting from harvesting is a function of the equipment used, terrain of the site, number of equipment passes, soil type, and soil moisture content at the time of trafficking (Koger *et al.*, 1984).

Compaction vs. Rutting

Compaction and rutting are distinctly different soil disturbances caused by heavy machinery traffic. Previous research has not distinguished between the two conditions; however, each may damage the site in different ways. The soil moisture content at the time of trafficking determines which disturbance occurs. Compaction occurs when the soil is moist, or near field capacity. At this moisture content, thick films of water surround and lubricate the soil particles, allowing the particles to be closely aligned. Then, as the soil particles are squeezed together into a smaller mass, the amount of air-filled pore space is reduced, and the soil is compacted (Burger, 1990; Greacen and Sands, 1980).

Rutting occurs when soil moisture contents surpass that soil's liquid limit (Greacen and Sands, 1980; Bodman and Rubin, 1948). In rutting, the soil pore volume is filled with water, thereby resisting soil compaction by the pressure of heavy machinery. Instead, the soil flows outward and upward from under the pressure, and a rut is formed. The saturated conditions allow the soil to be churned and separated into basic soil particles (Sharma and De Datta, 1986). In fact, Beacher and Strickling (1955) reported that puddling (rutting) is the antithesis of soil aggregation. Upon settling, the churned or puddled soil particles closely align, eliminating the air-filled macropores that once existed, forming a barrier that is relatively impermeable to water flow (Burger, 1990).

Compaction Effects on Soil Properties

Compaction adversely affects many soil properties. Bulk density and soil porosity are the most direct measures of soil compaction (Reisinger *et al.*, 1988). By definition, compaction increases soil bulk density, the weight of a given mass of soil per unit volume. Several studies have found increased bulk densities to adversely affect root development and, therefore, the growth and survival of pine seedlings (Gent *et al.*, 1983; Mitchell *et al.*, 1982; Reisinger *et al.*, 1988). This is especially important on wet sites as maximum bulk densities result when soils moisture contents are at or near field capacity. Reported increases in bulk density following machinery traffic include 17% (Gent and Morris, 1986), 20% (Dickerson, 1976), and even 50% (Hassan, 1977). The most significant increases usually occur during the first two passes; therefore, soils may be damaged by even one pass (Reisinger *et al.*, 1988). On wetland sites, Aust *et al.* (1991) also found continued significant bulk density increases after nine passes, as did Wimme (1987) after 27 passes. Increased bulk density usually results in decreased water flow through soil (Meek *et al.*, 1992).

Compaction may also increase soil strength (Burger, 1990). This can impede root growth and, therefore, impair tree growth. However, Burger *et al.* (1989) stated that trafficking of a poorly drained soil may actually decrease the strength of a soil by increasing the volumetric soil water content. This is not, however, a beneficial effect on wet sites where bulk density and soil strength rarely exceed their respective root-limiting points of 1.4 g/cm^3 and 2200 kPa (Reisinger *et al.*, 1988).

Perhaps the most serious site impact of harvesting on wet sites is reduction of hydraulic conductivity and aeration. Aust *et al.* (1993b) stated that decreases in soil aeration and drainage on already poorly drained sites have the potential to reduce overall site productivity. Compaction affects the hydraulic conductivity and aeration of a site by altering the inherent soil porosity. Greacen and Sands (1980) stated that porosity is largely governed by the arrangement of solid particles and can be negatively impacted through soil compaction. Roseberg and McCoy (1992) reported that root system development and water movement is controlled by the number and size of pores in a soil. Several researchers have reported decreases in total porosity of 53 to 68 percent following harvesting (Koger *et al.*, 1984; Incerti *et al.*, 1987; and Reisinger *et al.*, 1988). However, compaction does not always decrease total porosity; sometimes it only reduces the ratio of macropores to micropores. Reduction in volume and shape of macropores may inhibit gaseous exchange between the soil air and the atmosphere. Root growth and/or survival are significantly affected when soil macroporosity is reduced below ten percent (Greacen and Sands, 1980). Macropores are larger pores that are air-filled at field capacity and drain the site of excess water. When these pores are crushed, hydraulic conductivity is reduced. For example, hydraulic conductivity decreases of 78% (Reisinger *et al.*, 1988) to 93% (Koger *et al.*, 1984) have been reported for skid trails after harvesting. The loss of macropores can also inhibit gaseous exchange between the soil air and the atmosphere (Greacen and Sands, 1980). These phenomena can cause the soil of wetland sites to become chemically reduced and result in insufficient gas exchange, which may limit root growth (McKee, 1970). Decreased drainage can also decrease the availability of nitrogen and phosphorous on wetland sites (Voorhees, 1991; and McKee *et al.*, 1984).

Harvesting impacts that decrease drainage can also affect site water tables. Water table depth affects soil strength, saturated hydraulic conductivity, soil temperature, soil redox potential, and soil acidity (Aust, 1989). It also influences the available water and soil oxygen of a site which may affect plant growth. Root growth is restricted on many sites in the South by poor aeration during wet periods which consequently inhibits seedling survival and/or growth (Morris and Lowery, 1988). Hence, an accurate record of a site's fluctuating water table provides important information about soil aeration and affected plant growth. The water table depth in relation to the growing season is particularly important, especially on wetland sites.

Organic matter content is another soil property that is important when considering harvesting related disturbances. Organic matter is the solid, non-mineral portion of the soil originating from plant and animal residues and consisting of proteins, amino acids, fats, lignin, and waxes (Rawls, 1983). Organic matter affects the soil in many ways; on disturbed soils, organic matter may decrease bulk density, increase macro- and total porosity, and increase soil fertility through its decomposition and aggregate stabilization (Brady, 1990). The cation exchange capacity associated with organic matter is generally two to thirty times higher than that of soil colloids. Also, organic matter is the primary source of soil nitrogen and phosphorous which is extremely important on inherently phosphorous-deficient lower coastal plain soils (Bohn *et al.*, 1985). Organic matter is often removed or relocated by harvesting operations, and tree growth can suffer as a result of the loss in site nutrients (McKee and Hatchell, 1987).

Rutting Effects on Site and Soil Properties

Rutting and compaction have similar effects on many soil properties, but rutting presents some unique problems relating to the internal drainage of the site. The puddled walls of ruts become relatively impermeable to water due to decreased saturated hydraulic conductivity and macroporosity. Therefore, ruts may interrupt the horizontal flow of subsurface water through the affected soil layers of the site. Such horizontal subsurface water flow is important for drainage on many lower coastal plain sites because clayey subsoil (Bt) horizons have low hydraulic conductivities and restrict vertical water movement (Wimme, 1987). Aust *et al.* (1993b) examined harvesting impacts on such a site in the Francis Marion National Forest. They concluded that skid trails interrupted the horizontal drainage of water and consequently raised the site water table. This occurred although post harvest bulk density values remained below 1.0 g/cm^3. Perison et al. (1993) reported similar results on rutted sites in the coastal plain of South Carolina.

Harvesting Impacts on Tree Growth

Harvesting can decrease the survival and growth of tree seedlings by damaging the inherent properties of the soil. Hatchell *et al.* (1970) documented the growth reduction of loblolly pine (Pinus taeda) due to harvesting impacts on the soil. The growth and survival of tree roots can be impaired by increased bulk density and soil strength and decreased macroporosity. Gent *et al.* (1983) documented that root growth inhibition begins at a bulk density of 1.4 g/cm^3 and root growth stops when bulk density reaches 1.8 g/cm^3. Reduced root growth decreases absorptive surface areas available for nutrient uptake and may result in nutrient deficiencies in trees (Mitchell *et al.*, 1982). Nitrogen and phosphorous deficiencies can also result from the decreased aeration and drainage associated with harvest disturbances (Bicki and Siemens, 1991; McKee *et al.*, 1984). Vomocil and Flocker (1961) reported that reduction of macroporosity to below 10 percent will result in insufficient soil oxygen levels in the soil profile for root growth. This is the level at which the oxygen requirements for respiration in the soil exceed the rate at which oxygen in the soil air can be replaced from the atmosphere (Greacen and Sands, 1980). Consequently, height growth of pine seedlings planted in compacted soil has been found to be inversely proportional to the soil bulk density (Mitchell *et al.*, 1982, and Reisinger *et al.*, 1988). Lockaby and Vidrine (1984) reported 39 to 59 percent reductions in height growth among pine seedlings grown in trafficked soils compared to identical seedlings grown on undisturbed soils in the Louisiana coastal plain.

Ameliorative Practices

Soils in the South may require long periods of time to recover from harvesting damage. For example, Hatchell et al. (1970) estimated a natural recovery time of 18 years for compacted soils in the South. The extent to which compacted soils will recover depends on the soil type and the degree of compaction (Greacen and Sands, 1980). Unfortunately, rotation lengths in the South are relatively short, and soils do not have time to naturally recover between harvesting operations. Therefore, ameliorative practices such as bedding, disking, and fertilization are necessary to reduce or ameliorate harvesting effects. Hatchell (1981) reported that these site preparation techniques can increase pine seedling survival and growth. Williams (1988) stated that the primary goal of site preparation and regeneration is to establish a desirable stand on reclaimed or recently harvested forestland. Furthermore, in a survey by the American Pulpwood Association (APA), forest managers listed "growth optimization" as the most important criteria in selecting a site preparation treatment (Morris and Lowery, 1988).

Bedding is the most common mechanical site preparation technique used in the regeneration of southern pine stands (Belli *et al.*, 1993). It creates an elevated row on which seedlings are planted, similar to agricultural crops. The objective of bedding is to get the seedling roots above the water table, decrease the soil penetration resistance, and increase the exploitable volume of soil so that the pine seedlings will have favorable root system development conditions (Morris and

Lowery, 1988). Attiwill *et al.* (1985) found higher cation exchange capacities and available nitrogen and phosphorous concentrations in bed centers. McKee and Shoulders (1970) reported that higher beds increased the distance from the top of the bed to the water table and resulted in increased pine growth. Bedding has been shown to significantly increase early height and biomass growth rates in southern pine seedlings (Shiver *et al.*, 1990). McKee and Hatchell (1987) concluded that bedded loblolly pine seedlings had a significantly higher survival rate (73%) compared to seedlings on disked sites (64%). They also reported that 12-year-old loblolly pines on bedded sites were six to ten percent taller than similar trees on control sites. Bedding is also effective for competition control and micro-site improvement which both increase the survival and early growth of pine seedlings (Williams, 1988). Although bedding is known to greatly increase early height growth of planted pine seedlings, some studies have found that bedding provides no height growth advantage over a rotation of greater than 20 to 25 years (Lennartz and McMinn, 1973; Wilhite and Jones, 1981; and Derr and Mann, 1977). This would not affect stands being grown for pulpwood as the early height growth advantage would result in a higher volume of wood due to the short rotation; however, it might be less economical to bed long-rotation sawtimber stands such as is the policy on the Francis Marion National Forest (Wilhite and Jones, 1981).

Regardless of height growth, the most important advantage of bedding may be increased survival among pine seedlings. Torbert *et al.* (1993) examined 23-year-old experimental plantations in the coastal plain of Virginia and found that bedding increased total wood volume by 34 percent as compared to non-bedded plots. The increased wood volume was attributed to stocking, not tree diameter or height. In southwestern Louisiana, increased wood volumes were also reported for 15-year-old bedded loblolly and slash pines (Pinus elliottii) as compared to similar trees on disked sites despite an insignificant difference in height between the trees (Haywood, 1987). Bedding appears to be an indispensable site preparation treatment because it increases early survival and eventual volume of pine seedlings on the poorly drained sites common to the lower coastal plain. Harding and Hollis (1993) concluded that bedding is the best silvicultural option for slash pine management on poorly drained soils.

Disking is another site-preparation method used to alleviate traffic-induced site disturbance in the South (Dickerson, 1976); however, it is less common and more expensive than bedding (Belli *et al.*, 1993). Disking in forestry operations is performed before planting much like agricultural operations, although larger, more rugged equipment is used and operations are less intensive. Disking is used as an ameliorative practice to loosen and mix the soil (Williams, 1988). This lowers bulk density and increases porosity, thus increasing the amount of exploitable soil volume in which seedling roots can grow. Edwards and Shiver (1991) reported that disking improved pine seedling growth and survival in their site preparation study on the Georgia piedmont. McKee and Hatchell (1987) reported that disking increased pine seedling survival, but disking did not significantly increase 12-year-old crop tree height. Many forest land managers regard disking as an insufficient site preparation technique because it is only successful in ameliorating the top 7 to 12 centimeters of the soil profile; whereas, compaction that retards water movement often extends below 20 centimeters (Gent *et al.*, 1984). Despite this limitation, disking is still recommended for amelioration of compacted soils. Disking also severs the root systems of competing vegetation thereby helping in the establishment of pine seedlings (Williams, 1988).

Fertilization has become an important component of southern pine plantation management. Fertilization is relatively inexpensive costing an average $40.85 per acre while bedding and disking costs average $103.56 and $160.01 per acre, respectively (Belli *et al.*, 1993). McKee and Hatchell (1987) have also reported fertilization to be as effective as bedding in alleviating harvesting damage. They found that fertilization increased pine height growth, average diameter breast height (dbh), and total volume on trafficked sites in the South Carolina lower coastal plain. This effect was attributed to the low levels of available soil phosphorous and nitrogen on these poorly drained lower coastal plain sites. Many researchers have reported that pine growth is often limited by available soil nitrogen and phosphorous on such sites. (Allen and Campbell, 1988; Hart *et al.*, 1985). Hence, nitrogen and phosphorous are the two most commonly applied nutrients in this region.

Nitrogen and phosphorous fertilization is a highly specialized forest management operation resulting from extensive research that began in the mid-1960's. Before this time, fertilization of trees was mainly limited to nurseries and orchards (Pritchett and Fisher, 1987). The Cooperative Research in Forest Fertilization Program (CRIFF) began researching southern forest fertilization in 1973 and has examined responses of several types of southern yellow pine stands to varying rates and combinations of nitrogen and phosphorous fertilizers (Bailey *et al.*, 1989). In 1993, over 180,000 hectares of southern pine stands received nitrogen or phosphorous fertilization (Lee Allen, personal communication).

Phosphorous is perhaps the most limiting nutrient on poorly drained wet pine flats. In a study on such sites, Wilhite and McKee (1986) found five-year-old loblolly pine trees that received a phosphorous application one year after planting to be significantly taller than similar trees that received no phosphorous addition. Pritchett and Comerford (1982) also reported a significant height, diameter, basal area, and volume increase in slash pine when phosphorous was applied at time of planting. Therefore, this nutrient is usually applied at the time of planting during other site preparation activities (Pritchett and Fisher, 1987). However, McKee and Hatchell (1987) reported that phosphorous application decreased loblolly pine seedling survival rates due to the increased competition stimulated by the fertilization. Phosphorous is a very non-mobile nutrient which becomes available for plant uptake very slowly; as a result, one application of this nutrient may provide responses for the entire rotation of a stand of trees (Buford and McKee, 1987; Pritchett and Comerford, 1982). Phosphorous applications have also been suggested as a substitute for bedding by Langdon and McKee (1981), McKee *et al.* (1984), and McKee and Wilhite (1987). Their research has shown that southern pines receiving phosphorous applications grow as well as similar trees growing on bedded sites.

Nitrogen is applied to forest stands to improve upon the inherent fertility of the site and increase natural growth of the trees. Binkley (1986) reported that 90 percent of the world's forests would respond biologically to nitrogen fertilization. However, nitrogen applications are not usually required to insure seedling survival on the lower coastal plain as is the case with phosphorous. Nitrogen is a very mobile nutrient that must be applied more than once for optimum tree response. Nitrogen is often applied to southern pine plantations at planting and again at mid-rotation (Bailey *et al.*, 1989). Positive responses to nitrogen applications have been found to last for fifteen years or more in young pine stands (Pritchett and Fisher, 1987).

Competing Vegetation

Another purpose of site preparation is to control competing vegetation. Competing vegetation can reduce forest plantation growth rates and planted pine seedling survival through competition for sunlight and site nutrients (Campbell and Hughes, 1991; McKee and Hatchell, 1987; Smethurst and Nambiar, 1989). Competing vegetation in southern pine plantations includes woody species and herbaceous vegetation; however, herbaceous competition is most important when considering young pine plantations as this is the dominant vegetative form during this time period (Conde *et al.*, 1983). Control of herbaceous competition has also been reported to require three times the amount of herbicide as hardwood competition (Cain, 1991). Likens *et al.* (1970) attributed the increase in herbaceous competition following overstory harvesting to the increase in available light, moisture, and dissolved nutrients on sites following canopy removal. Herbaceous vegetation is a problem because as it has a much higher nutrient uptake capability than pine seedlings (Lockaby *et al.*, 1988; Escamilla *et al.*, 1991). Smethurst and Comerford (1993) reported a decrease in potassium and phosphorous uptake by slash pine seedlings in the presence of competing grasses.

Competition control has been shown to increase early growth rates of planted pine seedlings (Creighton and Zutter, 1985; Hatchell, 1964; Muntz, 1951; Newton *et al.*, 1987; Shoulders, 1955). This growth increase has also been shown to persist long into the stand rotation (Creighton *et al.*, 1986; Schmidtling, 1984). The enhanced survival and early growth of loblolly pine in plantations due to site preparation have been largely attributed their control of vegetative competition (Needham *et al.*, 1987). A 128 percent increase in merchantable volume in a 10-year-old loblolly pine stand with herbaceous weed control was reported by Creighton *et al.* (1986). Xydias (1987) concluded that the performance of any planted stand is influenced by the efficacy of site preparation in controlling competing vegetation.

METHODS and PROCEDURES

Study Site

The study site is located in Berkeley County, South Carolina on the Wambaw District of the Francis Marion National Forest (Appendix A). This area is in the Coastal Plain region of South Carolina, approximately 30 miles north of Charleston. This area has a subtropical climate with a mean annual precipitation of 119 centimeters and a growing season of approximately ten months (Soil Conservation Service, 1980).

In October of 1989, Hurricane Hugo devastated the 80-year-old loblolly and longleaf (Pinus palustris) pine stands that once occupied these sites. This natural disaster damaged four million acres of forest and downed eighty percent of the standing timber greater than eighteen centimeters (7 in.) in diameter on the Francis Marion National Forest (Jones *et al.*, 1991). The study sites were salvage harvested in order to utilize as much of the blown-down sawtimber as possible. Unfortunately, these salvage operations resulted in widespread site disturbance because they took place during coastal South Carolina's wet season.

The study sites were nearly level in topography with slopes between zero and one percent. Water tables on the study sites were shallow during the fall and winter. The residual overstory of the study sites was composed of longleaf and loblolly pine trees that survived Hurricane Hugo at densities of five to twelve trees per hectare (Tippett, 1992). Common understory species included broom sedge (Andropogon viginicus), blackberry (Rubus spp.), blueberry (Vaccinium spp.), and switch cane (Arundinaria gigantea).

The soil series of the study sites were deep, old, and fairly infertile ultisols derived from marine and/or fluvial deposits. They included the Bethera (clayey, mixed, thermic Typic Paleaquults), Goldsboro (fine-loamy, siliceous, thermic Aquic Paleudults), Lynchburg (fine-loamy, siliceous, thermic Arenic Paleaquults), and Rains (fine-loamy, siliceous, thermic Typic Paleaquults) series. Their family and subgroup names indicated that they were often acted upon by water. Drainage classes and textures for the soil series are shown in Table 1. Typical profile descriptions are provided in Appendix C.

Table 1. Drainage Class and Soil Texture of Major Study Site Soil Series.

Soil Series	**Drainage Class**	**Soil Texture (upper 1 meter)**	
		A Horizon	**B Horizon**
Bethera	Poorly	Loam	Clay
Goldsboro	Moderately Well	Loamy Sand	Sandy Clay Loam
Lynchburg	Somewhat Poorly	Sandy Loam	Sandy Clay Loam
Rains	Poorly	Sandy Loam	Sandy Clay Loam

* - Adapted from Tippett (1992)

Site Disturbance

The entire study consists of six sites (blocks)(Figure 1). Three blocks were compacted and three were rutted by salvage logging during wet soil conditions. Rutted sites were identified by the presence of displaced soil having been moved outward from the tire track (a berm), an indication of the soil moisture content having exceeded its liquid limit at the time of trafficking (Figure 2). Compacted sites were identified by physical depression of the soil in the tire tracks without soil displacement (Figure 2).

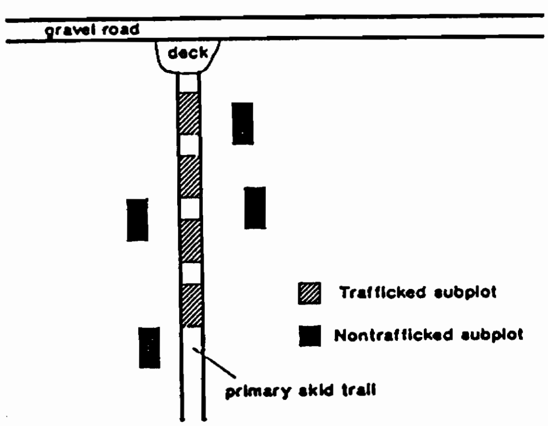

Figure 1. Diagram of one study site (block) layout.

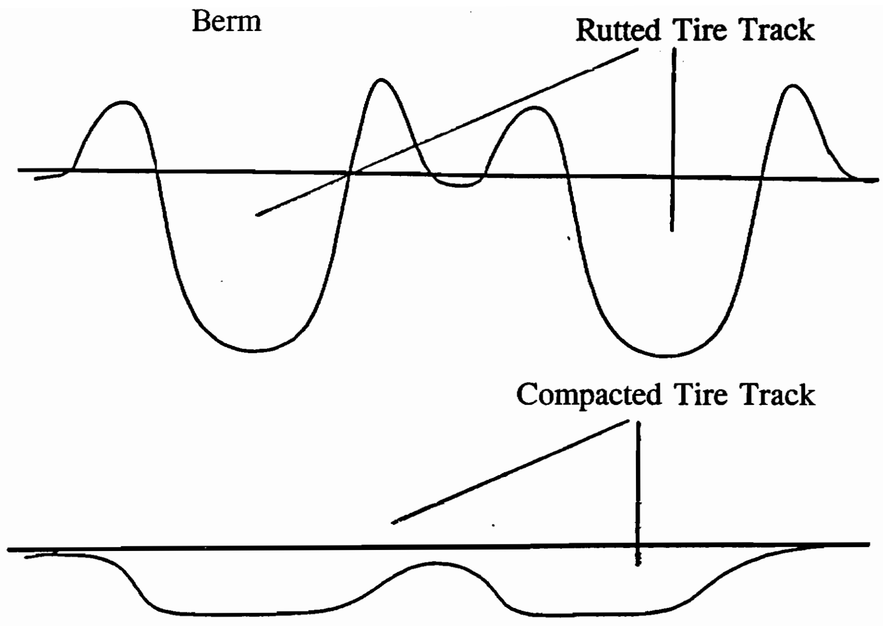

Figure 2. Generalized cross-section of rutted and compacted skid trails.

Treatment Plots

Each of the six study sites contained eight treatment plots that were 24.4 meters (80 feet) long and 7.6 meters (25 feet) wide (Figure 3). Four of the plots on each site contained rutting or compaction damage, and the other four contained undisturbed soils. The plots were further subdivided, one-half being fertilized with 227 kilograms per hectare (500 lbs/ac) of 10-10-10 fertilizer. Each plot contains four randomly-located transect lines that run perpendicularly across the width of the plot. Along each transect line, one water well and one soil and vegetation sampling station were established. All transect lines were at least three meters (10 feet) apart and at least three meters (10 feet) from the edge of the fertilization treatment to provide buffer areas. All plot corners were marked with four-foot high metal conduit stakes that had metal identification tags attached to them (Tippett, 1992).

Treatment Implementation

Four different site preparation treatments were performed on each site in order to assess their effectiveness in ameliorating soil compaction and rutting. The treatments were: 1) disked, 2) bedded, 3) disked + bedded, and 4) control (no treatment). Each treatment was installed on one trafficked and one non-trafficked plot per site (Tippett, 1992). The mechanical treatments were installed by a hired contractor. The fertilizer treatment consisted of 227 kg/ha of hand applied 10-10-10 fertilizer to half of each plot. Genetically-improved loblolly pine seedlings were planted on a 0.6 X 0.6 meter (2 X 2 foot) spacing on all study plots during the winter of 1992.

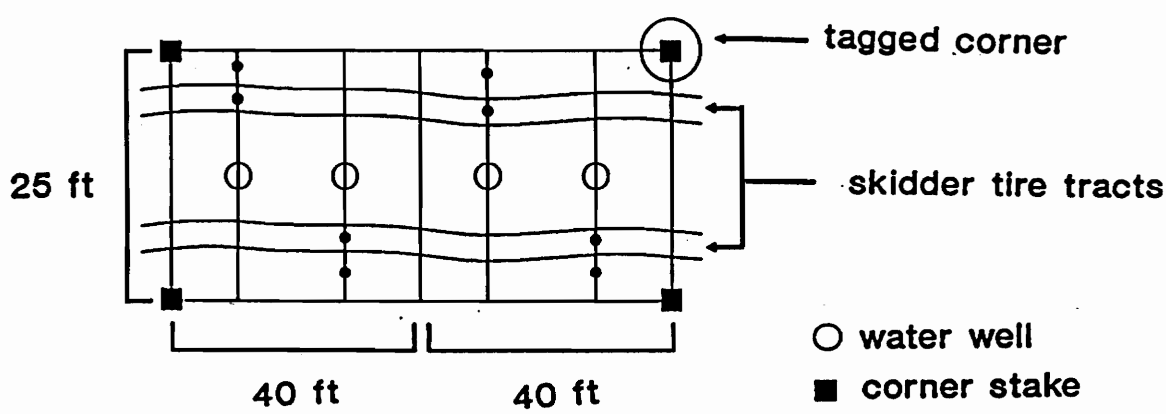

Figure 3. Diagram of trafficked treatment plot.

Bulk Density

Soil bulk density is the mass of oven-dried soil solids per total soil volume. Bulk density is commonly used as an indication of soil compaction (Greacen and Sands, 1980). The core method was used to obtain bulk density data in this study (Blake and Hartge, 1986). Ten centimeter (4 inch) cores and a bulk density hammer were used to take five soil cores from the surface soils of each of the four transect lines on each of the bedded plots. Three cores were taken from the disked and control plots due to their uniformity. On the bedded plots, one core was taken from the top of the bed, the furrow, and the side of the bed on each transect line. A soil core was taken in and between the tire tracks on the disked and control sites. One random soil core was taken on each transect line of the undisturbed disked and bedded plots. Bulk density cores were sampled once as bulk density is a fairly static property and would not change much over the time period included in this study.

In the laboratory, the cores were oven-dried at 105° C after being used to determine saturated hydraulic conductivity and porosity. The oven-dry weight of each core was divided by its total soil volume to determine the bulk density of the sample. The bulk densities from each treatment were all averaged to determine a mean bulk density value for that treatment.

Soil Porosity

Soil porosity is a direct quantitative measurement of soil compaction (Reisinger *et al.*, 1988). Soil porosity is the portion of the soil volume occupied by air and water (Danielson and Sutherland, 1986). The same soil cores used for bulk density sampling were used to quantify macro, micro, and total porosity. Soil porosity was measured by weighing undisturbed soil cores of a known volume at saturation, field capacity (1/3 kPa), and oven-dry. Saturated weights were determined by weighing the cores immediately following 36 hours of submersion under water. Field capacity weights were determined by placing the cores on a tension table until they reached equilibrium, and oven-dry weights were measured after 24 hours of drying in a 105° C oven. The following relationships were used to determine macro, micro, and total porosity (Danielson and Sutherland, 1986):

Macropore Space (%) = [(Saturated Wt.- Wt. @ 0.05 bars)/ (Total Soil Volume)] * 100

Micropore Space (%) = [(Wt. @ 0.05 bars - Oven-Dry Wt.)/ (Total Soil Volume)] * 100

Total Pore Space (%) = Macropore % + Micropore %

Hydraulic Conductivity

The hydraulic conductivity of a soil is a measure of its ability to transmit water. The constant-head method was used to measure the saturated hydraulic conductivity of the study site soils (Klute and Dirksen, 1986). This method utilized the same undisturbed soil cores collected for the bulk density and porosity procedures. To measure saturated hydraulic conductivity, the soil cores held in metal cylinders which were 5.08 cm in diameter and 10.16 cm long were saturated by slowly submersing them in water over a 36 hour period. They were then subjected to a constant 25 centimeter head of water. The volume of water flowing through the soil cores per unit time was measured to determine the saturated hydraulic conductivity using the following equation:

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

where, Ks = hydraulic conductivity (cm/hr)
Q = volume of water passing sample (cm^3)
A = cross-sectional area of cylinder (cm^2)
t = time (hr)
L = length of cylinder (cm)
H = hydraulic head (cm)

Water Table Depth

The water table is the surface in the soil/groundwater system where pore water is at atmospheric pressure (Freeze and Cherry, 1979). Water table depth was measured using unlined borehole wells in which slotted PVC pipes were inserted to prevent soil from filling the well (Faulkner *et al.*, 1989). There were four wells per plot, one on each transect line. The wells were five centimeters in diameter and 100 centimeters deep. A specialized well measuring rod was used to measure the wells twice a month during the summer and once a month during the rest of the year from July, 1992 to July, 1993 in order to accurately monitor the water table depth.

Seedling Height Growth

Relative seedling height growth differences between different site preparation treatments provide a good measure of site preparation treatment success (Morris and Lowery, 1988). Seedling height growth was measured three times; at planting, after one growing season, and after two growing seasons. Height was measured in centimeters on numbered seedlings using a meter stick. Due to tree spacings, 24 seedlings were measured on bedded plots, and 32 were measured on all other treatment plots. Measurement trees included the two rows on either side of each transect line.

Seedling Survival Rate

Adequate seedling survival is necessary to ensure an acceptable and productive mature stand (Williams, 1988). Therefore, seedling survival is a critical measurement for comparing the effectiveness of different site preparation treatments. Seedling survival rates were determined by counting all live and dead trees on each plot on two occasions; the first summer after planting and after the second growing season. All counted trees were marked with pin-flags to ensure accurate identification.

Topographic Profiles

Topographic soil profiles were measured in order to compare the effects of the different site preparation treatments on the site microtopography. To measure the soil profile, a levelled string was stretched perpendicularly across the plot. A meter stick was used to measure the distance from the string to the ground below (Tippett, 1992). This measurement was taken every 15.24 centimeters (6 inches) across the width of the plot at each transect line. The values were then averaged and corrected to obtain a mean topographic profile height for the transect line.

Competing Vegetation

Above ground biomass per unit area of woody and herbaceous competing vegetation was measured on each of the study plots. The competition was divided by species; however, herbaceous species completely dominated the sites. The vegetation was sampled by clipping at ground level all stems falling within a 0.25-meter X 7.62-meter plot located perpendicular to the length of the study plots. Four vegetation sample plots were taken on each of the treatment plots; they were located 0.46 meters from the centerline of each transect line. After clipping, the vegetation was gathered and separated by category. It was then placed in paper bags labelled with the plot and line number as well as the species of the vegetation. The vegetation samples were dried in a 65°C oven for two weeks (Slay *et al.*, 1987). The oven-dried competing vegetation samples were weighed to the nearest gram, and the values were converted to kilograms per hectare.

Soil Nutrient Analysis

Loose composite soil samples were used to determine the nutrient concentrations of the study site soils (Peterson and Calvin, 1986). One liter of soil was collected from the top 15 centimeters of the fertilized and unfertilized halves of each study plot using a push-tube sampler. The soil was air-dried and ground using a mechanical soil grinder. Soil samples were analyzed for nitrogen, phosphorous, and potassium contents these are the three nutrients that were added to the fertilized halves of each plot. The Total Kjeldahl Nitrogen (TKN) method was used to determine nitrogen contents, and phosphorous and potassium contents were analyzed using the double-acid extraction method and ICP procedures (Bremner and Mulvaney, 1982).

Organic Matter Content

Organic matter is the solid, non-mineral portion of the soil originating from plant and animal residues and consisting of proteins, amino acids, fats, lignin, and waxes (Rawls, 1983). Organic matter contents of the study soils were determined from the composite soil samples of the top six inches of the soil profiles. The composite soil samples were collected with a push-tube sampler and represent a thorough mix of the treatment plot soils. A LECO carbon analyzer was used to measure the amount of carbon in the soil samples, and organic matter was calculated using a conversion factor of 1.90 (Broadbent, 1953).

Foliar Nutrient Analysis

Foliar tissue samples were collected from a subset of the pine seedlings on each of the study plots in order to determine their nitrogen, phosphorous, and potassium contents. Only needles from the last full flush were collected. The Total Kjeldahl Nitrogen (TKN) method was used to determine the nitrogen contents of the needle tissue (Isaac and Johnson, 1976). The dry-ash procedure was used to prepare tissue samples for determination of phosphorous and potassium contents (Isaac and Kerber, 1971). The ash was dissolved in a 6N HCl solution and analyzed by spectroscopy for phosphorous and potassium contents.

Comparisons to Pre-Site Preparation Data

Numerous comparisons were made between the results of this study and the results of a previous study performed by Tippett (1992) on the same sites before the installation of the site preparation treatments. Parameters that were compared included soil bulk density, soil porosity, organic matter content, water table depth, hydraulic conductivity, and topographic profile height.

Statistical Analysis

The three compacted sites and three rutted sites were analyzed as two separate studies. The effects of trafficking (trafficked, non-trafficked), site preparation treatments (none, disked, bedded, and disked and bedded), and fertilization (fertilized, unfertilized) were analyzed as a split-split plot (Steele and Torrie, 1980). A generalized analysis of variance table is provided (Table 2). The control treatment plots were later excluded from the data set due to the accidental burning of four of the six control plots in the rutted study and the misplacement of the waterwells on two of the control sites in the compacted study. The Number Cruncher Statistical System (NCSS, 1990) program was used for data analysis.

Table 2. Generalized analysis of variance table

Source of Variation	Degrees of Freedom
Block (B)	2
Traffic (T)	1
Site Prep Trt. (SP)	2
B * SP	4
T * SP	2
B * T * SP	4
Fertilizer (F)	1
F * T	1
F * SP	2
F * T * SP	2
Error	14
Total (corrected)	35

RESULTS and DISCUSSION

RUTTED STUDY

Pine Seedling Response

Rutting reduced second-year height growth, total volume, and survival rate of the rutted site pine seedlings (Table 3). Seedlings growing on the non-trafficked sites exhibited 43 percent greater height growth, 90 percent greater volume, and 9 percent better survival than those on the rutted sites. Mitchell *et al.* (1982) reported similar height growth and volume results on trafficked soils, and Kozlowski (1986) explained that the rutting effects on soil aeration and water levels often result in decreased survival.

Table 3. Rutting effects on two-year old pine seedlings.

Pine Seedling Parameter	Units	Disturbance Class	
		Non-trafficked	Rutted
2nd Year Height Growth	cm	49 (b)	34 (a)
Seedling Volume	cm^3	219 (b)	115 (a)
Seedling Survival	%	91 (b)	82 (a)

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

Bedding resulted in 35 percent greater second-year height growth and 117 percent greater seedling volume than disking on the rutted sites; however, bedding + disking was no better than bedding alone (Table 4). These height growth results differ from those reported by Haywood (1987) who found no difference in height growth between bedded and disked seedlings; however, Haywood (1987) did find that bedded seedlings had greater volumes than disked seedlings. Survival at age two was not affected by site preparation treatment and was actually quite uniform among the three treatments only varying from 84 to 88 percent (Table 4). This result contradicts McKee and Hatchell (1987) who reported higher pine seedling survival on bedded sites than on disked sites on a poorly drained coastal plain soil.

Site preparation had no effect on pine seedling survival on the rutted sites after two years. However, it was noted that many seedlings growing in lower, wetter sites were in poor health, had not grown since planting, and may likely die in the next year or two. This phenomenon is explained by the small nutrient requirements and inherent hardiness of pine seedlings. The seedlings may be getting just enough resources for survival but not for any growth. The seedlings also may have been planted with just enough nutrient and energy reserves to last for two or three years in an unfavorable environment. This theory is supported by Wilhite and McKee (1986) who reported no site preparation effect on pine seedling survival five years after planting compared to Pritchett (1978) who reported a significant decrease in survival after eight years on similar sites.

Table 4. Site preparation effects on pine seedlings in the rutted study.

Parameter	Units	Site Preparation Treatment		
		Disked	Bedded	Disked & Bedded
2nd Year Height Growth	cm	34 (a)	46 (b)	45 (b)
Seedling Volume	cm^3	98 (a)	212 (b)	193 (b)
Seedling Survival	%	84	88	88

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

Fertilization increased pine seedling height growth and volume by 54 and 125 percent, respectively, on the rutted sites (Table 5). McKee and Hatchell (1987) also found increased seedling height growth and volume resulting from fertilization treatments on the coastal plain. The fertilization did not, however, affect the survival rate of the seedlings growing on the rutted sites (Table 5). These results disagree with Pritchett (1978) who reported that fertilization increased pine seedling survival on similar wet sites.

Table 5. Average fertilization effects on the pine seedlings in the rutted study.

Parameter	Units	Fertilization Treatment	
		Fertilized	Unfertilized
2nd Year Height Growth	cm	50 (b)	33 (a)
Seedling Volume	cm^3	232 (b)	103 (a)
Seedling Survival	%	87	87

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

There were no interactions between traffic, treatment, and fertilization for any of the pine seedling growth parameters (Appendix B). Of key interest is the non-interaction between site preparation and fertilization despite the main effect of each of these factors on the pine seedling responses. These results support the theory expressed by McKee and Wilhite (1986) that fertilization may be an inexpensive alternative to mechanical site preparation on wet sites such as those in this study. However, for the greatest growth potential, both bedding and fertilization are necessary as fertilization did have an additive effect on the pine seedling height growth and volume (Figures 4 and 5).

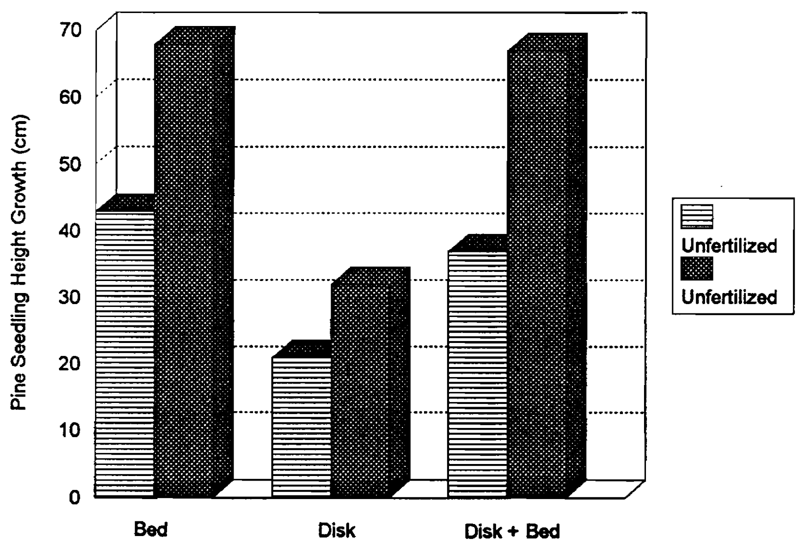

Figure 4. Additive effect of fertilization on pine seedling height growth.

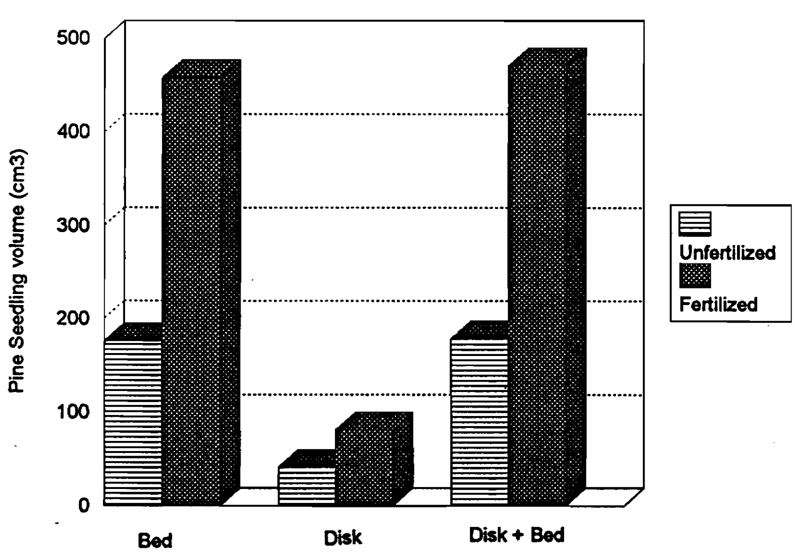

Figure 5. Additive effect of fertilization on pine seedling volume.

Significant Factors Influencing Pine Seedling Responses

Rutting Effects

The residual effects of rutting, after two years and site preparation, were exhibited by the lower growth and survival rates of the pine seedlings growing on the rutted plots. Rutting effects were found on two soil properties related to water movement and supply, saturated hydraulic conductivity and water table depth (Table 6). The rutted sites had slower saturated hydraulic conductivities and higher water table depths three years after rutting and two years after site preparation. Both of these conditions can be detrimental to pine growth on these poorly drained lower coastal plain sites. Reductions in saturated hydraulic conductivity due to rutting on poorly drained soils have been reported by several researchers (Aust *et al.*, 1991; Aust *et al.*, 1993; Gent *et al.*, 1983; Perison *et al.*, 1993). The reduced hydraulic conductivity probably resulted in insufficient aeration to the seedling roots, thereby increasing mortality and decreasing growth (Kozlowski, 1986).

A higher water table is also detrimental to pine seedling growth on poorly drained wetland sites. Aust *et al.* (1991) reported that rutting raised water tables on a wet pine flat in South Carolina by reducing drainage; this effect reduces the rooting zone oxygen supply and can drown seedling root systems. Especially important is the water table depth during the growing season. In southeastern South Carolina, the growing season is approximately ten months long, and the water tables are highest during the dormant period from December to February (Figure 6).

The rutting damage to these soil properties appears to be the reason for the reduced pine growth and survival on the rutted sites. No other soil properties were affected by rutting. The residual rutting effects on saturated hydraulic conductivity and water table depth prove that the site preparation treatments used in this study were unable to completely ameliorating the damage to these properties.

Table 6. Mean rutting effects on soil physical and chemical properties.

Soil Property	Units	Disturbance Class		P-Value
		Non-trafficked	Rutted	
Topographic Profile Height	cm	+11	+11	0.194
Bulk Density	Mg/m^3	1.27	1.30	0.353
Macroporosity	%	15	14	0.260
Microporosity	%	37	37	0.933
Total Porosity	%	52	51	0.532
Saturated Hydraulic Conductivity	cm/hr	3.05 (b)	0.81 (a)	0.005
Water Table Depth	cm	-26 (b)	-16 (a)	0.002
Organic Matter Content	%	4.0	4.4	0.207
Soil Phosphorous	g/kg	0.007	0.007	0.971
Soil Nitrogen	g/kg	0.395	0.387	0.971
Soil Potassium	g/kg	0.260	0.250	0.847

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

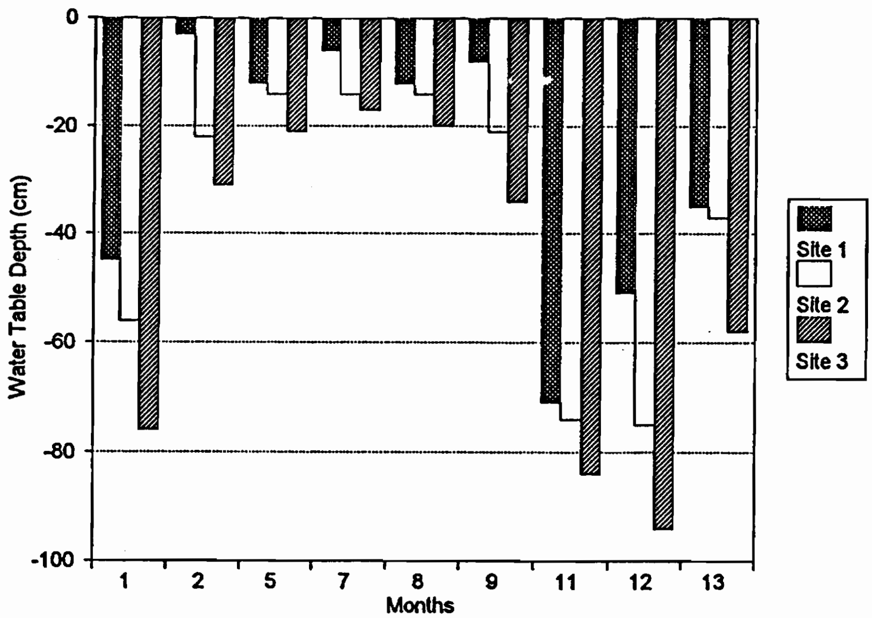

Figure 6. Typical water table of the rutted sites as measured from July, 1992 to July, 1993.

As mentioned, there were no residual rutting effects evident among the other physical and chemical soil properties examined in this study (Table 6). Site preparation eliminated the mean topographic elevation difference reported by Tippett (1992) between the rutted and non-trafficked plots. There was also no difference between the mean bulk densities of the rutted and non-trafficked sites (Table 6). While this phenomenon could be a result of the site preparation, Beacher and Strickling (1955) also reported that rutting did not affect soil bulk density. However, Tippett (1992) reported that rutting did increase the soil bulk densities on these same study sites. Site preparation lowered the bulk density of the rutted soils from 1.39 to

1.30 Mg/m^3, but it also increased the bulk density of the non-trafficked soils from 1.04 to 1.27 Mg/m^3 (Tippett, 1992). The rutted soil bulk densities were lowered because the tillage broke up and loosened the closely aligned soil particles; however, the non-trafficked soil bulk densities were increased because bedding and disking treatments involve trafficking the sites. Slay *et al.* (1987) also showed that site preparation increased bulk densities of non-trafficked soils. Regardless, neither the rutted or non-trafficked soil bulk densities were high enough to be considered root growth-limiting (Gent *et al.*, 1984).

Rutting had no effect on any of the three components of soil porosity (macro-, micro-, and total)(Table 6). This contradicts Dickerson (1976) who reported a 68 percent decrease in soil macroporosity following rutting. This result can be attributed to the ameliorative effects of the site preparation techniques. Indeed, the site preparation treatments doubled and tripled the macroporosity levels of the rutted and non-trafficked soils, respectively (Tippett, 1992)(Figure 7). Site preparation also increased the total porosity of the rutted and non-trafficked soils (Tippett, 1992) (Figure 8). The lack of difference between the post-site preparation micro- and total porosities of the rutted and non-trafficked soils, however, concurs with results reported by Aust *et al.* (1991). This phenomenon can be explained by the physical changes that occur during rutting in which the macroporosity suffers the greatest reduction.

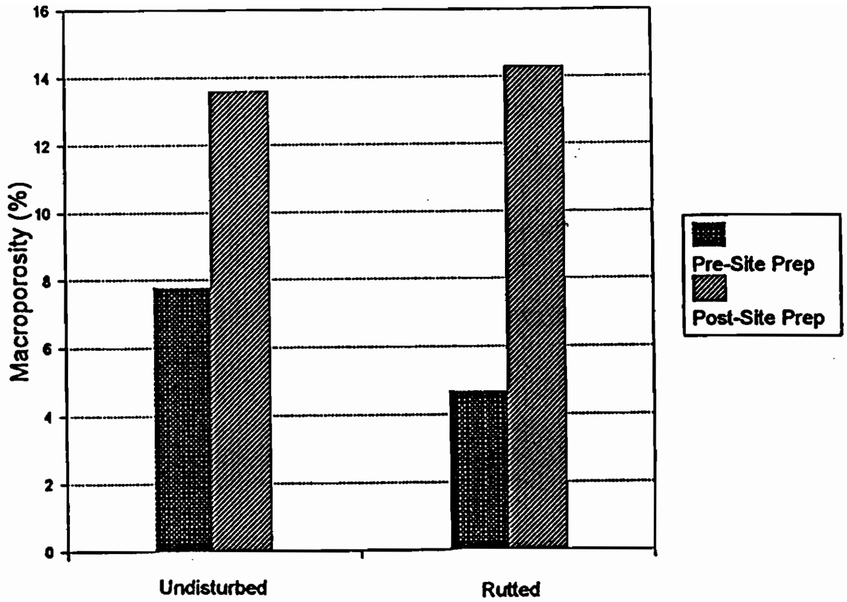

Figure 7. Pre- and post-site preparation macroporosities of the rutted and non-trafficked sites.

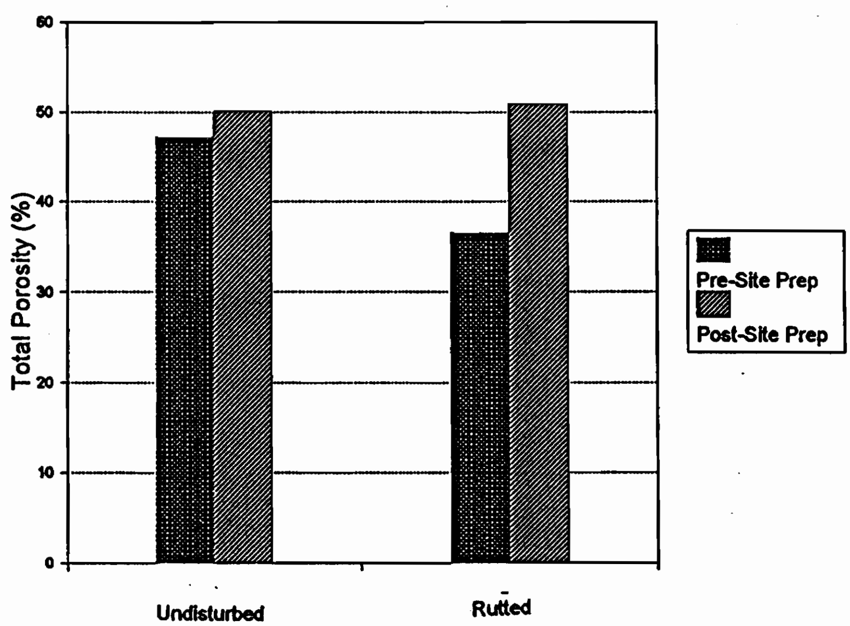

Figure 8. Pre- and post-site preparation total porosities of the rutted and non-trafficked soils.

Rutting also did not affect surface soil organic matter contents (Table 6). This result agrees with Morris and Lowery (1988) who reported that only operations involving relocation of organic matter will result in significant organic matter content differences. Furthermore, rutting had no effect on the mean phosphorous, nitrogen, or potassium contents of the rutted site surface horizons (Table 6); however, Aust (1989) reported trafficking to significantly affect soil phosphorous and nitrogen levels on a wet site in Alabama. Site preparation may have played a key role in the soil nutrient results as most of the rutting effects on the soil were neutralized.

Rutting had no effect on the competing vegetation or foliar nutrient data. Hence, none of these parameters were responsible for the rutting effects on pine seedling growth and survival. While Pavel and Kellison (1993) reported that skidder trafficking significantly increased vegetative competition in a river bottom, there were no rutting effects on competing vegetation in this study (Table 7). The site preparation treatments applied to these sites may be responsible for this result; however, no competing vegetation data were available from control plots to prove this theory.

Rutting also had no effect on the foliar phosphorous, nitrogen, or potassium contents of the pine seedlings (Table 7). Determining the reason for these non-significant differences would be difficult as trafficking effects on soil nutrient contents are not well documented.

Table 7. Average rutting effects on competing vegetation and foliar nutrients.

Vegetation Parameter	Units	Disturbance Class		P-Value
		Non-trafficked	Rutted	
Competing Vegetation Biomass	kg/ha	551	590	0.630
---------- Pine Seedlings ----------				
Foliar Phosphorous	g/kg	11.7	10.8	0.225
Foliar Nitrogen	g/kg	13.4	13.7	0.665
Foliar Potassium	g/kg	47.2	44.9	0.461

Site Preparation Effects

The seedlings growing on the bedded and bedded + disked plots exhibited mean second-year height growths 1.5 times greater than the seedlings growing on the disked plots of the rutted sites. Very similar results were reported by Pritchett (1978) for a study in Florida on eight-year-old slash pines; the trees growing on bedded sites were an average of 3.1 feet taller than the trees growing on disked sites. The seedlings growing on the bedded and disked + bedded plots also exhibited mean volumes three times greater than the seedlings growing on the disked plots.

These pine seedling responses to site preparation were attributed to water supply and movement because site preparation affected two of the measured soil parameters, saturated hydraulic conductivity and mean topographic profile height, both of which are related to soil water supply and movement (Table 8). On these poorly drained wet pine flats, pine seedling growth is often limited by high water tables (Pritchett, 1978). McKee and Shoulders (1970) reported that increasing the height of pine seedlings above the water table on wet sites increased growth. The site preparation treatments that involved bedding proved superior to disking for pine seedling growth because they elevated the pine seedlings further above the water table and increased the drainage of excess water from the rooting zone, thereby increasing aeration and exploitable soil volume (Kozlowski, 1986).

The pine seedling responses to site preparation were attributed to the differences in saturated hydraulic conductivity and mean topographic profile heights as there were no other differences among the site preparation results. Site preparation had no effect on the mean bulk density, macro-, micro-, or total porosity of the rutted site soils (Table 8). Slay *et al.* (1987), studying a variety of site preparation techniques, reported similar results with no bulk density or porosity differences resulting between site preparation treatments except for windrowing. Site preparation also did not affect the mean water table depth of the rutted sites (Table 8).

Table 8. Average site preparation effects on soil physical and chemical properties.

Soil Property	Units	Site Preparation Treatment			P-Value
		Disked	Bedded	Disked & Bedded	
Topographic Profile Height	cm	+1 (a)	+16 (b)	+15 (b)	0.002
Bulk Density	Mg/m^3	1.27	1.26	1.33	0.293
Macroporosity	%	14	15	16	0.207
Microporosity	%	38	38	34	0.187
Total Porosity	%	52	53	50	0.375
Saturated Hydraulic Conductivity	cm/hr	0.47 (a)	2.07 (b)	3.23(b)	0.136
Water Table Depth	cm	-24	-18	-23	0.193
Organic Matter Content	%	4.5	4.5	3.5	0.729
Soil Phosphorous	g/kg	0.006	0.008	0.007	0.836
Soil Nitrogen	g/kg	0.456	0.411	0.308	0.492
Soil Potassium	g/kg	0.356	0.237	0.246	0.377

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

Surface horizon organic matter contents did not vary between site preparation treatments on the rutted sites (Table 8). This result concurs with Morris and Lowery (1988) and Stransky *et al.* (1985) who reported that only operations involving piling or burning will result in organic matter content differences; these treatments have merely redistributed the organic matter throughout the surface soil horizon. Of note, however, is the reduction in soil organic matter content two years after site preparation. The pre-site preparation organic matter contents were double what they were two years after site preparation (Tippett, 1992)(Figure 9). Barber (1984) reported that 50 to 80 percent of freshly added organic matter decomposed within the first year in a temperate soil. The site preparation treatments probably increased decomposition rates on these sites by increasing porosity levels. High decomposition rates are indicators of good overall site health on these type of sites (Kimmins, 1987).

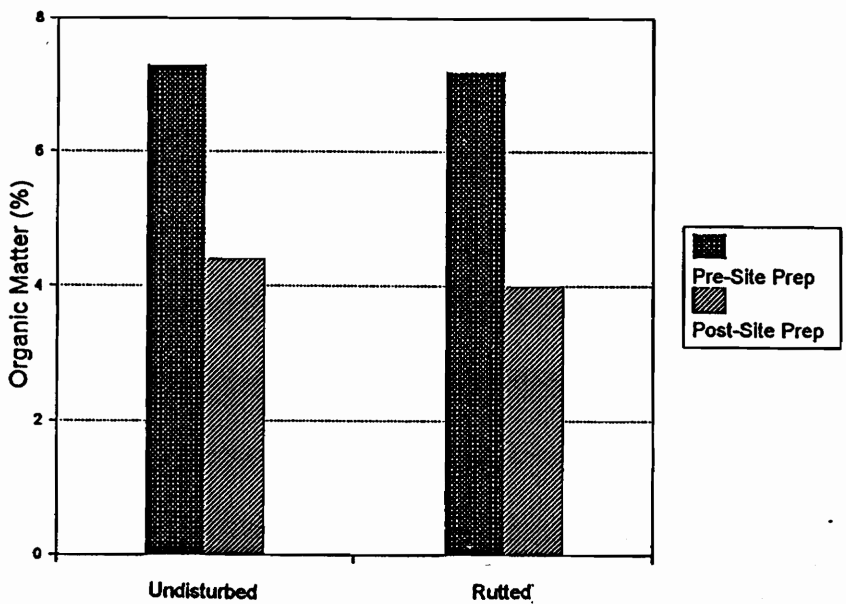

Figure 9. Pre- and post-site preparation organic matter contents of the rutted site soils.

Site preparation did not affect the phosphorous, nitrogen, or potassium contents of the rutted site soils, either (Table 8). Conversely, Wilhite and McKee (1986) reported that bedding increased the amount of available phosphorous in the surface soil of a wet coastal plain site. However, Morris and Lowery (1988) reported that consistent differences in soil phosphorous contents between site preparation treatments have not been found. Morris and Lowery (1988) also reported that site preparation treatments that do not involve burning or piling will not significantly affect surface soil nitrogen contents. Supporting the soil potassium result, Stransky *et al.* (1985) and Wilhite and McKee (1986) reported that site preparation treatments do not affect soil potassium contents. Furthermore, the lack of difference between the soil potassium contents may be the result of the relatively high mobility of the potassium ion which is readily leachable (Binkley, 1986); after two years, potassium levels likely levelled out.

The bedded + disked plots contained 75 percent more competing vegetation than the bedded or disked plots (Table 9). These results somewhat concur with those of Pritchett (1978) who reported no differences between bedding and disking treatments on a coastal plain site; however, his study did not include a combination treatment. It is normally accepted that increased site preparation intensity results in decreased vegetative competition (Conde *et al.*, 1983); however, the most intense treatment resulted in the most competition in this study. Rheney and Pienaar (1993) reported similar results on a study in South Carolina, Georgia, and Alabama in which their most intense site preparation treatment (shear, pile, and disk) resulted in the second highest amount of herbaceous competition. The combined advantages of finer tillage from the disking and greater elevation from the bedding may have caused this competing vegetation result.

Competing vegetation did not have a detrimental effect on pine seedling growth in the first two years as the treatment with the most competition also exhibited the highest pine seedling growth rates. Evidently, the two-year-old pine seedlings obtained sufficient resources despite the increased competition. Furthermore, it is possible that the increased competition actually aided the pine seedlings by taking up more water on these wet sites, thereby increasing aeration in the rooting zone of the pine seedlings and creating a more favorable growing environment. As the seedlings continue to grow, however, their nutrient requirements will increase, and the competing vegetation may have an adverse effect on pine growth. Weed control has been reported to increase pine height, volume, and survival after four to twenty years by many researchers (Creighton *et al.*, 1986; Haywood, 1987; and Smethurst and Comerford, 1993).

Table 9. Average site preparation effects on competing vegetation and pine seedling foliar properties in the rutted study.

Vegetation Parameter	Units	Site Preparation Treatment			P-Value
		Disked	Bedded	Disked & Bedded	
Competing Vegetation Biomass	kg/ha	485 (a)	449 (a)	774 (b)	0.062
---------- **Pine Seedlings** ----------					
Foliar Phosphorous	g/kg	13.0 (b)	10.6 (a)	11.1 (ab)	0.051
Foliar Nitrogen	g/kg	13.7	13.6	13.4	0.867
Foliar Potassium	g/kg	46.8	44.3	47.0	0.489

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

The seedlings on the disked sites had the highest foliar phosphorous content followed by those on the disked + bedded sites and those on the bedded sites in decreasing order (Table 9). This result is exactly opposite of that reported by Wilhite and McKee (1986). The foliar phosphorous results show a dilution effect as all of the pine seedlings apparently received a sufficient phosphorous supply, but the bedded and disked + bedded seedlings grew better despite their lower phosphorous contents. Indeed, all treatments exhibited foliar phosphorous contents above the 0.10 g/kg critical value below which pine seedlings are phosphorous-deficient (Burger, 1993)

Foliar nitrogen and potassium contents of the rutted site pine seedlings were not affected by site preparation (Table 9). Wilhite and McKee (1986) reported a lower foliar nitrogen content for seedlings growing on disked sites as opposed to seedlings growing on bedded sites, but they also reported that site preparation had no effect on pine seedling foliar potassium contents.

Fertilization Effects

Fertilization increased both pine seedling height growth and total volume (Table 5); therefore, the pine seedlings responded to an increased nutrient supply. The fertilizer had an additive effect to the site preparation effects which appeared to have more control over the pine seedling growth.

Fertilization increased the surface soil phosphorous and potassium contents of the rutted sites by 33 and 26 percent, respectively (Table 10). Van Lear (1980) also found phosphorous applications to increase soil phosphorous contents. Fertilization had no effect on surface soil nitrogen contents in the rutted study (Table 10). Pritchett (1978) also reported similar results with no difference between the nitrogen contents of fertilized and unfertilized soils. These results can be explained by the effect of a high water table and poor drainage on soil nutrients. High water tables tend to shift soil solution pH towards neutral and can increase leaching losses of mobile nutrients such as nitrogen ions. The additional nitrogen applied to the fertilized sites was probably lost via leaching (Binkley, 1986). Submergence also chemically reduces soils thereby affecting the oxidation state (i.e. plant availability) of soil nutrients (McKee, 1970). Phosphorous availability can be increased by submergence and this may explain the significantly higher amount of soil phosphorous resulting from fertilization on the rutted sites.

Table 10. Average fertilization effects on the soil chemistry of the rutted study.

Parameter	Units	Fertilization Treatment		P-Value
		Fertilized	Unfertilized	
Soil Phosphorous	g/kg	0.008 (b)	0.006 (a)	0.095
Soil Nitrogen	g/kg	0.402	0.383	0.556
Soil Potassium	g/kg	0.311 (b)	0.247 (a)	0.093

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

The greater soil phosphorous levels on the fertilized plots led to a higher foliar phosphorous content among the fertilized seedlings (Table 11). Similar results were reported by Torbert and Burger (1984) and Morris and Lowery (1988) who also reported increased foliar phosphorous contents as a result of phosphorous fertilization. Fertilization, however, had no effect on the mean pine seedling foliar nitrogen or potassium contents on the rutted sites (Table 11). Pritchett (1978) also reported that fertilization had no effect on foliar nitrogen content while Wilhite and McKee (1986) reported similar soil potassium results for their study on the South Carolina coastal plain. The lack of foliar nitrogen content difference between fertilization treatments is explained by the equal corresponding soil nitrogen contents, the high soil nitrogen contents, and the small nutrient requirements of the seedlings. The pine seedlings were not large enough to benefit directly from the nitrogen application. The lack of difference in the foliar potassium contents, despite an increase in the fertilized soil potassium content, is a result of potassium sufficiency on both the fertilized and unfertilized plots. Fertilization did not increase competing vegetation biomass on the rutted sites (Table 11); however, Jobidon (1993) reported an increase in vegetative competition as a result of fertilization.

Table 11. Average fertilization effects on the competing vegetation and pine seedling foliar properties in the rutted study.

Parameter	Units	Fertilization Treatment		P-Value
		Fertilized	Unfertilized	
Competing Vegetation Biomass	kg/ha	608	533	0.364
---------- Pine Seedlings ----------				
Foliar Phosphorous	g/kg	11.8 (b)	10.7 (a)	0.113
Foliar Nitrogen	g/kg	13.6	13.6	0.925
Foliar Potassium	g/kg	46.9	46.6	0.901

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

COMPACTED STUDY

Pine Seedling Response

Compaction reduced the second-year height growth and survival rate of the pine seedlings growing on the compacted plots by 31 and 14.5 percent, respectively (Table 12). These results agree with Hatchell *et al.* (1970) who reported that compaction decreased seedling height growth and Foil and Ralston (1967) who reported that compaction reduced pine seedling survival. Compaction did not, however, affect the total volume of the seedlings growing on the compacted sits; whereas, Mitchell *et al.* (1982) reported that soil compaction reduced seedling volume.

Table 12. Compaction effects on two-year-old pine seedlings.

Pine Seedling Parameter	Units	Disturbance Class	
		Non-trafficked	Compacted
2nd Year Height Growth	cm	51 (b)	39 (a)
Seedling Volume	cm^3	258	211
Seedling Survival	%	92 (b)	80 (a)

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

Bedding increased pine seedling height growth and total volume by 106 and 421 percent, respectively, over disking on the compacted sites; however, disking + bedding did not provide further growth increases over bedding alone (Table 13). Pritchett (1978) reported similar height growth results on a study in Florida in which eight-year-old disked slash pines were only an average of one foot taller than corresponding pines growing on flat-planted sites; whereas, bedded pines were an average of 4.1 feet taller. McKee and Hatchell (1987) reported similar volume results on a similar study in the South Carolina coastal plain. Site preparation did not, however, affect the survival rate of the seedlings planted on the compacted sites (Table 13). McKee and Hatchell (1987) contradicted this result as they reported that bedding increased pine seedling survival.

Table 13. Average site preparation effects on the compacted site pine seedlings.

Pine Seedling Parameter	Units	Site Preparation Treatment		
		Disked	Bedded	Disked & Bedded
2nd Year Height Growth	cm	27 (a)	55 (b)	52 (b)
Seedling Volume	cm^3	61 (a)	318 (b)	325 (b)
Seedling Survival	%	85	91	82

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

Fertilization increased mean second-year seedling height growth and volume of the pine seedlings growing on the compacted sites by 65 and 155 percent, respectively (Table 14). Pritchett (1978) also found that fertilization increased loblolly pine height and volume growth in a similar study in the coastal plain of Florida. Fertilization did not affect the pine seedling survival rate on the compacted sites (Table 14).

Table 14. Mean fertilization effects on pine seedling growth in the compacted study.

Parameter	**Units**	**Fertilization Treatment**	
		Fertilized	**Unfertilized**
2nd Year Height Growth	cm	57 (b)	34 (a)
Seedling Volume	cm^3	337 (b)	132 (a)
Seedling Survival	%	87	86

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

As in the rutted study, there were no interaction effects between trafficking, site preparation, and fertilization for the pine seedling parameters (Appendix B). However, the fertilization again had an additive effect on the pine seedling height growth and total volume (Figures 10 and 11). These results further suggest that fertilization may be an inexpensive alternative to mechanical site preparation on wet sites; however, bedding plus fertilization will provide the greatest amount of growth.

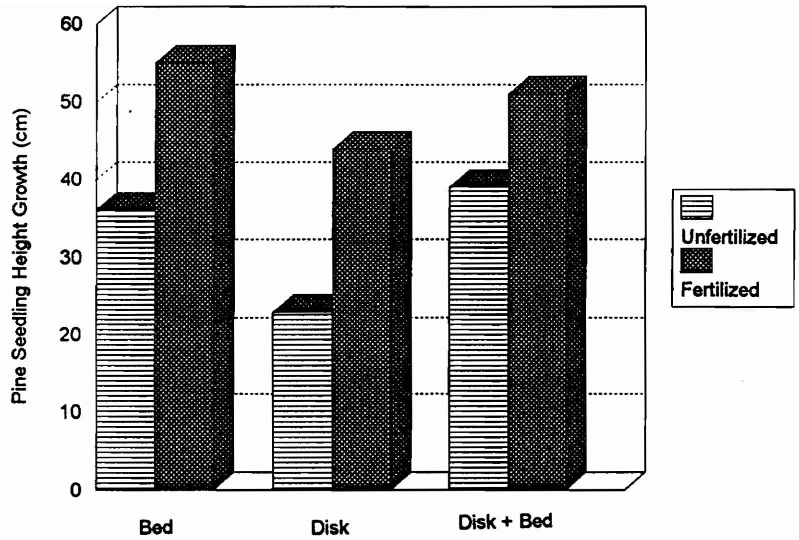

Figure 10. Additive effect of fertilization on compacted site pine seedling height growth.

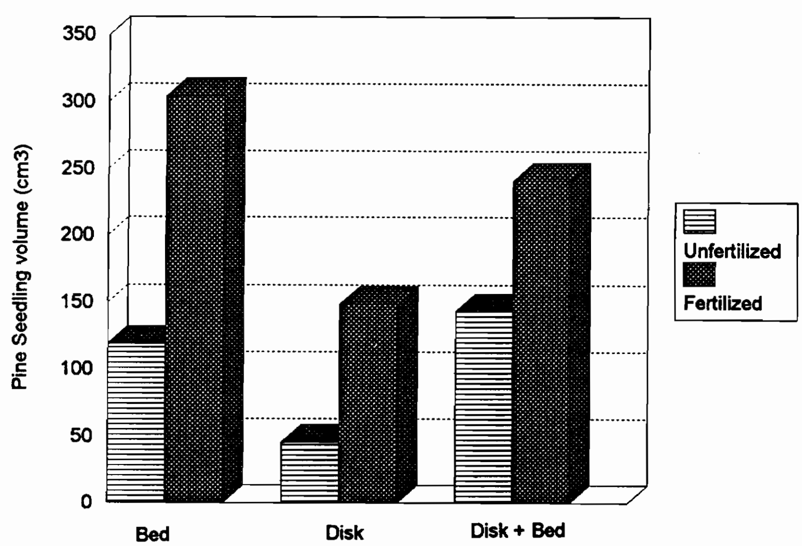

Figure 11. Additive effect of fertilization on compacted site pine seedling volume.

Significant Factors Influencing Pine Seedling Responses

Compaction Effects

Compaction still affected the mean bulk density, macro-, micro-, and total porosities, and depth to water table three years after trafficking and two years after site preparation (Table 15). As with the rutted sites, these parameters were related to water movement and supply.

Two years after site preparation, the mean bulk density of the compacted soils was higher than that of the non-trafficked soils; therefore, bedding and disking did not ameliorate the compaction effects on soil bulk density. In fact, site preparation increased the bulk density of both soils by 18 and 43 percent, respectively (Tippett, 1992). This was a result of further trafficking during the site preparation treatments. Regardless of this result, even the compacted soil bulk density was not high enough to be considered root growth limiting (Gent *et al.*, 1984). Furthermore, Burger (1990) stated that, regardless of the actual bulk density, soil strength is usually not a root growth limiting factor in wetland soils due their high moisture contents. Hence, the porosity and depth to water table differences were responsible for the pine seedling year height growth and survival rate reductions caused by compaction (Table 12).

Of the porosity components, macroporosity has the greatest effect on the drainage of water through soil due to larger pore diameters. Greacen and Sands (1980) reported that a macroporosity of at least ten percent is necessary for adequate drainage and aeration in the rooting zone. Both the compacted and non-trafficked macroporosity levels were well above this critical level due to site preparation. Site preparation increased the macroporosity of the compacted and non-trafficked soils by 35 and 54 percent, respectively (Tippett, 1992)(Figure 12). Microporosity has little effect on drainage; however, it does contribute the amount of void space in the soil and, therefore, creates a more favorable growing environment on wet sites as it increases. Total porosity is the sum of macro- and microporosity and, like microporosity, is a measure of improved root-growing environment as it increases. Site preparation also raised the total porosity levels of the compacted and non-trafficked soils (Tippett, 1992)(Figure 13). Because it increased drainage and aeration, the greater macroporosity level of the non-trafficked soils was the most important porosity factor in the pine seedling responses on the compacted sites.

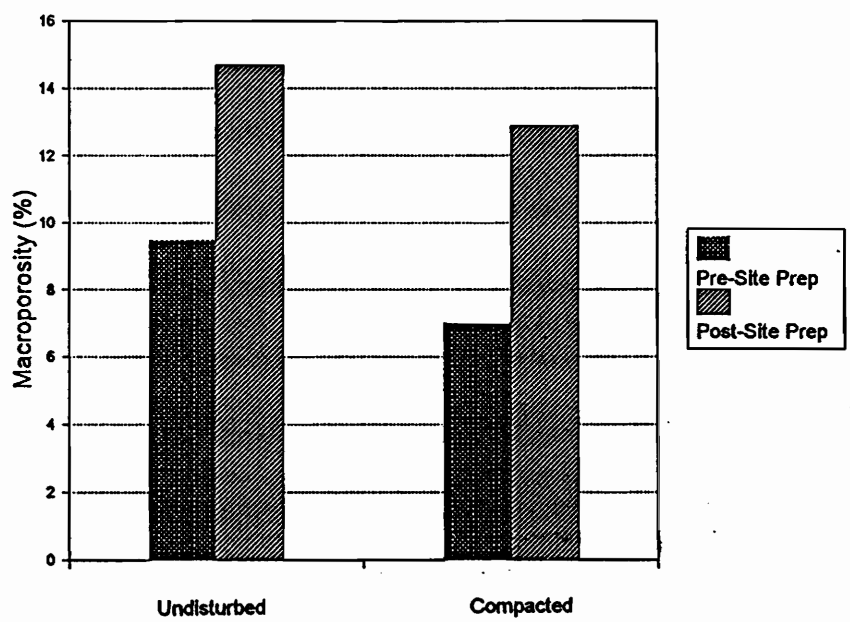

Figure 12. Pre- and post-site preparation macroporosity levels of the compacted and non-trafficked soils of the compacted study.

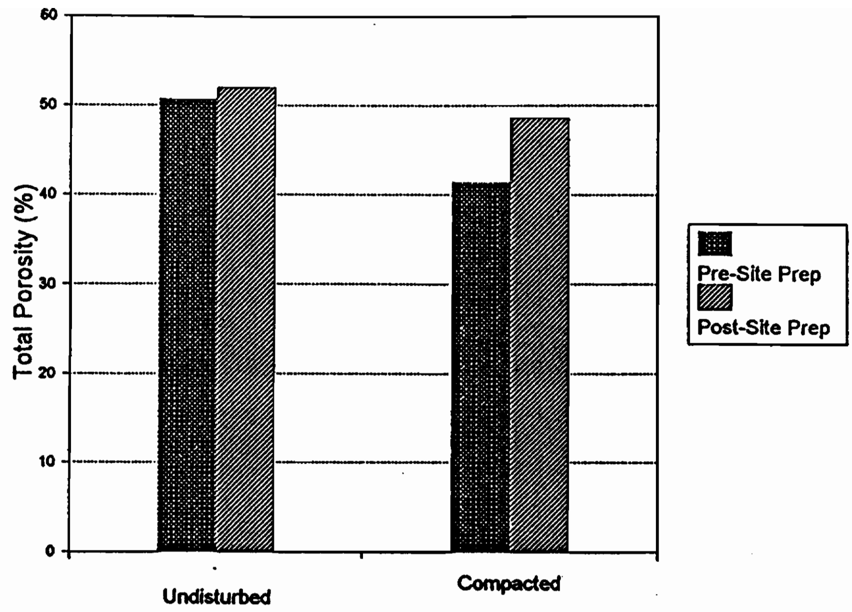

Figure 13. Pre- and post-site preparation total porosity levels of the compacted and non-trafficked soils in the compacted study.

The higher water tables on the compacted plots, however, were the major cause of the reduced pine seedling growth and survival in the compacted study. Aust *et al.* (1991) reported that trafficking raised water tables on a wet pine flat in South Carolina by reducing drainage; this effect reduced the rooting zone oxygen supply and can drown seedling root systems. Perison *et al.* (1993) also reported that trafficking raised site water tables. The water table was ten centimeters higher on the compacted plots compared to the non-trafficked plots. This difference provided the pine seedlings growing on the non-trafficked sites with greater aeration in the rooting zone. For two-year-old seedlings, ten centimeters may have been the difference between sufficient aeration and submersion of their root systems, thereby resulting in the greater pine seedling growth and survival responses on the non-trafficked sites. Especially important is the water table depth during the growing season. In southeastern South Carolina, the growing season is approximately ten months long, and the water tables were highest during the dormant period from December to February (Figure 14).

Table 15. Average compaction effects on soil physical and chemical properties.

Soil Property	Units	Disturbance Class		P-Value
		Non-trafficked	Compacted	
Topographic Profile Height	cm	+12	+12	0.378
Bulk Density	Mg/m^3	1.27 (a)	1.36 (b)	0.027
Macroporosity	%	15 (b)	13 (a)	0.022
Microporosity	%	37 (b)	36 (a)	0.064
Total Porosity	%	52 (b)	49 (a)	0.026
Saturated Hydraulic Conductivity	cm/hr	1.5	1.0	0.166
Water Table Depth	cm	-24 (b)	-13 (a)	0.003
Organic Matter Content	%	5.3	5.0	0.437
Soil Phosphorous	g/kg	0.011	0.012	0.692
Soil Nitrogen	g/kg	0.456	0.404	0.272
Soil Potassium	g/kg	0.257	0.244	0.619

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

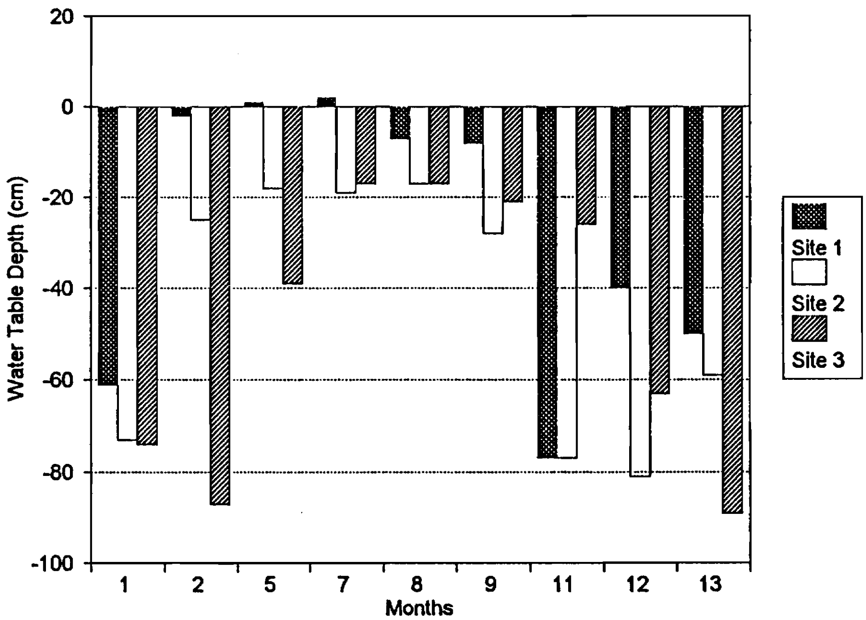

Figure 14. Typical compacted site water tables as measured from July, 1992 to July, 1993.

Two years after site preparation, compaction did not affect any of the other soil physical and chemical properties measured in this study. Hence, none of these parameters were factors in the pine seedling responses found on the compacted sites (Table 15).

Compaction did not affect the mean topographic profile heights of the compacted sites (Table 15) even though Tippett (1992) noted trafficking effects on topographic profiles on the same study sites. Site preparation nullified the compaction effects on this parameter as in the rutted study. Compaction also had no effect on mean saturated hydraulic conductivity in the compacted study (Table 15). Conversely, Aust et al. (1991) reported decreases in saturated hydraulic conductivity following compaction of moist soils. Site preparation caused this result; however, site preparation actually decreased the saturated hydraulic conductivities of the compacted and non-trafficked soils by 58 and 1160 percent, respectively. This result does not concur with the increased porosities, however, which usually increase hydraulic conductivity. The decreased saturated hydraulic conductivity values could be the result of an uneven spatial distribution of the site prepared soil which would result in irregular patches of soil with low hydraulic conductivities (Roseberg and McCoy, 1992).

Compaction did not affect the organic matter content of the surface soil horizons (Table 15). This result is explained by Morris and Lowery (1988) and Stransky *et al.* (1985) who reported that organic matter contents are not significantly affected by operations that do not involve relocation of organic matter. Compaction also did not affect surface soil phosphorous, nitrogen, or potassium contents (Table 15). Trafficking effects on soil nutrients are not well documented; hence, comparisons were hard to locate.

Compaction had no effect on the competing vegetation or pine seedling foliar nutrients in the compacted study (Table 16). Hence, none of these parameters caused the pine seedling responses to compaction. Compaction did not affect the amount of competing vegetation. Site preparation probably caused this result by eliminating most of the variation between the top six inches of the compacted and non-trafficked soils. Compaction also did not affect the mean pine seedling foliar phosphorous, nitrogen, or potassium contents (Table 16). Comparisons for the phosphorous and potassium contents were not found as trafficking effects on these foliar nutrients are not well documented. However, Voorhees *et al.* (1989) reported that compaction decreased nitrogen uptake by corn crops. Site preparation may have ameliorated compaction effects on these parameters.

Table 16. Compaction effects on competing vegetation and foliar nutrient contents.

Vegetation Parameter	Units	Disturbance Class		P-Value
		Non-trafficked	Compacted	
Competing Vegetation Biomass	kg/ha	416	400	0.748
---------- Pine Seedlings ----------				
Foliar Phosphorous	g/kg	11.0	10.0	0.160
Foliar Nitrogen	g/kg	12.9	12.6	0.678
Foliar Potassium	g/kg	41.6	38.9	0.274

Site Preparation Effects

Site preparation affected two of the soil parameters measured in this study, mean topographic profile height and macroporosity (Table 17). As with the trafficking results, these factors were related to water movement and supply and caused the pine seedling height and volume responses to the site preparation treatments.

The bedded and disked + bedded treatments resulted in average topographic profile heights at least 12 centimeters higher than the disked treatment (Table 17). The mounding effect of bedding plus the incorporation of large logging debris (small tree boles and large limbs) into the beds caused this topographic difference. The bedded and disked + bedded treatments also resulted in higher macroporosity levels than the disked treatment (Table 17); this was due to the physical processes associated with these techniques. Bedding loosened and turned larger chunks of soil while disking chipped up soil aggregates through its finer tillage.

These results indicate that the better drainage and aeration provided by the greater macroporosity and elevated topographic profile heights of the bedded treatments provided a better growing environment for the pine seedlings. Consequently, the bedded pine seedlings grew taller and larger than the seedlings growing on disked plots.

Table 17. Site preparation effects on soil physical and chemical properties in the compacted study.

Soil Property	Units	Site Preparation Treatment			P-Value
		Disked	Bedded	Disked & Bedded	
Topographic Profile Height	cm	+2 (a)	+19 (b)	+15 (b)	0.001
Bulk Density	Mg/m^3	1.29	1.29	1.37	0.326
Macroporosity	%	13 (a)	16 (b)	14 (ab)	0.002
Microporosity	%	39	36	35	0.251
Total Porosity	%	52	52	49	0.320
Saturated Hydraulic Conductivity	cm/hr	0.38	2.33	1.04	0.196
Water Table Depth	cm	-18	-18	-20	0.886
Organic Matter Content	%	4.9	4.9	5.6	0.313
Soil Phosphorous	g/kg	0.014	0.009	0.011	0.465
Soil Nitrogen	g/kg	0.405	0.460	0.420	0.559
Soil Potassium	g/kg	0.247	0.268	0.237	0.539

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

Site preparation had no effect on any of the other soil physical or chemical properties measured in this study. They did not affect the mean bulk density or mean micro- or total porosity of the compacted site soils (Table 17). Slay *et al.* (1987) also reported that site preparation treatments did not affect total porosity following site preparation. The site preparation treatments did not affect the saturated hydraulic conductivity of the compacted sites, even though the disked plots had a mean saturated hydraulic conductivity at least 2.5 times lower than those of the bedded and disked + bedded plots (Table 17). With a p-value of 0.196, this result was close to being statistically significant and may have affected the pine seedling response as the lowest saturated hydraulic conductivity corresponded with the lowest seedling height and volume responses.

Site preparation treatment did not affect the mean water table depths of the compacted sites (Table 17). The relatively shallow soil depth affected by bedding and disking may explain this result. It is possible that only operations that till at least the entire A horizon will affect water table depths. Soil organic matter contents also did not vary among site preparation treatments on the compacted sites (Table 17). Wilhite and McKee (1986) also reported that bedding and disking did not have an effect on surface soil organic matter content. Morris and Lowery (1988) explained that treatments that do not result in the relocation of organic matter will not affect soil organic matter contents. Of note, again, is the soil organic matter content reductions two years after site preparation (Tippett, 1992)(Figure 15). Barber (1984) reported that 50 to 80 percent of freshly added organic matter decomposed within the first year in a temperate soil. The site preparation treatments probably increased decomposition rates on these sites by increasing porosity levels. High decomposition rates are indicators of good overall site health on these types of sites (Kimmins, 1987).

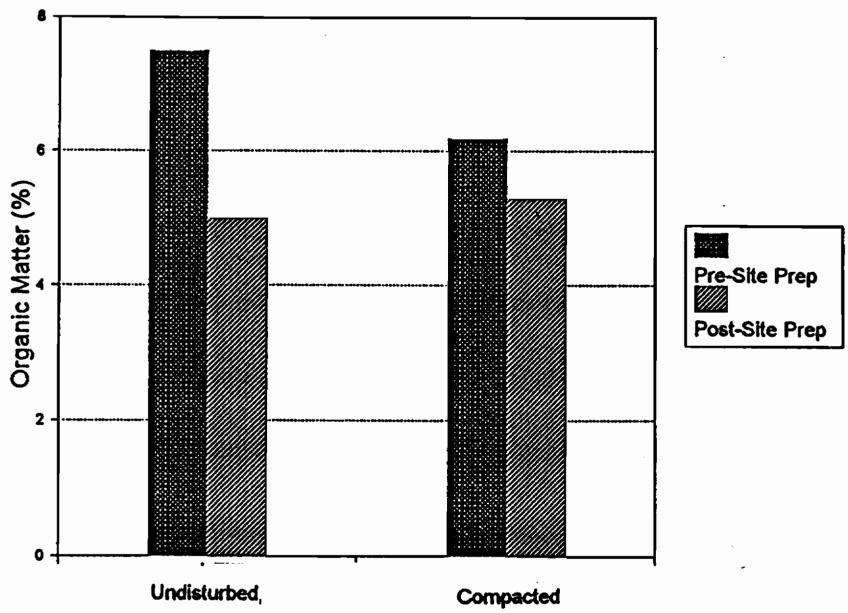

Figure 15. Compacted site soil organic matter decreases two years after site prep.

Site preparation had no effect on the mean surface soil phosphorous, nitrogen, or potassium contents of the compacted sites (Table 17). Wilhite and McKee (1986) also reported that bedding and disking did not affect surface soil phosphorous content; however, Wilhite and McKee (1986) reported a greater soil nitrogen content for disked soils than for bedded soils. Such a difference may have existed immediately after the site preparation treatments were installed, but the nitrogen levels are likely to have equalized after two years due to the mobility of nitrogen ions (Binkley, 1986).

Site preparation also did not affect competing vegetation or foliar nutrient contents in the compacted study (Table 18). Hence, the pine seedling responses to site preparation were not attributed to these parameters. Site preparation did not affect the mean total competing vegetation biomass on the compacted sites (Table 18). Slay *et al.* (1987) also reported that site preparation treatments similar to these did not affect competing vegetation biomass.

Site preparation also did not affect the mean foliar phosphorous, nitrogen, or potassium contents of the pine seedlings growing on the compacted sites (Table 11). Wilhite and McKee (1986) also reported no difference in foliar phosphorous contents between seedlings growing on bedded and disked sites on a poorly drained site; however, on somewhat poorly and moderately well drained sites, they found higher foliar phosphorous contents among seedlings growing on bedded sites. Wilhite and McKee (1986) found that bedded seedlings had higher foliar nitrogen contents than seedlings growing on disked sites.

Table 18. Site preparation effects on competing vegetation and foliar nutrient properties in the compacted study.

Vegetation Parameter	Units	Site Preparation Treatment			P-Value
		Disked	Bedded	Disked & Bedded	
Competing Vegetation Biomass	kg/ha	448	430	351	0.525
---------- Pine Seedlings ----------					
Foliar Phosphorous	g/kg	10.6	10.9	10.2	0.752
Foliar Nitrogen	g/kg	12.5	14.0	11.8	0.333
Foliar Potassium	g/kg	40.1	40.6	40.0	0.984

Fertilization Effects

Fertilization increased mean competing vegetation biomass and mean pine seedling foliar phosphorous and potassium contents in the compacted study (Table 19). Therefore, these factors have been determined to be responsible for the increased pine growth on the fertilized sites (Table 14).

Table 19. Fertilization effects on the competing vegetation and pine seedling foliar properties of the compacted study.

Parameter	Units	Fertilization Treatment		P-Value
		Fertilized	Unfertilized	
Competing Vegetation Biomass	kg/ha	469 (b)	351 (a)	0.061
---------- Pine Seedlings ----------				
Foliar Phosphorous	g/kg	11.1 (b)	9.9 (a)	0.087
Foliar Nitrogen	g/kg	13.1	12.4	0.364
Foliar Potassium	g/kg	42.2 (b)	38.3 (a)	0.131

* - Difference in alphabetical notation across rows indicates a significant difference as determined by Fisher's protected LSD test.

Fertilization increased mean total biomass of competing vegetation by 34 percent in the compacted study (Table 19). Pritchett (1978) also found fertilization to increase total competing vegetation biomass. Again, competition is generally viewed as a detriment to pine growth; however, the pine seedlings growing on the fertilized plots grew better despite the increased amount of vegetative competition. As in the rutted study, perhaps the increased competition is actually beneficial during early planted pine seedling growth on these wet sites. The competition may be helping to increase the aeration in the rooting zone of the pine seedlings by transpiring more water than the pine seedlings would alone. It is also doubtful that the competition was limiting the nutrient uptake of the two-year-old pine seedlings as their requirements would have been very small.

Fertilization increased pine seedling foliar phosphorous contents by 12 percent on the compacted sites (Table 19). This result concurs with those of Van Lear (1980) and Torbert and Burger (1984). Particularly important is the fact that the fertilized pine seedlings are above the accepted phosphorous critical level of 10.0 g/kg; whereas, the unfertilized seedlings are below this value (Burger, 1993). Also, wet pine flats in this study are inherently phosphorous deficient, and increasing the available phosphorous supply is extremely important. Hence, the increased foliar phosphorous content is the major reason for the pine seedling growth response to fertilization. The increased growth could also have been caused by the higher foliar potassium contents of the fertilized seedlings, but this is not as likely. These site are not known as being potassium deficient, and the seedlings in the rutted study responded to fertilization but only showed higher foliar phosphorous contents. Fertilization, however, did not affect the nitrogen content of the pine seedling foliar tissue on the compacted sites (Table 19). This was a result of the high soil nitrogen contents of both the fertilized and unfertilized plots, the high mobility of nitrogen ions in soil solution which probably equalized nitrogen levels shortly after fertilization (Binkley, 1986). Van Lear (1980) also reported no significant difference in foliar nitrogen contents ten months after fertilization.

Fertilization had no effect on the soil chemical properties; hence, these parameters were determined not to have caused the pine seedling responses to fertilization. Unlike the rutted sites, fertilization did not increase the mean soil phosphorous or potassium content of the compacted sites (Table 20). The phosphorous result contradicts the findings of Van Lear (1980) and Torbert and Burger (1984); however, the lack of soil potassium difference concurs with Wilhite and McKee (1986) who reported the same result for a similar study performed in the South Carolina coastal plain. Fertilization also did not affect surface soil nitrogen contents of the compacted site soils (Table 20). Van Lear (1980) also reported that, after ten months, there was no difference in soil nitrogen content between fertilized and unfertilized sites.

Table 20. Fertilization effects on the soil chemistry of the compacted study.

Parameter	Units	Fertilization Treatment		P-Value
		Fertilized	Unfertilized	
Soil Phosphorous	g/kg	0.012	0.010	0.339
Soil Nitrogen	g/kg	0.440	0.435	0.816
Soil Potassium	g/kg	0.261	0.240	0.401

Conclusions

Both rutting and compaction reduced pine seedling growth and survival despite the application of site preparation treatments. However, site preparation treatments did partially ameliorate trafficking impacts that reduced seedling growth. The bed and combination disk + bed treatments increased second-year pine seedling height growth and volume as compared to the disk treatment on both the rutted and compacted sites. Water supply and movement were determined to be the major factors controlling the pine seedling growth. Seedlings grew better with increased drainage, aeration, and increased distance to the water table.

Fertilization also increased pine seedling growth on both the rutted and compacted sites by increasing the available phosphorous supply. The fertilizer response is attributed to the increased phosphorous supply because the fertilized seedlings did not have significantly higher foliar nitrogen or potassium contents. Also, past studies have reported that fertilization of only phosphorous significantly increased pine growth on the South Carolina coastal plain (Buford and McKee, 1987). The fertilization had an additive effect to the site preparation treatments and, hence, should be used for optimum pine seedling growth. Fertilization also increased the total biomass of competing vegetation on the rutted and compacted sites. Apparently, both desired and competing species made use of the increased nutrient supply. It is possible that fertilization of only phosphorous might result in the same pine seedling growth increases but less competing vegetation because many of the competing species are believed to be more responsive to an increased nitrogen supply (Jobidon, 1993). As suggested, however, the increased competition may actually be beneficial to young pine plantations on wet sites due to its ability to transpire a much greater amount of water than the seedlings alone. This phenomenon may increase aeration in the rooting zone and, therefore, create a more favorable growing environment for the pine seedlings.

Soil macro- and total porosity were increased following site preparation on all soils. The increased porosities increased aeration and drainage in the rooting zone and increased pine seedling growth. Another indication of the increased aeration was the organic matter decomposition in the soils; contents were approximately half that of pre-site preparation levels. Site preparation negatively impacted the bulk density and saturated hydraulic conductivity of the compacted and non-trafficked (of both the rutted and compacted sites) soils but positively affected these parameters on the rutted soils. The site preparation trafficking was responsible for these results as the largest bulk density and hydraulic conductivity impacts occur in the first two passes of wheeled trafficking.

The overall conclusions of this study are that bedding and phosphorous fertilization appear to be the most effective site preparation treatments for the partial amelioration of rutting and compaction impacts on early pine seedling growth. None of these treatments, however, were completely effective. Additional site preparation treatments that affect the soil to a deeper extent may be the only way to completely ameliorate rutting and compaction damage in the first three years.

Increasing drainage, aeration, and depth to water table are the keys to increasing pine seedling growth on wet and poorly drained sites. This conclusion is supported by past research that has reported increased seedling growth with increase seedling elevation above the water table on poorly drained coastal plain sites. Phosphorous fertilization appears to be a profitable treatment on these lower coastal plain sites as it had an additive effect on pine seedling growth. Fertilization also increased the total biomass of competing vegetation, mostly herbaceous, but this may be beneficial to young pine plantations on wet sites because of the greater water transpiration and aeration in the rooting zone. As a final note, disking appears to be a completely ineffective site preparation treatment on these lower coastal plain sites.

This study should have major impacts on lower coastal plain wetland site management decisions. Rutting and compaction impacts from wet weather harvesting can not be completely ameliorated in the first three years by bedding, disking, or fertilization and such disturbances should be avoided when possible. This could be achieved by responsible harvest scheduling on wet sites, *i.e.* during the driest period of the year. Specialized wet-site harvesting equipment should also be used to minimize harvesting impacts on these sites. Finally, for the subsequent establishment of loblolly pine stands on these lower coastal plain sites, bedding and phosphorous fertilization are two site preparation techniques that should be considered; whereas, disking should not. Also, herbicide treatments should possibly be delayed until year four or five as competing vegetation was not detrimental to pine seedling growth in the first two years, and it may actually have been beneficial due to increased water transpiration on these wet, poorly drained sites.

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APPENDIX A - Map of study site and plot locations

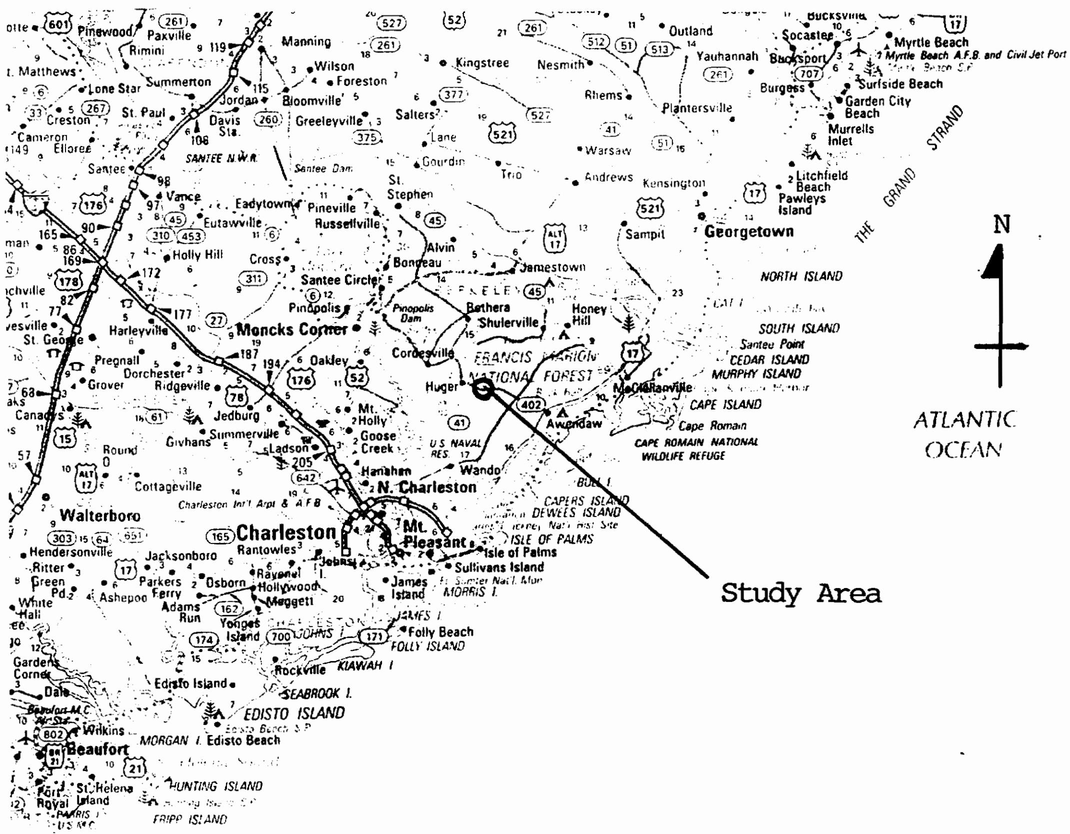

Figure 1. Map of eastern South Carolina with study area denoted.

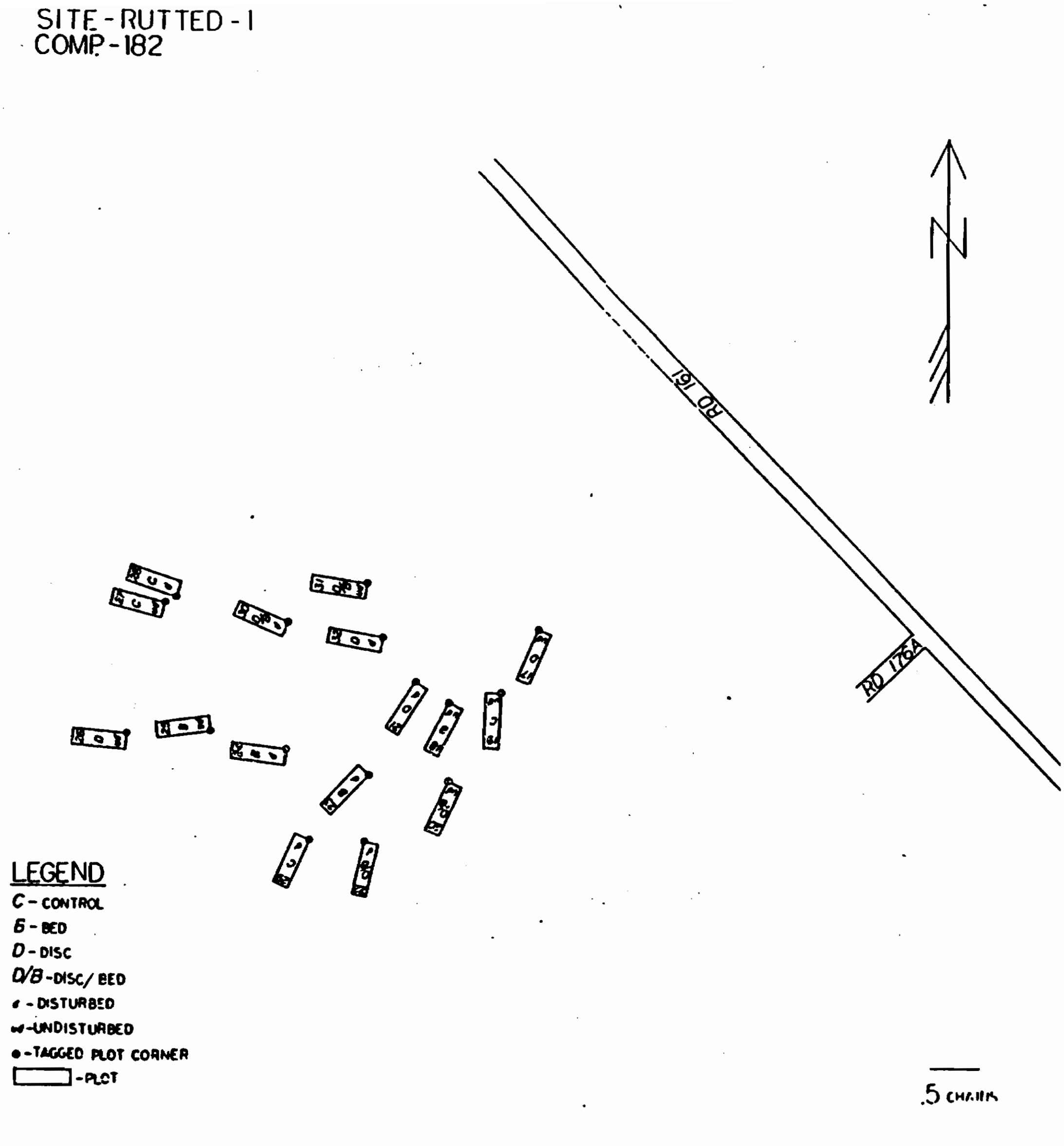

Figure 2. Site #1 of rutted study

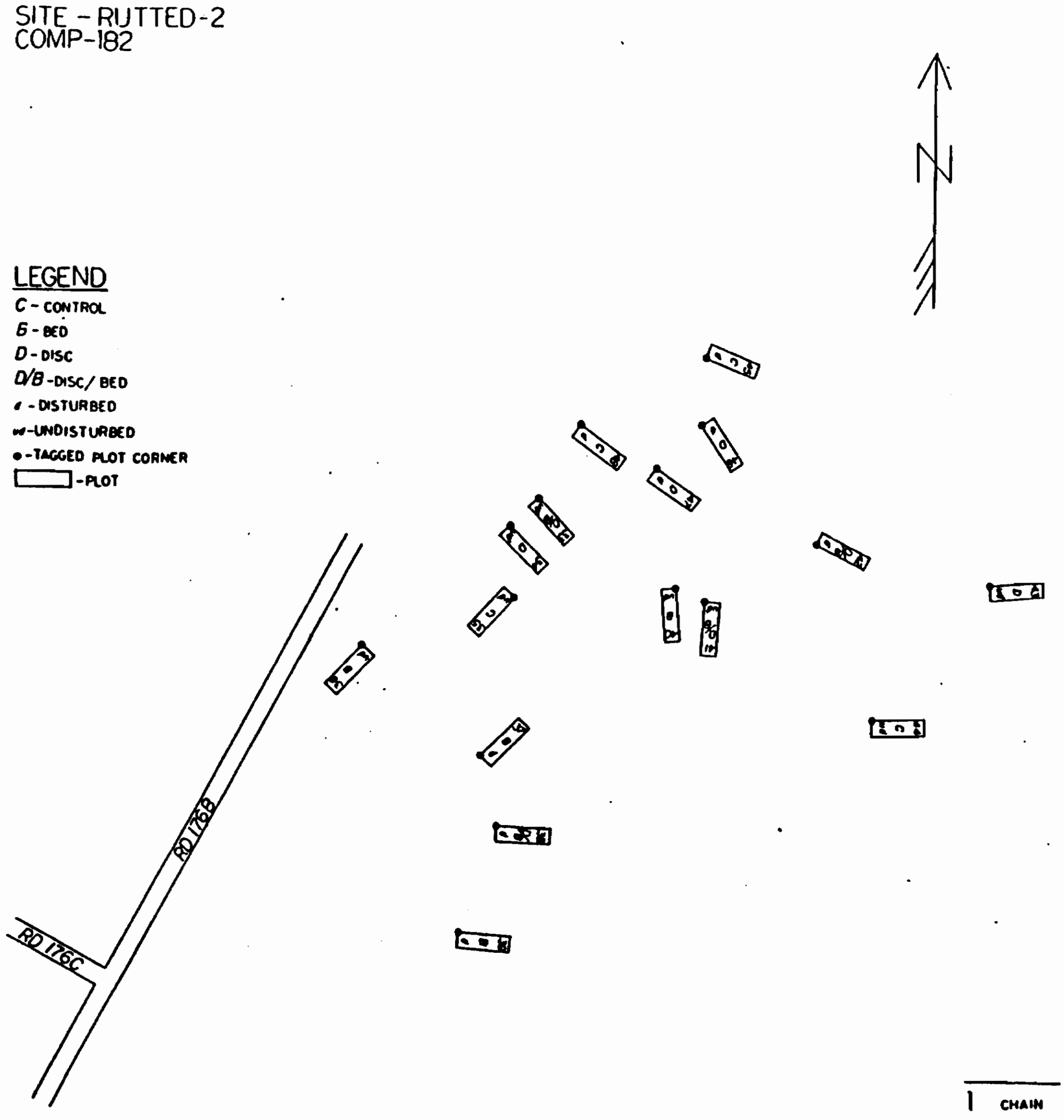

Figure 3. Site #2 of rutted study

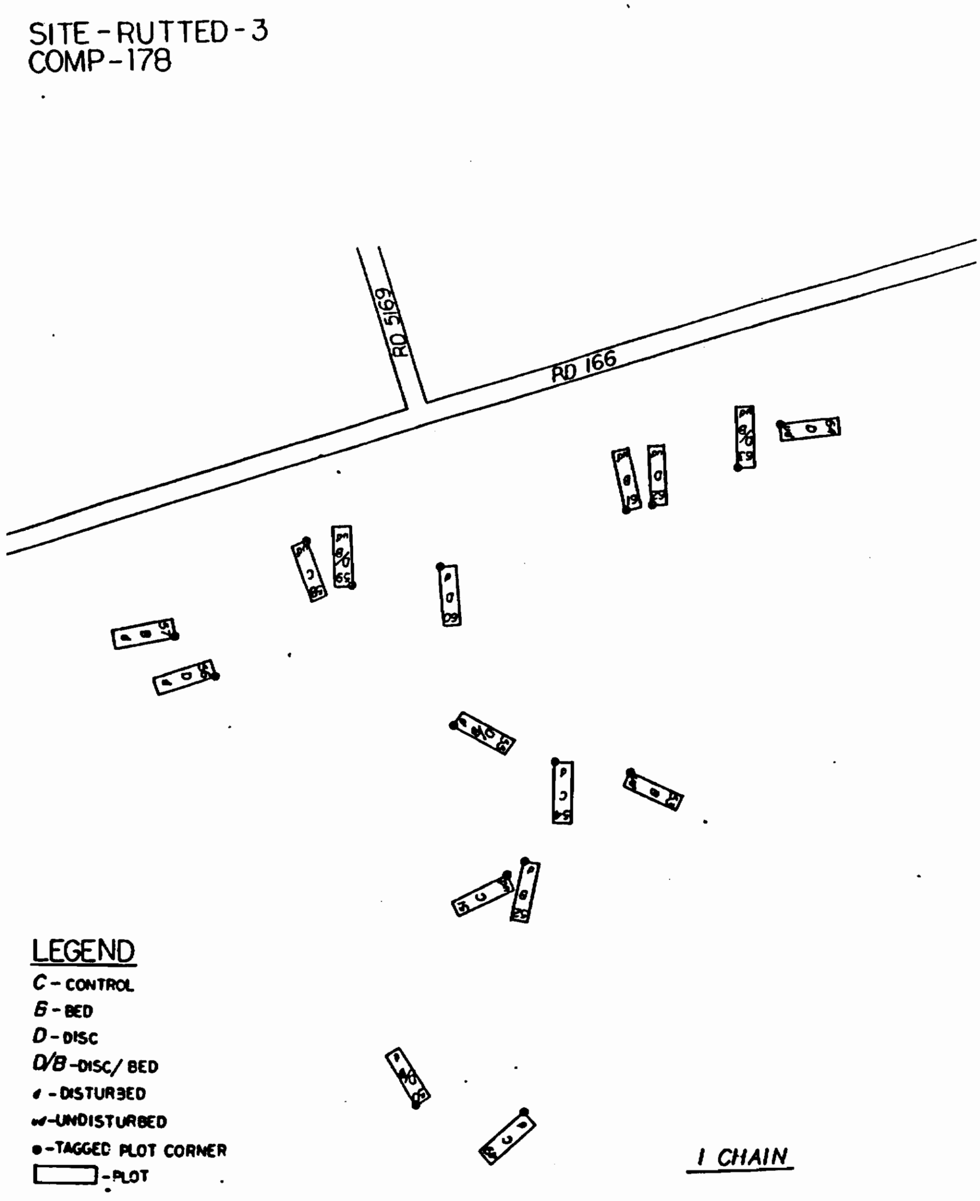

Figure 4. Site #3 of rutted study

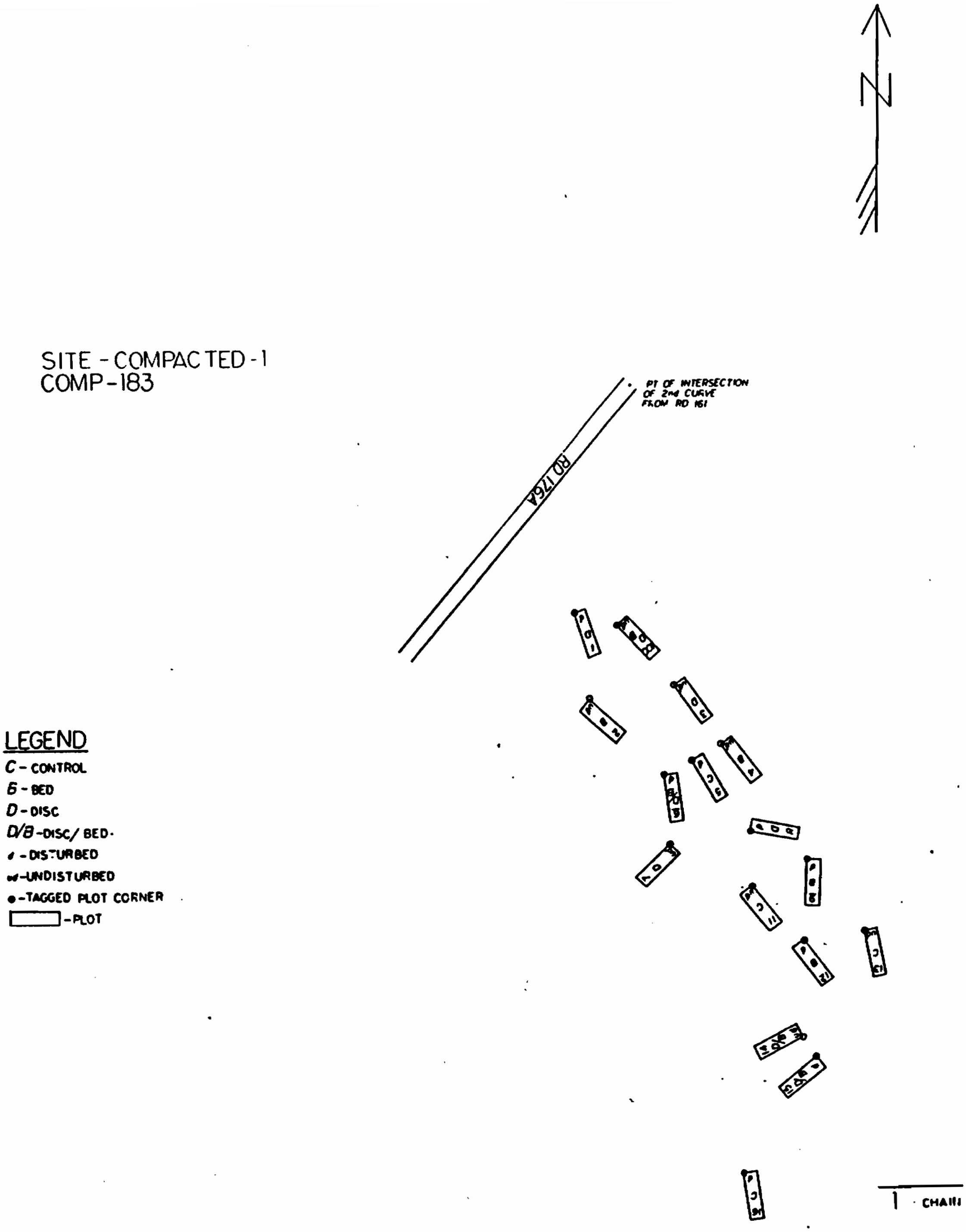

Figure 5. Site #1 of compacted study

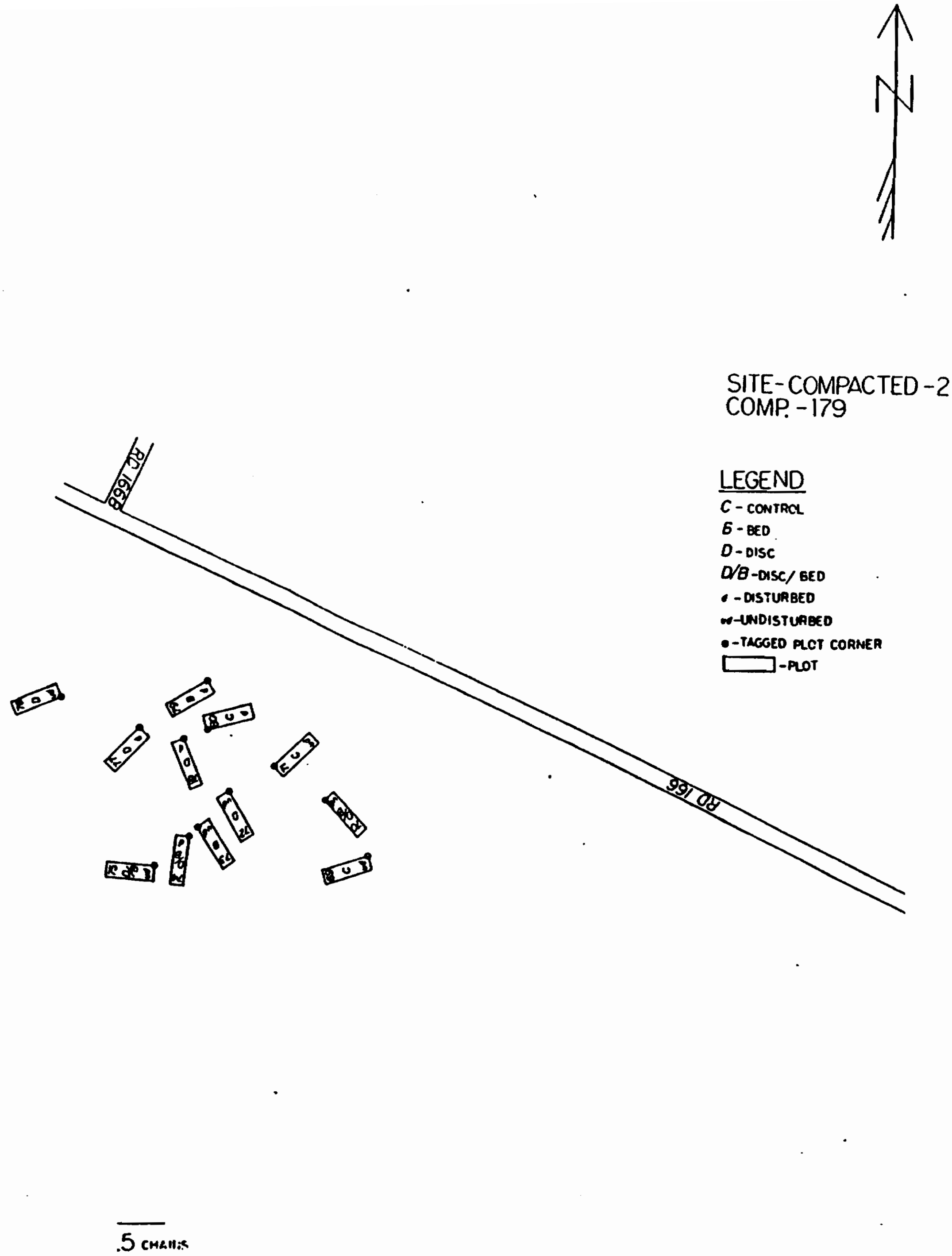

Figure 6. Site #2 of compacted study

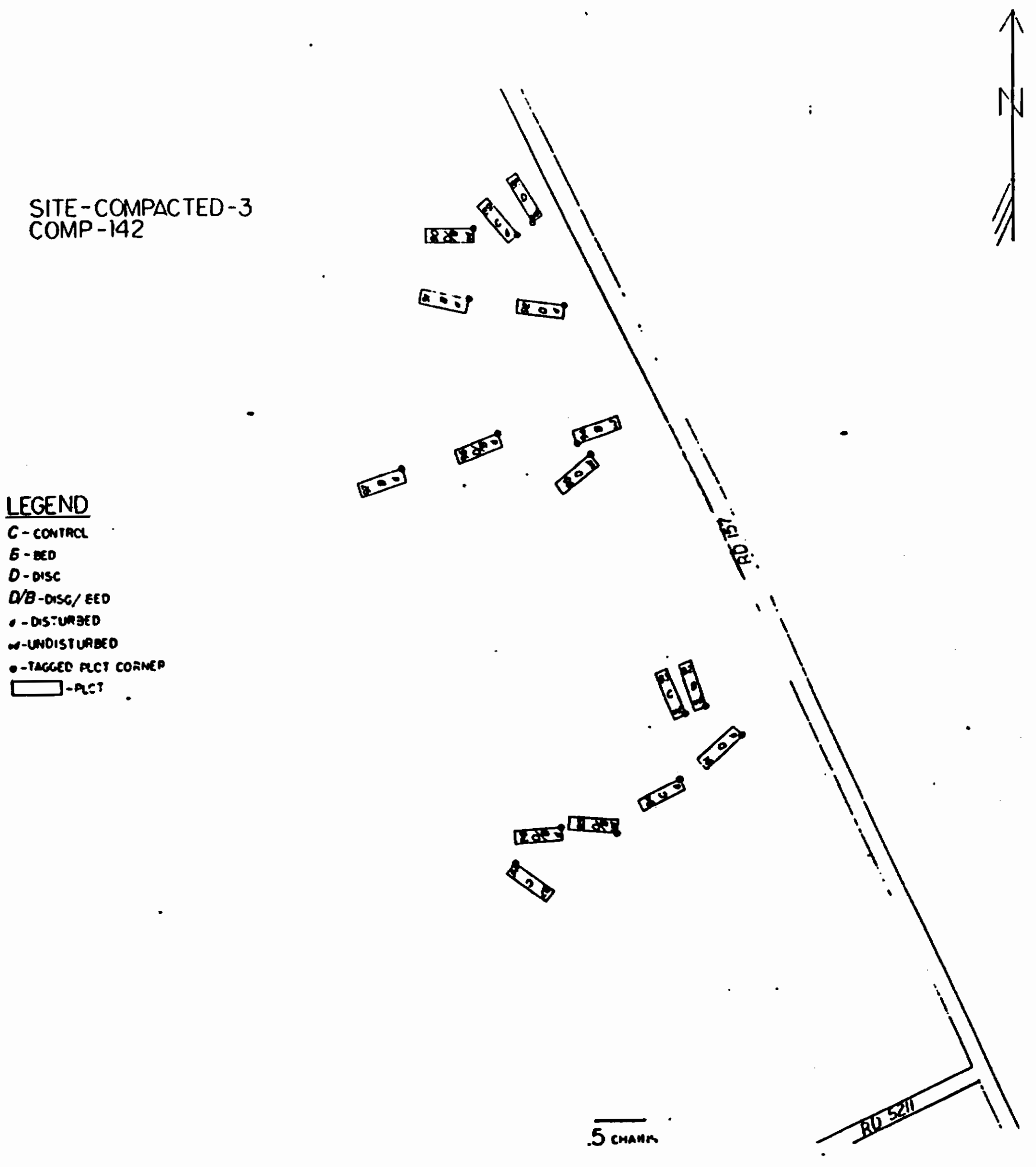

Figure 7. Site #3 of compacted study.

APPENDIX B - Partial GLM ANOVA Tables

Table 1. Partial GLM ANOVA table of topographic profiles for the rutted sites.

Source	df	Mean Square	F-Value	P-Value
Block	2	46.108	58.06	0.0000
Traffic	1	1.476	0.78	0.194
Treatment	2	840.972	48.99	0.002
Block *Trt	4	17.167	21.62	0.000
Traf * Trt	2	5.936	9.85	0.029
Block*Trf*Trt	4	0.603	0.76	0.569
Fertilizer	1	0.675	0.85	0.372
Traf *Fert	1	0.009	0.11	0.740
Trt * Fert	2	0.324	0.41	0.673
Traf*Trt*F	2	0.185	0.23	0.796
Error	14	0.794		
Total	35			

Table 2. Partial GLM ANOVA table of the compacted site topographic profiles.

Source	df	Mean Square	F-Value	P-Value
Block	2	17.098	11.54	0.001
Traffic	1	1.228	0.83	0.378
Treatment	2	1000.765	152.35	0.0002
Block *Trt	4	6.101	4.43	0.016
Traf * Trt	2	20.976	4.49	0.095
Block*Trf*Trt	4	3.790	2.56	0.085
Fertilizer	1	0.013	0.01	0.926
Traf *Fert	1	0.319	0.22	0.650
Trt * Fert	2	0.167	0.11	0.894
Traf*Trt*F	2	0.168	0.11	0.894
Error	14	1.482		
Total	35			

Table 3. Partial GLM ANOVA table of the rutted site mean bulk densities.

Source	df	Mean Square	F-Value	P-Value
Block	2	0.043	4.92	0.024
Traffic	1	0.008	0.92	0.353
Treatment	2	0.017	1.69	0.294
Block *Trt	4	0.010	1.14	0.379
Traf * Trt	2	0.015	1.26	0.377
Block*Trf*Trt	4	0.012	1.38	0.292
Fertilizer	1	0.002	0.25	0.626
Traf *Fert	1	0.001	0.13	0.727
Trt * Fert	2	0.0007	0.08	0.927
Traf*Trt*F	2	0.007	0.81	0.463
Error	14	0.009		
Total	35			

Table 4. Partial GLM ANOVA table of the compacted site mean bulk densities.

Source	df	Mean Square	F-Value	P-Value
Block	2	0.017	1.48	0.261
Traffic	1	0.070	6.08	0.027
Treatment	2	0.022	1.50	0.326
Block *Trt	4	0.015	1.28	0.324
Traf * Trt	2	0.067	6.43	0.056
Block*Trf*Trt	4	0.010	0.91	0.487
Fertilizer	1	0.004	0.33	0.575
Traf *Fert	1	0.002	0.15	0.704
Trt * Fert	2	0.008	0.65	0.535
Traf*Trt*F	2	0.001	0.10	0.908
Error	14	0.012		
Total	35			

Table 5. Partial GLM ANOVA table of the rutted site mean macroporosities.

Source	df	Mean Square	F-Value	P-Value
Block	2	14.734	4.22	0.037
Traffic	1	4.803	1.38	0.260
Treatment	2	13.482	2.40	0.207
Block *Trt	4	5.628	1.61	0.226
Traf * Trt	2	28.863	7.38	0.046
Block*Trf*Trt	4	3.911	1.12	0.386
Fertilizer	1	0.899	0.26	0.620
Traf *Fert	1	2.428	0.70	0.418
Trt * Fert	2	6.284	1.80	0.201
Traf*Trt*F	2	2.431	0.70	0.515
Error	14	3.488		
Total	35			

Table 6. Partial GLM ANOVA table of the compacted site mean macroporosities.

Source	df	Mean Square	F-Value	P-Value
Block	2	34.491	7.74	0.005
Traffic	1	29.503	6.62	0.022
Treatment	2	26.016	41.57	0.002
Block *Trt	4	0.626	0.14	0.964
Traf * Trt	2	2.630	0.36	0.719
Block*Trf*Trt	4	7.326	1.64	0.219
Fertilizer	1	0.777	0.17	0.683
Traf *Fert	1	0.585	0.13	0.723
Trt * Fert	2	6.071	1.36	0.288
Traf*Trt*F	2	2.440	0.55	0.590
Error	14	4.457		
Total	35			

Table 7. Partial GLM ANOVA table of the rutted site mean microporosities.

Source	df	Mean Square	F-Value	P-Value
Block	2	83.259	8.85	0.003
Traffic	1	0.068	0.01	0.933
Treatment	2	55.053	2.63	0.187
Block *Trt	4	20.960	2.23	0.119
Traf * Trt	2	0.047	0.00	0.997
Block*Trf*Trt	4	15.373	1.63	0.221
Fertilizer	1	6.631	0.70	0.415
Traf *Fert	1	9.353	0.99	0.336
Trt * Fert	2	3.717	0.39	0.681
Traf*Trt*F	2	7.002	0.74	0.493
Error	14	9.410		
Total	35			

Table 8. Partial GLM ANOVA table of the compacted site mean microporosities.

Source	df	Mean Square	F-Value	P-Value
Block	2	114.666	21.10	0.000
Traffic	1	22.074	4.06	0.064
Treatment	2	41.611	1.99	0.251
Block *Trt	4	20.880	3.84	0.026
Traf * Trt	2	131.126	6.25	0.059
Block*Trf*Trt	4	20.971	3.86	0.026
Fertilizer	1	1.643	0.30	0.591
Traf *Fert	1	5.832	1.07	0.318
Trt * Fert	2	3.064	0.56	0.581
Traf*Trt*F	2	0.955	0.18	0.841
Error	14	5.434		
Total	35			

Table 9. Partial GLM ANOVA table of the rutted site mean total porosities.

Source	df	Mean Square	F-Value	P-Value
Block	2	82.476	7.90	0.005
Traffic	1	4.285	0.41	0.532
Treatment	2	20.278	1.26	0.375
Block *Trt	4	16.036	1.54	0.246
Traf * Trt	2	32.910	2.89	0.167
Block*Trf*Trt	4	11.393	1.09	0.399
Fertilizer	1	3.157	0.30	0.591
Traf *Fert	1	1.823	0.17	0.682
Trt * Fert	2	1.098	0.11	0.901
Traf*Trt*F	2	9.761	0.94	0.416
Error	14	10.439		
Total	35			

Table 10. Partial GLM ANOVA table of the compacted site mean total porosities.

Source	df	Mean Square	F-Value	P-Value
Block	2	24.717	1.50	0.256
Traffic	1	102.617	6.24	0.026
Treatment	2	32.512	1.54	0.320
Block *Trt	4	21.176	1.29	0.321
Traf * Trt	2	98.452	6.44	0.056
Block*Trf*Trt	4	15.293	0.93	0.474
Fertilizer	1	4.680	0.28	0.602
Traf *Fert	1	2.723	0.17	0.690
Trt * Fert	2	10.311	0.63	0.548
Traf*Trt*F	2	1.350	0.08	0.922
Error	14	16.436		
Total	35			

Table 11. Partial GLM ANOVA table of the rutted site mean saturated hydraulic conductivities.

Source	df	Mean Square	F-Value	P-Value
Block	2	25.914	6.39	0.011
Traffic	1	44.961	11.09	0.005
Treatment	2	23.129	3.42	0.136
Block *Trt	4	6.764	1.67	0.213
Traf * Trt	2	31.387	2.82	0.172
Block*Trf*Trt	4	11.129	2.75	0.071
Fertilizer	1	24.721	6.10	0.027
Traf *Fert	1	25.732	6.35	0.024
Trt * Fert	2	11.061	2.73	0.010
Traf*Trt*F	2	9.372	2.31	0.136
Error	14	4.053		
Total	35			

Table 12. Partial GLM ANOVA table of the compacted site mean saturated hydraulic conductivities.

Source	df	Mean Square	F-Value	P-Value
Block	2	12.843	16.74	0.000
Traffic	1	1.642	2.14	0.166
Treatment	2	11.835	2.51	0.196
Block *Trt	4	4.706	6.13	0.005
Traf * Trt	2	2.043	0.46	0.662
Block*Trf*Trt	4	4.461	5.81	0.006
Fertilizer	1	0.152	0.20	0.663
Traf *Fert	1	3.722	4.85	0.045
Trt * Fert	2	1.617	2.11	0.158
Traf*Trt*F	2	1.461	1.90	0.186
Error	14	0.767		
Total	35			

Table 13. Partial GLM ANOVA table of the rutted site mean water table depths.

Source	df	Mean Square	F-Value	P-Value
Block	2	862.484	13.60	0.001
Traffic	1	894.708	14.11	0.002
Treatment	2	131.958	2.55	0.193
Block *Trt	4	51.680	0.82	0.536
Traf * Trt	2	553.352	2.94	0.164
Block*Trf*Trt	4	188.267	2.97	0.057
Fertilizer	1	31.828	0.50	0.490
Traf *Fert	1	65.907	1.04	0.325
Trt * Fert	2	13.823	0.22	0.807
Traf*Trt*F	2	2.931	0.05	0.955
Error	14	63.403		
Total	35			

Table 14. Partial GLM ANOVA table of the compacted site mean water table depths.

Source	df	Mean Square	F-Value	P-Value
Block	2	62.23	0.84	0.451
Traffic	1	918.797	12.44	0.003
Treatment	2	18.518	0.12	0.886
Block *Trt	4	148.203	2.01	0.149
Traf * Trt	2	219.776	2.67	0.184
Block*Trf*Trt	4	82.457	1.12	0.388
Fertilizer	1	21.731	0.29	0.596
Traf *Fert	1	16.906	0.23	0.640
Trt * Fert	2	11.060	0.15	0.862
Traf*Trt*F	2	46.032	0.62	0.551
Error	14	73.880		
Total	35			

Table 15. Partial GLM ANOVA table of the rutted site surface soil organic matter contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	4.916	4.18	0.038
Traffic	1	2.059	1,75	0.207
Treatment	2	3.770	0.34	0.729
Block *Trt	4	10.984	9.35	0.001
Traf * Trt	2	6.963	2.51	0.197
Block*Trf*Trt	4	2.774	2.36	0.103
Fertilizer	1	0.675	0.57	0.461
Traf *Fert	1	1.099	0.94	0.350
Trt * Fert	2	0.356	0.30	0.744
Traf*Trt*F	2	1.566	1.33	0.295
Error	14	1.175		
Total	35			

Table 16. Partial GLM ANOVA table of the compacted site mean surface soil organic matter contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	2.124	1.87	0.191
Traffic	1	0.728	0.64	0.437
Treatment	2	1.975	1.58	0.313
Block *Trt	4	1.252	1.10	0.394
Traf * Trt	2	2.157	0.94	0.463
Block*Trf*Trt	4	2.293	2.02	0.147
Fertilizer	1	1.951	1.72	0.211
Traf *Fert	1	0.150	0.13	0.722
Trt * Fert	2	0.503	0.44	0.651
Traf*Trt*F	2	0.989	0.87	0.440
Error	14	1.137		
Total	35			

Table 17. Partial GLM ANOVA table of the rutted site mean redox potentials.

Source	df	Mean Square	F-Value	P-Value
Block	1	10850.69	0.72	0.443
Traffic	1	1034.694	0.31	0.675
Treatment	2	8518.583	0.16	0.860
Block *Trt	2	52257.33	3.49	0.133
Traf * Trt	2	109828.6	0.69	0.593
Block*Trf*Trt	2	160178	10.69	0.025
Fertilizer	1	650.893	0.04	0.845
Traf *Fert	1	71912.89	4.80	0.094
Trt * Fert	2	19732.16	1.32	0.364
Traf*Trt*F	2	45080.16	3.01	0.159
Error	5	14982.19		
Total	21			

Table 18. Partial GLM ANOVA table of the compacted site mean redox potentials.

Source	df	Mean Square	F-Value	P-Value
Block	2	117743.1	1.45	0.273
Traffic	1	43750.7	3.25	0.213
Treatment	2	48143.08	1.59	0.310
Block *Trt	4	30223.42	0.37	0.824
Traf * Trt	2	2371.861	0.04	0.959
Block*Trf*Trt	4	56417.11	0.69	0.610
Fertilizer	1	42642.25	0.52	0.483
Traf *Fert	1	43194.7	0.53	0.480
Trt * Fert	2	46243.75	0.57	0.581
Traf*Trt*F	2	185330.9	2.28	0.145
Error	14	81292.03		
Total	35			

Table 19. Partial GLM ANOVA table of the rutted site mean surface soil phosphorous contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	0.017	3.13	0.131
Traffic	1	0.000008	0.00	0.971
Treatment	2	0.001	0.19	0.836
Block *Trt	4	0.006	1.00	0.484
Traf * Trt	2	0.007	4.50	0.095
Block*Trf*Trt	4	0.002	0.27	0.888
Fertilizer	1	0.024	4.24	0.095
Traf *Fert	1	0.003	0.47	0.523
Trt * Fert	2	0.002	0.42	0.677
Traf*Trt*F	2	0.009	1.69	0.275
Error	14	0.006		
Total	35			

Table 20. Partial GLM ANOVA table of the compacted site mean surface soil phosphorous contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	0.2617	8.36	0.004
Traffic	1	0.00514	0.16	0.692
Treatment	2	0.00453	0.93	0.465
Block *Trt	4	0.0486	1.55	0.241
Traf * Trt	2	0.1294	2.09	0.239
Block*Trf*Trt	4	0.0618	1.98	0.154
Fertilizer	1	0.0306	0.98	0.339
Traf *Fert	1	0.0230	0.74	0.406
Trt * Fert	2	0.0131	0.42	0.667
Traf*Trt*F	2	0.0141	0.45	0.646
Error	14	1.866		
Total	35			

Table 21. Partial GLM ANOVA table of the rutted site mean surface soil nitrogen contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	198314	6.01	0.013
Traffic	1	46.854	0.00	0.971
Treatment	2	206093.9	0.85	0.492
Block *Trt	4	242258.5	7.35	0.002
Traf * Trt	2	28444.11	0.21	0.822
Block*Trf*Trt	4	137993.2	4.18	0.020
Fertilizer	1	12008.14	0.36	0.556
Traf *Fert	1	12432.62	0.38	0.549
Trt * Fert	2	12580.72	0.38	0.690
Traf*Trt*F	2	23231.85	0.70	0.511
Error	14	32975.09		
Total	35			

Table 22. Partial GLM ANOVA table of the compacted site mean surface soil nitrogen contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	270526.6	18.05	0.000
Traffic	1	19597.67	1.31	0.272
Treatment	2	39971.05	0.67	0.559
Block *Trt	4	59257.59	3.95	0.024
Traf * Trt	2	102858.9	1.82	0.274
Block*Trf*Trt	4	56374.14	3.76	0.028
Fertilizer	1	838.778	0.06	0.816
Traf *Fert	1	17892.18	1.19	0.293
Trt * Fert	2	4414.766	0.29	0.749
Traf*Trt*F	2	2621.838	0.17	0.841
Error	14	14986.58		
Total	35			

Table 23. Partial GLM ANOVA table of the rutted site mean surface soil potassium contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	8.782	2.59	0.169
Traffic	1	14.432	4.25	0.094
Treatment	2	6.412	1.26	0.377
Block *Trt	4	5.103	1.50	0.328
Traf * Trt	2	4.199	1.04	0.432
Block *Trf*Trt	4	4.024	1.19	0.418
Fertilizer	1	14.521	4.28	0.093
Traf *Fert	1	0.137	0.04	0.849
Trt * Fert	2	5.743	1.69	0.275
Traf*Trt*F	2	0.268	0.08	0.925
Error	14	3.392		
Total	35			

Table 24. Partial GLM ANOVA table of the compacted site mean surface soil potassium contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	12.9645	3.59	0.055
Traffic	1	0.9344	0.26	0.619
Treatment	2	1.8566	0.72	0.539
Block *Trt	4	2.5608	0.71	0.600
Traf * Trt	2	0.9454	0.26	0.783
Block*Trf*Trt	4	3.6359	1.01	0.437
Fertilizer	1	2.7115	0.75	0.401
Traf *Fert	1	1.0000	0.28	0.607
Trt * Fert	2	.02693	0.07	0.929
Traf*Trt*F	2	1.0962	0.30	0.743
Error	14	3.615		
Total	35			

Table 25. Partial GLM ANOVA table of the rutted site mean total biomass of competing vegetation.

Source	df	Mean Square	F-Value	P-Value
Block	2	48618.22	9.04	0.003
Traffic	1	1304.173	0.24	0.630
Treatment	2	35419.77	6.06	0.062
Block *Trt	4	5849.177	1.09	0.400
Traf * Trt	2	7535.803	0.30	0.759
Block*Trf*Trt	4	25541.3	4.75	0.013
Fertilizer	1	4735.733	0.88	0.364
Traf *Fert	1	912.04	0.17	0.687
Trt * Fert	2	2904.726	0.54	0.595
Traf*Trt*F	2	2970.764	0.55	0.588
Error	14	5380.621		
Total	35			

Table 26. Partial GLM ANOVA table of the compacted site mean total competing vegetation biomasses.

Source	df	Mean Square	F-Value	P-Value
Block	2	20371.79	7.36	0.007
Traffic	1	297.448	0.11	0.748
Treatment	2	2920.615	0.76	0.525
Block *Trt	4	3840.985	1.39	0.288
Traf * Trt	2	7974.765	2.51	0.197
Block*Trf*Trt	4	3181.405	1.15	0.374
Fertilizer	1	11519.73	4.16	0.061
Traf *Fert	1	1061.891	0.38	0.546
Trt * Fert	2	1109.62	0.40	0.677
Traf*Trt*F	2	3884.722	1.40	0.278
Error	14	2767.386		
Total	35			

Table 27. Partial GLM ANOVA table of the rutted site mean foliar phosphorous contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	11.307	13.22	0.010
Traffic	1	7.410	8.66	0.032
Treatment	2	4.082	6.93	0.050
Block *Trt	4	0.589	0.69	0.631
Traf * Trt	2	2.704	2.63	0.187
Block*Trf*Trt	4	1.030	1.20	0.413
Fertilizer	1	7.046	8.24	0.035
Traf *Fert	1	0.235	0.27	0.623
Trt * Fert	2	0.725	0.85	0.482
Traf*Trt*F	2	0.853	1.00	0.432
Error	5	0.855		
Total	26			

Table 28. Partial GLM ANOVA table of the compacted site mean foliar phosphorous contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	44.026	11.58	0.001
Traffic	1	8.381	2.20	0.160
Treatment	2	1.596	0.31	0.752
Block *Trt	4	5.215	1.37	0.294
Traf * Trt	2	0.299	0.07	0.934
Block*Trf*Trt	4	4.287	1.13	0.383
Fertilizer	1	12.876	3.39	0.087
Traf *Fert	1	3.282	0.86	0.369
Trt * Fert	2	2.403	0.63	0.546
Traf*Trt*F	2	4.859	1.28	0.309
Error	14	3.802		
Total	35			

Table 29. Partial GLM ANOVA table of the rutted site mean foliar nitrogen contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	0.052	4.05	0.090
Traffic	1	0.003	0.21	0.665
Treatment	2	0.001	0.15	0.867
Block *Trt	4	0.009	0.67	0.640
Traf * Trt	2	0.0004	0.09	0.917
Block*Trf*Trt	4	0.004	0.34	0.843
Fertilizer	1	0.0001	0.01	0.925
Traf *Fert	1	0.008	0.61	0.471
Trt * Fert	2	0.005	0.36	0.716
Traf*Trt*F	2	0.007	0.53	0.619
Error	5	0.013		
Total	26			

Table 30. Partial GLM ANOVA table of the compacted site mean foliar nitrogen contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	0.016	0.28	0.759
Traffic	1	0.010	0.18	0.678
Treatment	2	0.145	1.47	0.333
Block *Trt	4	0.099	1.72	0.202
Traf * Trt	2	0.055	0.82	0.504
Block*Trf*Trt	4	0.067	1.17	0.367
Fertilizer	1	0.050	0.88	0.364
Traf *Fert	1	0.039	0.68	0.422
Trt * Fert	2	0.028	0.49	0.621
Traf*Trt*F	2	0.110	1.92	0.184
Error	14	0.057		
Total	35			

Table 31. Partial GLM ANOVA table of the compacted site mean foliar potassium contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	167.016	3.22	0.071
Traffic	1	67.24	1.30	0.274
Treatment	2	1.042	0.02	0.984
Block *Trt	4	62.749	1.21	0.350
Traf * Trt	2	41.497	0.62	0.585
Block*Trf*Trt	4	67.473	1.30	0.317
Fertilizer	1	133.403	2.58	0.131
Traf *Fert	1	111.800	2.16	0.164
Trt * Fert	2	74.078	1.43	0.272
Traf*Trt*F	2	99.438	1.92	0.183
Error	14	51.801		
Total	35			

Table 32. Partial GLM ANOVA table of the rutted site mean foliar potassium contents.

Source	df	Mean Square	F-Value	P-Value
Block	2	27.295	1.05	0.416
Traffic	1	16.521	0.64	0.461
Treatment	2	16.480	0.86	0.489
Block *Trt	4	19.177	0.74	0.604
Traf * Trt	2	9.835	0.85	0.491
Block*Trf*Trt	4	11.505	0.44	0.775
Fertilizer	1	0.443	0.02	0.901
Traf *Fert	1	4.147	0.16	0.706
Trt * Fert	2	0.911	0.04	0.966
Traf*Trt*F	2	12.595	0.49	0.642
Error	5	25.958		
Total	26			

Table 33. Partial GLM ANOVA table of the rutted site mean second-year pine seedling growths.

Source	df	Mean Square	F-Value	P-Value
Block	2	129.363	0.52	0.597
Traffic	1	1991.391	8.24	0.012
Treatment	2	530.962	13.16	0.017
Block *Trt	4	40.337	0.17	0.952
Traf * Trt	2	23.671	0.04	0.965
Block*Trf*Trt	4	652.023	2.70	0.074
Fertilizer	1	2778.52	11.50	0.004
Traf *Fert	1	13.189	0.05	0.819
Trt * Fert	2	56.8971	0.24	0.793
Traf*Trt*F	2	5.2238	0.02	0.979
Error	14	241.669		
Total	35			

Table 34. Partial GLM ANOVA table of the compacted site mean second-year pine seedling height growth.

Source	df	Mean Square	F-Value	P-Value
Block	2	351.021	2.10	0.160
Traffic	1	1297.44	7.76	0.015
Treatment	2	2922.25	12.22	0.020
Block *Trt	4	239.094	1.43	0.275
Traf * Trt	2	232.910	1.01	0.442
Block*Trf*Trt	4	230.592	1.38	0.291
Fertilizer	1	4315.176	25.81	0.000
Traf *Fert	1	12.936	0.08	0.785
Trt * Fert	2	283.249	1.69	0.219
Traf*Trt*F	2	45.832	0.27	0.764
Error	14	167.216		
Total	35			

Table 35. Partial GLM ANOVA table of the rutted site mean two-year-old pine seedling volumes.

Source	df	Mean Square	F-Value	P-Value
Block	2	5987.209	0.39	0.687
Traffic	1	97192.22	6.26	0.025
Treatment	2	44921.88	19.99	0.008
Block *Trt	4	2246.684	0.14	0.962
Traf * Trt	2	12586.88	0.25	0.793
Block*Trf*Trt	4	51163.2	3.30	0.042
Fertilizer	1	148661.7	9.58	0.008
Traf *Fert	1	1043.936	0.07	0.799
Trt * Fert	2	7328.655	0.47	0.633
Traf*Trt*F	2	675.083	0.04	0.957
Error	14	15525.56		
Total	35			

Table 36. Partial GLM ANOVA table of the compacted site mean two-year-old pine seedling volumes.

Source	df	Mean Square	F-Value	P-Value
Block	2	22445.59	1.19	0.334
Traffic	1	19708.42	1.04	0.325
Treatment	2	271519.9	23.87	0.006
Block *Trt	4	11276.62	0.60	0.668
Traf * Trt	2	15856.21	0.93	0.467
Block*Trf*Trt	4	17118.29	0.90	0.488
Fertilizer	1	378955.2	20.03	0.001
Traf *Fert	1	123.358	0.01	0.937
Trt * Fert	2	61018.76	3.22	0.071
Traf*Trt*F	2	1143.464	0.06	0.942
Error	14	18921.63		
Total	35			

Table 37. Partial GLM ANOVA table of the rutted site mean pine seedling survival rates.

Source	df	Mean Square	F-Value	P-Value
Block	2	191.480	1.98	0.175
Traffic	1	696.432	7.19	0.018
Treatment	2	49.682	0.47	0.653
Block *Trt	4	104.665	1.08	0.403
Traf * Trt	2	140.807	2.01	0.249
Block*Trf*Trt	4	69.971	0.72	0.591
Fertilizer	1	0.4853	0.01	0.945
Traf *Fert	1	7.7284	0.08	0.782
Trt * Fert	2	78.5687	0.81	0.464
Traf*Trt*F	2	36.6404	0.38	0.692
Error	14	96.801		
Total	35			

Table 38. Partial GLM ANOVA table of the compacted site mean pine seedling survival rates.

Source	df	Mean Square	F-Value	P-Value
Block	2	1180.584	5.00	0.023
Traffic	1	1205.826	5.11	0.040
Treatment	2	246.123	0.26	0.780
Block *Trt	4	929.651	3.94	0.024
Traf * Trt	2	783.600	1.07	0.426
Block*Trf*Trt	4	735.101	3.12	0.050
Fertilizer	1	7.719	0.03	0.859
Traf *Fert	1	12.076	0.05	0.824
Trt * Fert	2	32.667	0.14	0.872
Traf*Trt*F	2	52.183	0.22	0.804
Error	14	235.945		
Total	35			

APPENDIX C

Soil Series Descriptions

The Bethera soils are formed in clayey coastal plain sediment and are described as nearly level, deep, and poorly drained. This series has a slow or moderately slow permeability and a high available water capacity. The following is a typical profile (SCS, 1980):

A11 - 0 to 2 inches, very dark gray (10YR 3/1) loam; moderate fine granular structure; friable; many fine and medium roots; extremely acid (pH 4.3); abrupt wavy boundary.

A12 - 2 to 4 inches, dark gray (10YR 4/1) loam; weak fine granular structure; friable; many fine and medium roots; few fine pores; extremely acid (pH 4.4); abrupt wavy boundary.

A2 - 4 to 7 inches, gray (10YR 5/1) loam; weak fine granular structure; friable; many fine roots; many fine pores; very strongly acid (pH 4.6); abrupt wavy boundary.

B1g - 7 to 10 inches, grayish brown (10YR 5/2) clay loam; few fine faint gray (10YR 5/1) mottles and common fine distinct brownish yellow (10YR 6/6) mottles; weak fine angular blocky structure; firm, sticky, plastic; patchy faint clay films on faces of peds; few fine roots; few fine pores; very strongly acid (pH 4.6); clear wavy boundary.

B21tg - 10 to 41 inches, gray (10YR 5/1)clay; common medium distinct brownish yellow (10YR 6/6) mottles and common medium prominent red (2.5YR 5/8) mottles; moderate fine angular blocky structure; firm, sticky, and plastic; patchy distinct clay films on faces of peds; few fine roots; few fine pores; very strongly acid (pH 4.7); abrupt irregular boundary.

B22tg - 41 to 68 inches, gray (10YR5/1) clay; many medium distinct brownish yellow (10YR 6/8) mottles; moderate fine angular blocky structure; firm, sticky, and plastic; patchy distinct clay films of faces of peds; few fine roots; few fine pores; very strongly acid (pH 4.6); gradual wavy boundary.

Cg - 68 to 94 inches, mottled light brownish gray (2.5Y 6/2), gray (5Y 6/1), and light gray (10YR 7/1) clay; massive; firm, sticky and plastic; extremely acid (pH 4.3); clear smooth boundary.

The Goldsboro series are formed in loamy coastal plain sediment and are nearly level, deep, and moderately well drained. Goldsboro soils have a moderate permeability and a medium available water capacity (SCS, 1980). A typical profile description follows:

A1 - 0 to 7 inches, very dark grayish brown (10YR 3/2) loamy sand; weak fine granular structure; very friable; many fine and medium roots; very strongly acid (pH 4.7); abrupt smooth boundary.

A2 - 7 to 14 inches, light yellowish brown (2.5Y 6/4) loamy sand; weak fine granular structure; very friable; many fine and medium roots; very strongly acid (pH 4.8); clear smooth boundary.

B21t - 14 to 24 inches, yellowish brown (10YR 5/6) sandy clay loam; few fine and medium distinct yellowish red (5YR 4/8) mottles; weak fine subangular blocky structure; friable; sand grains coated and bridged; many fine and medium roots; very strongly acid (pH 4.9); clear smooth boundary.

B22t - 24 to 35 inches, yellowish brown (10YR 5/6) sandy clay loam; many coarse distinct gray (10YR 6/1) mottles, few medium prominent red (2.5YR 4/8) mottles, and few fine distinct yellowish red and strong brown mottles; moderate medium subangular blocky structure; friable; sand grains coated and bridged; common fine roots; very strongly acid (pH 4.7); clear smooth boundary.

B23tg - 35 to 57 inches, light gray (10YR 6/1) sandy clay loam; few coarse prominent yellowish red (5YR 4/6) mottles, common coarse prominent strong brown (7.5YR 5/6) mottles, and few medium distinct yellowish brown (10YR 5/8) mottles; weak medium subangular blocky structure; friable; sand grains coated and bridged; few fine roots; very strongly acid (pH 4.7); clear smooth boundary.

B31g - 57 to 63 inches, light gray (10YR 7/1) sandy clay loam; common medium distinct yellowish brown (10YR 5/8) mottles, few medium prominent red (2.5YR 5/8) mottles, and few fine prominent strong brown mottles; weak fine subangular structure; friable; few fine roots; few flakes of mica; very strongly acid (pH 4.8); clear smooth boundary.

B32g - 63 to 75 inches, mottled strong brown (7.5YR 5/6), light gray (10YR 7/1), yellowish red (5YR 5/8), yellowish brown (10YR 5/8), and light yellowish brown (2.5Y 6/4) sandy clay loam; weak fine subangular blocky structure; friable; few fine roots; few flakes of mica; very strongly acid (pH 4.8).

The Lynchburg series soils are formed in loamy coastal plain sediment and are nearly level, deep, and somewhat poorly drained (SCS, 1980). These soils have a moderate permeability and a medium available water capacity. A typical Lynchburg soil profile is as follows:

A1 - 0 to 4 inches, black (10YR 2/1) fine sandy loam; weak fine granular structure; very friable; many fine roots; very strongly acid (pH 4.5); clear smooth boundary.
A2 - 4 to 7 inches, light yellowish brown (2.5Y 6/4) fine sandy loam; common medium faint dark gray (10YR 4/1) mottles, and few fine faint dark brown mottles around old root holes; moderate coarse granular structure; very friable; many fine and medium roots; very strongly acid (pH 4.8); clear smooth boundary.
B1 - 7 to 12 inches, yellowish brown (10YR 5/4) fine sandy loam; few fine faint dark brown mottles around old root holes; weak fine subangular blocky structure; friable; many fine roots; very strongly acid (pH 4.7); clear wavy boundary.
B21tg - 12 to 28 inches, gray (10YR 5/1) sandy clay loam; pockets of sandy loam material around old root holes; common coarse distinct yellowish brown (10YR 5/6) mottles and few fine prominent red mottles; moderate medium subangular blocky structure; friable; sand grains coated and bridged; common fine rots; very strongly acid (pH 4.7); clear wavy boundary.
B22tg - 28 to 54 inches, gray (10YR 5/1) sandy clay loam; many coarse distinct yellowish brown (10YR 5/6) mottles, few fine prominent dark red mottles, and few fine faint light gray (10YR 7/1) mottles; moderate medium subangular blocky structure; friable; sand grains coated and bridged; common fine roots; very strongly acid (pH 4.7); clear smooth boundary.
B3g - 54 to 65 inches, mottled gray (10YR 6/1), light gray (10YR 7/1), and yellowish brown (10YR 5/6) sandy clay loam; pockets of sandy loam material around old root holes; weak fine subangular blocky structure; friable; few fine roots; very strongly acid (pH 4.7); clear smooth boundary.
Cg - 65 to 80 inches, gray (10YR 6/1) clay; pockets of sandy clay and sandy clay loam material; common medium distinct yellowish brown (10YR 5/6) mottles and few fine prominent red mottles; massive firm; few fine roots; extremely acid (pH 4.3).

The Rains series soils are formed in loamy coastal plain sediment and are nearly level, deep, and poorly drained. They have a moderate permeability and a medium available water capacity (SCS, 1980). A typical Rains soil profile is as follows:

A1 - 0 to 6 inches, black (N 2/0) fine sandy loam; weak medium granular structure; very friable; common fine and medium roots; very strongly acid (pH 4.5); clear wavy boundary.

A2 - 6 to 12 inches, gray (10YR 5/1) fine sandy loam; few fine distinct strong brown mottles and few coarse distinct black (N 2/0) mottles; weak fine subangular blocky structure; friable; common fine and medium roots; very strongly acid (pH 4.7); clear smooth boundary.

B1 - 12 to 24 inches, gray (10YR 5/1) fine sandy loam; few fine distinct yellowish brown mottles; weak fine subangular blocky structure; friable; common fine roots; very strongly acid (pH 4.5); clear smooth boundary.

B21tg - 24 to 32 inches, gray (10YR 5/1) sandy clay loam; few fine distinct pale brown mottles and common medium distinct strong brown (7.5YR 5/6) mottles; weak medium subangular blocky structure; friable; sand grains coated and bridged; common fine roots; very strongly acid (pH 4.5); clear smooth boundary.

B22tg - 32 to 45 inches, dark gray (10YR 4/1) sandy clay loam; common medium distinct strong brown (7.5YR 5/6) mottles and few fine distinct yellowish brown and pale brown mottles; moderate medium subangular blocky structure; friable; sand grains coated and bridged; few fine roots; very strongly acid (pH 4.6); clear smooth boundary.

B31g -45 to 62 inches, gray (10YR 5/1) fine sandy loam; few fine distinct strong brown and yellowish brown mottles and few fine faint white mottles; weak fine subangular blocky structure; friable; continuous sand skeletons on ped faces; few fine roots; common fine quartz grains and few fine flakes of mica; very strongly acid (pH 4.6); clear smooth boundary.

B32g -62 to 78 inches, gray (10YR 6/1) fine sandy loam; few fine distinct yellowish brown mottles and few fine faint brown mottles; weak fine subangular blocky structure; very friable; continuous sand skeletons on ped faces; few fine roots; common fine quartz grains and few fine flakes of mica; very strongly acid (pH 4.7).

VITA

The author was born in Rapides Parish, Louisiana on September 10, 1970. He has also lived in Decatur, Georgia and Manassas, Virginia. Summers from ages 14 to 19 were spent back on the family farm in Louisiana while the majority of his school years were spent in Manassas, VA where he graduated from Stonewall Jackson High School in June, 1988. Higher education took place at Virginia Tech where he received a B.S. degree in Forest Resource Management in May, 1992 and a M.S. degree in Forest Soils in October, 1994. He is a member of the Society of American Foresters and the Society of Wetland Scientists. He is currently employed as a research associate in Virginia Tech's forestry extension department working to develop forest and wildlife management plans for private landowners.