TIMBER HARVESTING AND SITE PREPARATION EFFECTS ON SOIL QUALITY FOR LOBLOLLY PINE GROWING ON THE LOWER COASTAL PLAIN OF SOUTH CAROLINA

by

Daniel L. Kelting

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FORESTRY

James A. Burger, Chairman
W. Michael Aust
John R. Seiler
Lucian W. Zelazny
Pu Mou
Harold E. Burkhart, Dept. Head

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(ABSTRACT)

The Lower Coastal Plain of the southeastern United States is a major wood producing region. The region is characterized by a combination of nearly-level topography, poorly-drained soils, and high rainfall, which results in a perched water table in some soils that inundates the surface several times each year. Harvesting timber under wet site conditions often results in extensive soil compaction, rutting, soil displacement, and waterlogging. Forest managers are concerned that these visually-displeasing soil disturbances may cause site damage and reduced productivity. These concerns were addressed in an operational-scale field experiment conducted in South Carolina. The objectives of this experiment were to determine: (i) if soil disturbance changes key soil properties and processes; (ii) if soil disturbance reduces loblolly pine productivity; and, (iii) if disturbance can be mitigated with site preparation practices? Three 20-ha, 20-yr-old loblolly pine (*Pinus taeda* L.) plantations were harvested under wet and dry conditions to create a broad gradient in soil disturbance. Within each harvested plantation, a subset of 3-ha plots were site prepared by either bedding, or mole-plowing plus bedding, then all sites were established as 3rd -rotation pine plantations. Prior to site preparation, each plot was classified and mapped using a 5 by 5 soil disturbance (none to churned) by organic debris (none to slash piles) classification matrix. Within each plot, data were collected on several soil physical, chemical, and biological properties over a 2-yr period following site preparation. Key soil properties were integrated into a Soil Quality Index (SQI) and compared to aboveground productivity of 2-yr-old loblolly pine trees growing on closely-spaced (30 by 30 cm) bioassay plots planted across the gradient of soil disturbance. The soil physical properties were used to determine the least limiting water range (LLWR), the range in soil water content within which root growth is not limited. Soil compaction and deep rutting reduced the LLWR. Retention of logging slash improved the LLWR for compacted and rutted soils. Site preparation improved the quality of the soil physical environment across all levels of soil disturbance. Soil disturbance had no effect on soil chemical or biological properties as evidenced by no change in soil pH, ECEC, base saturation, available P, or net N mineralization with disturbance. The base saturation exceeded 80 % on all sites, with Ca saturation controlling soil pH. The high base saturation buffered any redox-induced changes in soil chemistry that would have resulted from disturbance. The results showed that high fertility is an important mechanism for buffering the potentially-negative effects of soil disturbance on the soil nutritional environment. Site preparation changed soil chemical properties, but the changes were probably associated with tillage effects on organic matter and clay content, not redox processes. The SQI showed that surface soil compaction and deep rutting reduced soil quality, mainly by decreasing the LLWR and aeration depth. Site preparation mitigated the effects of most disturbances on soil quality, evidenced by similar aboveground biomass production among soil disturbance classes after bedding. A regression model was developed for predicting aboveground biomass production as a function of SQI. SQI explained 73 % of the variation in aboveground biomass production. The regression model showed that compression tracks and rutting decreased aboveground biomass production compared to undisturbed soils. The long-term effect of these disturbances on productivity will depend on natural soil recovery processes. However, these early results suggest that compaction and rutting should be minimized on similar sites, especially if sites will not be bedded before reforestation. The mole-plow / bedding treatment increased aboveground biomass production, indicating that this experimental treatment may be a viable practice for enhancing productivity.

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CHAPTER I. INTRODUCTION

STUDY RATIONALE

The pine plantations located in the Lower Coastal Plain region of the Southeastern United States are among the most intensively-managed forests in the country (Allen and Campbell, 1988). These plantations are examples of the "domesticated forest", as defined by Stone (1975), wherein site quality is subject to considerable manipulation via cultural practice. The malleability of site quality in the domesticated forest enables silvicultural technologies to continuously evolve towards ever higher management inputs with an expectation that higher inputs will produce higher outputs in the form of increased wood production per hectare and shorter rotations.

Commensurate with increasing inputs is a concern that intensive culture may ultimately have a negative impact on the long-term productivity of domesticated forests. The rationale behind our concern over long-term site productivity is rooted in the ethical responsibility of foresters to not degrade the forest site (Ford, 1983), and as Gessel (1981) stated, "It is less costly to maintain and /or enhance productivity than it is to restore it". Thus, for over thirty years, numerous site productivity studies have been conducted to answer the following questions. 1. Does intensive culture reduce the amount of harvestable biomass produced in successive rotations on the same site? 2. If so, what are the key factors causing the decline? 3. What codes of practice can be developed to prevent decline and sustain / enhance productivity? Within the Lower Coastal Plain region, site productivity studies are necessary for addressing concerns about the need for and / or adequacy of state and federal best management practices.

In the domesticated forests of the Lower Coastal Plain, long-term productivity concerns are centered around site hydrology because hydrology plays a major role in regulating both management access and productivity (Morris and Campbell, 1991). A combination of nearly-level topography, poorly-drained soils, and high rainfall results in a perched water table that inundates the soil surface several times each year. When timber is harvested under these wet conditions severe soil disturbances including compaction, displacement, and waterlogging can occur (Hatchell et al., 1970; Gent et al., 1983; Aust et al., 1993; Aust et al., 1995). The negative impacts of these soil disturbances can be at least partially mitigated through a combination of drum chopping, disking and /or bedding (McKee and Shoulders, 1974; Haines et al., 1975; Gent et al., 1983; Morris and Campbell, 1991). However, these practices also accelerate organic matter decomposition (McKee and Shoulders, 1974) and nitrogen mineralization (Vitousek and Matson, 1985; Burger and Pritchett, 1988), thereby disrupting the synchrony of nutrient supply and demand (Allen et al., 1990).

Because it takes a rotation-length study to definitively test if tree growth was affected by management practices, the benefits or deleterious effects of cultural practices on long-term site productivity are largely unknown (Morris and Miller, 1994). In a review of studies that reported tree productivity declines in domesticated forests located across the globe, Powers et al. (1990) concluded that declines were most likely explained by soil disturbance and organic matter removal. Tiarks and Haywood (1996) reported that discing and bedding reduced tree growth following two rotations on the same site. The negative growth response to discing was attributed to decreased root penetration in the second rotation, as evidenced by higher soil strengths measured using a cone penetrometer. Accelerated nutrient depletion with bedding during the first rotation was suggested as the cause for reduced growth with bedding in the second rotation.

Traditional field studies, such as the one reported by Tiarks and Haywood (1996), and the several reviewed by Morris and Miller (1994), are seldom conclusive with respect to management impacts on long-term productivity. There are several contributing factors that may explain the lack of definitive results. First, tree height, diameter, and aboveground volume of the crop species are almost always used as measures of productivity. However, these measurements only capture a portion of actual site productivity (Powers, 1991), with the remaining productivity being associated with competing species, roots, foliage, reproduction, and litter production; relying solely on aboveground volume data on the crop species may give us an incomplete and perhaps false indication of management impacts on long-term productivity. Second, the productivity measurements are exacerbated by additional factors that also affect our traditional growth measurements, namely the extrinsic site factors, genetic differences, competing vegetation, and catastrophic events (e.g. fire, insects, disease), which may all act together in either non-definable or non-defined ways unrelated to soil conditions to affect tree growth. When these factors are not defined, accounted for, and controlled, long-term productivity experimental designs are often confounded resulting in questionable and / or weak conclusions (Morris and Miller, 1994).

The soil quality concepts and methods currently being discussed and implemented within the agricultural community provide a useful framework for developing more soil-based assessments of management impacts on long-term productivity of forests. Focusing our efforts more on the key soil properties and processes that are affected by management should allow us to identify management practices that degrade or improve soil quality and tree productivity.

OBJECTIVES

This research addressed the following specific objectives.

1. Determine the effects of timber harvesting and site preparation on the soil physical environment.
2. Determine the effects of timber harvesting and site preparation on the soil nutritional environment.
3. Identify the soil-and site- based determinants of early loblolly pine productivity.
4. Develop a Soil Quality Index equation which integrates the management sensitive determinants into an overall measure of management impacts on soil productivity for loblolly pine growth.

CHAPTER II. LITERATURE REVIEW

REVIEW OF KEY SOIL ATTRIBUTES

Introduction

Site hydrology has long been recognized as a critical factor regulating both management access and productivity in the domesticated forests of the Atlantic Lower Coastal Plain (Morris and Campbell, 1991). The topography and climate of this region in conjunction with soils that have low hydraulic conductivity results in the water table being above, at, or near the soil surface several times during the year. The presence of a fluctuating water table, which occasionally inundates the entire surface soil, has a tremendous affect on soil chemical and biological processes, and plant growth. This section reviews water table effects on key soil chemical and biological processes as well as water table and soil effects on loblolly pine growth.

Water table effects on soil chemical and biological processes

In a well aerated soil, oxygen is the terminal electron acceptor in biological redox processes. As the soil becomes saturated with water, as in the case of a rising water table, the oxygen supply quickly depletes because oxygen diffuses through liquid approximately 10,000 times slower than through air (Bohn et al., 1985). Depending on the rate at which the oxygen is reduced, the oxygen supply is typically gone within one day after complete saturation (Patrick, 1977). With the depletion of oxygen supplies under waterlogged conditions, the new anaerobic population of microorganisms begins reducing available electron acceptors. Chemical species with high redox potentials are reduced first, as these species are depleted species with progressively lower redox potentials are sequentially reduced. Based on their high redox potentials, Nitrate and manganese would be reduced early on after the oxygen is depleted; however, nitrate is generally not reduced as denitrification is thermodynamically favored over nitrate reduction (McBride, 1994). Species such as carbon dioxide and sulfate, which have low redox potentials, are reduced last. The new forms of the reduced chemical species participate in other reactions in the soil which change soil chemical properties and processes (Patrick, 1977).

Ponnamperuma, 1972, provided a general overview of the chemical changes which take place in a submerged or waterlogged soil. When an aerobic soil is waterlogged, the electrochemical potential (Eh) is dramatically reduced from approximately 700 to 800 mV to around +300 to -200 mV. The reduction in Eh results from changes in oxidation or reduction activity and changes in pH; these changes occur together, therefore a measured change in Eh cannot be directly attributed to any one process. Reduction usually increases P availability due to (i) the reduction of ferric-P to water-soluble ferrous-P, (ii) release of occluded-P and P adsorbed on amorphous Fe and Mg oxides, and (iii) desorption from clays and Al-oxides and reduced Fe-oxides brought about by an increase in pH (in acid soils). Reduction in ferric iron increases the concentration of water-soluble ferrous iron, with the Fe^{2+} displacing K^+, Na^+, NH_4^+, Ca^{2+}, and Mg^{2+} from cation exchange sites thus increasing the solution concentration of these nutrients. Manganese solubility increases and sulfur availability decreases with decreasing Eh (at low Eh sulfate is reduced to H_2S). At low Eh, the lack of an electron sink severely inhibits aerobic respiration, favoring anaerobic microbial activity which can produce some toxic organic compounds (e.g., CH_4, ethylene, and organic sulfides). Net N mineralization is greater in anaerobic soils because microbial immobilization of N decreases under anaerobic conditions. Under anaerobic conditions, NH_4^+ is the end-product of N-mineralization, therefore flooding favors NH_4^+ accumulation. Because NO_3^- is unstable in saturated soils being lost through denitrification, flooding an aerobic soil will result in loss of any nitrate that accumulated while the soil was aerobic. The ionic strength of the soil solution usually increases with reduction. Waterlogging also changes soil pH, causing an increase in pH in acid soils and a decrease in pH in alkaline soils. The combination of increased ionic strength and pH should result in ECEC increases with waterlogging in acid soils. Mineral P is present as

Fe-P and Al-P at low pH, and present as Ca-P at higher pH. As the pH increases the solubility of Fe and Al phosphates increases as does desorption from surfaces of clays and Fe and Al oxides. The diversity of microbial species involved in organic matter decomposition changes dramatically with waterlogging. In aerobic soils decomposition is facilitated by a wide variety of organisms which function over a broad range of pH's, compared to decomposition by anaerobic organisms which function best around neutrality. Under anaerobic conditions, only a few species of bacteria are involved in organic matter decomposition; these organisms decompose organic matter at a much slower rate than the much larger and more diverse population that is present under aerobic conditions (Kozlowski et al., 1991). While waterlogging produces tremendous changes in soil chemical and biological properties and processes, the changes in chemistry are reversible, reaching pre-waterlogging aerobic conditions at approximately the same rate under which the reduction processes occurred (Pezeshki and Chambers, 1986).

The basic chemistry of waterlogging described by Ponnamperuma, 1972, has been corroborated by work done on forest soils both in the field and laboratory. In a laboratory study McKee, 1970, found that submergence decreased redox potential from 755 mV to 201 mV and increased pH from 4.58 to 6.44. The increase in pH was attributed to the use of hydronium ions in the reduction of ferric iron to ferrous iron; under reducing conditions, the highly mobile ferrous iron acts as a cation to neutralize soil acidity. Even though pH increased with waterlogging, ECEC did not change. McKee attributed the lack of change in ECEC to inappropriate laboratory procedures, because a liming treatment did increase ECEC, indicating the presence of some pH-dependent charge. After drying, levels of exchangeable Ca and Mg were lower in soils exposed to prolonged and periodic submergence compared to non-submerged soils. Calcium and Mg were most likely displaced from exchange sites by Fe with submergence. This effect is called ferrolysis (McBride, 1994) when soil and site conditions allow the base cations to leach from the profile, resulting in acidification. Periodic waterlogging may then affect the nutrient status of soils by reducing the availability of base cations. Waterlogging decreased levels of Al-P and increased Fe-P, the degree to which these reactions occur depends on pH, levels of exchangeable Al, and Fe availability.

McKee and Shoulders, 1974, looked at the relationship between three levels of site preparation (none, discing, and bedding), water table depth, soil reduction, and soil chemistry in a field study conducted on the same soils as in the previous laboratory study. Water table depth explained 94 % of the variation in redox potential. With total saturation (water table depth = 0 cm) redox potential dropped to approximately 240 mV, at a maximum water table depth of 45 cm redox potential increased to about 600 mV. Bedding increased the average depth to the water table, resulting in a higher overall redox potential than discing and no site preparation (596, 371, and 474 mV, respectively). Bedding and discing both reduced ECEC. Given the relationship between ECEC and redox, discing should have had the highest ECEC; however, discing and bedding reduced soil organic matter by 33 and 25 p%, respectively, which most likely resulted in decreased pH-dependent charge with these two treatments. Although there was no site preparation effect, total exchangeable bases declined between fall and spring (2.72 and 1.93 meq $100g^{-1}$, respectively) corresponding to an overall rise in the water table. During this same period, Fe-P increased as the water table rose.

Water table effects on tree physiological processes

Waterlogging the soil can have tremendous affects on tree growth. Kozlowski et al., 1991, provided a good overview of the effects of flooding on tree physiological processes and adaptation mechanisms. A summary of their review follows.

Anaerobic soil conditions brought about by flooding have been shown to reduce tree growth in many species, including eastern white (*Pinus strobus* L.), shortleaf (*P. echinata* Mill.), loblolly (*P. taeda* L.), pond (*P. serotina* Michx.), slash (*P. elliottii* Engelm.), jack (*P. banksiana* Lamb.), and red (*P. resinosa* Ait.) pines, white (*Picea glauca* Voss.) and black (*P. mariana* Mill.) spruce, and balsam fir (*Abies balsamea* Mill.). When soils are inundated with water CO_2 absorption is severely reduced due to stomatal closure, resulting in a rapid reduction in photosynthesis. Carbon fixation is further exacerbated in flood intolerant trees because flooding decreases leaf formation and expansion and causes premature abscission. Premature abscission may be linked with increased ethylene production under anaerobic conditions. Flooding reduces the ability of roots to acquire nutrients either through direct injury to the root system or through (i) inefficient anaerobic nutrient uptake, (ii) ion leaching through leaky root membranes, (iii) decreased P uptake because of loss of mycorrhizal associations, and (iv) decreased NO_3^- availability due to denitrification.

The extent to which trees are affected by waterlogging varies greatly depending on species, genotype, age, condition of the water, and the time and duration of flooding. In general, conifers are more sensitive to flooding than broad-leaf trees. Because older trees have greater photosynthetic surface area and their leaves are rarely under water, they survive flooding much better than young trees. Oxygen is the life-blood of aerobic processes, therefore trees growing in oxygen-rich water (e.g., flowing water) are less affected by flooding than tree growing in stagnate water. The growing season is characterized by a period of increased root growth, respiration, and nutrient uptake, therefore flooding during this period is more harmful than flooding during the dormant season. The ability of a tree to survive prolonged flooding depends partially on its ability to provide oxygen to the root system. Many flood-tolerant tree species have aerenchyma cells that transport oxygen down to the roots, forming a zone of oxidation around the root system (oxidized rhizosphere). Depending on the rate of oxygen supply, aerobic soil chemical and biological processes can be maintained in the oxidized rhizosphere, enabling the tree to withstand flooding.

Water table effects on loblolly pine growth

Lorio et al., 1972, examined the effects of microrelief (i.e., mounds versus flat terrain) on wet sites on loblolly pine root growth, morphology, and mycorrhizal colonization over a 2.5 year period. During this time the water table ranged from 50 to 100 cm further below the soil surface on mounded versus flat terrain. The water table covered the soil surface on flat terrain during the winter and was about 50 cm below the surface on mounded terrain during this period. Live roots on mounds had tight reddish-brown bark that exfoliated in thin layers compared to live roots on flat terrain which had thick dark-gray to black bark. Jackson and Hepting, 1964, (as cited in Lorio et al., 1972) stated that thick dark colored bark on roots was indicative of stressed physiological processes. Root surface area was significantly greater on the mounded sites, as was the surface area of mycorrhizal root tips. In general, the number of mycorrhizal root tips was positively correlated with water table depth. Examinations of excavated root systems showed that roots of all diameter classes were fairly evenly distributed throughout the soil profile down to 60 cm on mounded topography, compared to flats sites were the majority of roots occupied the surface 20 cm. Fine lateral roots tended to branch horizontally on flat sites, while on mounds the fine laterals branched in all directions. When roots were followed from excavated trees on mounds onto flat sites, root diameter and the number of fine laterals decreased noticeably. Trees growing on flat sites also had dense mats of fine laterals growing around their base.

DeBell et al., 1984, studied the response of loblolly pine root growth to three levels of water table treatment (drained, seasonally flooded during the dormant season, and continuously flooded) with and without phosphorus. Seasonal flooding resulted in the highest root weights, followed by the drained and continuously flooded treatments, respectively. Phosphorus addition increased root weight in all three water table treatments, with the increase being most pronounced in the continuously flooded treatment. As part of the same experiment, McKee et al., 1984, found seasonal flooding resulted in the highest aboveground biomass, followed by the drained and continuously flooded treatments, respectively. Phosphorus addition increased stem diameter by 137, 13, and 2 % relative to no P for the continuously flooded, seasonally flooded, and drained treatments, respectively. The greatest relative P treatment response was under continuous flooding, and illustrates the fact that tree roots take up minimal P without a mycorrhizal association. Seasonal flooding appears to result in the best soil conditions for seedling growth. Although the authors did not measure soil chemical responses within each treatment, the beneficial effects of seasonal flooding on growth could be due to some of the soil chemical changes presented previously; seasonal flooding may have increased nutrient availability by displacing essential elements into soil solution for later uptake by roots as the soil dried-down. Soil moisture was obviously increased by seasonal flooding compared to the drained treatment, which could have resulted in improved soil physical conditions for root growth and reduced moisture stress.

Foresters recognized the detrimental effects of flooding and waterlogging on pine growth many years ago. Based on observation and the results of scientific studies, it was realized that lowering the water table using drainage, increasing the depth to the water table via bedding, or a combination of the two resulted in significant increases in pine growth on low lying, poorly drained, sites (Soil Moisture...Site Productivity Symposium Proceedings, 1978). Bedding and drainage have become the standard and recommended mechanical site preparation techniques for increasing pine productivity in the lower Coastal Plain (McKee, 1989).

McKee and Shoulders, 1974, quantified the relationship between pine productivity and water table depth under three levels of site preparation (none, discing, and bedding) in an 8-year-old slash pine plantation growing in poorly drained soils on the lower Coastal Plain in Louisiana. Bedding increased biomass production by 25 % compared to discing and no site preparation, both of which produced similar amounts of biomass. The bedding effect was largely explained by an increase in arable rooting volume created when the bedding plow mounded the soil above the elevation of the original soil. A regression analysis showed that wood production was positively correlated with average depth to the water table during the winter; where, depth to the water table in winter explained 88 % of the variation in stemwood production. Based on the regression analysis, and corroborated by other research (e.g., Maki, 1960), the critical water table depth for maximum productivity was 45 cm, with productivity between 0 and 45 cm water table depth being predominantly controlled by the water table. The authors theorized that lower water tables during the winter allowed roots to penetrate deeper into the soil profile, increasing accessibility to water during summer droughts. McKee and Shoulders, 1974, also examined the relationship between biomass nutrient concentrations, soil nutrients, and water table depth in winter. No relationship was found between biomass nutrient content and soil nutrients; however, water table depth and biomass nutrients were positively correlated, with water table depth explaining between 60 and 80 % of the variation in biomass nutrient content. The strong relationship between water table depth and biomass nutrients suggests that the physical environment for rooting was more important for productivity than soil chemical properties.

No one has quantified the relationship between loblolly pine productivity and water table depth to the extent that McKee and Shoulders did for slash pine, but since the water table has such a significant impact on loblolly pine rooting, and studies have demonstrated the positive effects of drainage on loblolly pine productivity, loblolly pine should respond similarly to water table depth. Terry and Hughes, 1975, reported the results of several studies that tested the effects of drainage (water table lowering) on loblolly pine growth, and in all cases loblolly pine productivity increased significantly following drainage.

Nitrogen

Nitrogen ranks behind C, H, and O as the fourth most common element found in plant tissues, and is the nutrient element needed in the greatest quantities by plants. The nitrogen cycle is a complex biologically-mediated process involving all components of the soil-plant system. Nitrogen enters the soil-plant system through wet and dry deposition, lightning strikes, and N-fixation, and leaves the system via denitrification, leaching, herbivory, or crop-harvesting. Nitrogen is retained in the soil-plant system through fixation by organic and mineral soil constituents, temporary binding on charged surfaces of clays and organic matter, and by incorporation into plant and microbial biomass (Paul and Clark, 1989). Because plants uptake nitrogen in inorganic form as NH_4^+ and NO_3^-, the processes under which these compounds become available and the effects of both external and internal environmental factors on the processes are important to understand.

Nitrogen becomes available to plants through microbial decomposition of soil organic matter. Exocellular enzymes synthesized by soil microorganisms degrade high-N compounds such as amino and nucleic acids, and proteins in a process known as mineralization to form NH_4^+. Once mineralized, NH_4^+ can be (i) taken up by plants, (ii) adsorbed onto cation exchange sites on clays and organic matter, (iii) fixed into the interlayer of vermiculites, (iv) react with organic matter to form recalcitrant organic matter, (v) volatilized, (vi) immobilized into microbial biomass, or (vii) nitrified (Paul and Clark, 1989). The extent to which NH_4^+ is immobilized into microbial biomass depends on microbial N-requirements for growth and microbial activity, with microbial activity being dependent on the quantity and quality of available carbon and environmental factors (e.g., temperature, moisture, and pH). Nitrification is the oxidation of NH_4^+ to NO_2^- and NO_3^-, and is facilitated by chemoautotrophic bacteria. These bacteria are obligate aerobes that obtain their carbon source from CO_2 and carbonates and their energy from the oxidation of NH_4^+. The principle bacteria involved in nitrification in soils are *nitrosomonas* in the oxidation of NH_4^+ to NO_2^- and *nitrobacter* in the further oxidation of NO_2^- to NO_3^-. The oxygen atom used in oxidizing NO_2^- is obtained from water.

Environmental factors affecting N-mineralization

A significant amount of work has been done in determining the relationship between nitrogen mineralization and soil environmental factors, mainly with the objective of using these environmental factors in empirical models to predict nitrogen availability.

The majority of studies have examined the effects of temperature, moisture, and/or their interaction on N-mineralization. Because soil temperature and moisture conditions are such controlling factors in biological processes, soil microbial responses (and hence N-mineralization) are relatively consistent with respect to these two environmental factors. Nitrogen mineralization slows dramatically above 40^0C and below 5^0C, with activity following a exponential relationship between 5 and 35^0C (Paul and Clark, 1989). The Q_{10} function is the standard mathematical expression for N-mineralization responses to changing temperature, and on average a Q_{10} of 2 describes the relationship very well (Stanford et al., 1973; Kladivko and Keeney, 1987; Powers, 1990).

Studies have examined the relationship between N-mineralization and soil moisture content under a wide range of water potentials (from -0.01 to -4.0 MPa), and have found that under this wide range of soil water contents N-mineralization has a parabolic response to soil water. The maximum N-mineralization rates occur between -0.01 and -0.03 MPa, decreasing in a nonlinear way on either side of this range (Cassman and Munns, 1980; Myers et al., 1982; Kladivko and Keeney, 1987). Myers et al., 1982, found that N-mineralization was essentially zero at -4.0 MPa, and net immobilization occurred somewhere between -0.01 and -0.005 MPa for a variety of soils. The -0.005 MPa water potential is boarding on completely saturated soil, recalling that aerobic microbial activity eventually ceases in saturated soil because of oxygen depletion, the net immobilization results at very low water potentials agree with what is known about microbial activity in waterlogged soils.

Skopp et al., 1990, developed a conceptual framework and model for understanding the effects of soil water on microbial activity. Their model assumes that microbial activity is strongly influenced by soil water because soil water content affects oxygen and substrate diffusion rates. Sustained and enhanced microbial activity require constant supplies of electron acceptors (oxygen) and energy and nutrients (substrate). Higher water contents favor increased substrate diffusion and lower water contents favor increased oxygen diffusion. Because the maximum diffusion rates for the two processes directly oppose each other, microbial activity is highest at the water content at which the limiting effects of the two processes are minimized. Using literature-derived diffusion coefficients for oxygen and substrate, Skopp and others determined that the optimum water content (i.e., least limiting for both processes) was 60 % of total porosity. They partially verified the model using data from the literature, and found that optimum water contents for maximum microbial activity ranged between 55 and 61 % of total porosity for a variety of soils. In interpreting this optimum water content, they stated that because the diffusion coefficients for oxygen and substrate were very similar the theoretical optimum water content should be 50 % of total porosity; a shift towards a higher optimum water content suggests that substrate diffusion limits microbial activity more than oxygen diffusion for a variety of soils. An important additional point from Skopp and others work is that the effects of soil water on microbial activity are best described using soil water content as opposed to water potential because soil water content affects diffusion rates while water potential does not.

In examining the interaction between temperature and soil water, Cassman and Munns, 1980, developed a quadratic regression model that included temperature, soil water, and their interaction as independent variables. These independent variables explained 95 % of the variation in N-mineralization, with all the regression coefficients being highly significant. Gonçalves and Carlyle, 1994, observed that N-mineralization did not respond to temperature when the soil moisture level was below 5 %, indicating that very low moisture contents restricted microbial activity regardless of the temperature; the temperature response increased between 5 and 10 % moisture and then declined slightly above 10 %. Kladivko and Keeney, 1987, suggested that their soil moisture and temperature interaction study showed no significant soil moisture and temperature interaction; however, their conclusions were not very strong. A computer model developed by Bunnell and Tait, 1974, simulating the microbial response to increasing temperature and soil moisture content indicated that as soil temperature increased maximum microbial activity occurred at higher moisture contents. This simulated result suggests that microbial activity is limited by substrate diffusion at higher temperatures.

The oxidation of NH_4^+ to NO_3^- is very pH-dependent (Paul and Clark, 1989). In agricultural soils, nitrification is optimum between pH 6.6 and 8.0, then decreases rapidly below pH 6.0, and becomes negligible below pH 4.5. Nitrification in forest soils is much less sensitive to acidity, with significant nitrification still occurring around pH 4.5. The ability of nitrification to proceed at lower pH's in forest soils may be due to higher pH's in nitrification microsites brought about by ammonification, and/or heterotrophic nitrification which is less sensitive to acidity than autotrophic nitrification (Paul and Clark, 1989).

Fu et al., 1987, studied the effects of pH (4.0, 6.0, and 8.0, respectively) and crop residue on N-mineralization for 3 different agricultural soils using a 20-week laboratory incubation. Net N mineralization increased with increasing pH, resulting in a 20 to 30 % overall increase from pH 4.0 to 8.0. Nitrate was the predominant form of N mineralized between pH 6.0 and 8.0. Ammonium was only detected at pH 4.0, with the specific amounts differing with soil type. Crop residues with carbon to nitrogen ratios greater than 35 experienced net N immobilization at pH 4.0. Nitrogen mineralization increased with decreasing carbon to nitrogen ratios under all pH treatments.

Organic Matter Quality affects on N-mineralization

Within the constraints imposed on microbial activity by environmental factors, the quantity and quality of soil organic matter are important determinants of N-mineralization (Paul and Clark, 1989). Organic matter quality refers to its chemical make-up, age, resistance, and degree of protection, all of which determine the ability of soil organisms to degrade the material and mineralize nitrogen (Connell et al., 1995). Connell et al., 1995, investigated the effects of these organic matter quality determinants on N-mineralization for 27 different forest soils in Australia representing a wide range of soil properties. Nitrogen mineralization rates differed by a factor of 30, illustrating the tremendous effects of soil properties on N-mineralization. In examining the effects of soil properties on N-mineralization, they found significant positive linear correlations between N-mineralization and Total N, Organic C, and Total P. However, when they used a multiple linear regression model which included soil depth, organic C, total N, total P, C:N, C:P, N:P, coarse sand content, fine sand content, total sand content, silt content, clay content, and silt plus clay content, the model only explained 56 % of the variation in N-mineralization. I believe their ability to explain differences in N-mineralization using these variables was seriously decreased because of unaccounted for confounding factors having to do with differing forest management histories. An important results from their study relating to how organic matter quality and quantity and environmental conditions change with depth was that 75 to 85 % of N-mineralization occurred in the top 20 cm of soil; this result is confirmed by several other studies conducted on N-mineralization in forest soils (Federer 1983; Raison et al., 1987; Smethurst and Nambiar, 1990; Soudi et al., 1990; Raison et al., 1992).

Maimone et al., 1991, examined the relationship between aerobic N-mineralization potential and soil properties for a Lower Coastal Plain forest soil. Nitrogen mineralization potential determined using 98 day incubations was significantly and positively correlated with total N, organic C, and exchangeable acidity. There was a weak negative correlation between N-mineralization potential and the C:N ratio.

The importance of organic matter quality was well illustrated by Gilmour et al., 1985, who developed a computer model that used carbon mineralization rate constants, C:N ratios, and microbial use efficiency to predict N-mineralization based on CO_2 evolution. For different types of organic substrate (e.g., sludge, clover, alfalfa) carbon was divided into three fractions (very rapid, rapid, and slowly decomposable, respectively) each with their respective C:N ratios. They predicted N-mineralization using literature-derived decomposition coefficients and C:N ratios for each carbon fraction for each type of substrate. Their predicted N-mineralization rates correlated strongly with measured N-mineralization rates for these substrates (93 to 98 %), illustrating that the organic matter quality parameters they chose to model N-mineralization were correct. Based on their modelling effort which was conducted using a variety of plant tissues with varying organic matter quality, plant tissues with the highest total N, and lowest C:N ratios resulted in the highest N-mineralization levels. Their work also showed that rapidly decomposable materials yield the highest N-mineralization rates. Forest scientists have shown that organic matter decomposition rates in forests vary depending on the amount of total nonstructural carbohydrates, lignin, and N (Berg, 1984; McClaugherty et al., 1984; Fahey et al., 1988; Camiré et al., 1991), thus the quantities of these materials partly define organic matter quality in forests and should play a significant role in determining the quantity of N mineralized.

N-Availability affects on forest productivity

Most natural stands and plantations of Southern pines are nitrogen deficient (Maimone et al., 1991; Zhang and Allen, 1996). This is illustrated by the work of Ballard, 1981, who synthesized the results of several North Carolina State Fertilizer Coop studies on N fertilization to determine the biological optimum fertilizer rate for loblolly pine. Ballard fit a volume response curve as a function of increasing N fertilizer application rates from 0 to 300 lbs acre^{-1}, and used the model to predict the application rate at which the volume response would equal zero (i.e., biological optimum). His analysis showed that on average 200 lbs acre^{-1} would have to be applied to realize maximum biological productivity. The predicted application rates varied from 122 to 354 lbs acre^{-1}, which shows that N deficiency is limiting productivity on many loblolly pine sites.

Though the work of Ballard and others has shown that plantations generally respond positively to N fertilizer applications, very few studies have been successful in relating tree growth to measures of soil N availability (Maimone et al., 1991). Indices of available N, such as aerobic N mineralization potential, have been successfully related to Douglas fir (*Pseudotsuga menziessi* Mirbel.) productivity in the Pacific Northwest (Shumway and Atkinson, 1978), ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) site index in California (Powers, 1980), loblolly pine growth in the Southeast (Birk and Vitousek, 1986; Maimone et al., 1991), and aboveground biomass of northern hardwoods in Lower Michigan (Zak et al., 1989). Other studies have found weak to no relationships between measures of tree growth and indices of N availability.

The lack of consistent relationships between indices of N availability and tree growth is largely explained by not accounting for differences in environmental factors affecting N-mineralization in laboratory versus *in situ* field studies. Field studies of *in situ* net N-mineralization (N_{min}) have found significant relationships between tree growth and available nitrogen. Unfortunately, few published field studies that relate tree growth to N_{min} exist because such studies are labor intensive and time consuming.

Nadelhoffer et al., 1985, examined the relationship between aboveground net primary productivity (ANPP), belowground net primary productivity (BNPP), and soil N availability (net N-mineralization) for nine temperate forests in Wisconsin. Both ANPP and BNPP were positively correlated with increasing N availability. Annual net N_{min} ranged from 32 to 137 kg N ha^{-1} yr^{-1}, and explained 63 % of the variation in bole plus branch production. The biomass production response to increasing net N_{min} was linear, with a doubling of annual N_{min} corresponding to a 67 % increase in bole and branch production.

In a study which combined the data collected from the previous work by Nadelhoffer et al., 1985, with a new dataset collected from several forests in Massachusetts, Aber et al., 1991, demonstrated that the wood production response to increasing available N was similar among species (hardwoods and softwoods) and linear within the range of data collected (30 to 147 kg N ha^{-1} yr^{-1}). Net N_{min} explained 68 % of the variation in wood production across all species, with a doubling in N_{min} resulting in a doubling in wood production.

Reich et al., 1997, included some of the data from the previous two studies in a study to determine the relationship between ANPP and net N_{min} for 50 hardwood and softwood forests growing across a variety of soils in Wisconsin and Minnesota. Aboveground net primary production varied from 2 to 14 Mg ha^{-1} yr^{-1}, and was positively correlated with net N_{min} which varied from 20 to 137 kg N ha^{-1} yr^{-1}. Net N_{min} explained 54 % of the variation in ANPP and 50 % of the variation in wood production. The wood production response to increasing net N_{min} was very similar among species, but differed depending on soil type. The biomass response to a given level of net N_{min} on alfisols was greater than on entisols, but the relative response to increasing levels of net N_{min} was the same, as indicated by similar slopes. The apparent differential response among soil types is most likely explained by relief of other limitations (e.g., water shortages, inadequate base cation supply) on better soils (e.g., alfisols). A multiple regression model which included net N_{min} and soil texture (% silt + clay) as independent variables explained 65, 74 and 83 % of the variation in ANPP for all species combined, native species, and natural stands, respectively.

The results of these studies are important because they show that available soil N is highly correlated with ANPP in forests, and the relationship between available soil N and ANPP is very similar among species.

MEASURING FOREST PRODUCTIVITY

Introduction

The productivity of a forest is defined by its ability to produce biomass (plant or animal) over a specified length of time on a given area of land (Ford, 1983). The biomass produced by a forest is controlled by climate, topography, and soil limitations and also changes depending on the species', age of the forest, and management practices imposed on the forest (Gessel, 1981). The method used to express forest productivity largely depends on the goals of forest management (e.g., lumber production: expression is board feet; pulp wood production: expression is cubic feet; bioenergy production: expression is tons). Regardless of the method of expression, the goal of forest management for wood production is usually to maximize productivity across the landscape.

In order to maximize productivity, the actual and potential productivity of forests must be identified (Ford, 1983). Actual productivity is the productivity realized under given climatic, topographic, and soil conditions. Potential productivity is the productivity that could be realized if the limitations imposed under the actual productivity could be eliminated. Elimination of constraints to productivity has been a primary focus of forestry research since the 1950's, and remains a primary focus as forest management continues to intensify.

Forest Site Quality

Characterizing the actual productivity of a given tract of forest-land begins with understanding the quality of that land. The term that evolved for characterizing land quality is site quality, with site quality being defined as the productive capacity of an area of land (Coile, 1952) or more specifically for forest management, the ability of forest land to grow trees (Carmean, 1975). The traditional method for expressing site quality is the bioassay approach of measuring site index (Coile, 1952). Overall, site index has worked reasonably well as a method for characterizing site quality. There are several significant problems associated with using site index to characterize site quality, namely (i) trees must all ready occupy the site, (ii) they must be the proper age to use available site index curves, and (iii) the growth habits of a species may change on different sites, rendering available curves inaccurate (Carmean, 1975). Perhaps the most important problem with using site index is the measurement tells the forester nothing about the site limitations to potential productivity, and thus on it's own does not aid in making forest management decisions with respect to the potential for altering the productivity of a given site via management practices.

Forest researchers realized the limitations of site index early on (1940's), and beginning with the pioneering work of T. S. Coile, began to look at alternative ways to characterize site quality (Carmean, 1975). A forest site is a specific area of land defined by certain combinations of climatic, topographic, soil, and biological features; Coile, 1952, stated that relationships could be developed between tree growth and these features of site if the controlling properties of tree growth were correctly identified. The importance of choosing the correct variables to measure was later reiterated by Ford, 1983, who said in order to improve our ability to use site variables to predict productivity it is critical to choose variables that provide a "finger on the pulse" of the process.

Coil suggested that, within the additional constraint imposed by climate and topography, site quality would be determined by the soil properties limiting the quantity and quality of rooting volume. In several studies conducted on the North Carolina and Alabama Piedmont, Coile proved that soil features could be used in characterizing site quality for loblolly (*Pinus taeda* L.) and shortleaf (*Pinus echinata* Mill.) pines. In these studies, he used surface soil depth, subsoil texture, subsoil imbibitional water value, and surface drainage as independent variables in a multiple regression approach to predict tree productivity as a function of soil properties (Coile 1935, 1948, 1952, and 1959, as cited by Carmean, 1975).

Between Coile's initial work and Carmean's 1975 review of forest site quality evaluation, over 160 studies were conducted where tree productivity had been regressed against soil properties (Carmean, 1975). These studies, termed soil-site studies, often included a variety of extrinsic site factors (e.g., rainfall, slope position, percent slope, aspect, and elevation) as additional variables in the site quality regression model. As was previously discussed, the ability to successfully explain tree productivity as a function of site factors rests partly on the ability of the investigator to choose the correct variables, when the correct variables are chosen soil-site regression models often explained 65 to 85 percent of the variation in tree height (Carmean, 1975).

Concurrent with the soil-site studies, research and discussion were underway to integrate soils information with forest production (e.g., Youngberg, 1963). A consequence of the many soil-site studies that have been conducted over the years is the many relationships that have been developed between tree growth and site factors have increased our knowledge of site quality, enabling us to identify critical soil factors to key in on when classifying and mapping forest-land. Examples of critical soil factors and their relationship to tree growth are (i) soil depth, relates to rooting volume, (ii) soil texture, relates to available moisture, nutrition, drainage, and aeration, (iii) depth to mottling and subsoil color, both relate to drainage restrictions and aeration problems (Carmean, 1975).

Manipulating Site Quality

The evolution of the ability to identify critical soil factors relating to productivity has played a significant role in allowing forestry to move from accepting site quality as fixed to manipulating site quality for increased productivity. Recalling that site quality is the integration of the effects of climate, topography, and soils on tree productivity, it is only the soil and, to some extent, the topographic components that can be manipulated. The notion that soil could be manipulated to increase site quality helped forestry make the transition from the "Regulated forest", where site quality was considered fixed, to the "Domesticated forest", where site quality was considered malleable via cultural practice (Stone, 1975).

The potential benefits of increasing site quality and tree production by alleviating soil deficiencies through site preparation were exemplified in the writings of Terry and Hughes, and Haines et al. published in the 1975 proceedings of the 4th North American Forest Soil Conference (Bernier and Winget, 1975). In these papers, the authors suggested that intensive site preparation methods such as drainage, tillage, and weed control, combined with periodic fertilizer applications would substantially increase timber yields beyond the yields provided by natural regeneration methods (as per the Regulated forest). Variations of the intensive culture exposed by these authors have since become the standard forest management practice invoked by many large industrial forest-land owners, particularly in the Southeastern U.S.

Management Effects on Site Quality

Commensurate with the development and popularity of the Domesticated forest has been a concern that intensive culture may decrease long-term site productivity. Scientists have expressed their opinion that higher cultural inputs increase the potential for degrading site quality, a concern which has been expressed by numerous researchers at several symposia over the years (Youngberg and Davey 1968; Bernier and Winget, 1975; Stone, 1975; Balmer, 1978; Dyck et al., 1994). Concerns raised cover a broad spectrum of possible negative affects of intensive culture on site quality, from disrupting nutrient cycling to reducing the amount of rootable soil volume.

Studying the possible deleterious effects of intensive culture on long-term site productivity has been a mainstay of forest soils research for over thirty years. The rationale behind our concern over long-term site productivity is rooted in the ethical responsibility of foresters to not degrade the forest site (Ford, 1983), and as Gessel stated in 1981, "It is less costly to maintain and/or enhance productivity than it is to restore it". In this vain, the question that most long-term site productivity studies seek to answer is, does intensive culture reduce the amount of harvestable biomass produced in successive rotations on the same site?

Morris and Miller, 1994, sought to answer this question in their comprehensive review of scientific studies on intensive culture and long-term site productivity. Their review indicated that (i) nutrient removals via whole-tree harvesting may contribute to reduced productivity, (ii) mechanical site preparation techniques such as slash disposal can reduce productivity, particularly on nutrient impoverished sites, and (iii) soil productivity can be improved with fertilization, resulting in lasting changes in productivity often into the second rotation (on P-deficient sites). Soil tillage methods such as bedding, discing, and ripping have positive short-term affects on productivity, but their long-term affects are still unknown. Though no direct evidence existed, they also warned that continued nutrient removals via whole-tree harvesting and slash disposal coupled with accelerated nutrient mineralization resulting from mechanical site preparation may cause long-term reductions in site productivity that may not manifest for several rotations.

With the exception of P-fertilization studies, the lack of a clear picture of the effects of intensive culture on long-term site productivity is really confounded by the variety of study designs used to assess management impacts (Morris and Miller, 1994). A large number of studies suffer from (i) inadequate control over additional factors not related to the cultural treatments (e.g. climate, genetics, inherent site variation), (ii) weak or questionable experimental designs, and (iii) not allowing a sufficient amount of time to access long-term effects. Providing adequate control and designing the correct experiment are easily solved through good experimental technique, but time is a serious problem with long-term studies.

Because it takes a minimum of one rotation to determine if tree growth was affected by a particular cultural practice, very few studies have been completed. A study on site preparation and fertilizer effects on slash pine (*Pinus elliottii* Engelm. var. *elliottii*) growth over two successive rotations on the same sites was published by Tiarks and Haywood, 1996. At the end of the first rotation pines growing on bedded sites were significantly taller than on non-prepared sites, this effect was reversed in the second rotation, where bedding resulted in trees significantly lower in height. Discing had no effect on pine growth in the first rotation, but it also reduced height growth in the second rotation compared to no-preparation. The negative growth response to discing was attributed to decreased root penetration in the second rotation, as evidenced by higher soil strengths measured using a cone penetrometer. Tiarks and Haywood, 1996, speculated that the negative growth response to bedding in the second rotation was due to nutrient depletion during the first rotation; however, they were not able to substantiate this with soil tests nor did the fertilizer treatment response support their contention. The authors argue strongly that their study was very well controlled, meaning that climate, seedling quality, genetics, and competition were very similar between the two rotations. Because this study was well controlled and conducted over a long period of time, the results are definitive with respect to the effects of cultural practices on long-term site productivity, and it adds credence to the need for continued research into understanding the impacts of management on site quality.

Soil-based Site Index

Scientists and practitioners have been aware of the problems associated with tree bioassays, and over the years it has been suggested that we should use soil conditions as the criteria for assessing management impacts on site quality. Gessel, 1981, suggested that the same soil parameters that were being used to predict site quality in the soil-site studies could be used to examine site degradation, stating that adverse changes in the selected soil properties would be expected to decrease productivity. Carmean, 1975, stated that in order to design management practices to avoid degradation or improve productivity the critical soil parameters must be identified in soil-site studies conducted in undisturbed forests; the critical soil parameters could then be compared to the same ones measured in managed-forests to make judgments about site improvement or degradation. McClurkin and Duffy, 1975, asked what criteria should be applied to determine whether or not a site has been degraded, and suggested that regional standards should be developed for critical soil properties and processes which would be used for evaluating management impacts on site quality. Stone, 1984, suggested that soil and site specific "effective properties" (i.e., ones that regulate nutrient and water supply), should by identified and their relationships with productivity determined; he then stated that changes in productivity brought about by a given management practice do not depend on the intensity of the practice, but rather changes depend on how much the practice affects a marginal "effective property". Klock, 1983, coined a new term "soil productivity resilience", defined as "the ability of a particular forest soil to resist significant changes in its moisture, aeration, or nutrient availability characteristics that will affect the site's productivity capacity", and stated that "any evaluation of the effects of forest soil management on site productivity must be based on a study of soil properties controlling soil productivity resilience". Klock suggested that soils should be classified based on the ability of management practices to change critical intrinsic soil factors (i.e., soil moisture, aeration, and nutrient availability). Miller, 1983, stated that site productivity will be maintained as long as the soils' rooting volume and nutrient supplying capacity are ensured. Burger, 1996, in his critique of the use of bioassays for monitoring forest soil productivity, discussed the problems associated with using a bioassay approach (i.e., confounded by climate, genotype differences, and competition), and concluded that "management effects on soil productivity should be determined by measuring soil properties and processes directly". The common theme amongst all of these authors is that the effects of management practices on site quality and productivity can be evaluated through examining soil characteristics important to tree growth, i.e., not only using a bioassay. An obvious advantage to this approach is that it eliminates the confounding factors associated with the bioassay, and focuses management attention on the site factors that are being changed.

The necessity of a soil-based, versus only a bioassay-based, site quality index is illustrated by the USFS long-term site productivity study (LTSP) (Powers, 1991). The Forest Service is mandated by federal law not to significantly degrade the productivity of the land, and as such must monitor changes in land productivity, with land productivity being officially defined by the federal government as the soil's capacity to support plant growth (Powers, 1991). The provisions of the mandate are difficult at best for the Forest Service to comply with, and have forced the organization to use their experience and judgment to determine soil quality monitoring standards that are now being used to monitor changes in land productivity. In a substantial nationwide effort to add scientific rigor to their current standards, the agency is implementing the LTSP study which is designed to evaluate the effects of organic matter removal and soil compaction (the two most common disturbances) on forest productivity. Critical soil properties and processes are being evaluated through time on a range of sites representing the major forest and soil types in the US, the soil variables will be compared against net primary production (as opposed to tree growth only) so that quantitatively-derived threshold levels can be determined for the soil variables being monitored. The results of this study should allow the Forest Service, and others, to use soil properties and processes in a quantitative way to evaluate management effects on forest productivity.

Soil Quality Index

One of the advantages of the site index approach to measuring site quality was that site index is an easily interpretable and widely understood measurement. Using multiple soil variables to characterize site quality runs the risk of being difficult to interpret in terms of deciphering management effects and thus unused because of such difficulties. This and other problems were identified early on in the development of soil-site multiple regression models. Carmean, 1975, discussed the problems associated with soil-site regression models. Regression equations require quantitative values which are often difficult to determine for certain important site variables (e.g., landform, soil structure, and soil drainage). Relationships between tree growth and the desired variables are often nonlinear. Multiple interaction among the independent variables is a common problem with soil-site models because the vast majority of variables are not independent of each other (e.g., soil depth relates to percent slope and landform). Because of interactions, combined-variables must be used to represent the independent variables so that statistical assumptions are not violated. Variables that appeared important based on x-y plots may not appear in the final regression model due to elimination during the best-model selection process. The final predictive model may contain variables which are difficult and or costly to measure, therefore decreasing the usability of the model and increasing the probability that it will never be used. Perhaps the greatest problem with the soil-site regression model approach is that the model can only be applied to the same conditions under which it was developed; in this vain, it would be very difficult to develop a generally applicable regression model given the complex interactions among variables, changing importance of variables with site and species, and the high cost of collecting the necessary data for model-fitting and verification.

Paralleling the development of soil-site regression models in forestry was a movement in agriculture to use a "soil property rating system" to evaluate soil-site productivity (Huddleston, 1984). Agricultural soil scientists recognized early on that "soil was the most stable attribute of the land, being unaffected by non-land inputs that influence crop yield" (Huddleston, 1984), and therefore a productivity rating system should be based on soil. In general, the approach is based on our understanding of which soil-site variables are the most significant determinants of productivity. Based on our understanding of their importance to productivity, numerical values that relate the measure-variables to site productivity are assigned to each variable, and the values are then combined to arrive at a soil productivity index.

Agricultural soil productivity rating systems evolved to include a combination of inductive and deductive expressions, and are usually based on a percent scale ranging from 1 to 100 (Huddleston, 1984). Inductive ratings are determined mainly on subjective judgment concerning the effects of each soil property on the potential productivity of a soil. Deductive ratings are analogous to using site index to classify forest site quality, in that they are based solely on measurements of crop yield. They also suffer from the same criticisms as site index. A further problem with deductive ratings is that because of limited data, the ratings are limited to major crops growing on major soil types. One way around the limited data problem was to develop relationships between soil properties and yield on benchmark soils, and then adjust yield predictions for soil types without yield data based on soil property differences between the soils with no yield data and the benchmark soils (e.g., Fenton et al., 1971; Buntley and Bell, 1976; Bone and Norton, 1981). These studies are examples of combining inductive and deductive expressions of soil productivity.

As was previously stated, inductive ratings are based on inferences about the effects of soil properties, and occasionally other site-factors, on yield. Though yield data is not used in developing the rating system, the rating system is often calibrated and validated with yield data. Calibration and validation are important components in using an inductive rating system, otherwise the users of the system have no idea if reliable soil productivity ratings are being given (Huddleston, 1984).

There are three types of inductive rating systems, multiplicative, additive, and a combination of the two (Huddleston, 1984). With the multiplicative system, ratings are determined for each soil variable and then multiplied together to arrive at a single value expressing soil productivity. Because the individual values are multiplied together, any single value that numerically stands out from the rest will control the productivity rating (e.g., four variables have ratings of 100, 90, 80, and 30, respectively, the overall rating would be 22). Obviously, any soil management that might be done to raise the variable with the 30 rating closer to the other three would have a significant effect on the overall productivity rating. A problem with this approach is that if all four variables were rated at 90 the overall rating would only be 66. A way around this problem would be to take the geometric mean of the product of the individual ratings as the overall rating.

The first multiplicative soil productivity index was developed by Storie, 1933, using ratings developed for soil texture, soil depth, drainage, alkalinity, and profile morphology. Storie considered soil texture to be a surrogate for the general effects of soil porosity, permeability, and soil tilth on productivity. The general ratings for Storie's soil productivity index are illustrated in Table II.1. The range in possible scores under bad conditions illustrates the inductive part of evaluating soil productivity.

Storie and Wieslander, 1948, developed a productivity rating system for forest soils based on soil depth, permeability, alkalinity, soil drainage, and climate. The rating system was similar to the original system developed in 1933. The major difference being that after the forest soil productivity was rated, the site was assigned to one of five general forest productivity classes. Though this system was never adopted by the forestry community, it is interesting to note that an agricultural soil scientist developed a forest soil productivity index based on soil properties while the forestry community was still using site index to judge forest site quality.

Additive soil productivity rating systems have one distinct advantage over multiplicative systems, in that additive systems are more suited for combining larger numbers of soil variables together. Huddleston, 1984, stated that four or five variables is the practical upper limit for multiplicative rating systems: more than five variables makes the rating system difficult to interpret. A significant problem with additive systems is that when the majority of soil variables have a low rating, the overall rating is often a negative number. The possibility of obtaining a negative number when rating soil productivity suggests that purely additive systems are not logical.

Table II.1. General rating scheme for the Storie soil productivity index.

Soil Property	Good	Score	Bad	Score
Soil texture	loam	100	gravelly sand	20-30
Soil depth	deep	100	shallow	20-70
Drainage	well drained	100	waterlogged	10-40
Alkalinity	alkali-free	100	strongly alkaline	5-25

Combinations of additive and multiplicative systems have also been used, and are advantageous over additive systems because they do not produce negative numbers. Combination systems are often used to integrate factors which themselves are combinations of other factors. For example, Harris, 1949, developed a combination model that multiplied individual ratings together for water, soil, and climate. The water rating was determined by averaging quantity and quality estimates, this average was then multiplied by a water availability rating to arrive at an overall water rating.

Pierce et al., 1983, developed a combination model for determining the effects of soil erosion on soil productivity. The model used soil properties that affect the quantity and quality of available rooting volume: bulk density, available water, and pH. Sufficiency levels were determined for each soil property by horizon, and the product of the sufficiency levels was multiplied by a horizon weighting factor based on an ideal root distribution. The within horizon values were then summed across all horizons to obtain an overall soil productivity rating. The model has been partially validated with corn yield data and other productivity indices in southeastern Minnesota. The model represented a significant step because it not only could be used to estimate soil productivity, but it could also be used to determine the effects of agricultural management practices on soil productivity.

The potential of the Pierce et al., 1983, model was recognized by forest soil scientists Gale and Grigal, 1987, who adapted the model to estimate forest soil productivity in Minnesota. Their model, called the Productivity Index (PI) model, has accounted for 55 to 85 percent of measured aboveground biomass in white spruce (*Picea glauca* Voss.), aspen (*Populus tremuloides* Michx.), and jack pine (*Pinus banksiana* Lamb.) stands, indicating the model has tremendous potential for use in estimating soil productivity. They also suggest that the PI model could be used to evaluate management impacts on forest productivity. The PI model will be discussed in greater detail in the next section.

SOIL QUALITY MONITORING

Introduction

It is evident from the works discussed in the previous section that a considerable amount of scientific effort has been expended in determining ways to (i) characterize site productivity and (ii) maintain and enhance forest productivity. Results from soil-site studies and studies on the effects of management practices on soil properties, processes, and yield have provided us with a wealth of information, and based on such studies we know a lot about what is required of the soil to meet our management objectives. However, as illustrated by the LTSP study being implemented by the Forest Service, from a management and regulatory perspective very little has been accomplished in extending the results of the scientific work to the practitioners, in the form of a management system for ensuring that forest productivity is maintained and hopefully enhanced.

With the exception of some authors advocating that we use computer process models to predict the effects of different management practices on long-term productivity (e.g., Kimmins and Sollins, 1989), no other methods are currently available for evaluating management impacts. Given the problems associated with using tree growth as a bioassay of management impacts (Burger, 1996), what are the alternatives? What standards should be used to determine if long-term productivity is being maintained? Because as Gessel, 1981, stated "soil is the basic resource in forestry", and it is the soil that is altered by management, our measures of management impacts on long-term productivity should emphasize soil properties and processes affected by management and related to productivity. The previous section illustrated the feasibility of using soil properties to characterize site productivity. This next section builds on the PI model introduced in the previous section, and develops the concept of a soil quality monitoring system for determining the effects of management practices on long-term site productivity.

Soil Quality Monitoring System

Implementing a soil quality monitoring and improvement program requires converting often loosely defined qualitative descriptions of soil quality into meaningful and consistent quantitative measures of soil quality. Any successful farmer could give you a qualitative description of good soil quality for crop production. In describing good soil quality, the farmer would probably mention soil tilth as a necessary attribute of good soil quality. Soil tilth is a term that qualitatively integrates all the physical attributes of a soil that make the soil good for crop production. According to Yoder, 1937, a soil with ideal tilth would (i) allow unimpeded root growth, (ii) promote water infiltration and retention, (iii) have optimal gas exchange properties, (iv) have the ideal air/water ratio in the pore space, and (v) facilitate soil biological activity.

Yoder's five attributes of soil tilth represent the first step in bridging the gap between the ability to qualitatively and quantitatively describe soil quality. Through understanding the qualitative attributes of soil tilth as described by Yoder, Singh et al., 1992, developed a Soil Tilth Index as a method for quantitatively measuring soil tilth. Singh et al. made the transition from the qualitative to the quantitative by substituting bulk density, soil strength, aggregate uniformity, organic matter content, and plasticity index for the qualitative attributes of soil tilth. The soil tilth index was calculated using a multiplicative model made up of sufficiency relationships between crop production and each of the variables. Singh et al. found that their soil tilth index was significantly and positively correlated with crop yields. Thus in viewing each attribute of soil tilth separately, Singh et al. were successful in converting a qualitative description of soil tilth into a quantitative measurement of an important attribute of soil quality.

The first step in designing a soil quality monitoring program is to qualitatively describe the attributes of a high quality soil, much as Yoder, 1937, described the attributes of ideal soil tilth. The second step is to substitute quantitative measurements for the qualitative soil quality attributes (e.g., Singh et al.'s soil tilth index). Karlen and Stott, 1994, provided an excellent illustration of these steps in their example of evaluating soil quality with respect to a soils' resistance to erosion. They describe the attributes of a high quality soil that will resist erosion as a soil that (i) freely allows water infiltration, (ii) has optimum water transfer and adsorption characteristics, (iii) is resistant to physical damage, and (iv) promotes plant growth. They then developed a list of measurable soil quality indicator variables that could substitute for each attribute (Table II.2). With the exception of water infiltration, it was necessary to use several indicators in describing each soil quality attribute. In the situations where several indicators are used, Karlen and Stott integrate them into an index of the respective attribute using an approach similar to Singh et al. (1992). Notice there are no direct measurements for the indicators chosen to substitute for the promote plant growth attribute, in this situation, measurable indicators must be substituted for the non-measurable indicators; for example, measurements of organic carbon, pH, macronutrients, and micronutrients are substituted for the nutrient relations indicator.

Table II.2. Soil quality attributes and associated indicators.

Attribute	Weight	Indicator	Weight
Water Infiltration	0.50	Infiltration rate	1
Water Transfer and adsorption	0.10	Hydraulic conductivity	0.60
		Porosity	0.15
		Macropores	0.25
Resist Physical Damage	0.35	Aggregate stability	0.80
		Shear strength	0.10
		Soil texture	0.05
		Heat transfer capacity	0.05
Promote Plant Growth	0.05	Rooting depth	0.25
		Water relations	0.35
		Nutrient relations	0.30
		Chemical barriers	0.10

Modified from Karlen and Stott, 1994.

After defining the attributes of high soil quality, and identifying measurable indicators for each attribute, the indicators should be combined into an overall index of soil quality. By monitoring changes in the overall index through time, positive and negative management impacts on soil quality can be determined. If certain management practices are degrading soil quality, then the index will decrease over time. Tracking changes in the soil quality index through time under different management scenarios will allow us to identify and choose management strategies that result in improved soil quality.

Soil Quality Models

One of the earliest methods developed for combining soil quality indicators into an overall index of soil quality is the Productivity Index (PI) model developed by Kiniry et al. (1983). The PI model is a multiplicative model which integrates field measurements taken from several soil variables into an index which relates to plant productivity. The PI model is constructed based on the assumptions that (i) there is a direct positive relationship between root growth and aboveground productivity, and (ii) any soil property that restricts root growth will result in decreased aboveground productivity. Based on the PI model, the roots will assume an ideal distribution if no soil restrictions to root growth occur with depth, and if soil restrictions do occur with depth the roots will negatively deviate from the ideal distribution. Kiniry et al., 1983, chose five soil variables to include in their PI model: (i) available water capacity, (ii) bulk density, (iii) aeration, (iv) pH, and (v) electrical conductivity. The PI was then calculated using the model,

$$PI = \Sigma\,(A \times B \times C \times D \times E \times RI), \tag{1}$$

where, A, B, C, D, and E are values determined from sufficiency relationships developed for each variable with respect to root growth (e.g., Fig. II.1), and RI is a weighting factor based on the ideal root distribution. The PI is calculated by summing the product of the five variables times the weighting factor with depth. The sufficiency relationships and the RI were standardized between 0 and 1, so the PI is between 0 and 1. As the PI approaches 1, the root distribution approaches the ideal root distribution, and the site productivity increases. Because the PI model is based on the ideal root distribution, it must be modified for different plant species.

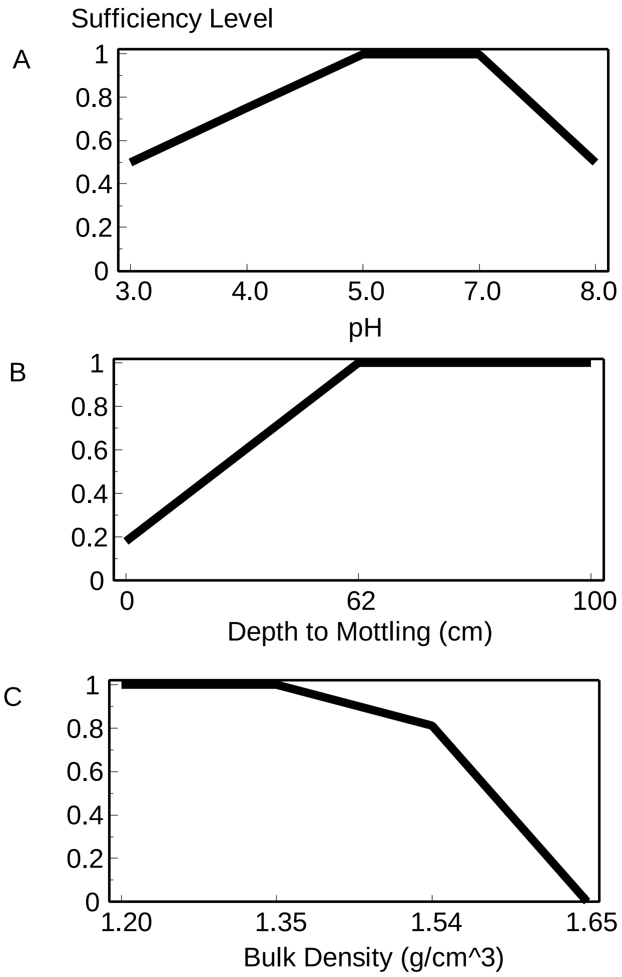


Figure II.1. Sufficiency curves that describe the relationship between root growth and soil pH (A), depth to mottling (B), and bulk density (C) using by Gale et al. (1991) for calculating the Productivity Index (PI) for spruce in the Lake States.

One problem with the PI model is that if all the soil variables are at the same level in one horizon, then their product will be lower than their individual sufficiency values; e.g., if all five sufficiency values are 0.95, then their product would be 0.77. This artifact of the model may cause it to underestimate the potential productivity of a site. Gale et al., 1991, modified the PI model by calculating the geometric mean rather than the product for each horizon,

$$\mathrm{PI} = \sum_{i=1}^{r} \left[\left(\mathrm{A}\ x\ \mathrm{B}\ x\ \mathrm{C}\ x\ \mathrm{D} \right)^{1/4} x \quad \mathrm{WF} \ \right] \ x \ \left(\mathrm{S}\ x \mathrm{CL} \right)^{1/2} \qquad [2]$$

where, the PI is determined by multiplying the geometric mean of the sufficiency values (A, B, C, and D) by a weighting factor, WF, which is similar to RI, and then summing the products across all horizons, r, present. In order to make the PI model more generally applicable, Gale et al., add sufficiency values for slope, S, and climate, CL, to their PI model. In evaluating their model, Gale et al., found that the modified PI model predictions were more highly correlated with aboveground biomass and mean annual biomass increment than our more traditional expression of site quality, Site Index.

Another method for determining an overall index of soil quality was developed by Karlen and Stott (1994). Soil quality (Q) is determined using an additive model,

$$\mathrm{Q} = \mathrm{q}_1\ (\mathrm{wt}) + \mathrm{q}_2\ (\mathrm{wt}) + \ldots. + \mathrm{q}_k\ (\mathrm{wt}) \qquad [3]$$

where, the q_k variables represent sufficiency values for different soil quality attributes, and the wt's are relative weights applied to each attribute. The relative weights represent the importance of each attribute in determining overall soil quality. In applying this model to the resistance to erosion soil quality attributes (Table II.2), the model would take the form,

$$\mathrm{Q} = \mathrm{q}_{wi}\ (0.50) + \mathrm{q}_{wt}\ (0.10) + \mathrm{q}_{rd}\ (0.35) + \mathrm{q}_{pg}\ (0.05), \qquad [4]$$

where, q_{wi}, q_{wt}, q_{rd}, and q_{pg} are sufficiency's for water infiltration, water transfer and adsorption, resistance to physical damage, and promoting plant growth, respectively, and the numbers are their relative weights (Table II.2). The performance of this model has not yet been tested using field data.

Additive models (equations 3 and 4) have been criticized because they may not allow for interaction among the variables in the model. Gale et al., 1991, argue that multiplicative models (equations 1 and 2) are better than additive models because multiplicative models allow the possibility of interaction among the model components, and therefore more closely follow basic biological principles (eg., Liebig's Law).

There is no question that many soil properties and processes interact at some level, and soil quality models should consider interactions where applicable. However, rather than arbitrarily building either a multiplicative or an additive model of soil quality, the extent of interaction among the variables in a soil quality model should be controlled based on current understanding of how the various soil components interact. If we know a priori that two or more components interact, as in the PI model (equations 1 and 2), then the components should be combined into a single expression using a multiplicative model. These single expressions derived from multiple components are examples of pedotransfer functions (Bouma, 1989).

The Soil Tilth Index (Singh et al., 1992) previously discussed is a good example of a pedotransfer function which combines five interacting soil variables into a single expression. Karlen and Stott's, 1994, soil quality model (equations 3 and 4) is actually a hybrid located somewhere between a multiplicative and an additive model. Three of the variables in their model are pedotransfer functions calculated based on individual multiplicative models; e.g., the water transfer and adsorption attribute (Table II.2, equation 4) is calculated by multiplying sufficiency values for hydraulic conductivity, porosity, and macroporosity together. In addition to the individual multiplicative models representing some attributes, by assigning relative weights to each attribute (equations 3 and 4), Karlen and Stott, are controlling the importance of each attribute in their soil quality model.

A basic feature of all soil quality models is the sufficiency curve. Sufficiency curves provide the link between the soil quality attributes and the goal of the soil quality model. If the goal of managing soil quality is to improve plant productivity, then the sufficiency curves must show the relationship between each soil quality attribute and productivity. The sufficiency curves for pH, depth to mottling, and bulk density, used by Gale et al., 1991, in their PI model illustrate the basic features and common shapes of sufficiency relationships (Fig. II.1). The sufficiency level on the y-axis represents the relative response in root growth to increasing levels of each variable. If the measure field pH was 4.0, then the sufficiency level would be 0.75, with the optimum soil pH for root growth being between 5.0 and 7.0. The sufficiency curves shown, parabolic for pH (Fig. II.1A), positive increasing with asymptote for depth to mottling (Fig. II.1B), and negative decreasing with asymptote for bulk density (Fig. II.1C), illustrate the three most common sufficiency relationships found for productivity responses to changes in soil variables. For example, (i) available water holding capacity follows the parabolic curve (Gale et al., 1991), and (ii) soil organic carbon and available nutrients follow the positive increasing curve (Aune and Lal, 1995). Sufficiency curves can be developed based on the literature, designed experiments, or personal experience.

Forest Soil Quality Model

The PI model (equation 2) and the soil quality model (equation 3) both have desirable elements that should be incorporated into a forest soil quality model. Timber harvesting and site preparation can result in soil disturbances (e.g., compaction, rutting, and churning) which may limit both root growth and overall tree growth (Greacen and Sands, 1980; Kozlowski et al., 1991). Therefore, the concept of an ideal root distribution, which is the basis of the PI model, is important to forest soil quality because our management practices can affect tree root distributions.

The five soil quality attributes described by Burger and Kelting (1999) for forest productivity are necessary for maintaining high levels of productivity; however, the relative importance of each attribute is not the same for all forests growing under all conditions; i.e., management intensity, soil type, climate, and topographic features all play roles in determining the relative importance of each soil quality attribute. For example, the promote root growth attribute would be more important to soil quality for soils with inherently high soil strength (Ultisols in the Piedmont Region), versus soils with inherently low soil strength (Alfisols in the Coastal Plain Region). Because of such differences in the importance of soil attributes, relative weights need to be assigned to the soil attributes, which was a concept introduced in the soil quality model (equation 3). The forest soil quality (SQI) model propose here incorporates the features of the PI and soil quality models,

$$SQI = \sum [(RG * wt_{RG} + SW * wt_{SW} + NC * wt_{NC} + GE * wt_{GE} + BA * wt_{BA}) * WF_d] \quad [5]$$

where, RG, SW, NC, GE, and BA are the sufficiency levels for promoting root growth, supplying water, cycling nutrients, gas exchange, and biological activity, respectively, and the wt's are the relative weights of each attribute. For soil quality attributes that cannot be measured, indicator constructs would be used in the model to substitute for the non-measurable attributes. Forest soil quality, SQI, is determined by multiplying the sum of the weighted sufficiency values by a weighting factor, WF, for each soil horizon, and then summing the products across all horizons, i, present. The SQI values will range between 0 and 1, with 1 being ideal soil quality for tree productivity.

Monitor Forest Soil Quality Through Time

After a forest manager has made a soil management decision, soil quality must be monitored through time in order to determine the effectiveness of the management decision. No changes in SQI would indicate maintenance of initial soil quality, positive changes in SQI would indicate increasing soil quality, and decreasing soil quality would be indicated by negative changes in SQI (Larson and Pierce, 1994).

The decision on when to measure soil quality through time should be based on when forest management activities have the potential to affect soil quality both through the life of a stand (rotation) and over successive rotations. At a minimum forest operations will affect soil quality when (i) the trees are harvested, and (ii) the site is prepared for the next rotation (Powers et al., 1990); therefore, soil quality must be measured at specific times during the rotation to determine the effects of these management practices on soil quality. Once we know how site preparation and harvesting individually affect soil quality, the proper forest soil management decisions can be made. If harvesting and site preparation impacts on soil quality are not separated, then soil quality cannot be managed because the trajectory of changing soil quality will not be understood.

Refine and Modify Model

The usefulness of the SQI predictions will only be as good as (i) the indicators chosen to represent each attribute, (ii) the correctness of the individual sufficiency curves, and (iii) the design of the SQI monitoring system. The criteria used to select appropriate indicators were previously discussed, and one criteria was that the indicators must have known relationships with productivity. It is necessary to know the relationship between the indicators and productivity so that sufficiency curves can be constructed for each indicator. First approximations of sufficiency curves can be made based on the literature, however, sufficiency curves can be validated and improved by measuring tree growth at the same time the soil quality indicators are measured. By pairing tree growth data with the indicator measurements, regression techniques can be used to fit better sufficiency curves as well as increase our understanding of the relationships between the soil quality attributes and tree productivity.

In order to (i) select the right indicators, (ii) apply the appropriate weights, and (iii) make the correct management decisions, definitive field experiments would be necessary for validating relationships between the indicators, management strategies, and forest productivity. These field experiments would be located on representative soil types, and would test several alternative management scenarios. Results from the field experiments would increase the level of confidence in the soil quality monitoring system by supplementing the management-level data with more scientifically controlled data.

The proposed forest soil quality model (equation 5) does not predict the long-term effects of management on soil quality, but rather the model combined with monitoring allows us to determine the long-term effects of management by monitoring soil quality through time and analyzing trends. Thus it will take several measurements of soil quality before we know exactly how forest management has affected long-term soil quality. Wagenet and Hutson, 1997, argue that dynamic soil quality models, rather than static models (our model), must be used to assess soil quality. Dynamic models would be composed of process models which would represent the components of soil quality. The process models would simulate the effects of management on soil quality, and as such would be advantageous over a static model because the effects of different management scenarios on soil quality could be predicted immediately from a one-time collection of field data. The dynamic soil quality model assumes that enough is known about the soil-plant system to allow modelling to substitute for monitoring. However, at this point enough is not known about the soil-plant system to construct process models with a high enough degree of confidence to substitute for an empirically-based soil quality monitoring program. The forest soil quality model is a first approximation model that should evolve over time into a dynamic soil quality model as advocated by Wagenet and Hutson, 1997. We suggest that the data gathered as part of the monitoring program should be used to develop, refine, and validate process models that could eventually be integrated into a dynamic model for forecasting the effects of different management scenarios on soil quality.

CHAPTER III. MATERIALS AND METHODS

STUDY SITE DESCRIPTION

The study sites are located on the lower coastal plain in Colleton County, South Carolina, approximately 65 km west of Charleston (Fig. III.1). The lower coastal plain is characterized by gentle to rolling topography consisting of a series of marine terraces paralleling the Atlantic coast (Runge, 1977). The region is nearly-level, being dissected by many broad valleys containing wide meandering streams which terminate in estuaries along the coast. Our study sites eventually drain into Horseshoe Creek (Fig. III.1) which merges with the Ashepoo River south of highway 64. Though Horseshoe Creek drains the larger watershed, the within site drainage systems are poorly defined, thus water moves slowly across the landscape. The area experiences a subtropical climate with a mean annual rainfall of 132 cm near the coast, dropping to about 122 cm inland. The majority of rainfall occurs during the summer months (May - September). The average growing season is between 240 and 280 days, with precipitation during this period fluctuating between 86 and 94 cm. Average summer and winter temperatures are 31 and 18 ^{0}C, respectively (Stuck, 1982). Soils in this region developed from nearly-level beds of unconsolidated sands, clays, and soft limestone. There has been very little to no erosion and almost all soils have restricted drainage. Five soils series are present on the study sites: (i) Hobcaw fine sandy loam (Fine-loamy, siliceous, thermic Typic Umbraquults), (ii) Yemassee loamy fine sand (Fine-loamy, siliceous, thermic Aeric Ochraquults), (iii) Nemours fine sandy loam (Clayey, mixed, thermic Aquic Hapludults), (iv) Argent loam (Fine, mixed, thermic Typic Ochraqualfs), and (v) Santee loam (Fine, mixed, thermic Typic Argiaquolls). All soils have A and E horizons with sandy loam textures, with both horizons combined averaging 40 cm deep. A deep (>140 cm) sand clay loam B horizon underlies the surface horizons. These soils were derived from marine and fluvial parent materials, and are poorly drained (<2% slopes). Inherent forest productivity on these soils is higher than productivity on soils on the lower coastal plain in the northern part of South Carolina. Higher productivity is thought to be due to higher amounts of available phosphorus weathering from the phosphate marl that underlies large

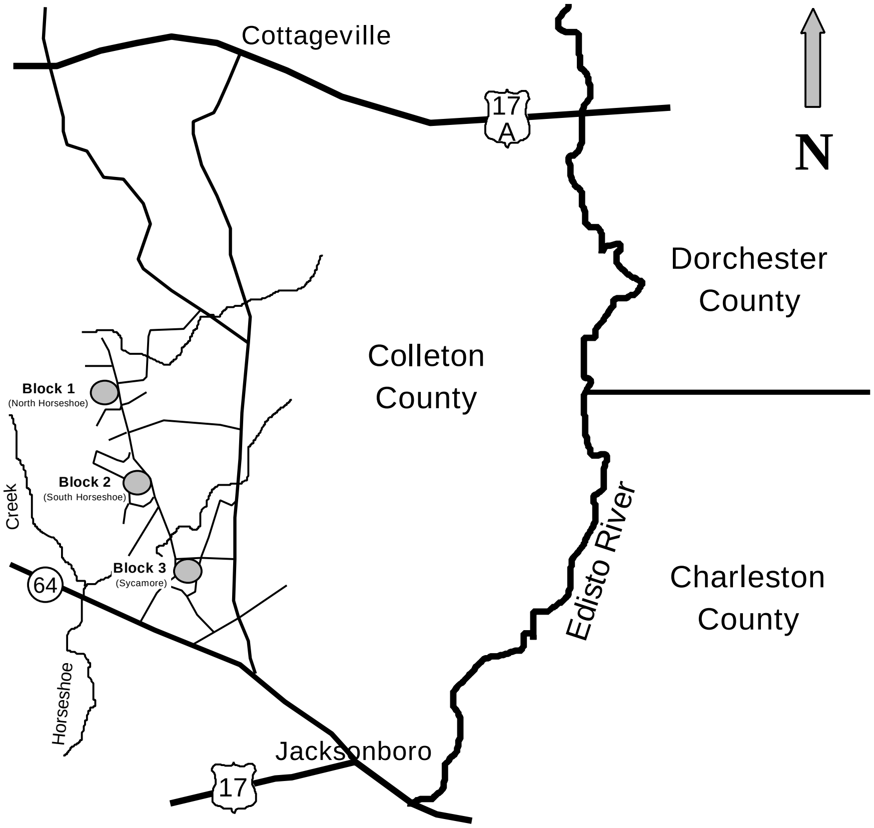


Figure III.1. Location of study sites.

parts of the southern region of South Carolina (Ellerbe and Smith, 1966). Pre-European settlement vegetation consisted of indigenous pines and hardwoods. The harvested stand was a second rotation loblolly pine plantation that was 20 years old when cut.

GENERAL EXPERIMENTAL DESIGN AND TREATMENT INSTALLATION

In 1991 three study blocks were selected based on similarity of drainage patterns and soil type (Fig. III.1). The Argent and Santee soils are found on Blocks 1 and 3, and the Hobcaw, Yemassee, and Nemours soils are found on Block 2. Each block was subdivided into six 3 ha plots, and two operational harvesting treatments were randomly assigned to five plots per block: (i) two dry harvests, and (ii) three wet harvests (Fig. III.2). Three levels of site preparation: (i) none, (ii) bedded, and (iii) mole plowed and bedded, were randomly assigned to the wet harvested plots (Fig. III.2). Two levels of site preparation were randomly assigned to the dry harvested plots: (i) none, and (ii) bedded. Five plots per block were operationally harvested during the fall of 1993 and spring of 1994. The stands were harvested when the volumetric moisture content of the surface soil exceeded 30 % for the wet harvest (March, 1994), and was below 15 % for the dry harvest (August, 1993). Harvesting was done with mechanized fellers (Hydro-Axe, Model 411, Blount Inc., Owatonna, Minnesota, USA; and Franklin, Model 105, Franklin Equipment, Franklin, Virginia, USA) and wide-tired (81.3 cm) skidders (Franklin, Model 170; Caterpillar, Model 518, Caterpillar Inc., Peoria, Illinois, USA; and Timberjack, Model 450C, Timberjack Group, Helsinki, Finland), with tire inflation pressures from 30 to 35 psi. The mole plow treatment was installed in October, 1995, with a mole plow constructed using Spoor's (1986) design. Mole channels were installed on a 20 by 20 m grid system at 80 cm deep, creating a 10 cm diameter channel in the Bt horizon for promoting water flow throughout the plot. The beds were installed in November, 1995, using a 6-disc bedding plow equipped with 91.4 cm discs (Model 110, Savannah Forestry Equipment, Inc., Savannah, Georgia, USA). Genetically improved loblolly pine seedlings grown at Westvaco Corporation's nursery located approximately 30 km from the study were then hand-planted on the sites in early February, 1996.

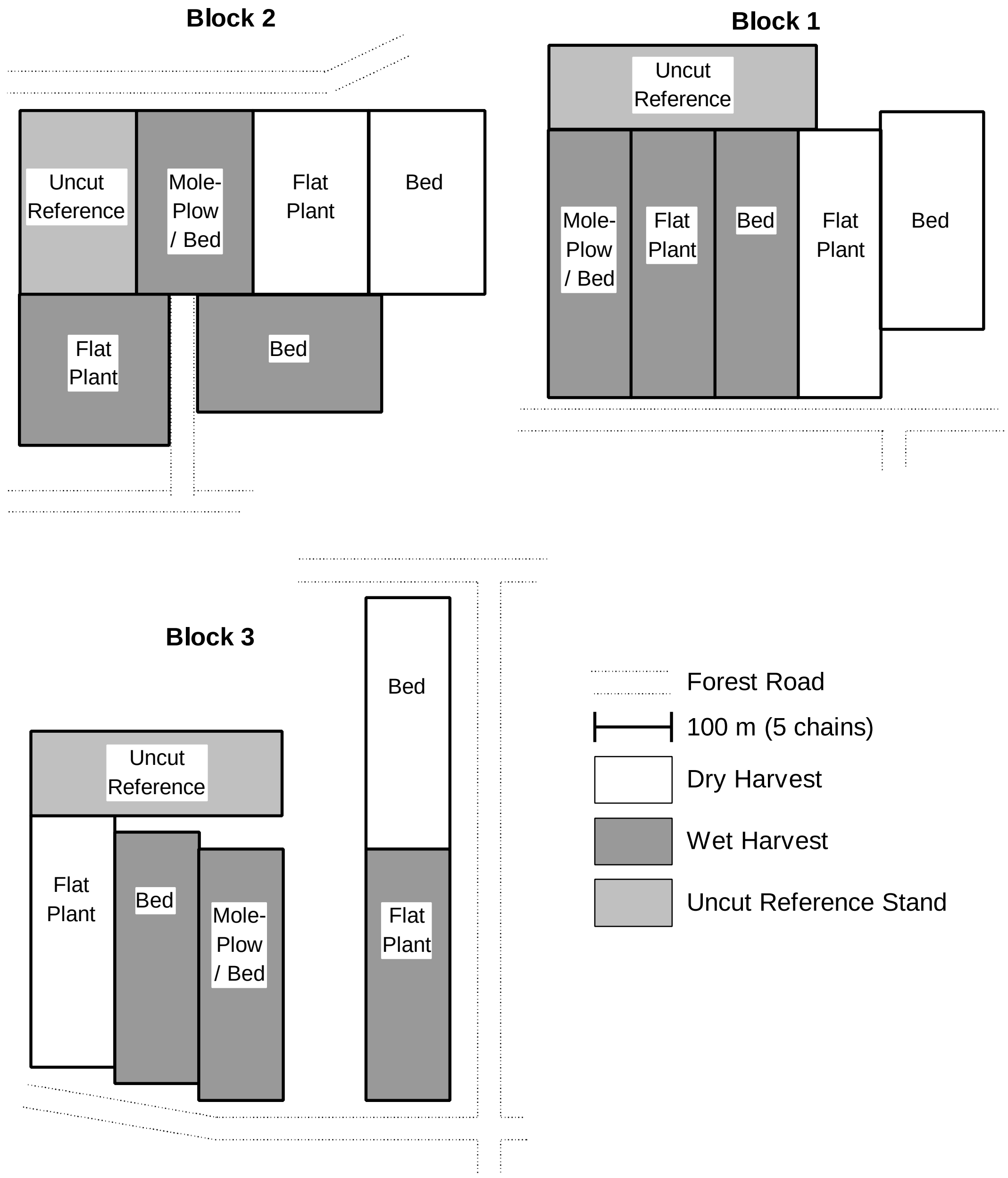


Figure III.2. Spatial layout of harvesting and site preparation treatments by block.

PRE-SITE PREPARATION MEASUREMENTS

In 1991, a 20 by 20-meter grid system was established in each plot. Shallow water table wells were installed at each grid intersection (Fig. III.3; approximately 80 wells per plot). Deep water table wells were installed on a 40 by 40-meter grid system adjacent to shallow wells (Fig. III.3; approximately 24 wells per plot). The shallow and deep water tables were then measured monthly for about one year. At each shallow well we measured the thickness of the soil horizons and collected tree species and volume data on a 1/50 acre plot. At each deep well we measured bulk density, porosity, particle size, and hydraulic conductivity by soil horizon, soil strength at 10 cm increments down to 60 cm, and surface litter weight and distribution. Total carbon and nitrogen were also determined from loose soil samples collected at each location.

The grid system of water table wells was reestablished following the harvest and again following site preparation.

SOIL DISTURBANCE AND ORGANIC DEBRIS RESPONSE SURFACE

Timber harvesting effects on soil quality and loblolly pine productivity were evaluated using a 5 by 5 organic debris (OD) and soil disturbance (SD) response surface that was defined (Fig. III.4.) and mapped spatially across each plot after harvesting (Preston, 1996). A 1/125 ha plot was established at each well on the 20 by 20 m grid (Fig. III.3) already in place for measuring shallow water table depth. The 1/125 ha plots were divided into quadrants, and the percent area covered by each organic debris and soil disturbance class was ocularly estimated to the nearest 10 % in each quadrant. The soil disturbance and organic debris classes were mapped spatially using the weighted averages from each quadrant (Fig. III.5).

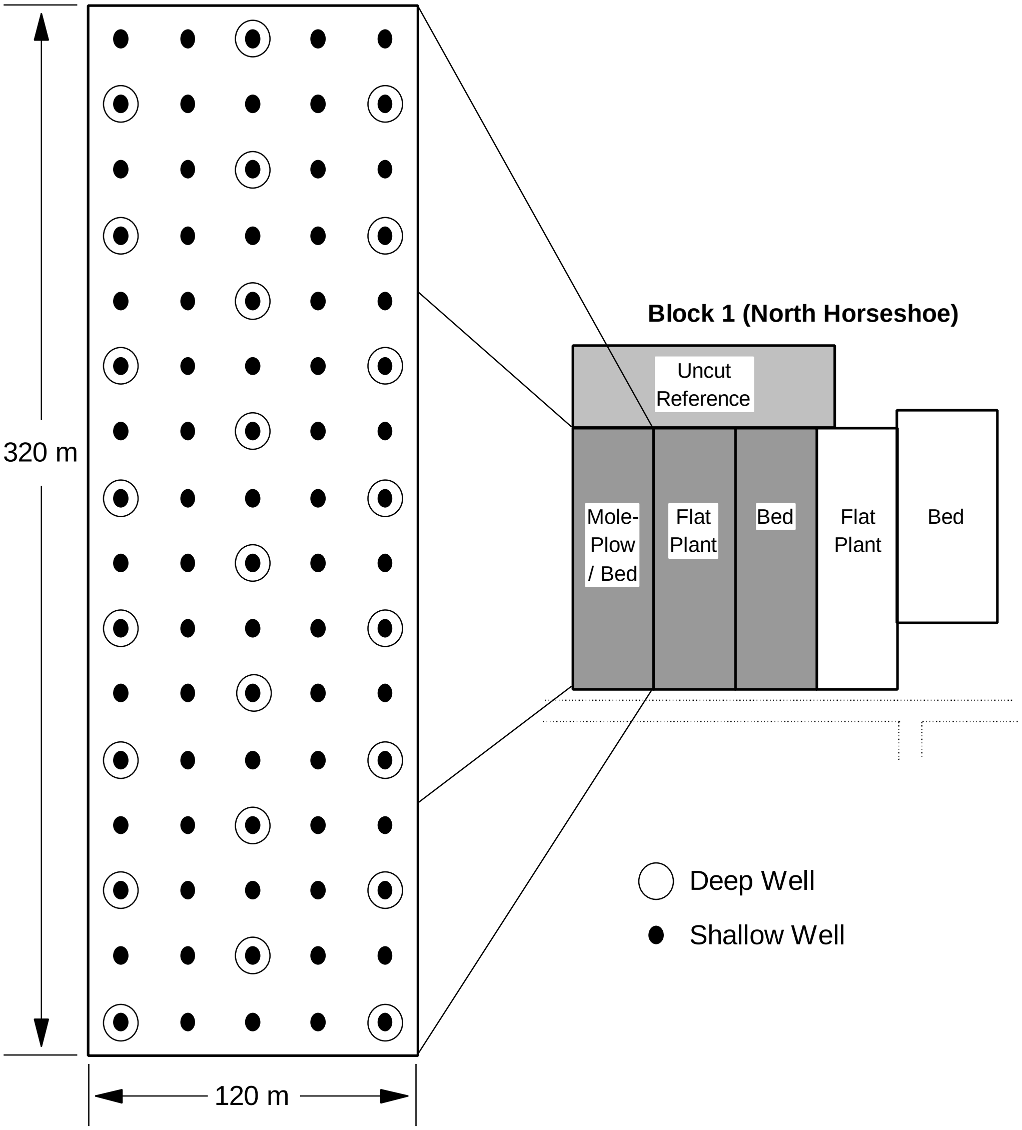
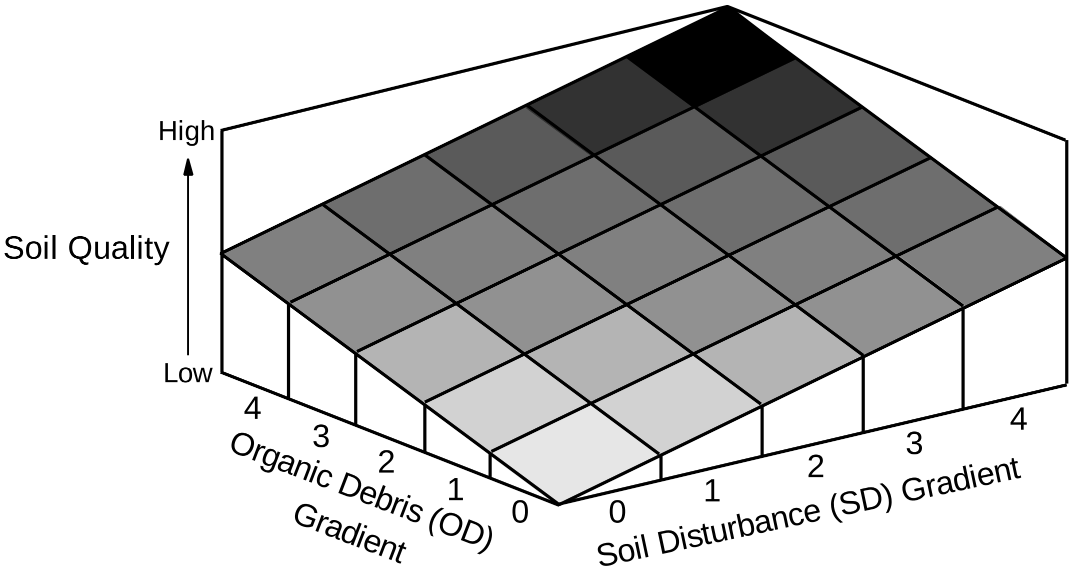


Figure III.3. Blowup of a plot in Block 1 showing the spatial layout of shallow (dots) and deep (open circles) wells used for measuring monthly water table depth.



Organic Debris (OD) Gradient	Soil Disturbance (SD) Gradient
4 O Horizon + Slash Pile	4 No Disturbance
3 O Horizon + Heavy Slash	3 Compression Track
2 O Horizon + Light Slash	2 Shallow Rut (<20cm)
1 O Horizon	1 Deep Rut (>20cm)
0 Bare Soil	0 Churned

Figure III.4. Five by five organic debris (OD) by soil disturbance (SD) response surface defined to test harvesting effects on soil quality and loblolly pine productivity.

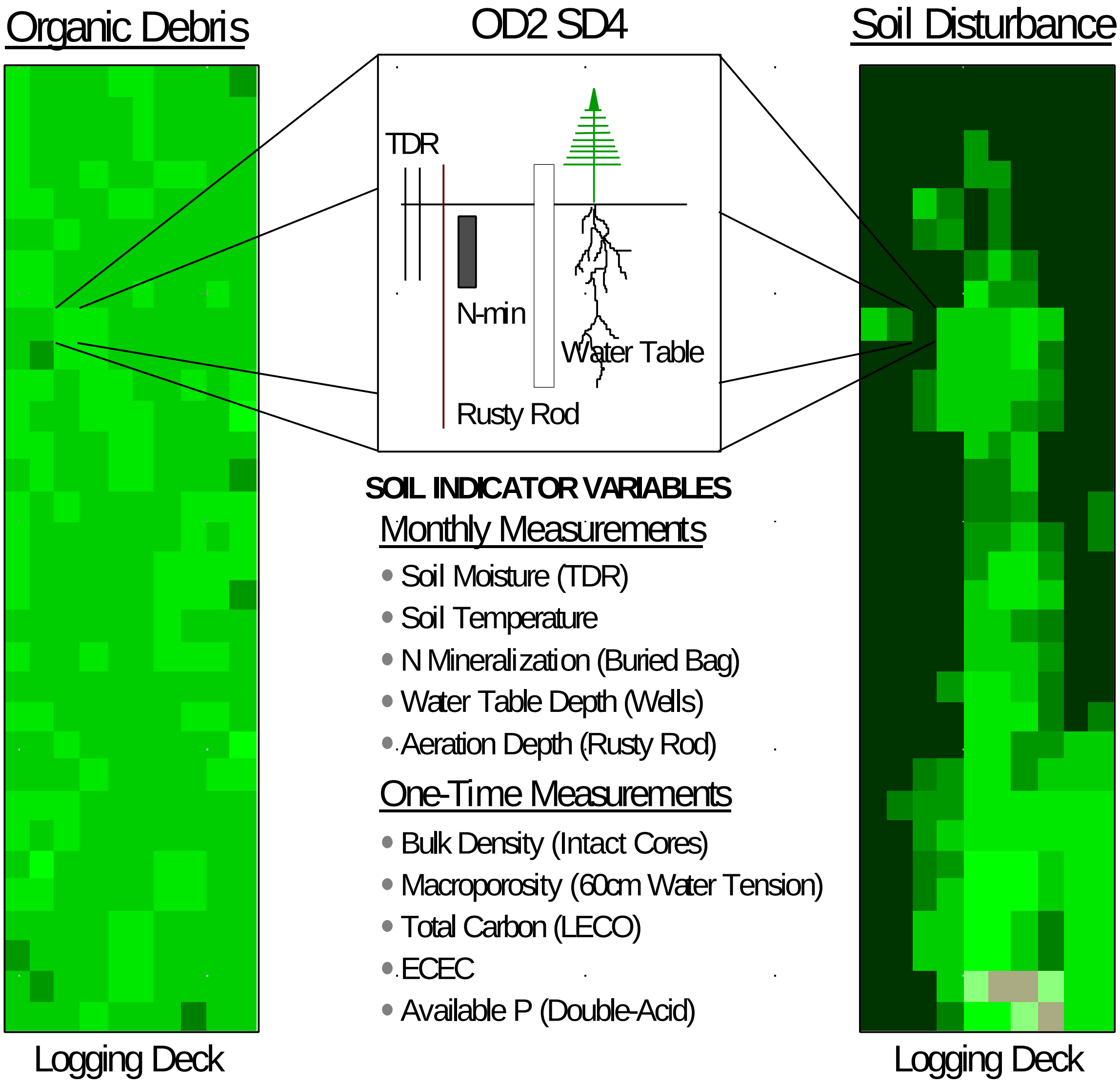


Figure III.5. Typical spatial distribution of organic debris and soil disturbance following a wet harvest. An example of a soil process measurement point at OD2 (O horizon + Light Slash) and SD4 (Undisturbed Soil) is also shown.

SELECTION OF SOIL SAMPLING POINTS

Measurement points were selected in each plot that represented the average condition with respect to each level of organic debris and soil disturbance that occurred in the plot (Fig. III.5). The 25 organic debris and soil disturbance combinations (Fig. III.4) did not occur in every plot; for example, the plot in Fig. III.5 had 4 organic debris levels and 5 soil disturbance levels, so 20 sample points were established in this plot, as such the number of sample points varied between plots. There were a total of 160 measurement points located across the harvest / site preparation treatments.

The lack of uniformity in the extent of soil disturbance and organic debris removal was an expected outcome of installing treatments operationally, whereby the real-world harvesting operation dictated what disturbances would occur and where. Given that organic debris removal and soil disturbance were outcomes of the operational harvesting treatment installation, evaluating the effects of the organic debris and soil disturbance classes on soils and tree growth is problematic from a pure experimental design / statistical viewpoint. The alternative would have been to artificially impose the organic debris and soil disturbance classes in factorial combination in a randomized complete block design; however, such an experiment would be of lower value operationally because of difficulties in being able to extrapolate the results to the real-world.

The experimental design concerns that may limit the approach used herein are lack of randomization within plots, and potentially high non-uniformity in "treatment" installation between plots. Harvesting operations result in predictable patterns of disturbance that largely depend on the location of the logging deck and plot geometry (e.g., Fig. III.5). As such, the organic debris and soil disturbance classes are not randomly distributed across each plot, resulting in sample points being concentrated in certain areas (see Appendix A for plot maps). Clustering of sample points is a problem if spatial variation in controlling and / or confounding variables is not accounted for when selecting sample points. I assumed that on our sites the controlling variables that would affect the results were surface soil texture and depth, and microsite elevation (as a surrogate for water table). I selected sample points to minimize variation in these properties based on the pre-treatment data collected by Burger (1994) and Preston (1996). One confounding variable which I could not control was the proximity to a forest road, as the high organic debris / high soil disturbance combinations only occurred more frequently closer to the logging deck. Two potential confounding problems with locating sample points near the road are enhanced drainage and dust particles.

To improve the uniformity of data obtained from sample points on the same organic debris / soil disturbance classes between plots, the sampling locations were chosen based on the "purity" of disturbance: greater than 80 % of the area had to be within the desired organic debris / soil disturbance class. Based on this and the previously-described criteria of selecting sample points with similar surface texture and depth, and microsite elevation, I feel that the experimental design / statistical concerns have been addressed well enough to justify using the organic debris and soil disturbance classes as treatments.

Sample points were positioned between the ruts and wheel tracks in the shallow and deeply rutted locations. This was done for three reasons: (i) it was generally not possible to collect samples from the ruts due to the high water table, (ii) changes in the soil physical environment in the ruts and wheel tracks were previously documented (Preston, 1996), and (iii) the trees were planted between the ruts, and we wanted to sample the soil environment in which the trees were growing.

FIELD AND LABORATORY METHODS AND ANALYSIS

At each of the 160 locations, perched water table depth (0- to 90-cm) was measured from 5 cm i.d. by 90 cm deep PVC observation tubes, volumetric soil moisture content in the surface 0- to 30-cm depth was measured using Time Domain Reflectometry (TDR; TRASE system, Soil Moisture Equipment Corp, Goleta, CA), and oxidation depth was measured on steel rods (McKee, 1978; Carnell and Anderson, 1986) on a monthly basis, from May 1996 through June 1997. An example of a soil measurement point is shown in Figure III.5.

During June 1997, two 5 cm i.d. by 10 cm long intact soil cores were collected from the 10- to 20-cm depth adjacent to the TDR rods using a hammer-driven core sampler. The cores were used to determine bulk density (Blake and Hartge, 1986), total porosity, and macroporosity (Danielson and Sutherland, 1986). Also at this time, a composite loose soil sample consisting of 10 subsamples was collected at each location using a 2.5 cm i.d. by 30 cm long push tube soil sampler. This sample was air-dried and passed through a 2-mm sieve and used to determine total C and N, available P, exchangeable base cations, exchangeable acidity, particle size, and soil pH.

Total carbon was determined via infrared analysis (LECO Total Carbon Analyzer, LECO Corp., Saint Joseph, MI). Total N was determined on a 5 g soil sample using the macro-Kjeldahl digestion method (Bremner and Mulvaney, 1982) followed by colorimetric analysis (Technicon Autoanalyzer II, Terrytowne, N.Y.). An index of available P was determined by double-acid (0.05 N HCl + 0.025 N H_2SO_4) extraction in a 1:4 soil to solution extract (Watanabe and Olsen, 1962) followed by colorimetric analysis (Spectronic 20D$^+$, Spectronic Instruments, Inc., Rochester, N.Y.). Exchangeable base cations (Ca, Mg, and K) were determined by extraction with 1 M NH_4OAc (pH 7) in a 1:10 soil to solution extract (Thomas, 1982) which had been extracted for 1 h on a reciprocating shaker. Concentrations of base cations were determined using inductively coupled plasma (ICP) spectroscopy (Jarrell-Ash Corp., Franklin, M.A.). Exchangeable acidity was determined with 1 M KCl in a 1:50 soil to solution extract (Thomas, 1982). The sample was mixed on a reciprocating shaker for 1 h, centrifuged at 2000 rpm for 2 min, and titrated to a phenolphthalein end-point (Mettler DL12 Autotitrator, Hightstown, N.J.). The hydrometer method (Gee and Bauder, 1986) was used for particle size analysis. Soil pH was determined with a 1:5 soil to water extract.

Net N-mineralization was determined using the buried bag method (Eno, 1960) on an approximate monthly basis from June 96 through August 97. Ten soil samples were collected monthly at a subset of locations using a 2.5 cm i.d. by 30-cm-long push tube soil sampler. The subsamples were composited in the field, and one-half of the sample was incubated in a polyethylene bag buried vertically in the A horizon. The initial inorganic N was determined from the remaining non-incubated sample. Monthly net N-mineralization was calculated as the difference in inorganic N concentration between the incubated and initial samples. The inorganic N was extracted from all soil samples with 2 *M* KCl and analyzed for NO_3-N and NH_4-N using a Technicon Autoanalyzer II (Technicon, 1973).

The chemical data were corrected for soil moisture content and converted to kg ha^{-1} based on the bulk density measurements and a sampling depth of 30 cm.

SHORT-TERM LOBLOLLY PINE BIOASSAY PLOTS

Without adequate controls, it can be difficult to establish quantitative relationships between soil properties and tree productivity, as the tree productivity we measure is the final expression of environmental and genetics effects in combination with complex genetics times environment interactions (Kozlowski et al., 1991). Because young loblolly pine trees planted at commercial spacing have low demand for site resources: e.g., only needing about 5 kg N ha^{-1} yr^{-1} for the first few years (Dougherty, 1996), soil resource limitations on tree growth may not be apparent until after stand closure when the trees are under intense competition with each other for soil resources. Thus, we may not be able to rely only on the short-term response of the commercially-planted trees to tell us how soil disturbance, organic debris removal, or site preparation may have affected the soils' ability to provide the resources adequate for tree growth. It is also likely that the lack of competition for soil resources would result in poor correlations between soil properties and the commercially-planted trees, since these resources would not be limiting tree growth at this time.

To address these problems, relationships between loblolly pine productivity and soil properties were determined from “bioassay” plots collocated with a subset of soil process measurement points. Fifty-four identically-spaced loblolly pine bioassay plots were planted concurrently with the operational planting (i.e., February, 1996). The plots were

2.1 by 6.3 m, and the seedlings were planted at 30 by 30 cm spacing within each plot by the same two-person crew. The exact spacing eliminated the effects of variation in stand density on tree growth, and use of one crew ensured uniformity in tree growth response to planting technique. The plot dimension was chosen so that the plot would span an entire soil disturbance class, and the close spacing was chosen to ensure stand closure during the first growing season. Competing vegetation was controlled within each plot by a combination of chemical and hand vegetation control.

The theory behind these plots was that the close spacing of the seedlings would encourage early competition for soil resources, in effect simulating how the trees planted at commercial spacing would respond to limited soil resources after stand closure. Thus, if soil resources are limiting then good relationships should be found between soil resources and tree growth, and the tree growth response on the bioassay plots should also give us some insight on the likely response of the commercially-planted trees to soil resources after stand closure. This assumes there are no changes in soil quality (i.e., natural amelioration) over time.

The total heights and ground line diameters of the trees in the internal rows (external row was left as a buffer) were measured in March, 1998, two years after planting. Each tree was classed into one of four microsite types on the bedded plots: (i) top of bed, (ii) side of bed, (iii) furrow, and (iv) interbed, and into one of two microsites on the non-bedded plots: (i) in rut and (ii) not in rut. The 'top of bed' and 'not in rut' microsites correspond with the locations where the soil / site data were collected.

After the trees were measured, 12 trees were selected from across the height distribution in each plot and harvested. The foliage and stems were oven-dried at 70 ^{0}C for at least 72 hr for biomass determinations. These data were used to develop regression functions to predict the aboveground biomass for the remaining trees in each plot based on the oven-dried subsamples.

STATISTICAL ANALYSIS PROCEDURES

The main analysis tool was ANOVA. When harvesting effects were evaluated for the 5 by 5 organic debris / soil disturbance matrix (Fig. III.4), a complete factorial design was used, with 3 replicates (blocks) of 5 levels of organic debris and 5 levels of soil disturbance (Table III.1). Site preparation effects were evaluated using an unbalanced ANOVA with soil disturbance classes nested within site preparation treatments (Table III.2). Where appropriate, analysis of covariance was applied using pre-treatment data to try and reduce the MSE and improve significance testing.

Table III.1. The ANOVA for the 5 by 5 factorial design used to test harvesting disturbance and organic debris effects on soil properties and processes, and tree growth.

Source	Degrees of Freedom	Mean Square Error	F test
Block (b)	b-1 = 2	MSb = SSb / 2	
Soil Disturbance (d)	d-1 = 4	MSd = SSd / 4	MSd / MSE
Organic Debris (o)	o-1 = 4	MSo = SSo / 4	MSo / MSE
d x o	(d-1)(o-1) = 16	MSdo = SSdo / 16	MSdo / MSE
Error (a)	b(d-1)(o-1) = 48	MSE = SSE / 48	
Total	bdo - 1 = 74		

Table III.2. The ANOVA for nested design for testing disturbance class within site preparation effects and site preparation effects on soil properties and processes, and tree growth.

Source	Degrees of Freedom	Mean Square Error	F test
Block (b)	(b-1) = 2		
Site Preparation (s)	(s-1) = 4	MSs = SSs / 4	MSs / MSsd
Soil Disturbance within Site Preparation (d)	s(d-1) = 20	MSsd = SSsd / 20	MSsd / MSE
Error (a)	b(s-1)(d-1) = 48	MSE = SSE / 48	
Total	bsd - 1 = 74		

Regression techniques were also heavily employed in addition to ANOVA. Site preparation and soil disturbance effects on relationships between variables were explored by adding the class variables to regression models as dummy variables, and interactions were explored with the addition of slope terms. Multilinear regression analysis was also used to explore linear, quadratic, and interactive effects of independent variables on response variables.

CHAPTER IV. FOREST HARVESTING AND SITE PREPARATION EFFECTS ON THE SOIL PHYSICAL ENVIRONMENT

ABSTRACT

Surface soil disturbance and removal of organic debris due to forest management practices may reduce the quality of the soil physical environment for tree growth and long-term site productivity. The objectives of this work were to (i) determine if surface soil disturbance and removal of organic debris negatively impact the soil physical environment, and (ii) determine if site preparation mitigates negative impacts if they occur. This work was conducted as part of a long-term operational-scale study in intensively-managed loblolly pine plantations on the Lower Coastal Plain of South Carolina, a region where long-term productivity concerns center around site disturbance resulting from wet-weather harvesting. Three 20 ha, 20-yr-old loblolly pine plantations were harvested under wet and dry conditions to create a broad gradient in site disturbance. Within each harvested plantation, a subset of 3 ha plots were site prepared by either bedding or mole-plowing plus bedding, then all sites were established as 3rd - rotation pine plantations. Prior to site preparation, each plot was mapped using a 5 by 5 soil disturbance (none to churned) / organic debris matrix (none to slash piles), and within each plot data was collected on several soil physical properties and processes at locations representative of each cell in the 5 by 5 matrix. The soil physical data were used to calculate the Least Limiting Water Range (LLWR) and the 'percentage of time the soil moisture water was within the LLWR' (P_{in}) as measures of management impacts on the soil physical environment. The P_{in} was strongly related to soil disturbance and the level of organic debris. High levels of organic debris (slash piles) substantially improved the P_{in} for rutted and churned soils. At medium and most abundant level of organic debris (O horizon + light slash), P_{in} was near 0 for compression tracks and deep ruts. Site preparation improved the quality of the soil physical environment across all levels of soil disturbance (as measured by improved P_{in}), but not up to the level of the bedded / undisturbed soil. These results show that retention

and redistribution of logging slash and other organic debris across disturbed soils prior to site preparation is probably an effective strategy for mitigating soil physical damage from harvesting on these Lower Coastal Plain sites.

INTRODUCTION

Surface soil disturbance and organic matter removal during forest harvesting are two areas of concern associated with the potentially negative effects of forest management practices on soil productivity (e.g. Gholz and Fisher, 1983; Powers et al., 1990; Aust et al., 1998ab). A number of researchers have examined the effects of soil disturbance and organic matter removal on soil properties and processes thought to be important measures of management impacts on soil productivity (e.g. Hatchell et al., 1970; Greacen and Sands, 1980; Froehlich and McNabb, 1984). Much knowledge has been obtained from past research efforts; however, enough uncertainty exists today for continued, and even expanded (e.g. Powers, 1991), research into this area of forest soil science.

Researchers have historically used bulk density changes to assess disturbance impacts on the soil physical environment (da Silva et al., 1994). However, a change in bulk density alone may not be a useful measure of changes in the soil physical environment that affect tree growth; other factors such as strength and water and air movement work together with bulk density to affect the soil physical environment. Partly because of other factors, relationships found between bulk density and either root- or above-ground biomass production have been positive, negative, and non-existent (e.g. Trouse and Humbert, 1960; Greacen and Sands, 1980).

Several factors will determine whether or not a change in bulk density causes a commensurate change in biomass production. Decreased macroporosity, interpreted as an aeration problem (e.g. Aust et al., 1998a), may not be a problem if the soil rarely becomes saturated (aeration limited). A high bulk density, interpreted as causing soil strength problems, may or may not be important depending on soil texture. For example, the critical bulk density (i.e., where root growth would be considered severely restricted from high soil strength) for sand, silt, and clay textured soils are approximately 1.70, 1.55, and 1.40 g cm^{-3}, respectively (Pierce et al., 1983). Organic matter content and volumetric soil moisture content (θ) must also be considered when interpreting bulk density effects on soil strength (Greacen and Sands, 1980; da Silva et al., 1994). For example, based on pedotransfer functions (PTFs) developed by da Silva and Kay (1997a), a sandy loam surface soil with 2.0 % organic matter (typical forest soil) and an average θ of 30 %, and assuming 2 MPa as a root growth limiting soil strength (Taylor and Gardner, 1963; Taylor and Ratliff, 1969), then the bulk density would have to exceed 1.65 g cm^{-3} before root growth would be considered limited by soil strength. Compared to a density of about 1.5 g cm^{-3} for soils of lower organic matter and water content.

The previous example highlights the problem with bulk density interpretations; the relationship between bulk density and tree growth depends on site moisture dynamics (Greacen and Sands, 1980) as well as soil texture and organic matter content. Soil strength or lack of available water will limit root growth at lower bulk densities on drier sites while aeration problems will limit root growth at lower bulk densities on wetter sites. Thus, our interpretations of bulk density need to take site water differences into account.

Several researchers / scientists have been working on more integrative and interpretive measures of management impacts on the soil physical environment that recognize the importance of soil moisture dynamics. Letey (1985) introduced a concept called the "nonlimiting water range", defined as the range of water contents within which plant growth limitations associated with aeration, soil strength, and available water were minimal. The limits of the range were the upper and lower water contents above or below which plant growth would decrease. A similar concept was developed by Childs et al. (1989), called the "root growth window", which was defined by excessive soil strength at low soil moisture content and inadequate aeration at high soil moisture content; the width of the root growth window decreased as bulk density increased.

Letey's concept was further developed by da Silva et al. (1994) into the Least Limiting Water Range (LLWR), which retains the same basic definition as Letey while recognizing that growth will change along a continuum of soil moisture contents and not at discrete levels, which Letey's term suggests. The operational definition of LLWR is "the range in soil water content within which limitations for plant growth associated with matric pressure, aeration, and mechanical resistance are minimal" (da Silva et al., 1994). The range in θ is determined by first selecting critical levels of matric pressure, aeration, and mechanical resistance, and then determining the θ associated with each critical level. Critical levels selected by da Silva et al. (1994) were: matric pressure at field capacity (-0.01 MPa) and wilting point (-1.5 MPa), 10 % air-filled porosity (AFP) for aeration, and 2 MPa soil resistance for mechanical resistance. The θs at field capacity (θ_{fc}), wilting point (θ_{wp}), and 2 MPa soil resistance (θ_{sr}) can be calculated using the PTFs developed by da Silva and Kay (1997a). The PTFs use measured bulk density, % clay, and % organic carbon to predict the θ at each critical level. The θ at 10 % AFP (θ_{afp}) is θ at saturation (θ_{sat}) minus 0.10. The upper limit of the LLWR (θ_{upper}) is the drier of θ_{afp} or θ_{fc}, and the lower limit of the LLWR (θ_{lower}) is the wetter of θ_{wp} or θ_{sr}. The LLWR is then calculated as θ_{upper} minus θ_{lower}.

An example of the behavior of the LLWR for a sandy loam soil with 2.5 % organic matter is shown in Figure IV.1. At low bulk density θ_{fc} and θ_{wp} define θ_{upper} and θ_{lower}, respectively. Within the range of more typical forest soil bulk densities (i.e., above 1.10 g cm^{-3}), θ_{afp} defines the upper limit. Soil strength doesn't begin to limit growth until a bulk density of around 1.3 g cm^{-3}, where θ_{sr} crosses above θ_{wp}. As bulk density increases, the LLWR decreases, approaching 0 at a bulk density of about 1.64 g cm^{-3}. An important feature of da Silva et al. (1994) LLWR is that it recognizes that water availability may limit tree growth before soil strength (Fig. IV.1), an important point also recognized by others (Greacen and Sands, 1980).

The implication of a decreasing LLWR is that as the LLWR narrows the likelihood that the soil moisture content will fall outside of the LLWR increases (da Silva and Kay, 1997b). As the frequency of soil moisture content falling outside of the LLWR increases, the quality of the soil physical environment for plant growth decreases, resulting in reduced plant growth (da Silva and Kay, 1996).

We felt that the LLWR would provide a meaningful assessment of forest management impacts on the soil physical environment. Using the LLWR as a surrogate indicator for the soil physical environment for tree growth, the objectives of this work were to (i) determine if surface soil disturbance and removal of organic debris negatively impact the soil physical environment, and (ii) determine if site preparation mitigates negative impacts if they occur.

MATERIALS AND METHODS

Detailed descriptions of the study site, treatment installation and layout, and field and laboratory measurements are found in Chapter III.

Calculating the LLWR

The LLWR was calculated for each location using the methods described by da Silva et al. (1994), with slight modification. We modified the upper limit of the LLWR, which da Silva et al. (1994) had defined as the drier θ of either field capacity (θ_{fc}) or 10 % air-

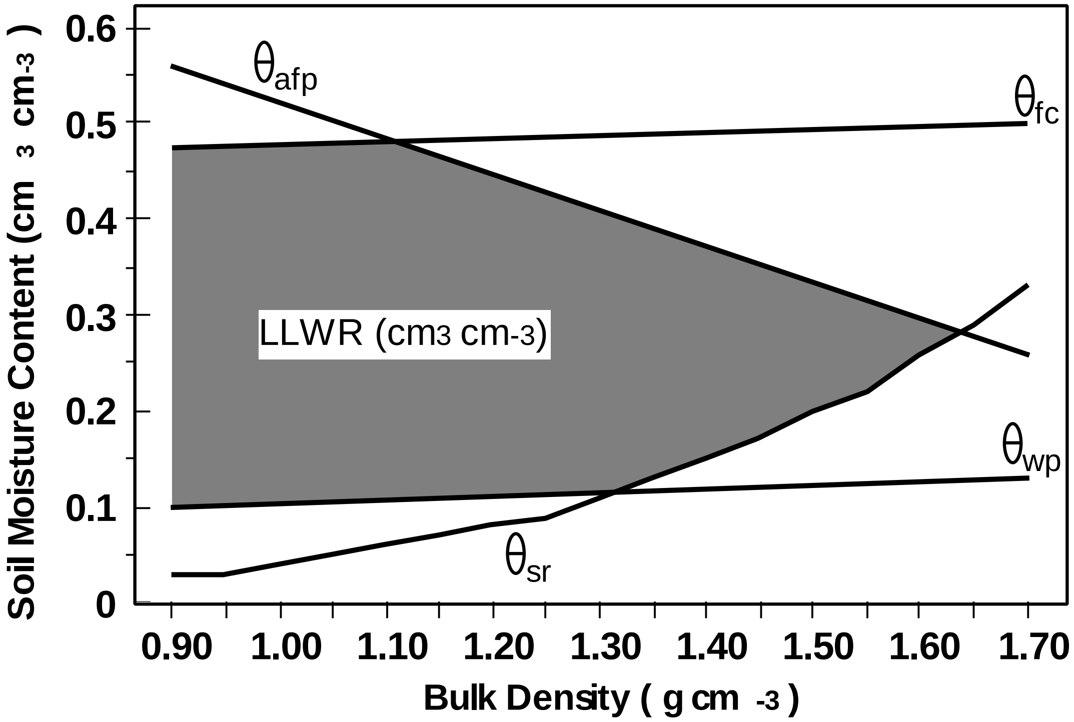


Figure IV.1. Variation in the Least Limiting Water Range (LLWR) as a function of increasing bulk density for a sandy loam soil with 2.5 % organic matter. Critical soil moisture levels (θs) were calculated using pedotransfer functions developed by da Silva and Kay (1997a).

filled porosity ($\theta_{afp} = \theta_{sat} - 0.1$). We did not consider θ_{fc} to be a meaningful upper limit for our sites given their inherently high θ due to poor drainage, nor did we feel that θ_{afp}, as the authors defined it, adequately represented aeration-limiting porosity: i.e., the upper θ limit above which inadequate air-filled porosity severely restricts gas diffusion. Several studies have reported decreased root growth rates at air-filled porosities exceeding 20 % (Greacen and Sands, 1980).

We know that gas diffusion decreases exponentially as air-filled porosity decreases (Freijer, 1994). The critical θ where gas diffusion becomes negligible varies depending on soil texture, structure, and organic matter content (Freijer, 1994), and aggregate size and shape (Renault and Stengel, 1994). Several studies have shown that the critical upper θ limit for root growth to be sustained is 10 % macroporosity (e.g. Foil and Ralston, 1967; Childs et al., 1989; Theodorou et al., 1991). As with gas diffusion, macroporosity also changes depending on soil properties, making the 10 % macroporosity critical level less arbitrary than the air-filled porosity limit chosen by da Silva et al. (1994).

Our decision matrix for choosing the upper limit of the LLWR (θ_{upper}) was as follows: (i) if macroporosity equaled or exceeded 10 %, then θ_{upper} equaled θ_{afp} (as defined by da Silva et al., 1994); but, (ii) if macroporosity was less than 10 %, then we assumed that exponentially greater air-filled porosity was required to maintain adequate gas diffusion rates as macroporosity approached zero. The required air-filled porosity was determined using the following equation,

$$\mathrm{AFP} = 50 \times 0.851^{\mathrm{MAP}}, \qquad [1]$$

where, the air-filled porosity (AFP) needed to maintain adequate gas diffusion rates increases exponentially as a function of decreasing macroporosity (MAP). The exponential shape of Eq. [1] is arbitrary, but the bounds were chosen so AFP equals total porosity at 0 % MAP and AFP equals MAP at 10 % macroporosity. Based on the equation, soils with 3 and 8 % macroporosity would require 30.7 and 13.6 % air-filled pore space, respectively, to maintain similar gas diffusion rates as a soil with 10 %

macroporosity. For soils with less than 10 % macroporosity, θ_{upper} was calculated as θ_{sat} minus AFP calculated from Eq. [1].

Our modifications are not in disagreement with da Silva et al., 1994, who suggest that the parameters of the LLWR may need to be modified depending on management considerations and field conditions.

The lower limit of the LLWR (θ_{lower}) was determined using PTFs developed by da Silva and Kay (1997a) which use bulk density, percent clay, and organic carbon to predict the θ at ψ_{wp} = -1.5 MPa (θ_{wp}; for available-water-limiting), and soil strength = 2.0 MPa (θ_{sr}; for soil-resistance-limiting), as previously described. Our data fell within the range of data they used to develop their prediction equations. The higher θ of θ_{wp} or θ_{sr} represented θ_{lower}, and the least limiting water range was calculated as LLWR = θ_{upper} - θ_{lower}.

Calculating Pin LLWR

As shown in Fig. IV.1, at a given soil texture and organic matter content, the width of the LLWR decreases with increasing bulk density. The soil moisture content should fall within the LLWR more often in a soil with a wide LLWR versus one with a narrow LLWR. We hypothesized that 'the percentage of time the soil moisture content fell within the LLWR' (P_{in}) would be a meaningful and sensitive measure of management impacts on the soil physical environment. In addition, by incorporating the *in situ* soil moisture content with the field/laboratory-derived LLWR, we are adding a dynamic "real-world" component to our characterization of the soil physical environment.

To calculate P_{in}, we predicted the daily soil water content at each location using a combination of two simple linear regression equations for the period beginning in March 1996 (approx. 1 month after planting) through June 1997. The first equation predicted soil water content based on a regression of soil water content as a function of water table depth. The second equation predicted water table depth based on a regression of monthly water table as a function of daily water table. We were then able to predict daily soil water content using both equations. A scatter plot of actual versus predicted soil water content showed that the predicted soil water content followed the 1 to 1 line very well, with a maximum residual of about 8 %, and the majority of points within 4 % of the measured soil water content (results not shown).

Examples of predicted daily soil water content for two locations along with their corresponding LLWRs are shown in Fig. IV.2. The two locations represent contrasting LLWRs. The location with the high LLWR (Fig. IV.2a) exhibited large fluctuations in soil water content through time; however, the soil water content always fell within the LLWR, suggesting that physical limitations to tree growth are minimal. In contrast, the soil water content was above the upper limit of the LLWR often during the same time period for the location with the low LLWR (Fig. IV.2b); in this case, because the upper limit is exceeded, poor soil aeration will likely limit tree growth.

The predicted soil water contents were used in conjunction with the LLWRs to calculate P_{in} by location for the dormant season. The dormant season was chosen for two reasons. First, McKee and Shoulders (1974) showed that pine growth was positively correlated with depth to the water table during the winter; they found that lower water tables during the winter allowed roots to penetrate deeper into the soil profile, thereby increasing accessibility to water during summer droughts. Second, transpirational losses of soil moisture are minimal during the dormant season (Kramer, 1983), which reduces the problem of lack of independence between soil water and tree growth.

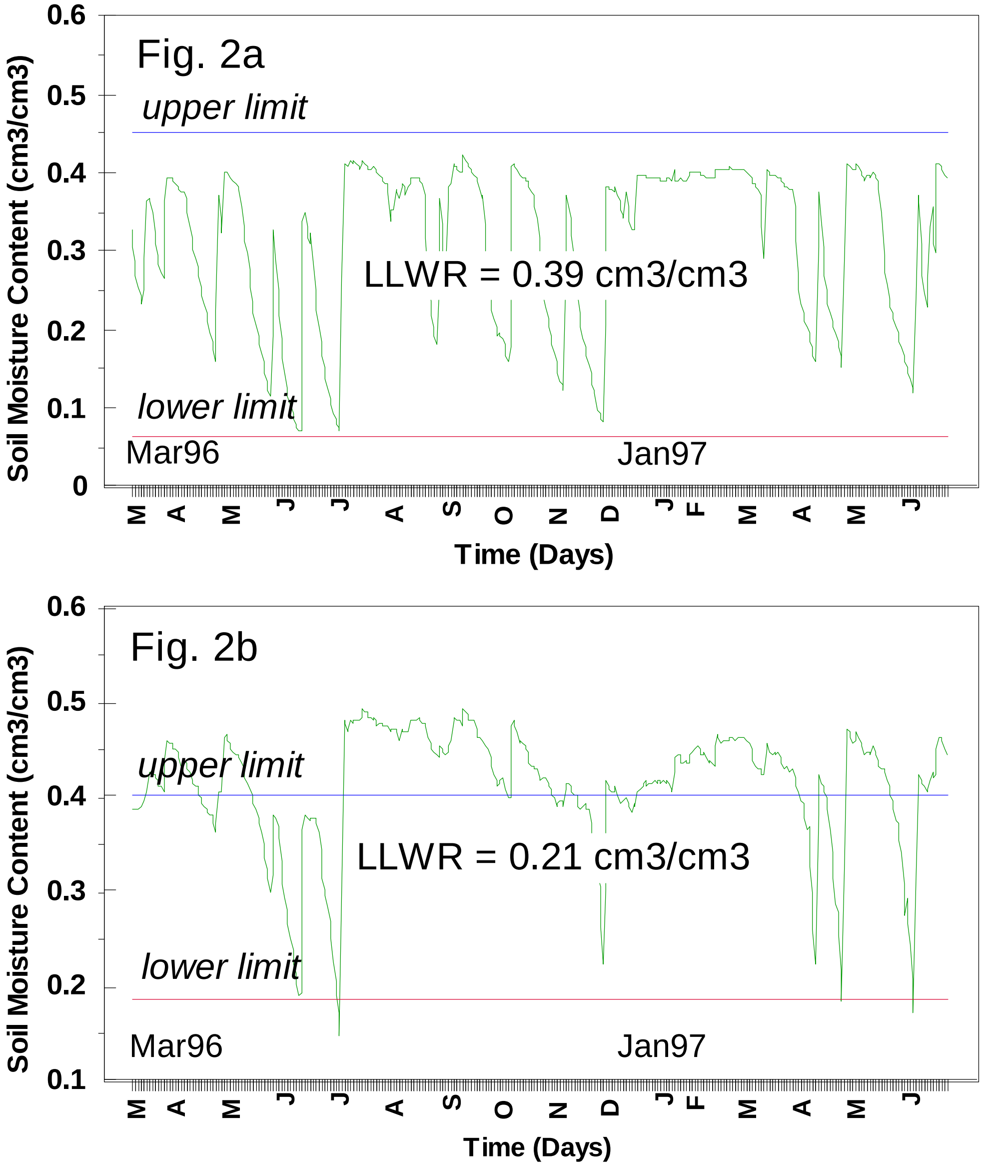


Figure IV.2. Daily fluctuations in soil water content for a point with a wide LLWR (Fig. IV.2a) and one with a narrow LLWR (Fig. IV.2b).

Data Analysis

Multilinear regression was used to test the strength of the relationship between Pin and LLWR, and treatment effects on this relationship. The P_{in} was regressed as a function of block, treatment, and LLWR, where block and treatment were included as dummy variables and LLWR as a continuous variable. Intercept and slope terms (Myers, 1990) were included in the model to test for both treatment and interaction effects on P_{in}.

Harvesting disturbance effects on P_{in} were examined using the data from the non-site prepared plots only. The wet and dry harvest treatment data was pooled within blocks to obtain three replications of the 5 by 5 organic debris and soil disturbance response surface ($n = 75$); this was necessary because not all cells of the 5 by 5 matrix were represented in each treatment. Harvesting disturbance effects on P_{in} were evaluated using multilinear regression, wherein block and disturbance class were included as dummy variables and organic debris class was included as a continuous variable. Intercept terms tested the disturbance class effect on P_{in}, and slope terms tested for interaction between disturbance class and organic debris class. The simple effects of soil disturbance on P_{in} were evaluated with separate ANOVAs for each level of organic debris using an RCB design with 3 blocks of 5 treatments (i.e., 5 soil disturbance levels; $n = 15$). In cases where treatment was significant (alpha = 0.10), Duncan's multiple range test (Ott, 1988) was used for means separation.

Site preparation treatment effects on P_{in} were examined with ANOVA using an RCB design with 3 blocks X 3 site preparation treatments X 5 soil disturbance classes nested within site preparation treatment ($n = 45$). The 3 site preparation treatments were: (i) none, wet harvest with no site preparation, (ii) bedded, wet harvest with bedding, and (iii) mole plow / bedded. The dry harvested plots were excluded from the analysis because they did not have enough 5 by 5 matrix cells in common with the wet harvested plots. The arcsin $\sqrt{P_{in}}$ was used for all data analysis.

RESULTS AND DISCUSSION

Relationship between LLWR and P_{in}

The scatter plot of P_{in} versus LLWR shows a strong relationship between P_{in} and the LLWR, with the LLWR explaining about 45 % of the variation in P_{in} (Fig. IV.3). The relationship between P_{in} and LLWR is not as strong as that reported by da Silva and Kay (1997b), wherein the LLWR explained about 72 % of the variation in P_{out} (the opposite of P_{in}). Their data were collected from across a small farm with comparatively flat topography and more homogenous surface soils (from years of agricultural tillage), versus rolling topography and greater soil heterogeneity with our data. Topography affects water table depth, and soil heterogeneity affects the relationship between the moisture content of the surface soil and water table depth, with the combined effect being a diminished relationship between P_{in} and LLWR.

The LLWR ranged from 0 to about 0.6 $cm^3\ cm^{-3}$, and P_{in} covers the entire spectrum from 0 to 100 %. While the relationship between P_{in} and LLWR is fairly strong, several observations with low LLWRs (< 0.2 $cm^3\ cm^{-3}$) have P_{in} greater than 80 %; conversely, several observations with higher LLWRs (> 0.2 $cm^3\ cm^{-3}$) have P_{in} of around 0 %. This apparent disconnect between P_{in} and LLWR is most likely explained by differences in microsite elevation; the P_{in} was calculated from water table measurements which are strongly influenced by elevation.

I hypothesized that the elevation effect on P_{in} would result in a different relationship between P_{in} and LLWR for the site prepared treatments, as bedding elevates the microsite (Terry and Hughes, 1975). The model R^2 increased from 0.45 to 0.49 and the mean square error (MSE) decreased from 0.197 to 0.188 (Table IV.1) when the site preparation treatments were added to the model using dummy variables. The dry and wet non-site prepared and dry and wet bedded treatments were pooled into two treatments because a separate analysis showed no differential effects (result not shown). The intercept term for bedding, X3, borders on significant at the 0.1 level (Table IV.1). This borderline

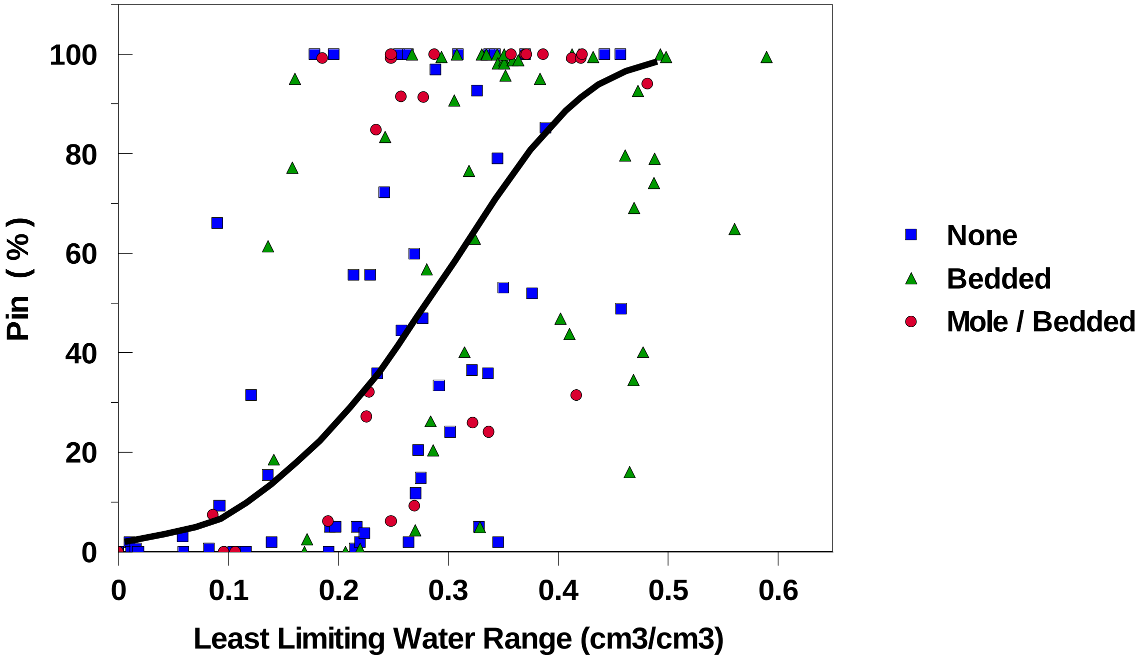


Figure IV.3. The relationship between 'the percentage of time the soil moisture content fell within the LLWR' (P_{in}) and the LLWR by site preparation treatment. Solid line is a simple linear regression fit of all the data; where, arcsin√ Pin LLWR = LLWR; $R^2 = 0.45$; N = 160.

Table IV.1. Results from the multilinear regression analysis that tested site preparation treatment effects on the relationship between P_{in} and LLWR.†

Variable	df	Parameter Estimate	T	P > | T |
Intercept	1	-0.0876	-0.79	0.4306
Slope (LLWR)	1	3.2266	8.08	0.0001
<u>Block Effects</u> ‡				
X1	1	-0.0796	-0.94	0.3475
X2	1	0.1611	1.83	0.0692
<u>Treatment Effects</u> §				
Intercept Terms				
X3 (Bedded)	1	0.2683	1.55	0.1229
X4 (Mole plow / Bedded)	1	0.0567	0.24	0.8095
Slope Terms				
X3*LLWR (Bedded)	1	-0.8210	-1.43	0.1539
X4*LLWR (Mole plow / Bedded)	1	0.2382	0.29	0.7719

† Model, $\{ = b_0 + b_1X1 + b_2X2 + b_3X3 + b_4X4 + b_5LLWR + b_6X3{*}LLWR + b_7X4{*}LLWR$

where,

	<u>X1</u>	<u>X2</u>		<u>X3</u>	<u>X4</u>
Block = 1	0	0	Treatment = None	0	0
Block = 2	1	0	Treatment = Bedded	1	0
Block = 3	0	1	Treatment = Mole plow / Bedded	0	1

$\{$ = arcsin √ Pin LLWR; $R^2 = 0.49$; *MSE* = 0.188; *N* = 160.

‡ Block effects tested using dummy variables X1 and X2.

§ Treatment effects on the intercept and slope (i.e. interaction) tested using dummy variables for none (wet and dry combined), bedded (wet and dry combined), and mole plow / bedded.

significance for bedding combined with the lower MSE with the dummy variables included, suggests that bedding did have a significant effect on the relationship between the P_{in} and LLWR. The intercept term for bedding adjusts the intercept to about 0.2, so even at very low LLWRs the soil moisture content is within the LLWR 20 % of the time with bedding. This result illustrates one of the reasons why bedding is such an effective site preparation treatment; i.e., bedding facilitates evaporation and drainage from microsites (Terry and Hughes, 1975), creating favorable soil moisture dynamics even in soils of apparently low physical quality (ie., low LLWR).

Surface Soil Disturbance and Organic Debris Effects on P_{in}

I hypothesized that increasing levels of soil disturbance have a progressively more negative effect on P_{in} and increasing organic debris would buffer this disturbance effect. To test this hypothesis, Pin was regressed as a function of surface organic debris with soil disturbance included as a dummy variable. The P_{in} increased as the surface organic debris level increased (Fig. IV.4). This effect is explained by a combination of the strong negative correlations between organic matter and bulk density (r = -0.55; p = 0.0001), and between macroporosity and bulk density (r = -0.49; p = 0.0001). When the soil moisture content fell outside the LLWR during the dormant season, it occurred above the upper limit 95 % of the time, showing that aeration is the most critical limiting factor influencing the soil physical environment on our sites. Since the upper limit was defined based on macroporosity, it follows then that the higher organic debris levels are having a positive effect on macroporosity, which in turn improves the soil physical environment, as suggested by Greacen and Sands (1980).

Soil disturbance and organic debris have a strong effect on P_{in}, with these two factors explaining about 78 % of the variation in P_{in} (Table IV.2). The strong relationship between P_{in} and the soil disturbance and organic debris classes shows that these visually-assessed management impacts are related to management-induced changes in the soil physical environment. The significance of the linear and quadratic slope terms for the undisturbed, compression track, and deep rut soil disturbance levels shows that there is a strong interaction between the amount of organic debris and soil disturbance. The significantly-higher adjusted quadratic slopes for compression track and deep ruts (0.0689 and 0.1315, respectively), show that as the surface organic debris level decreases, P_{in} decreases at a faster rate for these disturbances versus the remaining disturbances. This result is seen in Fig. IV.4, where the P_{in} for deep ruts and compression tracks are 100 and 60 %, respectively, with high levels of organic debris (slash piles), with both falling off rapidly to near 0 % at medium organic debris (light slash + O horizon).

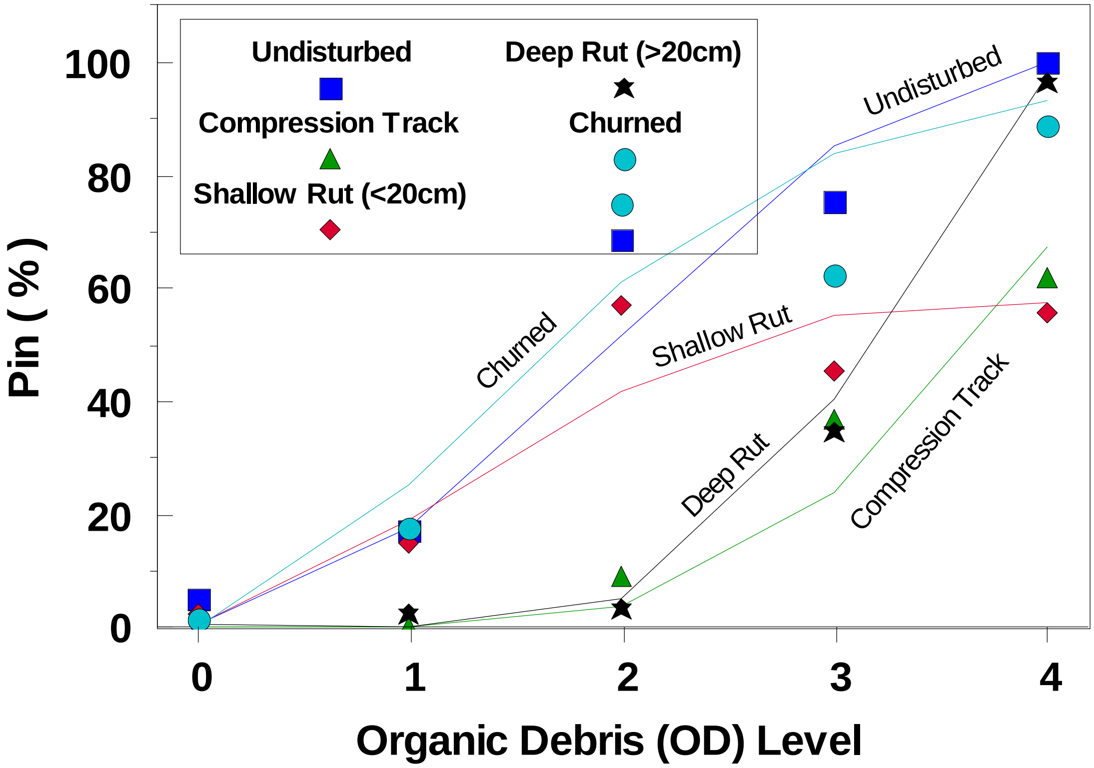


Figure IV.4. Surface soil disturbance and organic debris effects on 'the percentage of time the soil moisture content fell within the LLWR' (P_{in}). The evaluation is based on the multilinear regression model shown in Table IV.2.

Table IV.2. Multilinear regression results for the model testing the effects of surface soil disturbance and organic debris removal on P_{in}.†

Variable	df	Parameter Estimate	T	P > |T|
Intercept (Undisturbed)	1	-0.3573	-1.02	0.3104
Slope (OD)‡ (Undisturbed)	1	0.4906	1.84	0.0701
Slope^2 (OD^2) (Undisturbed)	1	-0.0478	-1.10	0.2767
Intercept Terms§				
X1 (Compression Track)	1	0.4395	0.89	0.3771
X2 (Shallow Rut)	1	0.0908	0.18	0.8547
X3 (Deep Rut)	1	0.7610	1.54	0.1287
X4 (Churn)	1	-0.1490	-0.30	0.7640
Slope Terms¶				
X1*OD	1	-0.6564	-1.74	0.0863
X2*OD	1	-0.1481	-0.39	0.6955
X3*OD	1	-0.9449	-2.51	0.0148
X4*OD	1	0.0969	0.26	0.7977
X1*OD^2	1	0.1161	1.89	0.0640
X2*OD^2	1	0.0521	0.85	0.4004
X3*OD^2	1	0.1793	2.91	0.0050
X4*OD^2	1	0.0052	0.08	0.9335

† Model, ⎨ = $b_0 + b_1X1 + b_2X2 + b_3X3 + b_4X4 + b_5OD + b_6X1*OD + b_7X2*OD + b_8X3*OD + b_9X4*OD + b_{10}OD^2 + b_{11}X1*OD^2 + b_{12}X2*OD^2 + b_{13}X3*OD^2 + b_{14}X4*OD^2$

where,

Soil Disturbance Class	X1	X2	X3	X4
Undisturbed	0	0	0	0
Compression Track	1	0	0	0
Shallow Rut	0	1	0	0
Deep Rut	0	0	1	0
Churned	0	0	0	1

⎨ = arcsin √ Pin LLWR; $R^2 = 0.78$; $N = 75$.

‡ The organic debris (OD) level was treated as a continuous variable.

§ Soil Disturbance class effects on the intercept were tested with dummy variables.

¶ The interaction between soil disturbance and organic debris was tested with linear and quadratic slope terms.

The strong interaction shown by the dummy variable regression shows that the simple effects of soil disturbance at each organic debris level should be tested separately (Table IV.2). At the highest level of organic debris (slash piles), the two highest levels of soil disturbance (deep ruts and churned) have P_{in}'s comparable to the undisturbed soil, while the P_{in}'s for compression tracks and shallow ruts are significantly lower than the undisturbed soil (Table IV.3). Deep rutting and churning incorporate the organic debris into the soil profile, a process which decreases the bulk density and increases macroporosity (Greacen and Sands, 1980). In contrast, compression tracks and shallow ruts do not incorporate the organic debris, so there is less beneficial effect on the soil physical environment at high levels of organic debris for these types of soil disturbances, except for perhaps buffering the surface against further disturbance.

The P_{in} response for churned soil was similar to that of the undisturbed soil throughout the range of organic debris (Fig. IV.4; Table IV.3). This response would suggest that churning had no effect on the soil physical environment, when in actuality churning increased the bulk density from 1.26 to 1.46 g cm^{-3} and decreased the macroporosity from 13 to 7 % (Aust et al., 1998a); however, churning also elevated the soil surface about 15 cm (Preston, 1996), which increased the depth to the water table, thus improving soil aeration status.

Table IV.3. Soil disturbance effects on P_{in} within surface organic debris levels.†

	Surface Organic Debris Level				
Soil Disturbance Level	None	O Horizon	O Horizon + Light Slash	O Horizon + Heavy Slash	Slash Piles
Undisturbed	0.05	0.17 ab‡	0.69 a	0.76	1.00 a
Compression Track	0.00	0.00 b	0.09 b	0.37	0.62 bc
Shallow Rut	0.02	0.15 a	0.57 a	0.45	0.56 c
Deep Rut	0.00	0.02 ab	0.03 b	0.35	0.97 ab
Churned	0.02	0.18 a	0.75 a	0.62	0.89 a

† Analyzed with ANOVA using an RCB design with 3 blocks of 5 treatments (n=15).
‡ Means separation with Duncan's Multiple Range Test. Values within columns followed by different letters are significantly different at alpha = 0.1.

Soil disturbance had the greatest effect on P_{in} at the medium level of organic debris (O horizon + Light Slash), where the P_{in}'s for compression tracks and deep ruts are near 0, versus a low of 57 % for the remaining soil disturbance classes (Table IV.3). The P_{in}

response at this level closely follows the saturated hydraulic conductivity results reported by Preston (1996), with undisturbed . churned > shallow rut > deep rut . compression track. This pattern of saturated hydraulic conductivity helps explain the low P_{in}'s for deep ruts and compression tracks; the low saturated hydraulic conductivity is impeding drainage on these disturbances, thus they exceed the upper limit of the LLWR (poor aeration), which was the primary reason for low P_{in}.

The compaction forces on the mineral soil surface increase as the amount of surface organic debris decreases because the interlocking web of material decreases the ground pressure of logging equipment (which is why operating harvesting equipment on a mat of debris remains a good idea). The end results of compaction, increased bulk density and decreased macroporosity are well known (e.g. Greacen and Sands, 1980), and explain the very low P_{in} for compression tracks with decreasing levels of organic debris.

The response of P_{in} to deep rutting at the medium level of organic debris is more difficult to explain. Because rutting is soil displacement (Karr et al., 1990), versus compaction, which is soil compression, the impact of rutting on the soil physical environment may be much different from compaction. The most likely explanation has to do with the effects of deep rutting on lateral water movement (site drainage). The sides of deep ruts are smeared with a thick layer of churned material which usually extends down into the Bt horizon (Miwa, 1999). The saturated hydraulic conductivity of the churn, as reported by Aust et al. (1998a) for our sites, is about 1.2 cm h^{-1} versus 9.0 cm h^{-1} for the undisturbed soil. This wall of puddled soil effectively creates a dam which prevents (or severely restricts) lateral water movement, resulting in a higher water table in the deeply rutted areas (Aust et al., 1998a). At higher levels of organic debris, large branches and logs are mixed with the puddled soil, and as the organic debris decays, channels are created which will likely facilitate drainage.

The extent to which shallow rutting (<20cm) will affect P_{in} depends on the thickness of the surface horizons (A + E horizons) and changes in soil physical properties between the ruts. If enough undisturbed soil remains between the bottom of the rut and the top of the Bt horizon, then lateral water movement may continue relatively unimpeded (Miwa, 1999). Since there was no difference in the P_{in} of undisturbed soil versus the soil between the ruts, this suggests that the soil physical environment between the shallow ruts was unaffected by the disturbance, which is supported by another study in the region on similar soils which found that soil physical properties were not affected between tire tracks of shallow ruts (Tippett, 1992). The relationship between rut depth, depth to the subsurface, and lateral water movement on these types of sites warrants further investigation.

As the level of surface organic debris continues to decrease, the effect of soil disturbance on P_{in} decreases to the point where disturbance has no effect on P_{in} when no surface organic material is present (Table IV.3). This effect is again explained by the close correlations between organic matter and bulk density, and between macroporosity and bulk density. The results presented in Fig. IV.4 and Table IV.3 show that retention of high levels of organic debris on the site has a positive effect on the soil physical environment, and also has a mitigative effect when the soil has been disturbed.

Site Preparation Effects on P_{in}

Site preparation effects on P_{in} were evaluated at the medium level of organic debris (O horizon + light slash). This level was selected because (i) the medium level of organic debris is the most commonly occurring organic matter level, covering over 58 % of the harvested area (Kelting et al., 1999a); and (ii) the greatest differentiation between disturbance classes was observed at this level (Table IV.3).

The effects of site preparation on P_{in} are shown on a gradient going from what was considered the highest level of soil disturbance (churned) to undisturbed soil (Fig. IV.5).

Examining the two levels of soil disturbance that were shown to decrease P_{in} (compression tracks and deep ruts), both bedding and mole plow / bedding improved the P_{in} for these disturbances up to a level equivalent to the non-site prepared undisturbed soil (none). In order to judge whether or not this result means that both site preparation treatments successfully mitigated the disturbance effect, a proper baseline must be chosen against which to compare (Burger and Kelting, 1999ab). Site preparation significantly improved the P_{in} for the undisturbed soil, going from 70 to 100 % (Fig. IV.5). Since bedding has been the standard management practice for poorly-drained soils on the Lower Coastal Plain for years (Terry and Hughes, 1975), it can be argued that the P_{in} response to bedding the undisturbed soil serves as the baseline. If we accept the bedding response as the appropriate baseline, then site preparation did not mitigate the effects of deep rutting and compression tracks on P_{in} at this organic matter level.

CONCLUSIONS

The P_{in}, derived from a combination of the LLWR and daily soil moisture fluctuations, was a sensitive measure of management impacts which allowed us to detect soil disturbance, organic debris, and site preparation effects on the soil physical environment. Compression tracks and deep ruts reduced the P_{in} to near 0 at the most commonly occurring organic matter level. Site preparation improved the quality of the soil physical environment, but not up to the level of the bedded / undisturbed soil. Retention of high levels of organic debris has a positive effect on the soil physical environment, and also has a mitigative effect when the soil has been disturbed. Therefore, a strategy for improving the overall site-level soil physical environment would be to spread coarse debris out across compacted and rutted areas prior to bedding.

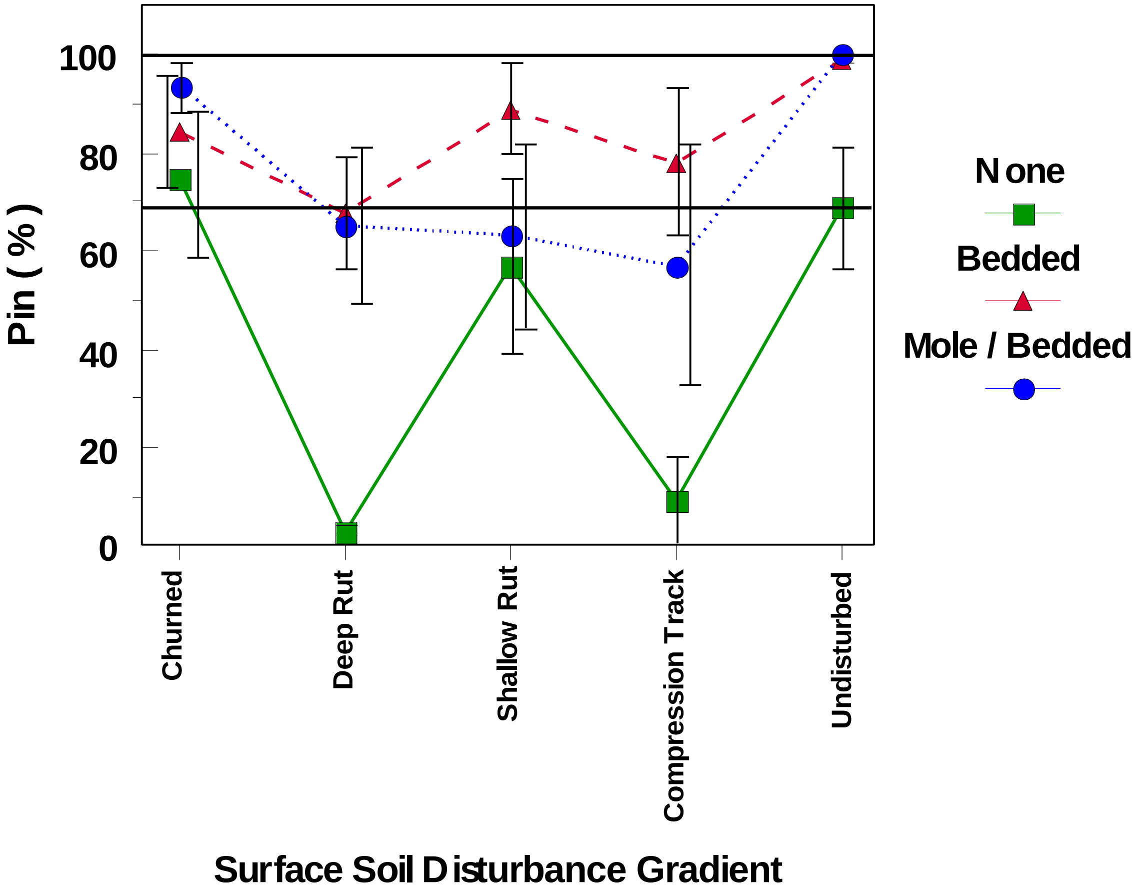


Figure IV.5. Site preparation treatment effects on 'the percentage of time the soil moisture content fell within the LLWR' (P_{in}) by surface soil disturbance level. This analysis was conducted at the medium organic debris level (O horizon + light slash). Vertical bars are +/- one standard error of the mean (n = 3 per bar).

CHAPTER V. TIMBER HARVESTING AND SITE PREPARATION EFFECTS ON THE SOIL NUTRITIONAL ENVIRONMENT

ABSTRACT

Harvesting timber under wet-site conditions can result in extensive soil disturbance which may create an oxygen-poor environment for root growth and disrupt normal soil biochemical activity. These anoxic conditions can result in profound changes in soil chemical properties which are important determinants of the quality of the soil nutritional environment for tree growth. The objectives of this study were to (i) determine if the typical soil disturbances that result from harvesting timber on wet-sites cause changes in the soil nutritional environment, and (ii) determine if mechanical site preparation treatments are effective in mitigating any negative changes if they occur. Three 20 ha, 20-yr-old loblolly pine plantations were harvested under wet and dry conditions to create a broad gradient in site disturbance. Within each harvested plantation, a subset of 3 ha plots were site prepared by either bedding or mole-plowing plus bedding, then all sites were established as 3rd - rotation pine plantations. Prior to site preparation, each plot was mapped using a 5 by 5 soil disturbance (none to churned) / organic debris matrix (none to slash piles). Harvesting disturbance and site preparation effects on soil aeration were examined with commonly measured indicators: water table depth, oxidation depth, and air-filled porosity. All of the indicators of soil aeration showed that compression tracks and deep ruts reduced soil aeration status during the winter, particularly at lower levels of organic debris. The air-filled porosity results suggested that oxygen diffusion was probably limiting aerobic soil processes for all soil disturbance levels at low levels of organic debris during the winter. However, though soil disturbance negatively impacted the soil physical environment, this did not translate to negative effects on the soil chemical or biological environment. Soil pH, ECEC, base saturation, and available P were not affected by either soil disturbance or organic debris removal during the first year following site preparation. Site preparation did change the soil chemical environment, but the changes were probably associated with tillage effects on organic matter and clay content,

not oxidation / reduction processes. Calcium saturation appeared to control soil pH, thus buffering any redox-effects on soil chemical properties. This, combined with a low potential for reducing conditions, based on modeling redox as a function of water table, explained the lack of any redox-induced treatment effects on soil chemical properties. Net nitrification, a surrogate indicator for soil biological activity, was not affected by soil disturbance or organic debris removal. Dry-harvest and mole-plow / bedding increased net nitrification, but wet-harvest / bedding did not. Thus, bedding the wet-harvested sites did not improve the soil biological environment over non-bedded soil; however, the net N mineralization rates within all the treatments were most likely sufficient to meet the nutritional demands of the vegetation at this time. These results demonstrate the important role of high fertility in buffering potentially-negative effects of forest management practices on the soil nutritional environment.

INTRODUCTION

The wet-pine flats of the lower coastal plain region are among the most productive forest soils in the US (Aust et al., 1998a). High pine productivity on these soils is obtained through combinations of drainage, bedding site preparation, and often fertilization (Allen and Cambell, 1988). Drainage and bedding are necessary for lowering the inherently-high water tables and creating an aerated rooting volume for seedling establishment and fast early growth. Thus, while these sites are highly-productive, their continued productivity depends on the successful management of soil water.

Wet-site timber harvesting can result in extensive surface soil compaction and rutting, upwards of 85 % of the harvested area (Aust et al., 1998a). Compaction and rutting have been shown to increase bulk density, and reduce macroporosity and hydraulic conductivity (Tippett, 1992; Preston, 1996), with the end-result being impeded site drainage and commensurate high water content (Preston, 1996). There is a general feeling within the forestry community that, if left unmitigated, such changes in soil physical and hydrologic properties and processes may lead to long-term decreases in site productivity. One of the main reasons for concern is restricted oxygen supply, as oxygen supply is a critical factor directly affecting physiological processes (Kozlowski et al., 1991), and soil biological and chemical processes which are important determinants of soil fertility (Ponnamperuma, 1984). With soil fertility being the "status of a soil with respect to its capacity to provide plants with nutrients in the amount, rate, and balance needed for optimum growth" (Ponnamperuma, 1984).

Oxygen diffusion decreases exponentially as the soil water content increases (Freijer, 1994). The critical soil water content where oxygen diffusion becomes negligible varies depending on soil texture, structure, and organic matter content (Freijer, 1994), and aggregate size and shape (Renault and Stengel, 1994), but a general critical level above which the soil water content severely restricts oxygen diffusion is 10 % macroporosity (Foil and Ralston, 1967; Childs et al., 1989; Theodorou et al., 1991). Once the critical soil water content is exceeded, continued microbial oxidation of soil organic matter depletes the soil oxygen supply within 1 to 3 days of continuous waterlogging (Patrick, 1977). The resultant shift from an aerobic to anaerobic soil environment can result in large changes in soil biological and chemical processes.

The oxidation / reduction (redox) conditions resulting from periodic waterlogging can have a profound effect on the soil nutritional environment as redox, as with pH, has been identified as a master variable exerting strong influence on major soil chemical and biological processes (Bohn et al., 1985; McBride, 1994): adsorption-desorption; ion-exchange (McKee, 1970); mineral precipitation-dissolution (Brennan and Lindsay, 1998); ion-pair, complex or chelate formation (McKee and McKevlin, 1993); and nitrification-ammonification (Paul and Clark, 1989).

Site disturbance studies have documented chemical reduction and increased soil pH with soil disturbance on poorly-drained soils (Aust and Lea, 1992). Dulohery et al. (1996)

measured lower rates of CO2 efflux from trafficked (skidder damage) / bedded soils. This decrease may be attributed to slower organic matter decomposition under anaerobic conditions which is indicative of reducing conditions (Ponnamperuma, 1984; McKee and McKevlin, 1993).

Based on the relationships between waterlogging, redox, and soil biological and chemical processes found in other studies, we would expect that soil disturbance during wet-site harvesting would alter the soil nutritional environment, and bedding would have an opposite and perhaps mitigative effect (oxiding environment). The objectives of this analysis were: (i) to determine if harvesting disturbance results in conditions which favor an anaerobic soil environment, (ii) to determine if harvesting disturbance changes soil biological and chemical properties and processes, and (iii) determine the effects of site preparation on disturbance-induced changes in the soil nutritional environment.

MATERIALS AND METHODS

Detailed descriptions of the study site, treatment installation and layout, and field and laboratory measurements are found in Chapter III.

Statistical Analysis

Two different experimental designs were used to examine treatment effects. The first design was an RCB design consisting of the 5 levels of soil disturbance and organic debris (Fig. III.2) in 3 blocks. The effects of soil disturbance and organic debris were analyzed as a complete factorial. For this analysis, the data from the wet- and dry-harvested non-site prepared plots were pooled within blocks to obtain 3 replicates (blocks) of 25 treatment combinations (n = 75). The pooling was justified based on a post harvest analysis which suggested no differences in soil physical properties within soil disturbance classes in comparing wet versus dry-harvested plots (Preston, 1996).

The second design evaluated the effects of the site preparation treatments on soil properties using an RCB design with soil disturbance classes nested within site preparation treatments. This design allows for testing site preparation treatment effects on soil disturbance classes, but does not allow a test for interaction. Disturbance and site preparation effects on soil properties were evaluated at surface organic debris level 2 (O horizon plus light slash) only. This was an unbalanced design, as only two disturbance classes, undisturbed and compression tracks, occurred in the dry-harvested / bedded treatment (n = 51).

For all ANOVAs, treatment differences were considered significant at an alpha of 0.10. The effects of pre-treatment covariates: elevation, soil carbon, and clay content, on treatment means and significance levels were also evaluated by adding the covariates to the model and examining their effects on the mean square error and P values. In addition to ANOVA, correlation and multilinear regression analysis were used to explore relationships between variables.

RESULTS AND DISCUSSION

Indices of Soil Aeration

Harvesting Effects

Surface soil disturbance and organic debris removal effects on soil aeration were evaluated with four common indices: water table depth, redox potential, oxidation depth, and air-filled porosity. The data were pooled into two seasons, winter (November 96 through February 97) and summer (June 97 through August 97) to examine the seasonal effects of disturbance on soil aeration. The soil disturbance effect on each index of soil aeration is plotted as a function of increasing levels of surface organic debris (Fig. V.1 and V.2). The accompanying ANOVA results are shown in Table V.1.

Table V.1. Summary of ANOVAs for testing the effects of soil disturbance and organic debris on the indicators of soil aeration.†

	Indicator of Soil Aeration							
	Water Table Depth		Redox Potential		Oxidation Depth		Air-Filled Porosity	
Factor	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
	- P values -							
Soil Disturbance (5 levels)	0.021	0.101	0.019		0.000	0.004	0.009	0.008
Organic Debris (5 levels)	0.063	0.101	0.004		0.020	0.063	0.000	0.000
Interactions	0.972	0.983	0.649		0.415	0.469	0.914	0.934

† Data analyzed by season using a complete factorial design with 3 blocks of 25 treatments.

Soil disturbance and organic debris removal both had significant effects on average water table depth in winter, but there was no interaction (Fig. V.1; Table V.1). Water table depth decreased from an average high of 35 cm to a low of 25 cm as the organic debris level decreased (Fig. V.1A). The exception was the churned soil, wherein the water table depth increased at the lowest level of organic debris. Compression tracks and deep rutting decreased the winter water table depth from 33 cm (undisturbed soil) to 25 and 27 cm, respectively, while shallow rutting and churning had no effect on the water table depth in winter (Table V.2). The water table depth response to soil disturbance and organic debris removal is weaker during the summer (Table V.1), but the trends are basically the same (Fig. V.2) with compression tracks and deep rutting still having significantly lower water table depths than the undisturbed soil (Table V.2).

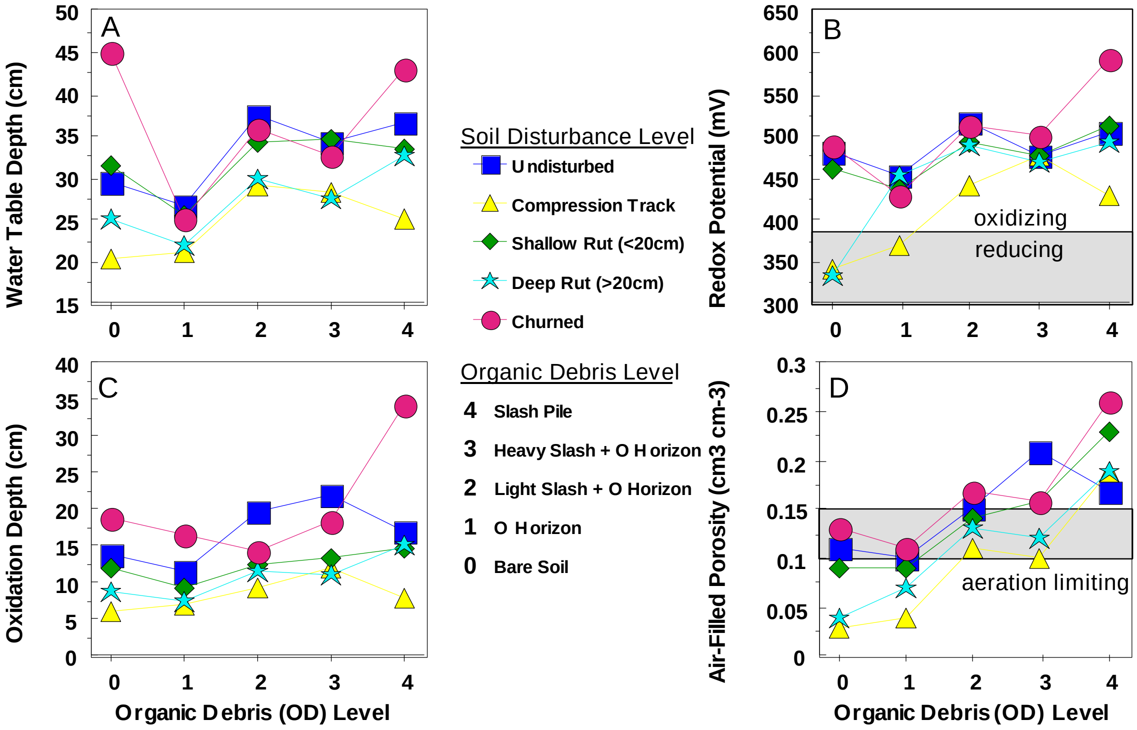


Figure V.1. Surface soil disturbance and organic debris effects on water table depth (A), predicted redox potential (B), oxidation depth (C), and air-filled porosity (D) during the winter, November through February.

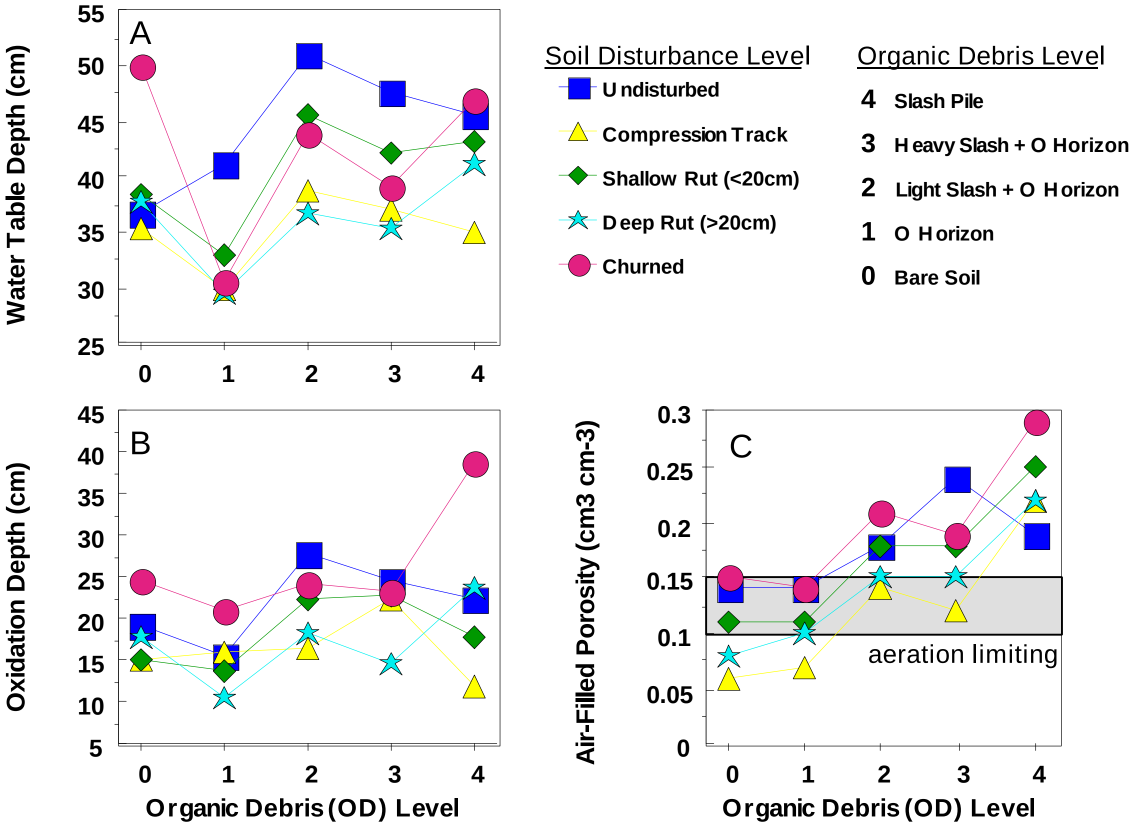


Figure V.2. Surface soil disturbance and organic debris effects on water table depth (A), oxidation depth (B), and air-filled porosity (C) during the summer, June through August.

Table V.2. Main effects of soil disturbance on the indicator variables.

	Indicator Variable							
Soil Disturbance Level	Water Table Depth (cm)		Redox Potential† (mV)		Oxidation Depth (cm)		Air-Filled Porosity (%)	
	Winter¶	Summer	Winter	Summer‡	Winter	Summer	Winter	Summer
Undisturbed	33 a	45 a	487 a		17 a	22 ab	0.15 a	0.18 ab
Compression Track	25 b	35 b	412 b		8 c	16 c	0.09 b	0.12 c
Shallow Rut (<20cm)	32 ab	41 ab	476 a		13 bc	19 bc	0.14 ab	0.17 abc
Deep Rut (>20cm)	27 b	36 b	449 ab		10 c	17 bc	0.11 b	0.14 bc
Churned	36 a	42 ab	505 a		20 a	27 a	0.17 a	0.20 a

† Redox potential predicted from water table measurements using McKee and Shoulders (1970).

‡ Water table data fell outside the range of McKee and Shoulders (1970) regression equation.

The average winter redox potential was predicted using a regression equation developed by McKee and Shoulders (1970) which predicts the redox potential based on the average water table depth. Since the redox potential was predicted from the water table depth data, the predicted redox values show basically the same soil disturbance and organic debris effects as the water table results (Fig. V.1B; Table V.1 and V.2), but the redox values allow a more direct interpretation of disturbance effects on soil aeration (McKee and Shoulders, 1970; Aust and Lea, 1992). Surface soil compaction reduced the predicted redox potential from 487 to 412 mV (Table V.2). The soil pH ranged from 5.02 to 6.18, within this range the approximate redox potential below which the soil condition would change from an oxidizing to a reducing environment is about 375 mV (McBride, 1994). So even though the redox potential was reduced with compression tracks, it was still above the threshold level of 375 mV. However, the redox potential does fall below the 375 mV threshold at lower levels of organic debris for compression tracks and deep ruts (Fig. V.1B), indicating that compression tracks and deep rutting did result in anaerobic soil environments at low levels of organic debris. The redox potentials were not predicted for the summer because many values fell outside the range of water table depths McKee and Shoulders (1970) used to develop their regression equation.

Oxidation depth on steel rods followed the same trends as redox potential and water table depth (Fig. V.1C and V.2B), but oxidation depth was a more sensitive indicator of disturbance effects on soil aeration as suggested by the lower P values for oxidation depth than the other variables (Table V.1). Compression tracks decreased the average oxidation depth during the winter from 17 to 8 cm, a greater than two-fold decrease (Table V.2). Shallow and deep rutting also decrease the average oxidation depth during the winter by about 4 and 7 cm, respectively, while churning had no effect on oxidation depth. Oxidation depth followed the same trends with soil disturbance and organic debris removal during the summer (Fig. V.2B), but the separation between treatments decreased (Table V.1). Compression tracks had the only negative effect on oxidation depth during the summer, with a decrease of about 6 cm compared to the undisturbed soil (Table V.2).

Air-filled porosity ranged from 0.26 to 0.02 cm^3 cm^{-3} during the winter, following the same trends as the other indicators of soil aeration (Fig. V.1D). Using 0.10 to 0.15 cm^3 cm^{-3} as a critical range below which lower air-filled porosity would limit soil aeration and gas exchange (Dulohery et al., 1996), aeration becomes limiting for compression tracks and deep ruts at organic debris level 3 (heavy slash plus O horizon) (Fig. V.1D). Aeration becomes limiting for the remaining soil disturbance classes at organic debris level 2 (O horizon). These effects are the same for the summer results (Fig. V.2C). The main effects of soil disturbance on air-filled porosity show that compression tracks on average (i.e., across all levels of organic debris) have air-filled porosity below the critical level for adequate gas exchange regardless of season (Table V.2). Deep ruts also have critically-low air-filled porosity during the winter, but not during the summer.

The churned soil consistently had the highest overall average values for each indicator of soil aeration compared to the other levels of soil disturbance (Table V.2). Soil churning elevated the soil surface, resulting in a generally lower water table with soil churning (Preston, 1996) and higher values for the other indictors as they are all related. The consistent trend of increasing values of each indicator with increasing organic debris is most likely explained by better soil physical properties for soil drainage with increasing organic matter content, as was discussed in the previous chapter. The weaker treatment effects during the summer are attributed to the vegetation, with transpiration partially controlling soil water dynamics during the growing season (Kozlowski et al., 1991).

Oxidation depth on iron rods was the most sensitive indicator of soil disturbance effects on soil aeration based on the high significance of the P values (Table V.1). The rod integrates the effects of fluctuating soil water content on soil aeration over time (McKee, 1978), and the oxidation depth on the rod is a weighted average of the soil water dynamics between measurement periods.. Compared to water table and soil moisture dynamics, which are subject to sudden changes that may not reflect the average conditions between measurement periods, iron rod oxidation measurements are less variable and not as susceptible to transient changes in water content because it takes time for the oxidation or reduction to form on the rod.

Site Preparation Effects

Site preparation effects on the indices of soil aeration were evaluated at organic debris level 2 only (light slash plus O horizon). Redox potential was not predicted for the site preparation treatments because the water table data fell outside the range of McKee and Shoulders (1970) regression equation.

Site preparation resulted in large increases for all three indices of soil aeration (Table V.3). The increase in water table depth was greater with bedding the wet-harvested sites versus the dry-harvested sites, with wet / bed and mole / bed doubling the average winter water table depth. The summer water table depth was also greater for the wet-harvested sites compared to dry / bed and no site preparation. I hypothesized that the greater water table depth with wet-harvest bedding versus dry-harvest bedding may have been due to pre-treatment elevation gradients within each block possibly biasing the water table results, but a reanalysis of the data with pre-harvest elevation included as a covariate indicated no such bias (results not shown).

Table V.3. Site preparation effects on indices of soil aeration.†

	Index of Soil Aeration					
Treatment	Water Table Depth (cm)		Oxidation Depth (cm)		Air-Filled Pore Space ($cm^3 cm^{-3}$)	
	Winter	Summer	Winter	Summer	Winter	Summer
None	25 c	39 c	16 b	21 c	0.15 b	0.18 b
Dry / Bed	37 b	49 b	28 a	29 b	0.27 a	0.31 a
Wet / Bed	49 a	57 a	32 a	37 a	0.26 a	0.28 a
Mole / Bed	49 a	62 a	33 a	41 a	0.27 a	0.28 a

† Values within columns followed by different letters are significantly different at alpha = 0.10.

Though the water table depth results suggest that wet-harvest / bedding may have resulted in more favorable soil aeration conditions than dry-harvest / bedding, the oxidation depth and air-filled porosity results for the winter show that all three bedding treatments resulted in similar oxidation depths and air-filled porosity (Table V.3).

Site preparation treatment effects on the soil aeration indices for winter and summer were also examined for each level of soil disturbance (Fig. V.3 and V.4). The shaded areas on each figure represent +/- one standard error of the index response to the dry-harvest / bedding treatment. The response to the dry-harvest / bedding treatment with no harvesting disturbance acts as the baseline against which to compare other treatment responses, as the dry-harvest would be the minimum impact soil disturbance and bedding is the standard site preparation method in the region (Terry and Hughes, 1975). The interpretation is that if the error bar for any given soil disturbance class / site preparation treatment falls within the shaded area, then that disturbance is considered mitigated.

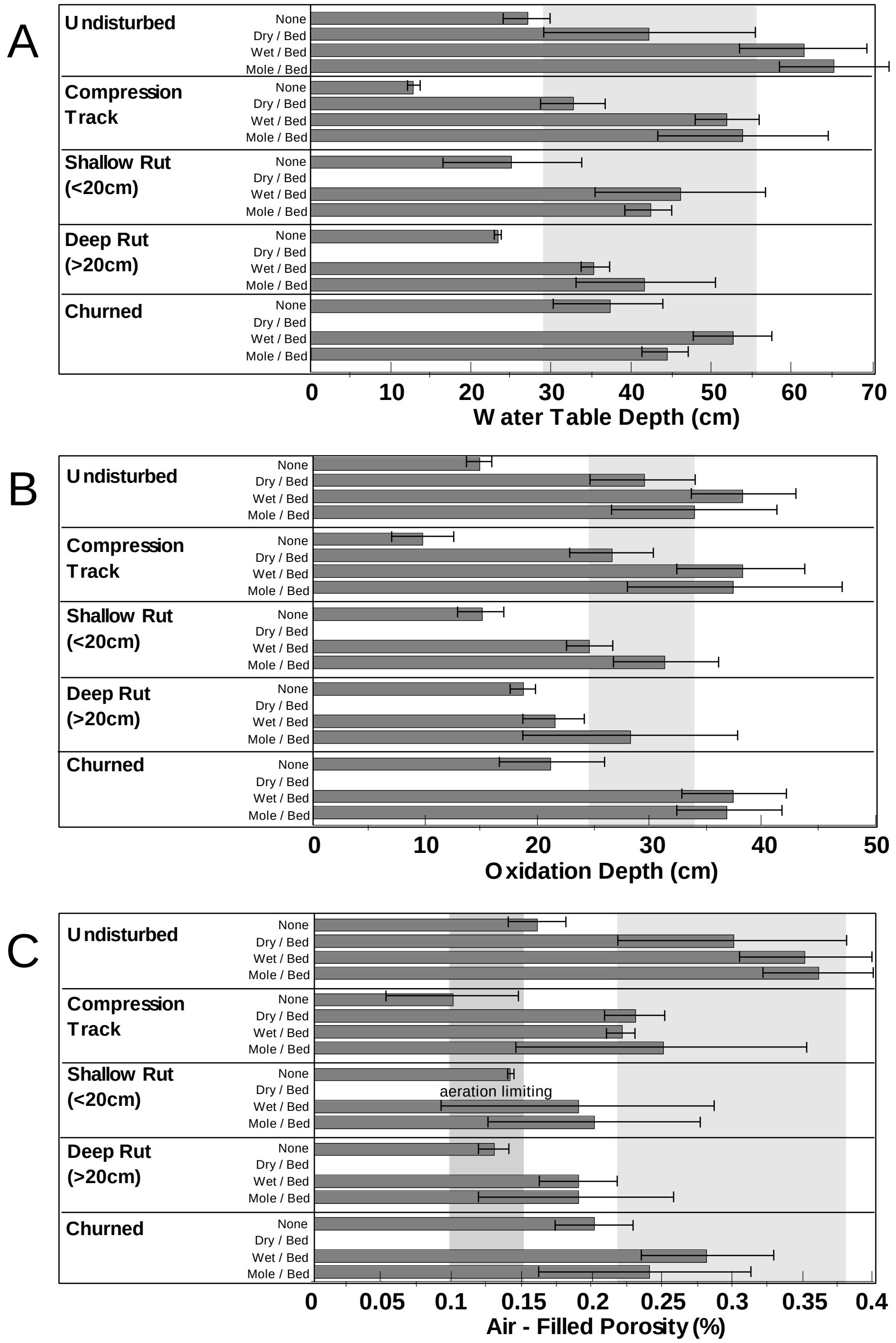


Figure V.3. Site preparation and soil disturbance effects on water table depth (A), oxidation depth (B), and air-filled porosity (C) during the winter, November through February. Bars represent +/- one standard error of the mean (n = 3).

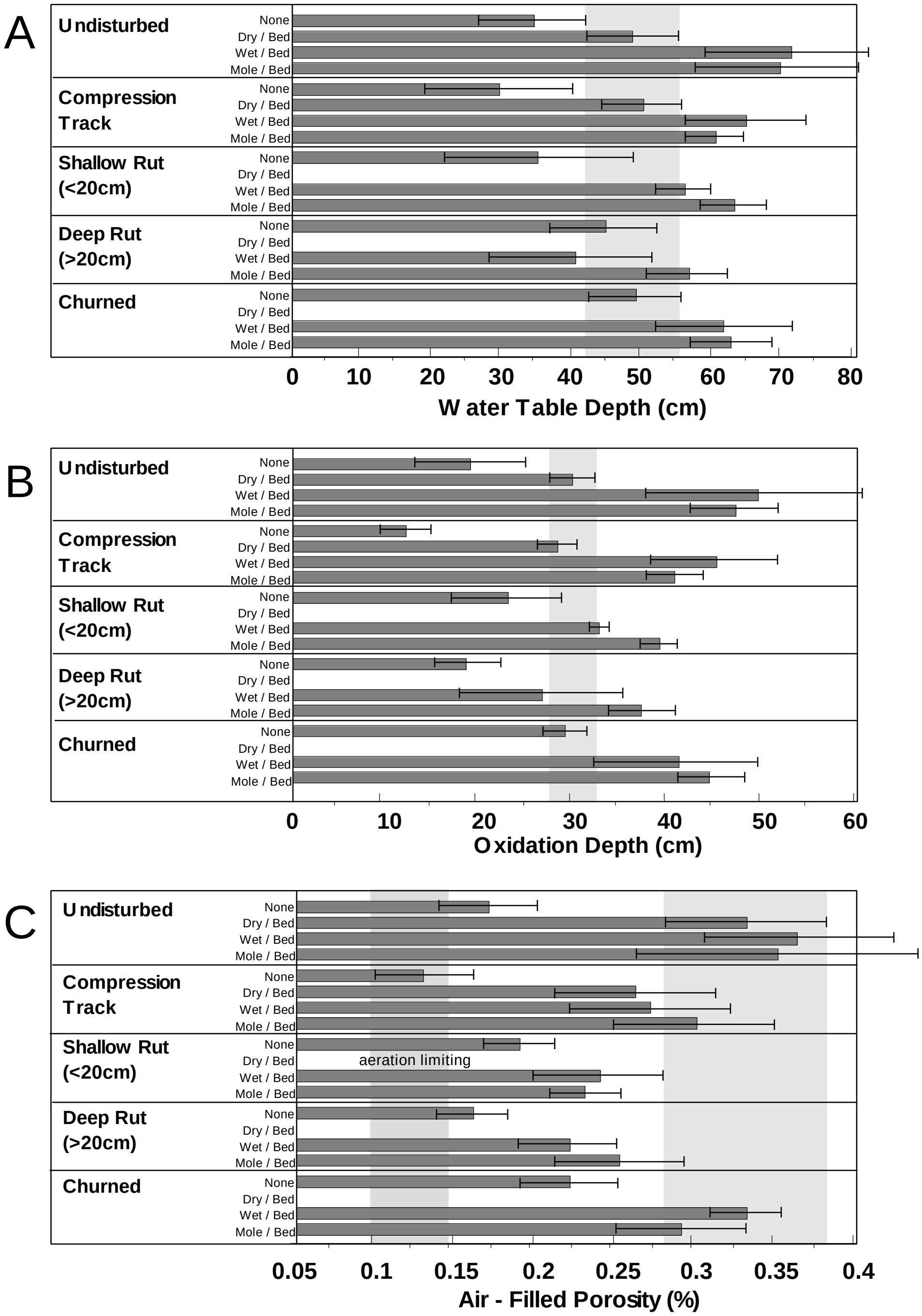


Figure V.4. Site preparation and soil disturbance effects on water table depth (A), oxidation depth (B), and air-filled porosity (C) during the summer, June through August. Bars represent +/- one standard error of the mean (n = 3).

Water table depth met or exceeded the dry / bed treatment effect for the undisturbed soil at all levels of soil disturbance for the wet / bed and mole / bed treatments for both winter and summer (Fig. V.3A and V.4A). The mole / bed treatment mitigated the effects of all levels of soil disturbance on winter oxidation depth and air-filled porosity (Fig. V.3B, C and V.4B, C). The wet / bed treatment mitigated the disturbance effect on winter oxidation depth and air-filled porosity at all levels of disturbance except for deep ruts (Fig. V.3B). The summer air-filled porosities for bedding deep ruts and mole / bedding shallow ruts were significantly lower than the dry / bedded undisturbed soil (Fig. V.4C). When the site preparation treatments did not mitigate the disturbance effect on air-filled porosity, the values were still above the level where gas exchange would become limiting.

Based on these results, it would appear that the decreases in the soil aeration indices observed with soil disturbance following harvesting were reversible, being mitigated by site preparation. The results also suggest that, although the mole plow treatment tended to have higher values than bedding alone, the additional treatment was unnecessary for mitigating soil damaged during harvesting.

Soil Chemical Properties

Harvesting Effects

The indices of soil aeration suggested that anaerobic soil conditions most likely existed at some levels of soil disturbance and organic debris removal, thus we expected to see changes in soil chemical properties associated with reducing conditions. However, the plots of soil chemical properties typically altered under reducing conditions show no clear trends (Fig. V.5), and the ANOVAs indicated that the variation is more or less random and not a function of either soil disturbance or the amount of organic debris (Table V.4).

Table V.4. Summary of ANOVAs testing the effects of soil disturbance and organic debris levels on key soil chemical properties.

	Soil Chemical Property			
Factor	Soil pH	ECEC ($\mathrm{cmol_c\ kg^{-1}}$)	% Base Saturation	Available P ($\mathrm{mg\ kg^{-1}}$)
	- P values - - - - - - - - - - - - - - - - - - -			
Soil Disturbance (5 levels)	0.428	0.550	0.542	0.425
Organic Debris (5 levels)	0.298	0.997	0.787	0.317
Interactions	0.783	0.755	0.553	0.750

Based on the disturbance effects on oxidation depth and air-filled porosity, we would have expected increased soil pH, ECEC, base saturation, and available P with compression tracks and deep ruts. Consumption of hydrogen ions under anaerobic conditions increases the pH of acid soils (Ponnamperuma, 1984), resulting in a commensurate increase in pH dependent charge. Continuous and cyclic submergence can also decrease levels of exchangeable acid cations, as the higher pH reduces the dissociation of Al (McKee, 1970). We also expected that increasing levels of organic debris would have intensified the changes in soil chemical properties with reduction, as soil organic matter is the fuel for redox, providing electrons for reduction of electron acceptors (McKee and McKevlin, 1993). With increasing labile organic matter, high microbial activity (OM oxidation) releases large amounts of electrons which quickly overwhelm available electron acceptors (oxygen in aerobic soils), and thus secondary electron acceptors are more or less sequentially reduced, driving down the redox potential (McBride, 1994).

The *in situ* soil pH probably did increase with waterlogging on these sites, but since the effects of water logging on soil chemical properties are slowly reversible (McKee and McKevlin, 1993), in the absence of long-term inundation by water, the soil chemical properties are not altered on average. *In situ* studies have documented increased soil pH with waterlogging (Aust and Lea, 1992), but these effects reverse during dry periods,

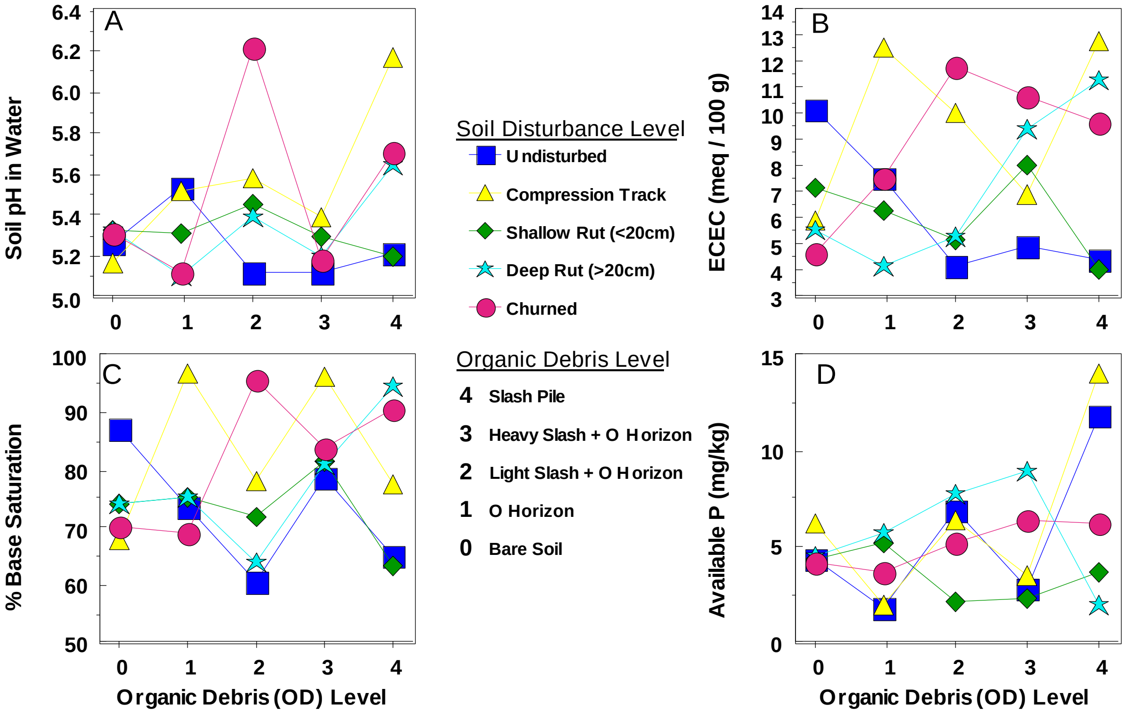


Figure V.5. Surface soil disturbance and organic debris effects on soil pH (A), ECEC (B), % base saturation (C), and available P (D).

with the soil pH decreasing to a level dictated by the partial pressure of CO_2 (Ponnamperuma, 1984). Other studies have documented *in situ* changes in soil pH that were still measurable even after oven-drying at 105 C (McKee, 1970), so it appears that if redox-induced changes in soil chemical properties existed they would have been detected with the air-dried samples.

Double-acid extractable P was not affected by either soil disturbance or organic debris (Table V.4). The slight trend in increasing double-acid extractable P with increasing levels of organic debris would be expected as decomposition of organic P would add to the inorganic P pool (Barber, 1995). Given the low levels of soil aeration for the compression tracks and deep ruts, I expected to see increased available P under these disturbances due to increased P-solubility from the reduction of Fe-P (Ponnamperuma, 1984); however, no trends in this direction occurred. Double-acid extractable P ranges from 2 to 14 mg kg^{-1}. Based on a soil critical level of 6 mg kg^{-1} for loblolly pine growth response to P (Prichett, 1979), there may be some opportunity for additional productivity-enhancement on these sites through P-fertilization.

Site Preparation Effects

The site preparation treatments had no effect on soil pH in water (Table V.5). Soil pH ranged from 4.75 to 6.25 (Fig. V.6), with the majority of values occurring in the 5.1 to 5.35 range. Four observations with soil pHs over 7 were deleted; these observations were within 20 m of the haul road, and I was suspicious that road dust may have had a liming effect on the soil near the road (the roads are surfaced with calcareous marl, the local rock). I had hypothesized that increased soil aeration observed with bedding would have lowered the soil pH, as oxidation would have liberated H ions.

Site preparation did affect the concentrations of exchangeable base cations (Table V.5). The Mg concentration was doubled for the dry-harvest / bedded treatment, compared to the other two bedding treatments which had no effects on Mg. The K concentration was also higher for the dry-harvest / bedded treatment. There were significant differences among the other treatments for K as well, but given the closeness of the values I don't think these differences have any practical significance.

Table V.5. Site preparation effects on key soil chemical properties.†

		Exchangeable Base Cations			KCl -		Base	Total	Available
Treatment	Soil pH	Ca	Mg	K	Acidity	ECEC	Saturation	Carbon	P
		---------------------------- $cmol_c\ kg^{-1}$				----------------------------	---------- %	----------	$mg\ kg^{-1}$
None	5.18	3.91	0.92 b‡	0.08 bc	1.36	6.27 b	78	2.37 b	7.1
Dry / Bed	5.27	5.36	1.97 a	0.14 a	1.71	9.18 a	81	3.46 a	5.1
Wet / Bed	5.29	3.30	0.80 b	0.07 c	1.44	5.61 bc	74	2.31 b	6.9
Mole / Bed	5.24	3.26	0.83 b	0.09 b	0.81	4.99 c	84	2.27 b	9.8

† ANOVAs for an unbalanced nested design.

‡ Values within columns followed by different letters are significantly different at alpha = 0.10.

The dry-harvest / bedded treatment had the highest ECEC, which also corresponds with this treatment having the highest total carbon by over 1 % (Table V.5). The wet-harvest / bedded and non-site prepared treatment had similar ECECs, and the mole-plow / bedded treatment had the lowest ECEC. This gradient in ECEC corresponds very well with the gradient in total carbon.

All treatments had high base saturation, with values ranging from 74 to 84 % of the ECEC (Table V.5).

I suspected that the higher total carbon and ECEC with dry-harvest / bedding may have been an artifact of gradients in pre-treatment soil carbon levels, as an analysis of pre-harvest soil carbon and clay content data collected by Burger (1994) showed that these two properties varied along gradients that may bias the treatment effects on soil chemical properties. However, when pre-harvest soil carbon and clay content and their interaction were included as covariates in the ANOVAs for each variable, neither variable had significant effects on any soil chemical property (results not shown).

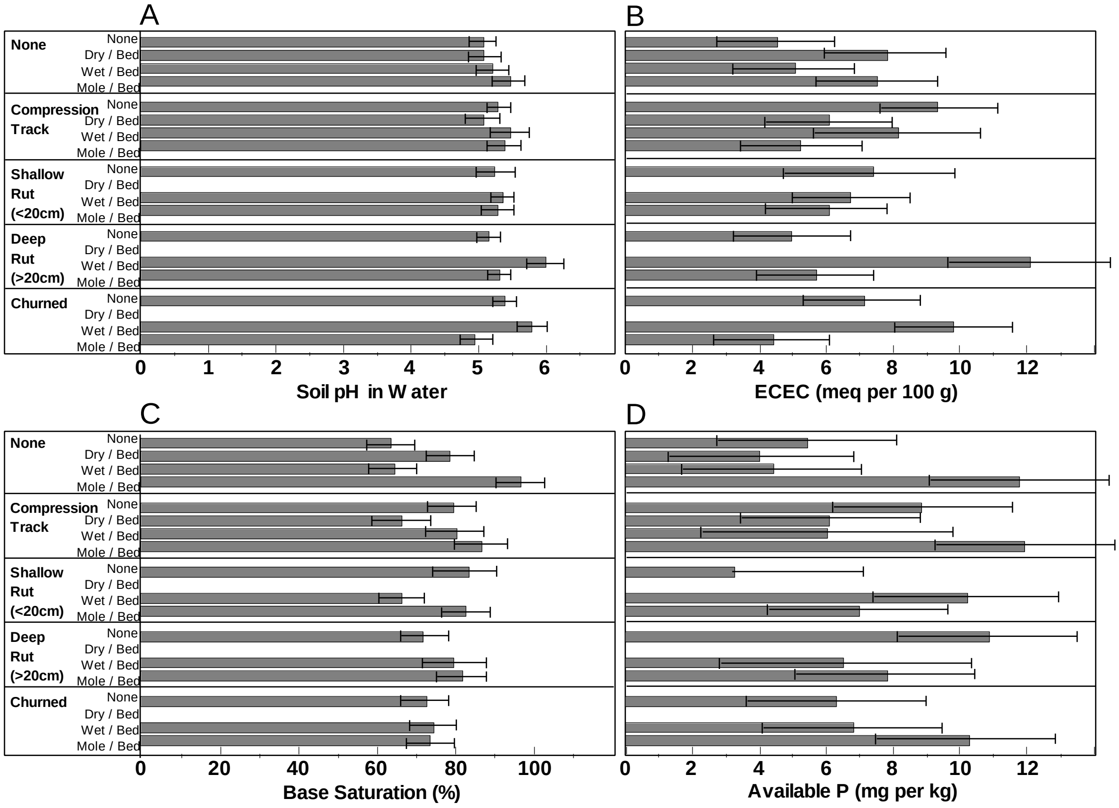


Figure V.6. Site preparation and soil disturbance effects on soil pH (A), ECEC (B), % base saturation (C), and available P (D). Bars represent +/- one standard error of the mean (n = 3).

Even though the statistical analysis showed that the pre-treatment differences had no effect on the post-treatment results, the pre-treatment data may still offer an explanation for the differences observed (Table V.6). All the plots were intensively-surveyed for several important soil parameters prior to harvest. A qualitative examination of these pre-treatment survey data shows some trends that should affect the treatments. The four treatments started at approximately the same level of total carbon and clay in the A horizon prior to harvest, with a slight trend of higher clay and carbon in the dry-harvested / bedded treatment (Table V.6). The most important differences are in the thickness of the surface horizons, with the dry-harvested / bedded treatment having a 16 cm thick A horizon overlying a 2 cm thick E horizon. The other treatments have comparable surface horizon thickness, averaging 15 and 13 cm thick for the A and E horizons, respectively. The bedding plow was equipped with 91.4 cm discs, making it capable of turning soil up into beds from a depth of 40 cm. The mole-plow / bedded treatment had the greatest combined A and E horizon thickness, 32 cm, so the bedding plow would pull clay from the Bt horizon up into the beds for all the bedding treatments. This is evidenced by the increased post-treatment clay content for all bedding treatments (Table V.6). The clay

Table V.6. Summary table of pre-treatment horizon thickness, clay and carbon content, and post-treatment carbon and clay content.

	Pre-Treatment				Post-Treatment	
Treatment	Total Carbon†	Clay	A Thickness‡	E Thickness	Total Carbon	Clay
	----------- % -----------		---------- cm ----------		----------- % -----------	
None	3.75	9	14	11	2.37	12
Dry / Bed	4.17	11	16	2	3.46	16
Wet / Bed	4.19	8	12	12	2.31	12
Mole / Bed	3.59	7	16	16	2.27	10

† Total LECO carbon and percent clay in the A horizon, average of 36 samples per treatment collected along a systematic grid by Burger (1994).

‡ A horizon thickness collected on a 20 by 20 m grid system in each plot by Preston (1996)(n = 240 per treatment).

content also increased for the non-site prepared treatment, as soil churning and rutting mixed clay from the Bt horizon into the surface while harvesting. The total carbon contents in the E and Bt horizons were similar, ranging from 1.25 to 1.76 %. The net effect of mixing the Bt into the surface, and mixing the A and E horizons together as well, is a dilution of the carbon concentration in the surface: note that all of the post-treatment total carbon values are lower than pre-treatment (Table V.6). The explanation for the dry-harvest / bedding treatment having the highest total carbon in the surface, 3.46 %, is most likely that the Bt horizon located only 18 cm below the surface prevented the discs from reaching their maximum depth, thus there was less dilution with this treatment. I realize that some of the decrease may be attributed to accelerated decomposition of organic matter following harvesting and site preparation, but accelerated decomposition probably could not account for such large decreases in total carbon.

Table V.7. Relationship between ECEC and soil pH, organic matter, and clay content. Analysis with multilinear regression.†

Variable	Parameter Estimate	Standardized Estimate	P value
Intercept	0.582	0.000	0.000
Carbon (%)	-0.321	-0.590	0.180
Clay (%)	-5.504	-0.532	0.173
Carbon x soil pH	0.092	0.898	0.043
Clay x soil pH	2.166	1.179	0.005

† Model: ln (ECEC) = -0.582 - 0.321 Carbon - 5.504 Clay + 0.092 (Carbon x soil pH) + 2.166 (Clay x soil pH), R-square = 0.85, N = 160.

The effects of diluting the surface organic matter content and increasing the surface clay content are evident in the ECEC results (Table V.5). A multiple regression analysis showed that ECEC was strongly related to organic matter and clay content, and the interactions between these properties and soil pH (Table V.7), with these variables explaining about 85 % of the variation in ECEC. Multicolinearity caused by the interaction terms makes two of them non-significant; however, retention of these variables in the model increases the R-square from 60 to 85 %, and reduces the mean square error from 0.126 to 0.048, so clearly they are important explanatory variables which should be retained. That ECEC is strongly related to carbon, clay, and soil pH, is well known (e.g., Curtin et al., 1998), showing the importance of a combination of variable charge based on the interactions, and permanent charge based on the singular importance of clay in describing the ECEC. Based on the standardized estimates, carbon and its interaction with soil pH has the strongest effect on ECEC. This effect of carbon and soil pH in combination with the post-treatment clay % results (Table V.6), explains the treatment effects on ECEC shown in Table V.5. The absolute differences in exchangeable Mg and K (Table V.5) are simply a reflection of their relative contributions to the ECEC, which are essentially the same. Interestingly, the ECEC explanation model improved when block was added as a dummy variable (results not shown), probably reflecting differences in clay mineralogy between the blocks.

Based on the ECEC regression model, the pre-harvest ECECs would have been slightly higher than the post-treatment ECECs (Table V.5) because of the higher soil carbon content in the A horizon before harvest. Other studies have documented decreased ECEC following bedding which was also linked with decreased surface organic matter (McKee and Shoulders, 1974). Still others, however, have documented increases in C and N concentrations in surface soils following bedding (Haines et al., 1975; Attiwill et al., 1985), so we cannot generalize the bedding effect on soil chemistry. The effect of bedding on cation exchange should come mainly through its effects on organic matter and clay content, the two variables most-affecting cation exchange capacity along with soil pH (Table V.8). Therefore, if the bedding operation concentrates organic matter from surface horizons, then it will most likely increase ECEC. However, if the operation "dilutes" the organic matter content by incorporating lower organic matter horizons (E), then the opposite will occur. If clay is brought up from the subsurface through deeper tillage operations, then the ECEC should be increased as the clay content of the surface increases. Thus, the bedding effect on soil chemistry is highly site- and method-specific.

It would be beneficial to increase the ECEC of the surface horizon as a management technique for improving the soils' capacity to hold and release base cations.

Table V.8. Site preparation effects on key soil chemical properties, area basis.

	Exchangeable Base Cations			KCl -		Base	Total	Available
Treatment	Ca	Mg	K	Acidity	ECEC	Saturation	Carbon	P
	-----------------------		Kmol$_c$ ha^{-1}	-------------------------		%	Mg ha^{-1}	kg ha^{-1}
None	162.3	34.9 b	3.1	47.8	248.1	81	91.2	26.4 b
Dry / Bed	152.5	55.7 a	3.8	42.9	254.8	83	90.1	15.8 b
Wet / Bed	184.7	29.7 b	2.8	46.1	263.3	82	82.8	22.8 b
Mole / Bed	124.7	32.1 b	3.4	31.7	191.9	83	86.6	38.4 a

Although the site preparation treatments did have effects on concentrations of base cations, ECEC, and total C, these effects were essentially negated when the results were expressed on a per hectare basis (Table V.8). The more extensive surface soil compaction which resulted from harvesting the wet-sites (Preston, 1996), was only partially mitigated by bedding, thus the wet-harvested / bedded and mole-plow / bedded treatment have higher surface soil bulk density than the dry-harvested / bedded treatment. The higher bulk density with the wet-harvested treatments increased the chemical concentrations per unit volume of soil, thus minimizing the concentration effects reported previously (Table V.5), though the trend of lower ECEC with the mole-plow / bedded treatment is still evident (Table V.8). The beneficial effects of increasing bulk density on soil nutrient status are well known (Greacen and Sands, 1980).

Double-acid extractable P increased significantly with the mole-plow / bedding treatment (Table V.8). This increase in available P with mole-plow / bedding may reflect the slightly better aeration conditions with this treatment. Increased soil biological activity with improved aeration (Doluhery et al., 1996) would stimulate decomposition of fresh organic debris and potentially mineralize organic P in the process (Barber, 1995). Large net releases of P have been reported from the early decomposition of forest floor litter in loblolly pine plantations (Polglase et al., 1992).

Though the site preparation treatments did have some effects on the soil chemical environment, these effects were largely explained by differences in the organic matter and clay contents of the surface soil (Table V.6). Therefore, the hypothesis that increased soil aeration from bedding would decrease the soil pH, resulting in a commensurate decrease in ECEC and base saturation, was not supported. The lack of detectable redox-induced changes in soil pH or ECEC with either bedding or soil disturbance is most likely explained by a combination of high Ca concentrations and high base saturation, and the seasonal dynamics of water table and soil temperature.

These soils have high Ca concentrations compared with similar non-limed pine plantation soils in the region with reported exchangeable Ca concentrations of approximately 0.9 to 2.2 $\mathrm{cmol_c\ kg^{-1}}$ (McKee and Shoulders, 1974; Tuttle et al., 1984), and base saturations of less than 30 % (McKee and Shoulders, 1974). The higher exchangeable Ca concentration and base saturation on our sites is a function of the parent material, atmospheric deposition, nutrient cycling, weathering, and minimal leaching. The calcareous marl parent material lying 2 m below the surface provides a rich Ca source on our sites (Ware et al., 1993). The Ca concentration on soil exchange sites in the A horizon has most likely aggraded over time through a combination of Ca inputs of up to 400 $\mathrm{mol_c\ ha^{-1}\ yr^{-1}}$ from atmospheric deposition (Johnson and Lindberg, 1992), mineral weathering, and deep mining by tree roots (deep mining brings base cations up from deeper in the profile, eventually depositing them in the soil through nutrient cycling, which enriches the nutrient status of the surface horizons). Unlike many other southeastern soils and sites which can experience large net losses of Ca via nutrient leaching off-site (Richter and Markewitz, 1996), the nearly-impermeable Bt horizon on our sites prevents, or severely restricts, nutrient leaching, thus allowing the base cations to be maintained at high levels.

The apparent stability of the soil pH, regardless of how soil disturbance and site preparation affect soil aeration, is explained by the high exchangeable Ca and base saturation. Calcium saturation (exch. Ca / ECEC) is strongly related to soil pH (Fig. V.7), following a curvilinear relationship which describes Ca-Al exchange and Al solubility (Reuss et al., 1990). At above 50 % Ca saturation, Ca on exchange sites exchanges with Al in solution, increasing the soil pH. Below 50 % Ca saturation, the reverse reaction occurs, and the soil pH decreases. As the soil pH drops below 5.0 (approx. pH where gibbsite solubility increases) greater amounts of Al go into solution. The extent to which the soil pH will drop depends on the extent to which Ca can exchange with Al and buffer the soil pH. These mechanisms explain the relatively flat soil pH line from 20 to 75 % Ca saturation (Fig. V.7). The ability of Ca and Mg to exchange with Al and H in solution and vice versa, called exchangeable base cation buffering (McBride, 1994), keeps the soil pH, and pH-dependent soil properties (e.g., ECEC, Fe and Al-P solubility), from changing appreciably with the redox reactions. This is supported by McKee (1980) who found that waterlogging soils with high base saturation also had no effects on soil pH. Thus, the inherently-high Ca saturation of our soils makes them very resistant to any changes in the soil chemical environment resulting from soil disturbance.

The seasonal dynamics of soil temperature and water table are the second reason for no apparent redox-induced changes in the soil chemical environment. Recalling that redox is a biologically-mediated process, whereby soil organic matter is oxidized by microorganisms, the *in situ* redox conditions will partly depend on the activity of soil organisms. Because microbial activity has a strong positive relationship with temperature, the highest rates of microbial activity occur during the growing season (Dulohery et al., 1996). Water table depth also has a strong effect on redox conditions, as shown by McKee and Shoulders (1974) regression equation. Coupling microbial activity as driven by soil temperature with water table dynamics, the highest opportunity

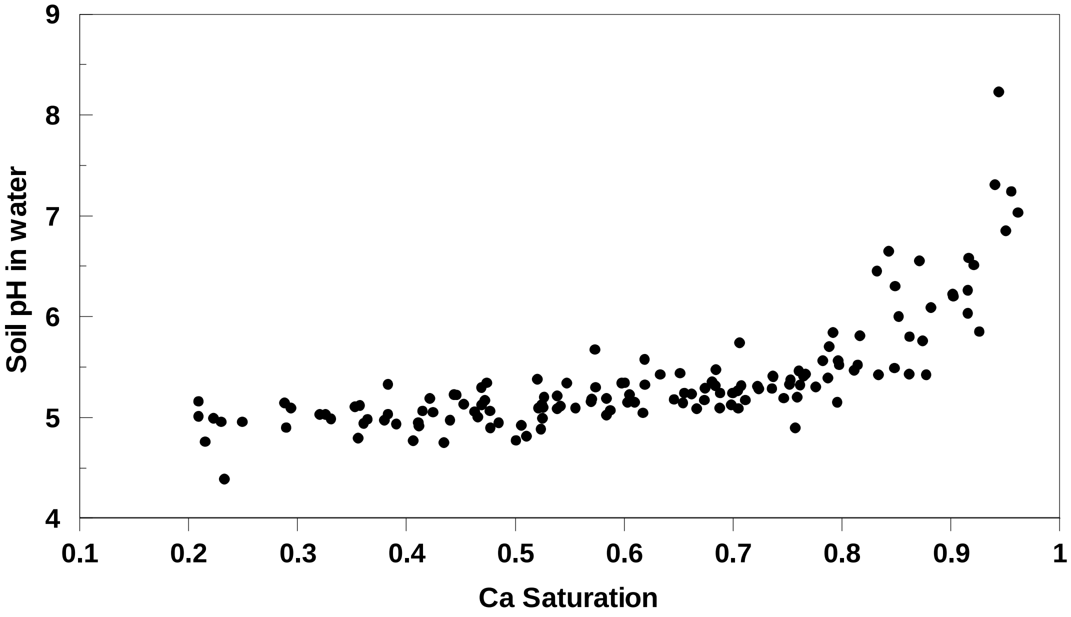


Figure V.7. The relationship between soil pH and Ca saturation.

for reducing conditions should occur when the soil surface is saturated with water during the growing season. Figure V.8 shows the average daily fluctuation in soil temperature on our sites for the study period. The plot is overlain with the redox potential predicted for the same period from daily water table measurements collected at one of the wettest locations on the site (Miwa, 1999). Thus, this plot represents a worst-case-scenario for redox. The 375 mV redox potential below which reducing conditions would occur is superimposed on the plot. Reducing conditions do occur during the growing season (050196 - 090196 and 050197 - 090197) each year, but less than 20 % of the time. Based on the seasonal dynamics of soil temperature and predicted redox potential, the soil is oxidized about 80 % of the time during the most active time of the year. The conclusion from this plot is that an oxidizing environment dominates our sites. Thus, an oxidizing environment combined with exchangeable base cation buffering explains the lack of redox-induced changes in the soil chemical properties. This conclusion is consistent with McKee and Shoulders (1974) who found that while site preparation did have significant effects on water table depth and redox potential, these changes "were not sufficient to cause any pronounced difference in soil chemical properties before or after saturation of part or all of the soil profile".

Nitrogen Mineralization

Harvesting Effects

Using the net nitrification rate for the undisturbed soil at the medium level of organic debris (O horizon plus light slash) as a baseline reference level against which to compare, with a net nitrification rate during the first year following site preparation of 27 kg N per hectare, we see a trend of increasing net nitrification with decreasing surface organic debris, and a slight divergence of net nitrification with disturbance (Fig. V.9A). The same trends are evident with net N mineralization (Fig. V.9B).

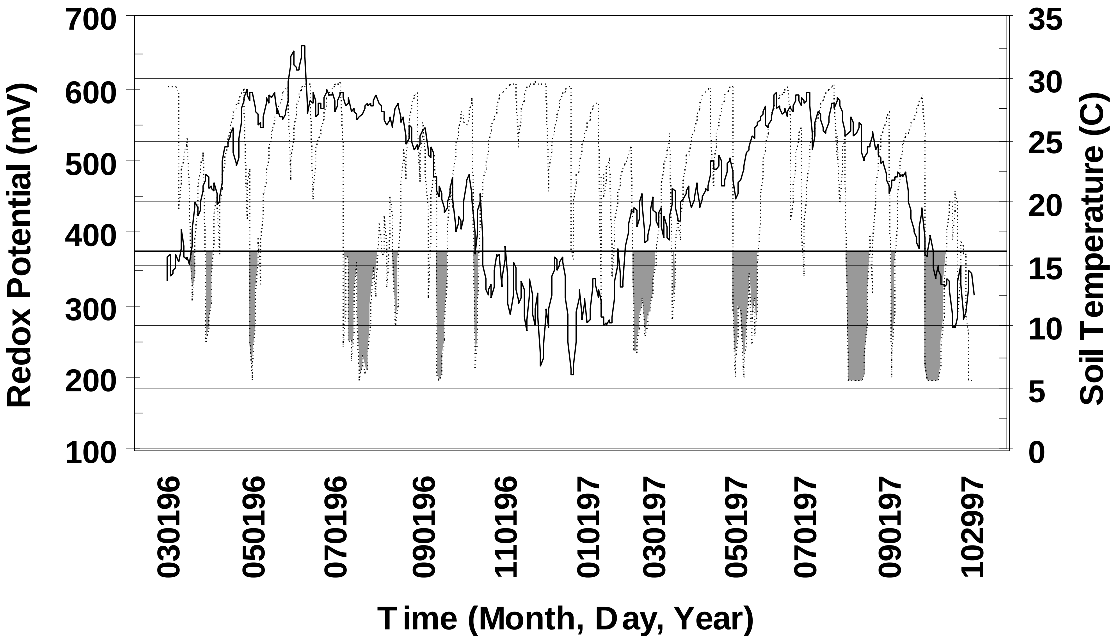


Figure V.8. Daily soil temperature (solid line) and predicted redox potential (dashed line) fluctuations during the measurement period. Soil temperature was recorded at a weather station located on the site. Redox potential was predicted using a regression equation that relates perched water table depth to redox potential (McKee and Shoulders, 1970). Water table depth was measure continuously a several locations within each block (Miwa, 1999).

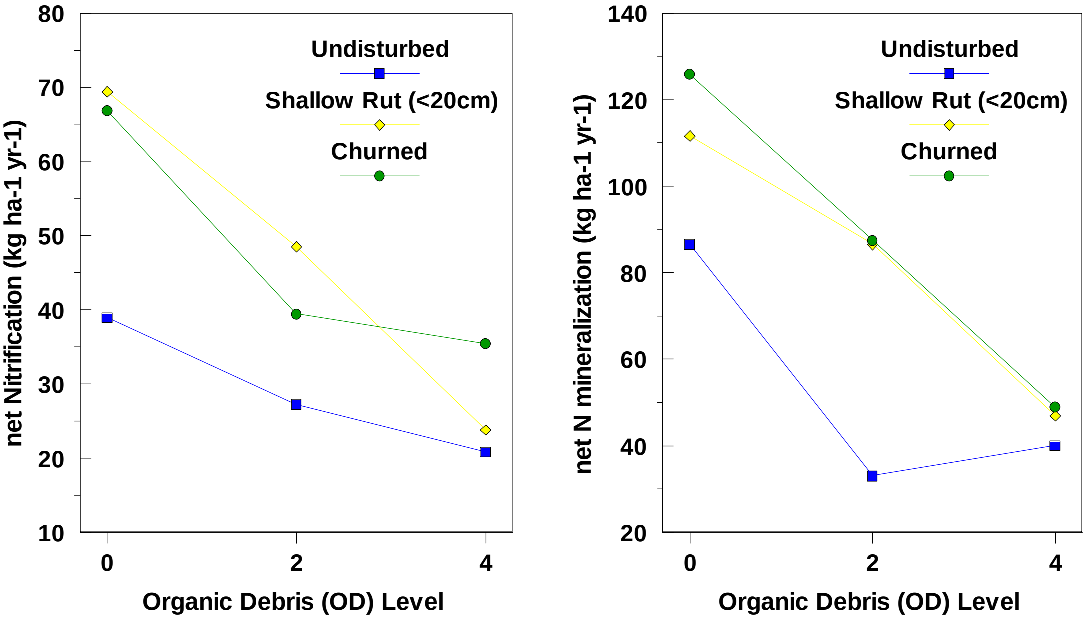


Figure V.9. Surface soil disturbance and organic debris effects on net nitrification (A) and net N mineralization (B).

Table V.9. Summary of significance levels for ANOVAs for soil disturbance and organic debris effects on net nitrification and net N mineralization.

Factor	net Nitrification	net N mineralization
	- - - - - - - - - - - - P value	- - - - - - - - - - - -
Soil Disturbance (3 levels)	0.616	0.212
Organic Debris (3 levels)	0.301	0.228
Interactions	0.700	0.629

However, the data were highly variable and there were no significant effects of soil disturbance, organic debris, or their interaction, on either net nitrification or mineralization (Table V.9).

The lack of significant differences between soil disturbance levels for net nitrification suggests that the nitrifiers were unaffected by disturbance. Nitrifiers are much more sensitive to changes in soil environmental conditions than ammonifiers, requiring well aerated, warm, moist soil with a pH that is neither too high nor too low (Sparling, 1997), therefore net nitrification should be a useful measure of management impacts on the soil biological environment. The ANOVA results (Table V.9), then, may be interpreted as meaning that shallow rutting and soil churning had no harmful effects on the soil biological environment. Also, the high levels of net nitrification relative to net N mineralization support the contention that soil reduction was not a significant factor: in a reducing environment nitrate would be lost via denitrification (McBride, 1994), and inorganic N would build as ammonium (Ponnamperuma, 1984).

The lack of disturbance effects on net N mineralization and nitrification is consistent with the changes in the soil aeration indices observed with disturbance (Table V.2), with shallow ruts and churned soil having aeration levels similar to the undisturbed soil. Unfortunately, I did not measure net N mineralization for the compression track and deep rut soil disturbance levels, which coincidentally were the only disturbance levels which indicated physical soil damage from harvesting (Table V.2). I was not able to establish any simple relationships between any other soil properties and net N mineralization other than the C:N ratio, so I'm not able to predict how compression tracks and deep rutting may have changed net N mineralization. However, based on the soil temperature and probable redox potential dynamics through time (Fig. V.8), and the lack of disturbance effects on any soil chemical properties (Fig. V.5), I hypothesize that compression tracks and deep rutting had no effects on net N mineralization.

The trends of increasing net nitrification and mineralization with decreasing organic debris are partly explained by a weak, negative, correlation between these indices of N availability and the C:N ratio of organic matter (*r* = -0.25; p = 0.015). The average C:N ratio for organic debris levels 0 (none), 2 (light slash + O horizon), and 4 (slash piles) were 18, 22, and 31, respectively. This trend of increasing C:N ratio reflects the age of the organic debris, with fresh logging slash constituting some of organic debris level 2 and most of organic debris level 4. N availability limits microbial oxidation of organic matter at C:N ratios greater than about 25 (Paul and Clark, 1989). In this case, mineral N is utilized by soil organisms while decomposing organic matter, decreasing the net N mineralized.

Site Preparation Effects

The dry-harvest / bedding and mole-plow / bedding treatments resulted in large increases in net N mineralization compared to the non-site prepared undisturbed soil (Fig. V.10). Site preparation of shallow rutted and churned soil had no effects on net N mineralization compared to the non-site prepared treatment. In fact, wet-harvest / bedding had no effects at all on net N mineralization. I expected to see a proportional response to mole-plow / bedding the disturbed soils based on the net nitrification response to mole-plow / bedding the undisturbed soil. That this response did not occur for mole-plow / bedding, and the lack of any response for wet - harvest / bedding, suggests that bedding did not mitigate the soil biological environment for rutted and churned soils. This interpretation is supported by Doluhery et al. (1996), who showed that soil respiration (an index of soil biological activity) of bedded skid trails was lower than that of bedded undisturbed soil. They showed that lower soil respiration under bedded skid trails was related to reduced air-filled porosity, which was limiting gas diffusion. Though our results for air-filled porosity showed that bedding disturbed soils appeared to mitigate disturbance effects on air-filled porosity, there was still a trend of

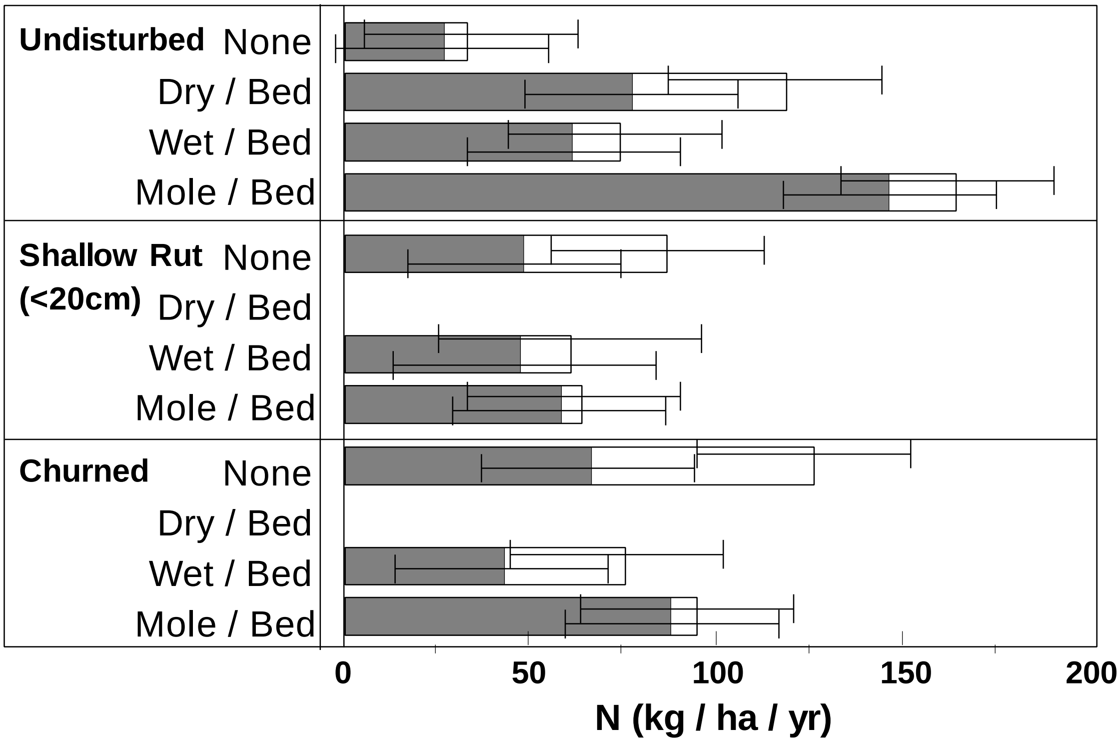


Figure V.10. Site preparation and soil disturbance effects on net nitrification (solid bar) and net N mineralization (open bar). Bars represent +/- one standard error of the mean (n = 3).

lower air-filled porosity for bedded disturbed soils (Fig. V.4C). This trend may help explain the lower net nitrification rates for the bedded disturbed soil.

The overall effects of site preparation on net N mineralization show that wet-harvest / bedding did not increase N availability over the non-site prepared treatment (Table V.10). However, looking at the treatment effects on the actual rates of net N mineralization, they are all mineralizing much more N than is required of a 2 to 3 year old loblolly pine tree, which has an annual N uptake requirement of about 5 kg ha^{-1} (Dougherty, 1996). A study on the South Carolina piedmont found that N accretion in all biomass (herbaceous vegetation, legumes, pines and hardwoods) was 45 kg ha^{-1} two years following a conventional harvest of mature loblolly pine (Cox and Van Lear, 1985). Forty-five kg ha^{-1} over the first two years would be a conservative uptake estimate for our sites given their inherently higher productivity than a typical piedmont site. But it is probable that the net N mineralization rates exceeded the uptake requirements of the vegetation on our sites.

Table V.10. Site preparation treatment effects on net nitrification and mineralization and total N.

Site Preparation Treatment	net Nitrification (kg / ha / yr)	net N mineralization (kg / ha / yr)	Total N (kg / ha)
None	48 b†	82 ab	4444
Dry / Bed	78 ab	119 a	4313
Wet / Bed	51 b	70 b	3964
Mole / Bed	98 a	107 a	4163

† Values within columns followed by different letters are significantly different at alpha = 0.10.

It is difficult to interpret the meaning of higher net N mineralization rates with site preparation in terms of the long-term sustainability of soil nutrition. Though increased net nitrification does equate to higher microbial activity, which I interpreted as an indicator of high soil biological quality, there is a long-standing concern that disturbance-induced accelerated net N mineralization in the first few years following site preparation may result in an N deficit after stand closure when the N demand increases (Burger and Prichett, 1984; Allen et al., 1990). This concern is also extended to subsequent rotations as part of the long-term productivity decline hypothesis (Powers et al., 1990).

If the total quantity of organic N is high relative to the amount mineralized, then the risk of a deficit is probably lower than if the quantity is low. On average, 2.2 % of the total soil N was mineralized during the first year following site preparation. Assuming that all of the vegetation on the site was able to sequester one-half of the net N mineralized, with the remaining mineralized N being lost via denitrification and leaching, then 1.1 % or 46.4 kg ha^{-1} of N was probably lost from the site during this time.

The previous calculation assumes that the net N mineralized came entirely from the soil organic matter pool, when in fact some of the mineralized N could have come on-site via biological N-fixation. The wetland environment is ideal for N-fixation (Ponnamperuma, 1984). In this environment, free living N-fixers and N-fixers in symbiotic association with plants can fix up to 400 kg N ha^{-1} yr^{-1} (Ponnamperuma, 1984) and then release about 50% of it as ammonium (Paul and Clark, 1989, p. 183). We did not measure N-fixation, but our study sites were invaded in the spring of 96 following site preparation by *Sesbania* spp., a nodulated, fast-growing, annual which fixes between 100 and 150 kg N ha^{-1} during the growing season (Rao and Gill, 1993). Based on the probability of high levels of N-fixation for the first couple of years following harvesting, and the relatively small amount of total organic N that was probably lost via denitrification during accelerated N mineralization, N loss is most likely not a concern for these sites.

CONCLUSIONS

Surface soil compaction and deep rutting reduced soil aeration, indicating that reducing conditions probably existed. However, no redox-induced changes in soil chemical properties were observed with soil disturbance or organic debris removal. Bedding mitigated the disturbance effect on soil aeration. Bedding also changed the ECEC. This effect was not attributed to changes in redox, but rather to mixing of clay and organic matter, which had major effects on ECEC. The lack of redox effects on soil chemistry with either soil disturbance or bedding was explained by the inherently high base status and Ca saturation, which buffered any redox-induced changes in soil pH. Also, an analysis of soil temperature and water table dynamics showed that an oxidizing environment existed the majority of the time. Net nitrification and mineralization were not affected by disturbance, indicating that the quality of the soil biological environment was not reduced during wet-site harvesting. Bedding increased net N mineralization overall, but rates were lower for shallow rutted and churned soils. Though soil disturbance negatively impacted the soil physical environment, this did not translate to negative effects on the soil chemical or biological environment, as these sites are very resistant to disturbance-induced changes in soil fertility.

CHAPTER VI. EARLY LOBLOLLY PINE GROWTH RESPONSE TO CHANGES IN THE SOIL ENVIRONMENT

ABSTRACT

Identifying the critical soil and site based determinants of pine productivity is a critical part of developing management practices that facilitate maintenance and enhancement of long-term site productivity. The objectives of this analysis were to (i) determine the relationships between soil and site properties controlling early loblolly pine productivity, and to (ii) determine the effects of site preparation on these relationships. Fifty-four loblolly pine bioassay plots were established across a gradient of soil disturbance, organic debris removal, and site preparation methods. These mini-stands were designed to simulate the commercially-spaced tree growth response to the disturbance / site preparation gradient at stand closure. Several soil and site properties were selected as indicators of the three dominate soil attributes controlling tree productivity: (i) promote root growth, (ii) air / water balance, and (iii) soil fertility, and they were measured at each of the 54 bioassay plots. A multilinear regression analysis showed that soil oxidation depth (air / water balance), the Least Limiting Water Range (LLWR) (promote root growth), and net nitrification (soil fertility) were the most important variables controlling pine productivity. A multiple interaction model with dummy variables included for the site preparation methods showed that oxidation depth interacted strongly with the LLWR and net nitrification, with the model explaining 87 % of the variation in 2-yr-old tree height. The model showed that oxidation depth was the most important soil variable affecting early tree growth, having large positive effects on tree height even for soils with very poor physical quality (low LLWR). There was an optimum oxidation depth above and below which tree growth declined, showing that these sites experienced both aeration and available-water-limiting conditions. The optimum oxidation depth was 30 cm, which corresponded to an average water table depth in winter of 43 cm. High soil fertility (high net nitrification) offset the negative effects of high oxidation depths; trees growing on well-drained, fertile locations with oxidation depths in excess of 30 cm outgrew trees growing on well-drained locations with similar oxidation depths and lower fertility. These

results suggest that tree growth will decline around stand closure on low fertility sites with tall planting beds and / or good internal drainage. This may mean that with taller beds, and with internal drainage treatments like the mole-plow, soil fertility may have to be increased with fertilization if the inherent levels of fertility are low and the goal is to maximize pine production.

INTRODUCTION

The forest industry understands that its economic survival and prosperity is partly tied to its ability to maintain and enhance site productivity. Success in this endeavor depends on understanding how different management practices affect sites, good or bad, and an ability to employ management strategies to correct both inherent problems and those induced by management. Thus, we need to know what site factors control productivity (i.e., critical factors), and how to correct them when they are found deficient either through neglect or inherent limitations.

In the pine plantations of the Lower Coastal Plain, productivity concerns are centered around site hydrology, which plays a major role in regulating both management access and productivity (Morris and Campbell, 1991). A combination of nearly-level topography, poorly-drained soils, and high rainfall results in a perched water table which inundates the soil surface several times each year; when timber is harvested under these wet conditions severe soil disturbances including compaction, displacement, and waterlogging can occur (Hatchell et al., 1970; Gent et al., 1983; Aust et al., 1993; Aust et al., 1995). The potentially-negative impacts of these soil disturbances are at least partially mitigated through a combination of drum chopping, disking and / or bedding (McKee and Shoulders, 1974; Haines et al., 1975; Gent et al., 1983; Morris and Campbell, 1991).

Because it takes a rotation-length study to determine if tree growth was affected by management practices, the benefits or deleterious effects of cultural practices on long-term site productivity are largely unknown (Morris and Miller, 1994). In a synthesis of studies conducted across the globe, Powers et al. (1990) hypothesized that tree productivity declines were most likely explained by soil compaction and removal of organic debris. Based on this hypothesis, the USDA Forest Service began a series of rotation-length studies to investigate the effects of soil disturbance and organic matter removal on long-term site productivity (Powers, 1991).

Soil disturbance and organic matter removal affect long-term site productivity by disrupting the soil air / water balance and / or depleting soil fertility (Burger and Kelting, 1999a). The extent to which site productivity will be degraded, if at all, depends on the soils' ability to either resist or recover from damage. These abilities are soil / site specific, requiring an understanding of the effects of organic matter removal and soil disturbance on soil fertility and air / water balance for all major soil / site types under forest management.

We began a study in 1991 to determine the effects of organic matter removal, soil disturbance, and mitigative practices on the long-term productivity of a site located on the Lower Coastal Plain. Within this study, soil properties hypothesized to be key determinants of tree productivity were monitored across a range of management scenarios. This paper reports the relationships found between the soil properties and early loblolly pine growth, and the effects of site preparation on these relationships.

MATERIALS AND METHODS

Detailed descriptions of the study site, treatment installation, and layout are found in Chapter III.

Soil Productivity Indicators

Soil productivity indicators were chosen based on their known or hypothesized relationship with soil attributes that determine tree growth (Table VI.1). The soil productivity indicators shown are the best variables, in our estimation, to represent the attributes, and were selected for measurement based on: (i) their close relationship to the attribute, (ii) documented relationships with plant growth, and (iii) relative ease of measurement. Detailed descriptions of the field and laboratory measurements are found in Chapters II and IV.

Table VI.1. Soil attributes for the forest soil function of maintaining site productivity, and the soil indicator variables used to measure them. †

Soil Attribute	Soil Indicator Variable	Unit of Measure
<u>1. Promote Root Growth</u>	Bulk Density	g cm^{-3}
	Aeration Porosity	% by volume (cm^3 cm^{-3})
	Least Limiting Water Range (LLWR)	% by volume (cm^3 cm^{-3})
	% of time within the LLWR	%
<u>2. Maintain Air / Water Balance</u>	Surface Soil Depth	cm
	Water Table Depth	cm
	Oxidation Depth	cm
<u>3. Maintain Soil Fertility</u>	Net N mineralization	kg N ha^{-1} yr^{-1}
	Exchangeable Ca	cmol$_+$ kg^{-1}
	Exchangeable Mg	cmol$_+$ kg^{-1}
	Exchangeable K	cmol$_+$ kg^{-1}
	Double-Acid Extractable P	kg ha^{-1}

† Adapted from Burger and Kelting (1999b).

Statistical Analysis

Simple and multilinear regression analyses were used to investigate relationships between the average height of trees growing on the 'top of bed' and 'not in rut' microsites and the soil / site properties collected at those microsites. The primary objective of the multilinear regression analysis was to obtain a model that explained the maximum amount of variation in tree height with the minimum number of soil variables. The first step in the process was to remove variables with high multicolinearity using standard multicolinearity diagnostic techniques (i.e., Variance Inflation Factors and Condition Indices; Montgomery and Peck, 1992). Then the most discriminating variables were determined using the All Possible Regressions procedure (Montgomery and Peck, 1992), wherein a "best" model was selected based on the criteria of maximizing the Adjusted R-square and minimizing the Mean Square Error (MSE). Another selection criterion was to have at least one soil property from each of the three attributes (Table VI.1) of soil productivity represented in the final model. The criteria of having the 3 attributes in the final model allows interpretation of how much, and in what way, each attribute contributes to explaining tree growth. Residual plots were used in each step in the model development process to qualitatively evaluate the validity of the model. Multilinear regression on standardized (normal 0, 1) data was used to ascertain the relative importance of the variables included in the best model. A primary assumption underlying the modeling was that the soil / site properties measured would capture most of the variation in tree growth associated with harvesting disturbance and site preparation. Thus, there should be no additional blocking, disturbance, or site preparation effects on tree growth when these factors are added to the model. This assumption was tested by adding block, disturbance, and site preparation treatment to the final model as dummy variables.

RESULTS AND DISCUSSION

Simple Linear and Quadratic Effects

Individual relationships between the indicators of soil productivity and tree growth were explored with simple linear and quadratic regression models.

There was a weak, negative, relationship between tree height and bulk density (Table VI.2). The bulk density ranged from 0.36 to 1.63 g cm^{-3}. The surface soil texture was relatively uniform across the study site, falling in the sandy loam textural class. In this textural class, bulk density begins to limit tree growth at around 1.5 g cm^{-3} (Pierce et al., 1983), a level which was exceeded in 13 % of the samples. Other studies have reported quadratic effects for bulk density for coarse-textured soils, where higher bulk densities can increase water holding capacity and nutrient diffusion rates (Greacen and Sands, 1980). There was a quadratic effect of aeration porosity on tree growth, with tree growth decreasing on either side of 21 % aeration porosity. The decrease above 21 % aeration porosity probably reflects lower available water from a commensurate reduction in field capacity. The LLWR had a strong, positive, relationship with tree growth, explaining 36 % of the variation in 2-yr-old tree height. This relationship improved when the LLWR was used to calculate the Pin (from Chapter IV), with Pin explaining 57 % of the variation in tree height. The strong relationships between the LLWR, Pin, and tree growth illustrate the importance of maintaining or creating the proper soil physical conditions for root growth. Though this is the first attempt at relating tree growth to the LLWR, others have been successful in relating the LLWR to the growth of agricultural crops (da Silva and Kay, 1996).

The indicators of air / water balance all had positive relationships with 2-yr-old tree height (Table VI.2). Surface soil depth (depth to Bt) has often been found to have a positive effect on tree growth (Carmean, 1975), as surface soil depth is an indicator of

Table VI.2. Linear and quadratic relationships between soil productivity indicators and the height of 2-yr-old loblolly pine trees.† The soil productivity indicators are grouped by attribute.

Soil Productivity Indicator	R^2	Adj. R^2	Linear Effects Direction‡	Linear Effects P-Value	Quadratic Effects Direction	Quadratic Effects P-Value
Promote Root Growth						
Bulk Density	0.12	0.11	–	0.009		n.s.¶
Aeration Porosity	0.16	0.13	+	0.022	–	0.063
LLWR	0.36	0.35	+	0.000		n.s.
Pin LLWR	0.57	0.54	+	0.000		n.s.
Air / Water Balance						
Depth to Bt Horizon	0.11	0.10	+	0.013		n.s.
Water Table Depth	0.54	0.52	+	0.002	–	0.070
Oxidation Depth	0.72	0.71	+	0.000	–	0.020
Soil Fertility						
Net N Mineralization	0.11	0.09	+	0.015		n.s.
Net Nitrification	0.23	0.20	+	0.009	–	0.103
Exch. Ca				n.s.		n.s.
Exch. Mg				n.s.		n.s.
Exch. K				n.s.		n.s.
Extractable P				n.s.		n.s.

† General model was: Tree Height = $b_0 + b_1$ Indicator + b_2 $(\text{Indicator})^2$; n = 54.

‡ Direction is the sign of the slope estimate for the soil productivity indicator.

¶ Not significant if the overall model P-value was greater than 0.10.

effective rooting volume and has been found to correlated well with indicators of soil air / water balance: soil texture, soil color, available water, and soil pH (Rhoton and Lindbo, 1997). The weak relationship between the depth to Bt and tree growth reflects the probability that the quantity of rooting volume is not as important as the quality of the rooting volume on these sites. This interpretation is supported by the strong relationships found between water table depth and tree growth, and oxidation depth and tree growth, with these variables explaining 54 and 72 % of the variation in tree height, respectively. The strong positive linear relationship between these variables and tree height reflects the importance of soil aeration in determining the quality of the rooting environment for tree growth on wet-sites (McKee, 1994). The significant negative quadratic effect shows that there is a maximum aeration depth, which, once exceeded, tree growth decreases from inadequate water availability; thus, water table depth and oxidation depth are good indicators of air / water balance. The quadratic effect was demonstrated in a bedding study which showed that pine growth decreased on high beds from drought conditions (Mann and McGilvery, 1974). Oxidation depth shows the same effect as water table depth because these variables are strongly correlated, as first demonstrated by McKee, 1978. Oxidation depth is a more direct measure of soil aeration than water table depth. This, combined with the integrative nature of the rusty rod measurement, probably explains the stronger relationship between tree growth and oxidation depth.

The only indicators of soil fertility that were related to tree growth were net N mineralization and nitrification (Table VI.2). Both had weak positive relationships with tree height. The positive relationship reflects the obvious importance of N availability, as has been found in many studies (e.g., Nadelhoffer et al., 1985; Birk and Vitousek, 1986; Zak et al., 1989), but the low correlation suggests that soil fertility does not limit tree growth on these sites as much as the quality of the soil physical environment. This statement is supported by the quadratic effect for net nitrification, which indicates that N availability slowly becomes non-limiting.

The higher R-square for net nitrification versus net N mineralization suggests that nitrate-N is the more significant source of N on these sites. Net nitrification constituted from 60 to 90 % of the mineralized N on our sites following site preparation, thus nitrate was the most abundant source of N available for uptake during the first 2 years of growth. Net nitrification was highest during the summer on our sites, as has been found by others (Nadelhoffer et al., 1984; Vitousek and Matson, 1985; Zak and Pregitzer, 1990). Nitrate uptake increases with increasing temperature, surpassing ammonium uptake at around 23 ^{0}C (Barber, 1995; Kudoyarova et al., 1997). The soil temperature on our sites exceeded 23 ^{0}C in May of each year, staying above this temperature until September. The combination of high net nitrification rates during the summer and soil temperatures that favor nitrate adsorption probably explains the stronger correlation for net nitrification over net N mineralization. The stronger relationship for nitrate versus ammonium is supported by Nadelhoffer et al. (1984), who found that nitrate supplied most of the annual N uptake in 8 different temperate forest ecosystems.

No relationships were found between the levels of exchangeable base cations and tree growth. McKee and Shoulders (1974) also found no relationship between exchangeable base cations, P, and tree growth in poorly-drained pine plantations. Their conclusion was that the quality of the physical rooting environment was more important for tree growth than soil chemical properties. Their conclusion, along with the results from this study, illustrates the important role the physical rooting environment plays in soil nutrient availability; i.e., nutrient availability is not only a function of the quantity of nutrients, but also the ability of the roots to access nutrients.

Multilinear Effects

The multilinear regression analysis started with a full model containing all of the variables listed in Table VI.1. This model explained 83 % of the variation in tree height and had an MSE of 588. The residual plot shows that the full model did a poor job describing the relationship between the soil properties and tree growth, showing a strong quadratic effect in the residuals (Fig. VI.1A). The multicolinearity diagnostics identified strong correlations between oxidation depth and water table depth, and between net N mineralization and net nitrification. Through an iterative process of including and removing each of these variables from the full model, net N mineralization and water table depth were found to have weaker explanatory ability and were discarded.

The best model selected based on the criteria described in the Methods was a three-variable model with LLWR, oxidation depth, and net nitrification, representing the 'promote root growth', 'air / water balance', and 'soil fertility' attributes, respectively (Table VI.3). The criterion of having a variable from each attribute in the final model resulted in a weaker model based on a reduced R-square and increased MSE, but the

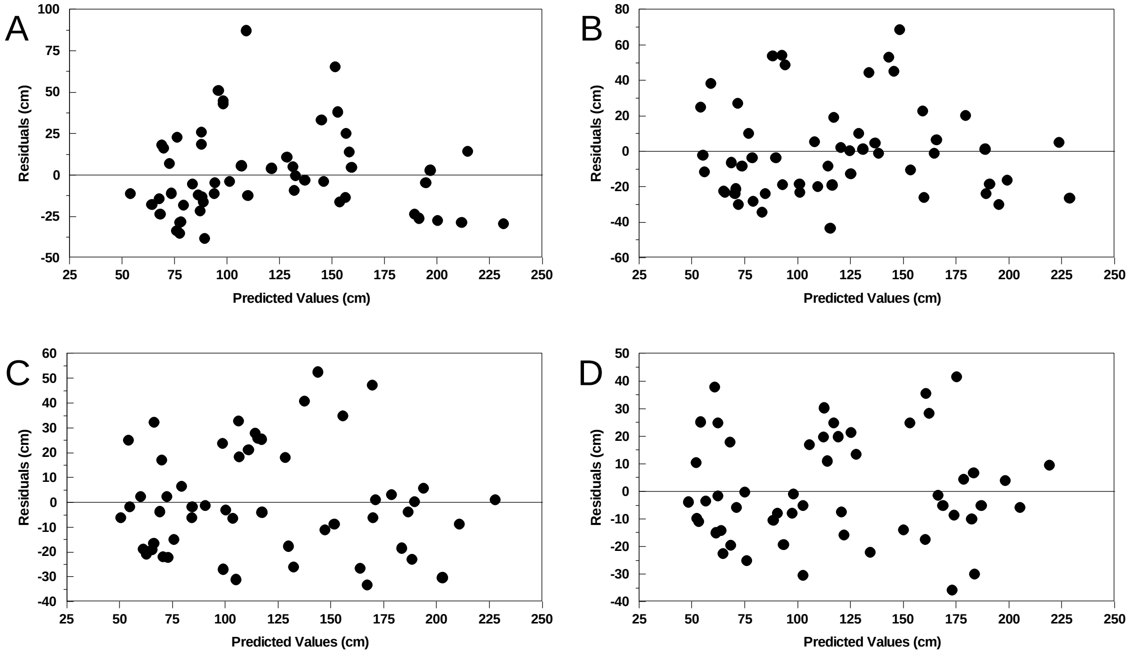


Figure VI.1. Residual plots for the full model (A), the best 3 variable model (B), the best 3 variable model with intercept terms for site preparation (C), and the final model with interactions and intercept terms for site preparation (D).

Table VI.3. Final multilinear regression model for relating 2-yr-old tree height to soil productivity indicators.†

Parameter	Parameter Estimate	Standardized Estimate	P Value
<u>Promote Root Growth</u> LLWR (cm^3 cm^{-3})	127.193	0.302	0.000
<u>Air / Water Balance</u> Oxidation Depth (cm)	3.681	0.629	0.000
<u>Soil Fertility</u> Net Nitrification (kg N ha^{-1} yr^{-1})	0.094	0.123	0.124

† Model: Tree Height (cm) = -19.319 + 127.193 LLWR + 3.681 Oxidation Depth + 0.094 Net Nitrification; *R-Square* = 0.74; *MSE* = 752; *N* = 54.

residual plot shows a more even distribution of residuals and a much reduced quadratic effect (Fig. VI.1B).

Oxidation depth and the LLWR are significantly more important than net nitrification in explaining the variation in tree height (Table VI.3). The standardized estimates show the relative importance of each of the variables in the model, with oxidation depth, LLWR, and net nitrification weighted at 0.6, 0.3, and 0.1, respectively. So, about 90 % of the explanatory power of the model can be attributed to the effects of the soil physical environment on tree growth.

Treatment Effects

Blocking and soil disturbance class had no effect on the model (results not shown), but inclusion of site preparation treatment effect improved the model significantly (Table VI.4). With site preparation treatment included, the model explains 84 % of the variation in tree height, with a large reduction in the MSE. The residual plot also indicates a better model, with a more random distribution of residuals about the predicted line (Fig. VI.1C).

Table VI.4. Site preparation treatment effects on the relationship between 2-yr-old tree height and the soil productivity indicators.†

Parameter	df	Parameter Estimate	T	P > |T|
Treatment Effects				
Intercept (Wet / Flat)	1	-1.729	-0.15	0.879
Intercept Terms‡				
X1 (Dry / Flat)	1	-4.089	-0.43	0.672
X2 (Wet / Bed)	1	23.622	2.11	0.040
X3 (Dry / Bed)	1	34.376	3.01	0.004
X4 (Mole / Bed)	1	46.096	4.26	0.000
LLWR (cm^3 cm^{-3})	1	91.435	2.96	0.005
Oxidation Depth (cm)	1	2.802	5.86	0.000
Net Nitrification (kg N ha^{-1} yr^{-1})	1	0.076	1.47	0.149

† Model: Tree Height = $b_0 + b_1$ X1 + b_2 X2 + b_3 X3 + b_4 X4 + b_5 LLWR + b_6 Oxidation Depth +
b_7 Net Nitrification

where,

Treatment	X1	X2	X3	X4
Wet / Flat	0	0	0	0
Dry / Flat	1	0	0	0
Wet / Bed	0	1	0	0
Dry / Bed	0	0	1	0
Mole / Bed	0	0	0	1

R-Square = 0.84; *MSE* = 533; *N* = 54.

‡ Site preparation treatment effects tested with dummy variables.

The intercept term for the dry-harvest / flat treatment was not significantly different from the wet-harvest / flat (Table VI.4). The site preparation treatments had a significant effect on the intercept, increasing the mean tree height over the non-site prepared treatments by about 24, 34, and 46 cm, for the wet-harvest / bedded, dry-harvest / bedded, and mole-plow / bedded treatments, respectively (Table VI.4). This additive effect of site preparation is shown by the mean values for each of the soil productivity indicators (Table VI.5), with the site preparation treatments increasing the baseline level of the indicators resulting in an additive increase in tree height. The trend in the intercept terms for the site preparation treatments is explained by the net nitrification and LLWR values for each treatment (Table VI.5). which show that mole-plow / bedding had the highest net nitrification followed by dry-harvest / bedding, and dry-harvest / bedding had the highest LLWR. The significantly higher LLWR with dry-harvest / bedding shows that bedding following harvesting under dry conditions results in a soil with better soil physical conditions.

Table VI.5. Site preparation effects on the average values of the soil properties used as indicators of soil productivity.†

	Soil Productivity Indicators		
Site Preparation Treatment	Oxidation Depth (cm)	net Nitrification (kg N ha^{-1} yr^{-1})	LLWR (cm^3 cm^{-3})
None	16 b‡	48 b	0.24 c
Dry / Bed	28 a	78 ab	0.41 a
Wet / Bed	32 a	51 b	0.34 b
Mole / Bed	33 a	98 a	0.32 b

† Treatment effects tested with ANOVAs for an unbalanced nested design.

‡ Values within columns followed by different letters are significantly different at alpha = 0.10.

Interactions Between Soil Properties

The model was further developed by exploring nonlinear effects and interactions between the regressors (Table VI.6). This analysis resulted in an improved final model with a well balanced residual plot (Fig. VI.1D) and significantly reduced MSE. The site preparation treatments and soil productivity indicators explain 87 % of the variation in tree height. Oxidation depth interacts significantly with the LLWR and net nitrification, reflecting the overall importance of soil aeration, as previously shown by the standardized estimates (Table VI.3) and the simple linear effects (Table VI.2). Oxidation depth and net nitrification were also shown to have significant quadratic effects. The interactions between oxidation depth and LLWR, and between net nitrification and oxidation depth were explored visually (Fig. VI.2).

The interactive effects of increasing the LLWR and oxidation depth on tree height were determined while holding fertility constant (Fig. VI.2A). The slight positive slope for tree height versus increasing LLWR at 15 cm of oxidation shows that oxidation depth is controlling tree growth at low aeration. Increasing the oxidation depth to 25 cm increases the slope of the relationship between tree growth and the LLWR, showing a positive interactive effect of aeration and LLWR on tree growth at 25 cm of oxidation depth. However, when the oxidation depth is increased to 35 cm, the slope of the relationship between tree height and LLWR decreases, becoming negative somewhere between 35 and 45 cm of oxidation depth. The gradual transition from a strong positive relationship to a negative relationship shows the gradual change from a soil environment in which aeration is limiting tree growth (low oxidation depth) to a soil environment in which water availability is limiting tree growth (high oxidation depth). The slope change occurs at 30 cm oxidation depth, which corresponds with a 43 cm water table depth. The 43 cm water table depth agrees remarkably well with McKee and Shoulders (1970 and 1974) 45 cm optimum water table depth determined for maximum productivity in 6 to 8 yr-old slash pine (*Pinus elliottii* Engelm. var.elliottii) plantations. The fact that we see the same relationship in 2-yr-old trees suggests that the concept of using bioassay plots to simulate the tree growth response to the soil environment in later years has merit.

The functional relationship between water table depth and productivity has also been observed with sugarcane in Florida, where the optimum water table depth was also around 45 cm, decreasing on either side of this level (Obreza et al., 1998). The 45 cm optimum water table depth is probably not a magic number, but rather the optimum will depend on the upward water flux - water table depth relationship (Obreza et al., 1998). The upward water flux - water table depth relationship depends on soil texture, density, and hydraulic head (Jury et al.,1991). A general relationship would probably be: the higher the % silt + clay fraction, the deeper the optimum water table depth.

The interactive effects of soil fertility and oxidation depth on tree height were examined while holding the LLWR constant (Fig. VI.2B). Soil fertility does not have any substantial effects on tree height until the effects of inadequate aeration are overcome, between 25 and 35 cm of oxidation depth. Even after overcoming the effects of poor aeration, tree growth only increases about 15 cm over the entire range of net nitrification.

Table VI.6. Best regression model for explaining the effects of site preparation and the soil productivity indicators on the height of 2-yr-old loblolly pine trees.†

Parameter	df	Parameter Estimate	T	P > |T|
Treatment Effects				
Intercept (Wet + Dry / Flat)‡	1	33.312	2.24	0.030
Intercept Terms¶				
X1 (Wet / Bed)	1	26.538	2.64	0.011
X2 (Dry / Bed)	1	33.326	3.31	0.002
X3 (Mole / Bed)	1	40.466	4.00	0.000
LLWR	1	-234.347	-2.19	0.034
LLWR x Oxidation Depth	1	24.862	3.87	0.000
Oxidation Depth^2	1	0.047	1.92	0.061
LLWR x Oxidation Depth^2	1	-0.447	-3.69	0.001
Net Nitrification^2	1	-0.001	-1.64	0.109
Oxidation Depth x Net Nitrification	1	0.010	2.11	0.041

† Model: Tree Height = $b_0 + b_1$ X1 + b_2 X2 + b_3 X3 + b_4 LLWR + b_5 LLWR x Oxidation Depth + b_6 Oxidation Depth^2 + b_7 LLWR x Oxidation Depth^2 + b_8 Net Nitrification^2 + b_9 Oxidation Depth x Net Nitrification

where,

Treatment	X1	X2	X3
Wet + Dry / Flat	0	0	0
Wet / Bed	1	0	0
Dry / Bed	0	1	0
Mole / Bed	0	0	1

R-Square = 0.87; *MSE* = 460; *N* = 54.

‡ Wet and dry harvest / flat pooled into one treatment as previous analysis showed they did not have significantly different effects on the intercept (Table 4).

¶ Site preparation treatment effects tested with dummy variables.

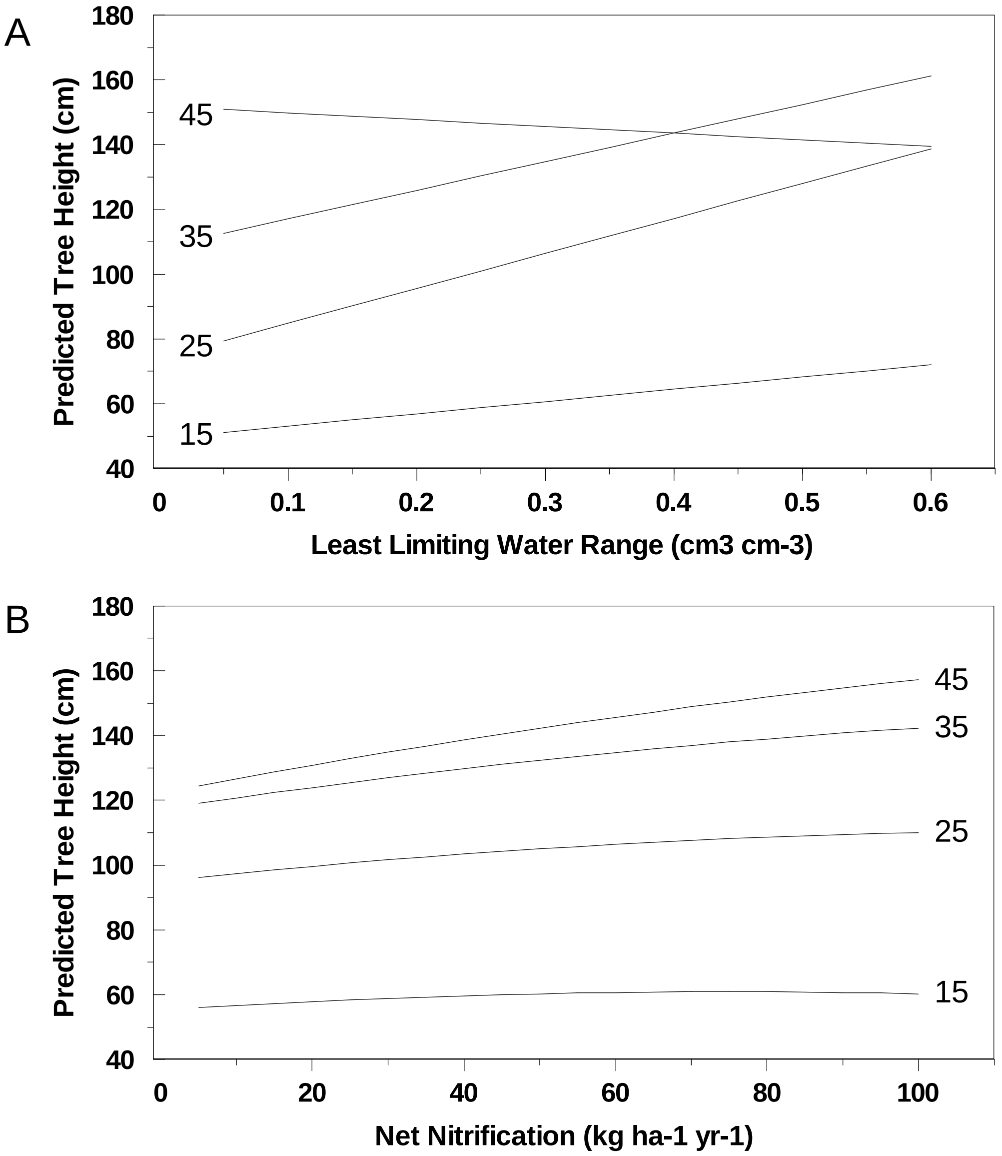


Figure VI.2. The predicted tree growth response to increasing LLWR at constant fertility (60 kg N ha^{-1} yr^{-1}) (A), and to increasing fertility at constant LLWR (0.3 cm^{3} cm^{-3}) (B), at 15, 25, 35, and 45 cm oxidation depth, respectively. Predictions made using equation at bottom of Table VI.6 for the non-site prepared treatments.

The slope of the relationship between net nitrification and tree height is in contrast with the relationship between the LLWR and tree height, wherein the height growth response to improving soil physical conditions (i.e., higher LLWR) is much stronger after the limiting effects of aeration are removed: the height growth response at 25 cm oxidation depth to increasing LLWR is about 40 cm. The importance of oxidation depth on its own is clearly demonstrated by the large increase in tree height with increasing oxidation depth for soils with very poor physical conditions for root growth (LLWR = 0.05 cm^3 cm^{-3}). It is clear from this relationship that even if bedding did not improve the soil physical condition (increase the LLWR), the improved oxidation depth from elevating the soil would still result in increased tree growth.

Though the relationship between the LLWR and oxidation depth indicates a negative interactive effect on tree height at high oxidation depths (Fig. VI.2A), a decrease in tree height at high oxidation depths was not observed. A horizontal asymptote was approached at about 40 cm oxidation depth. The lack of a decrease in tree height at higher oxidation depths is explained by soil fertility. Nitrogen fertilization studies have demonstrated that higher soil fertility decreases carbon allocation belowground for fine-root production (Haynes and Gower, 1995; Albaugh et al., 1998), with a resultant increase in aboveground production (Albaugh et al., 1998). This relationship seems to hold true for droughty and well-watered soils (Albaugh et al., 1998), and explains why N fertilization studies have reported large increases in aboveground production even on dry-sites (Dougherty, 1996).

The effect of soil fertility on carbon allocation may explain the lower intercept term reported for the wet-harvested / bedded treatment (TableVI.4) compared with the other site preparation treatments. The oxidation depths for the wet-harvested / bedded and mole-plow / bedded treatments are both above the 30 cm threshold level were water availability begins to limit tree height (Table VI.5). The higher soil fertility with the mole-plow / bedded treatment enables tree height growth to be maintained, while height growth decreases with the wet-harvested / bedded treatment because of low soil fertility.

CONCLUSIONS

The height of 2-yr-old trees was found to have significant and meaningful relationships with several indicators of soil productivity. The three most important soil properties affecting tree growth at this age were oxidation depth, the LLWR, and net nitrification, in decreasing order of importance. Oxidation depth and the LLWR describe the quality of the soil environment for root growth in terms of air / water balance (oxidation depth) and the soil physical condition (LLWR). The strong interaction between oxidation depth and the LLWR showed that these soils can be aeration or available-water limiting. The critical oxidation depth for minimizing the limiting effects of aeration and available water on tree growth was 30 cm. This finding has important implications for optimizing bed height for maximum productivity, and suggests that the growth of trees planted on tall beds with oxidation depths in excess of 30 cm will decline after stand closure. The extent to which tree growth will be affected by droughty conditions depends largely on soil fertility, with high soil fertility buffering the effects of low available water on tree growth. This may mean that with taller beds and internal drainage treatments like the mole-plow, soil fertility may have to be increased with fertilization if the inherent site fertility is low.

CHAPTER VII. TIMBER HARVESTING AND SITE PREPARATION EFFECTS ON SOIL QUALITY

ABSTRACT

The forest industry needs guidelines to meet their commitments to sustainable forestry as well as practical methods for determining if their goals of increasing productivity are being achieved. From a soils perspective, simple techniques are needed to determine what forestry practices degrade and enhance soil productivity. A technique was developed from the soil quality concepts developed in agriculture that combines indicators of soil productivity in an easily-interpretable Soil Quality Index (SQI). The SQI is an additive model that measures the effects of management practices on three key growth-determining attributes of forest soils: 1., promote root growth; 2, air / water balance; and 3, soil fertility. The SQI model explained 73 % of the variation in aboveground biomass production of 2-yr-old loblolly pine trees, showing that the SQI is a good method for measuring management impacts on soil quality. The SQI was used to measure harvesting disturbance and site preparation effects on soil productivity. The SQI showed that surface soil compaction and deep rutting reduced soil quality, mainly through their effects on 'air / water balance'. This reduction in soil quality translated to a predicted decrease in aboveground biomass production with these disturbances. Site preparation was generally successful in mitigating the effects of these disturbances on soil quality. This result was confirmed by the bioassay which showed that soil disturbance had no effects on aboveground biomass production after site preparation. Mole-plow / bedding consistently had the highest level of soil quality resulting in significantly more aboveground biomass production with this treatment at this early age. Without bedding site preparation, and in the absence of natural recovery processes, soil compaction and / or rutting during harvesting may reduce soil quality and loblolly pine productivity.

INTRODUCTION

Evidence of long-term productivity decline, public perception of forest practices, and an ethical responsibility of land stewardship have spurred several national and international sustainable forestry initiatives (e.g., AF&PA Sustainable Forestry Initiative 1995; Montreal Process, 1995). The most significant initiative at the global level that will affect US forests is the Montreal Process, which culminated in a list of criteria, "a category of conditions by which sustainable forest management may be assessed", and indicators, "a quantitative or qualitative measure of an aspect of the criterion", for sustainable forest management. The agreement culminated from a multi-national discussion on defining the principles of and criteria and indicators for sustainable forest management.

It is generally agreed, from a production oriented perspective, that the definition of sustainable forestry includes providing the forest products needs of today's society without compromising the ability of future generations to meet their own needs. The Montreal Process identified seven criteria for sustainable forest management: five criteria relate to the bio- and ecological aspects of forest management, addressing the importance of biodiversity, ecosystem productivity, forest health, soil and water conservation, and global carbon cycling, and the remaining criteria relate to the long-term maintenance and enhancement of the socioeconomic benefits derived from forests. The criteria defined by the Montreal Process have largely been endorsed by the forestry community; in fact, the AF&PA Sustainable Forestry Initiative is an industry-sponsored version of the same criteria. However, while there is a consensus on criteria, there is a large ongoing discussion on both how to measure each criterion (i.e., the indicators) and how to integrate the measurements in a way that leads to meaningful interpretation.

A common thread shared among the five bio- and ecological criteria of sustainable forest management is soil quality. Soil quality is a concept that has been explored in detail within the agricultural community (e.g., Doran et al., 1994; MacEwan and Carter, 1996), and has been defined as "the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health" (Doran et al., 1998). It should be recognized that the criteria for sustainable forest management are largely embraced by this definition of soil quality. Thus, we argue that sustainable forest management can be assessed in part by measuring soil quality, and soil quality measurement can be used as a tool for developing codes of practice for broad scale implementation to achieve sustainability.

Burger and Kelting (1999b) use the term Sustainable Forestry Practices (SFPs) to encompass those codes of practice necessary for achieving sustainable forestry. To ensure the scientific basis for SFPs, they advocated (i) conducting research on representative sites to identify productivity enhancing / degrading practices, (ii) developing the SFPs based on the research results, and (iii) then implementing the SFPs across similar site types. Sustainable forest management would then be judged based on compliance with the SFPs. A similar research and application approach is being conducted by the USDA Forest Service (Powers, 1991), and others have also concluded that this approach is the most practical way to implement national and international sustainable forestry criteria (Raison and Khanna, 1995).

In addition to the public and private commitments to meeting sustainable forestry criteria, site-specific soil management to improve soil quality is becoming more prevalent and required for more intensive silviculture. Techniques are needed that allow ready assessment of soil conditions under different management scenarios, so managers can develop technologies for improving soil quality under more intensive management. Again, we believe that monitoring soil quality would be an effective tool for assessing soil conditions and determining a course of action to improve site conditions for intensive silviculture. Implementation and extension of the output from the soil quality monitoring program would be the same as in SFP development, and in fact both should be done in concert.

We are conducting long-term sustainability research in loblolly pine (*Pinus taeda* L.) plantations located on the lower coastal plain of the southeastern US, a region where long-term sustainability concerns center around soil / site disturbances resulting from harvesting timber on wet sites. Our concern is that the common wet-site disturbances, soil compaction, displacement, and waterlogging, may have detrimental effects on the key soil properties and processes that partly determine tree productivity in this region. We are also concerned that the commonly employed site mitigation technology, drum chopping and bedding, may not ameliorate soil conditions that may have been damaged during wet-site harvesting.

An operationally-scaled, replicated, field experiment began in 1991 to determine the consequences of soil disturbance on the long-term sustainability of loblolly pine plantations in this region. As part of this study, we implemented a soil quality monitoring system to both evaluate the potential of using soil quality concepts in assessing management impacts on soils, and to use measures of soil quality for evaluating the effects of various management practices on soil productivity for tree growth. The objectives of this manuscript are to (i) introduce the idea of using soil quality concepts in forestry, (ii) develop and evaluate the performance of a SQI model, and (iii) use the SQI model to measure and interpret management impacts on soil productivity for loblolly pine growth.

MEASURING SOIL QUALITY

Historical Context

Burger (1996), in his critical evaluation of using bioassays to assess soil productivity change due to management, demonstrated that tree growth was not always a reliable measure of management-induced productivity change, concluding that management impacts on long-term productivity should be assessed by direct measurements of soil properties and processes. An obvious advantage of measuring soil properties rather than a bioassay, is management attention is focused on the productivity-determining factors that are being manipulated.

Agricultural soil scientists recognized the problems of using bioassays, observing that "soil was the most stable attribute of the land, being unaffected by non-land inputs that influence crop yield" (Huddleston, 1984), and therefore a productivity rating system should be based on soil properties. The first soil productivity index was developed by Storie (1933), using ratings developed for soil texture, soil depth, drainage, alkalinity, and profile morphology. Storie considered soil texture to be a surrogate indicator for the general effects of soil porosity, permeability, and soil tilth on productivity. Numerical ratings ranging from 0 to 100 % were assigned to each soil property using an inductive rating system that was developed based mainly on subjective judgment concerning the effects of each soil property on the overall potential productivity of the soil. Though yield data were not used to develop the rating system, soil productivity ratings were calibrated with yield data as a check on system reliability. Storie's soil productivity index has been used successfully to classify sites into potential yield classes for various agricultural crops.

Based on the work of Kiniry et al. (1983), Pierce et al. (1983) developed a model for determining the effects of soil erosion on soil productivity. The model used soil properties that affect the quantity and quality of available rooting volume: bulk density, available water, and pH. Sufficiency levels were determined for each soil property by horizon, and the product of the sufficiency levels was multiplied by a horizon weighting factor based on an ideal root distribution. The within-horizon values were then summed across all horizons to obtain an overall soil productivity rating. The model has been partially validated with corn-yield data and other productivity indices in southeastern Minnesota. The model represented a significant step because it could not only be used to estimate soil productivity, but it could also be used to determine the effects of agricultural management practices on soil productivity.

The potential of the Pierce et al. (1983) model was recognized by forest soil scientists Gale and Grigal (1988) who adapted the model to estimate forest soil productivity in Minnesota. Their model, called the Productivity Index (PI) model, successfully accounted for 55 to 85 % of measured aboveground biomass in white spruce (*Picea glauca* Voss.), aspen (*Populus tremuloides* Michx.), and jack pine (*Pinus banksiana* Lamb.) stands, indicating the model has tremendous potential for use in estimating soil productivity in managed forests. They also suggested that the PI model could be used to evaluate management impacts on forest productivity, a statement that is supported by the conclusions of Burger (1996).

Soil Quality Models

The PI model approach is the basis of current models being developed for measuring soil quality. Detailed discussions of soil quality model development and monitoring as a component of sustainable forest management are provided by Burger and Kelting (1999a), so the process will only be outlined here.

Soil quality is a concept that has been explored in detail within the agricultural community (e.g., Doran et al., 1994; MacEwan and Carter, 1996), and has been defined as "the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health" (Doran et al., 1998). It should be recognized that soil productivity, which is typically equated with biomass or crop production, is contained within this definition of soil quality.

Soil is a complex living body of myriad interacting chemical, physical, and biological processes which are constantly in flux, heterogeneous in nature, and often elusive to measurement; combine this with a definition of soil quality that recognizes the multiple functions of soil, and we quickly realize that measuring the quality of such a complex system will be difficult at best. Agricultural scientists have dealt with these difficulties by explicitly defining the functions of soil quality, identifying the attributes of each function, and then selecting a minimum data set of indicators to measure each attribute (Doran and Parkin, 1994; Karlen and Stott, 1994; Larson and Pierce, 1994).

The functions of soil quality are what soils "do" for us; in the domesticated forest, the function of greatest interest is maintaining tree productivity. In other situations, other functions may be of greater interest; thus, soil quality, and the relative importance of its components, is defined by the objectives of the "user". Burger and Kelting (1999b) give several examples of soil functions in forest systems.

The attributes are a qualitative list of the key components of a given function. For example, the attributes of the soil quality function 'maintaining tree productivity' are: the soil must (i) promote root growth, (ii) accept, hold, and supply water, (iii) hold, supply, and cycle nutrients, (iv) promote optimum gas exchange, and (v) promote soil biological activity (Larson and Pierce, 1994). Intuitively we know that when these five soil attributes operate at their full potential on a given site, high soil quality and tree productivity should be achieved.

Soil scientists have been studying the five attributes of maintaining productivity for decades, so we have amassed considerable knowledge on various components of each attribute. Agricultural scientists have used this knowledge to select soil properties to use as "indicators" of the attributes for use in soil quality modeling. Indicators should be selected based on their (i) close relationship to the attribute, (ii) low resistance to disturbance, (iii) known relationships with the chosen function, and (iv) relative ease of measurement. To minimize costs and complexity, and thereby maximize the likelihood that the approach will be adopted by practitioners, a minimum data set of indicators should be selected.

Once the minimum data set of indicators is selected, sufficiency curves need to be developed for each indicator. Forest scientists should be familiar with using sufficiency curves, as they are analogous to the critical-level approach used in diagnosing nutrient deficiencies in trees (Lambert, 1984; Olsen and Bell, 1990). Sufficiency curves provide the link between the soil quality attributes and the desired function of the soil quality model. If the function of the soil quality model is to improve plant productivity, then the sufficiency curves must show the relationship between each soil quality attribute and productivity. Sufficiency curves are developed based on the literature, experimentation, and professional expertise.

For integrating the sufficiency values into a single assessment of soil quality, Karlen and Stott (1994) suggested a simple model which is similar in basic principle to the PI model. With their model, soil quality (Q) is determined using an additive model,

$$Q = q_1\,(wt) + q_2\,(wt) + \ldots + q_k\,(wt)\,. \qquad [1]$$

where, the q_k variables represent sufficiency values for different soil quality attributes, and the wt’s are relative weights applied to each attribute. The relative weights represent the importance of each attribute in determining soil quality on a given site, and they are assigned based on the literature, experimentation, and professional expertise.

Burger et al. (1994) used a soil quality model in a study that examined changes in productivity due to mined land reclamation. Their research and that of others showed that the minimum data set of indicator variables for reclaimed mined land were bulk density, pH, P fixation, and excess soluble salts. They developed sufficiency curves for each variable and predicted soil quality for 36 different mine soils. Their soil quality predictions were highly correlated with growth measurements of 10-yr-old white pine (*Pinus strobus* L.) located on the same sites. Using the average productivity of natural white pine stands growing in the same region as a productivity standard, they were able to develop a soil quality standard using the model predictions. Reclaimed sites with predicted soil qualities less than the standard would need to undergo remedial treatments to bring their soil qualities up to the standard.

This work by Burger et al. (1994) demonstrates the use of a soil quality model for assessing productivity of disturbed sites and developing soil quality standards for reclaimed sites. However, soil quality assessments must be soil, site, and objective specific; the same attributes would be measured, but the indicators of each attribute and their respective threshold levels may change with differing soils, sites, and objectives.

SQI - an Integrated Assessment

A additive model was used to combine the five soil attributes of forest productivity to arrive at a Soil Quality Index (SQI) rating that detects management-induced changes in soil quality. The SQI model was,

$$\mathrm{SQI} = \mathrm{PRG}*\mathrm{WT} + \mathrm{AHSW}*\mathrm{WT} + \mathrm{HSCN}*\mathrm{WT} + \mathrm{POGE}*\mathrm{WT} + \mathrm{PBA}*\mathrm{WT} \qquad [2]$$

where, PRG, AHSW, HSCN, POGE, and PBA are the sufficiency's of (i) promoting root growth, (ii) accepting, holding, and supplying water, (iii) holding, supplying, and cycling nutrients, (iv) promoting optimum gas exchange, and (v) promoting biological activity, respectively. Each attribute is multiplied by a weighting factor (WT) which adjusts the relative importance of the attribute for a given site. This model was further reduced to a 3 attribute SQI model,

$$SQI = PRG*WT + AWB*WT + PSF*WT \qquad [3]$$

where, the attributes AHSW and POGE were combined into Air / Water Balance (AWB), and the attributes HSCN and PBA were combined into Promote Soil Fertility (PSF). This modification simplified the model by recognizing that it is the opposing forces of adequate moisture and adequate aeration that define the state of the soil for the sufficiency of air and water. These opposing forces form the parabolic tree growth response to soil water content (McKee, 1994), and can be described by one measurement, AWB. The HSCN and PBA attributes were combined because an easily-measured indicator of PBA was not found, and the attribute 'promote soil fertility' recognizes the combined importance of soil biological and chemical processes in determining soil fertility.

MATERIALS AND METHODS

Detailed descriptions of the study sites, treatment installation and layout, and field and laboratory measurements are provided in Chapter III.

Soil indictor properties were chosen for measurement based on their known or hypothesized potential relationship with the soil attributes for tree growth (Chapter VI, Table VI.1). The soil indicators are our best-current approximations of the attributes, and were selected for measurement based on: (i) their close relationship to the attribute, (ii) documented relationships with plant growth, and (iii) relative ease of measurement. The multilinear regression analysis results from Chapter VI showed that the LLWR, oxidation depth, and net nitrification were the most significant soil indicators of the 'promote root growth', 'air / water balance', and 'soil fertility' attributes of soil quality for tree growth. The LLWR and oxidation depth were selected as soil indicators for the SQI model, but net

N mineralization was selected over net nitrification as the soil indicator for 'promote soil fertility'. Net N mineralization was substituted into the SQI model because more information was available in the literature for developing sufficiency curves for net N mineralization. The standardized parameter estimates for these variables (Chapter VI; Table VI.3) were used as weighting factors, resulting in a final SQI model:

$$SQI = 0.3*PRG + 0.6*AWB + 0.1*PSF. \qquad [1]$$

Development of Sufficiency Curves

Using the field data, sufficiency levels of the indicator variables were determined for each location based on sufficiency curves developed using the scientific literature and the results from Chapter VI. The sufficiency values were substituted into Eq. [1] to obtain point-level SQI estimates.

The LLWR describes the "range of soil water content within which limitations to plant growth associated with water potential, aeration and mechanical resistance to root penetration are minimal" (da Silva and Kay, 1996). A wide LLWR describes a soil with excellent structural quality for root growth, thus plant growth should increase with increasing LLWR. The LLWR was found to have a strong positive correlation with tree growth, explaining 36 % of the variation in tree height (Chapter VI; Table VI.2). In a study of the shoot growth rate of corn, da Silva and Kay (1996) found the LLWR explained 80 % of the variation in growth. In their study, the shoot growth rate reached a horizontal asymptote at an LLWR of 0.3 $cm^3\ cm^{-3}$. The regression analysis of tree height versus LLWR showed no evidence of quadratic effects (Chapter VI; Table VI.2), and a scatter plot indicated only a linear response in tree height from 0.01 to 0.6 $cm^3\ cm^{-3}$ of LLWR (result not shown). Based on the tree growth versus LLWR relationship shown previously, a sufficiency curve for 'promote root growth' was constructed that describes a linear increase in sufficiency from 0 to 0.6 $cm^3\ cm^{-3}$ of LLWR (Fig. VII.1A).

The oxygen supply is quickly depleted in a saturated soil because oxygen diffuses through liquid approximately 10,000 times slower than through air (Bohn et al., 1985). The resultant anaerobic soil conditions reduce root growth (Ouyang and Boersma, 1992) and dramatically alter soil chemical and biological processes (Ponnamperuma, 1972). The dormant season has been defined as a critical period for good soil aeration (McKee and Shoulders, 1974; Terry, 1978), with studies showing that the critical water table depth in winter for maximum productivity is 45 cm (White and Pritchett, 1970; McKee and Shoulder, 1974). This study confirmed the 45 cm critical water table depth, but also found oxidation depth on iron rods to be better correlated with tree growth (Chaper VI; Table VI.2). A 45 cm water table depth corresponds with a 30 cm oxidation depth on our sites. Based on this relationship, a sufficiency curve for 'air / water balance' was constructed for tree growth response to oxidation depth (Fig. VII.1B).

Most natural stands and plantations of Southern pines are N deficient (Dougherty, 1996); therefore, we would expect a general trend of increasing biomass production with increasing N availability. This is supported by Reich et al. (1997) who showed that across a wide climatic and soils gradient, and across both hardwood and softwood species, wood production increased linearly with net N-mineralization, with net N-mineralization explaining 50 % of the variation in wood production. Based on Reich et al. (1997) regression equation combined with an estimated annual aboveground production of 11.5 Mg ha^{-1} yr^{-1} calculated using inventory data collected from the last rotation, it would take about 140 kg N ha^{-1} yr^{-1} to achieve the level of production measured on the previous rotation on our sites. This estimate falls slightly outside the 20

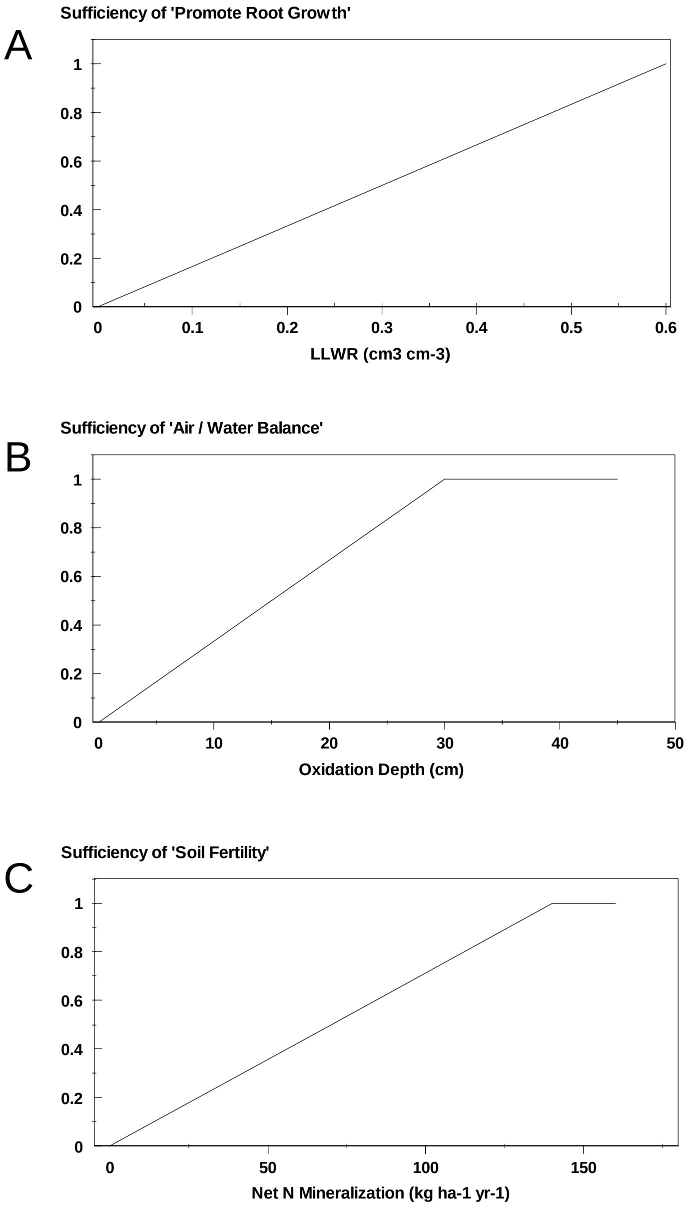


Figure VII.1. Sufficiency curves for determining the sufficiency's of 'promote root growth' (A), 'air / water balance' (B), and 'soil fertility' (C) based on the field measurements of the LLWR, oxidation depth in winter, and net N mineralization.

to 137 kg ha^{-1} yr^{-1} net N-mineralization range Reich et al. (1997) used to develop their equation, so the validity of our estimate is unknown. Wells and Jorgensen (1975) estimated the annual N requirement for a 16-yr-old loblolly pine plantation growing on the Piedmont in North Carolina at 117 kg ha^{-1} yr^{-1}, with about 25 % of this requirement being met through retranslocation. Assuming that atmospheric deposition supplies about 10 kg N ha^{-1} yr^{-1} in the Southeastern US (Allen and Gholz, 1996), then the remaining 78 kg ha^{-1} yr^{-1} must be supplied by the soil, which is about 60 kg ha^{-1} yr^{-1} less than the amount estimated for our sites. Our annual production estimate is about 35 % higher than those reported by Wells and Jorgensen, so our calculated annual N-mineralization requirement may be reasonable given the much higher productivity. Certainly, the work reported by Reich et al. (1997), as well as other studies conducted in forest stands ranging from 29 to greater than 100 years of age (Lennon et al., 1985), has shown that N-mineralization can supply large amounts of N in forest soils. Reich and others regression function was used to develop a sufficiency curve for net N-mineralization (Fig. VII.1C). The curve's asymptote is 140 kg N ha^{-1} yr^{-1} which corresponds with the estimated N required to achieve the same production level measured from the first rotation.

Statistical Analysis

Three different experimental designs were used to examine treatment effects.

The first design was an RCB design consisting of soil disturbance and organic debris classes in 3 blocks. The effects of soil disturbance and organic debris were analyzed as a complete factorial. For this analysis, the data from the wet- and dry-harvested non-site prepared plots were pooled within blocks to obtain 3 replicates (blocks) of 25 treatment combinations for analyzing effects on SQI (n = 75), and 3 replicates of 9 treatment combinations for analyzing effects on aboveground biomass (n = 27). The pooling was justified based on a post harvest analysis which showed no significant differences in soil physical properties within soil disturbance classes in comparing wet versus dry-harvested plots (Preston, 1996).

The second design evaluated the effects of the site preparation treatments on SQI and aboveground biomass using an RCB design with soil disturbance classes nested within site preparation treatments. Disturbance and site preparation effects on soil properties were evaluated at surface organic debris level 2 (O horizon plus light slash). This was an unbalanced design, as only two disturbance classes, undisturbed and compression tracks, occurred in the dry-harvested / bedded treatment (n = 51).

The third design looked at microsite differences in aboveground biomass between the site preparation treatments. Disturbance and site preparation effects were evaluated at four levels of microsite using an RCB for an unbalanced crossed-nested design (n = 84).

Regression analysis was used in addition to ANOVA to examine the relationship between SQI and tree height.

RESULTS AND DISCUSSION

Harvesting Effects on Indicators and SQI

Soil disturbance had significant effects on all three soil quality attributes and the SQI (Table VII.1). Organic debris removal had significant effects on the 'promote root growth' and 'soil fertility' attributes. There was a significant interactive effect of organic debris and soil disturbance on the 'soil fertility' attribute. No other interactions were significant. I expected an interaction between organic debris and soil disturbance for the 'promote root growth' attribute, as the Pin (Chapter IV) was shown to have a strong interaction. The Pin and Pout (da Silva and Kay, 1997b) are more sensitive measures of management impacts on the soil physical environment, which may explain the lack of significant interaction for the LLWR.

Table VII.1. Significance levels from ANOVAs testing the effects of organic debris removal and soil disturbance on the sufficiency's of 'promote root growth', 'air / water balance', and 'soil fertility', and the Soil Quality Index (SQI).†

Factor	Soil Quality Attributes			SQI
	Promote Root Growth	Air / Water Balance	Soil Fertility	
	---------------------------- P values ----------------------------			
Organic Debris (5 levels)	0.001‡	0.578	0.006	0.445
Soil Disturbance (5 levels)	0.000	0.000	0.001	0.000
Interactions	0.229	0.580	0.007	0.468

† SQI = 0.3 (Promote Root Growth) + 0.6 (Air / Water Balance) + 0.1 (Soil Fertility).
‡ P-values computed from ANOVAs for a complete factorial. N = 75.

The main effects of soil disturbance show that compression tracks and deep ruts significantly decreased the sufficiency levels of the 'promote root growth' and 'air / water balance' soil quality attributes (Table VII.2). The effect appears greatest for compression tracks, with a sufficiency level nearly one-half that of the undisturbed soil. The low sufficiency levels for compression tracks and deep ruts are consistent with the findings in Chapters IV and V, which showed that these disturbances negatively-impacted the Pin (Chapter VI) and oxidation depth (Chapter V). Because of the high relative importance of the 'promote root growth' and 'air / water balance' attributes, the SQIs were also significantly lower for compression tracks and deep ruts (Table VII.2).

The trend of SQI with undisturbed < shallow rut < churned (Table VII.2) partly reflects the trend in air / water balance. But the significantly higher SQI with churning versus undisturbed soil is explained by a generally higher level of the 'soil fertility' attribute with churning (Table VII.3). Churning has the higher net N mineralization rates (soil fertility) at the higher levels of organic debris. The effect reverses at the lowest level of organic debris, with the churning having the lowest net N mineralization rate with bare soil. At high organic debris, churning incorporates the organic matter into the soil (much like tillage) which brings the material into contact with soil microorganisms and stimulates microbial activity (Paul and Clark, 1989). The comparatively higher net N mineralization rate with churning may result from a priming effect (Paul and Clark, 1989) of decomposing the low C:N ratio native organic matter along with the high C:N ratio fresh debris.

Table VII.2. Main effects of soil disturbance on the sufficiency's of 'promote root growth' and 'air / water balance', and the Soil Quality Index (SQI).†

	Soil Quality Attributes		
Soil Disturbance	Promote Root Growth	Air / Water Balance	SQI
	------------------- Sufficiency, 0 to 1 -------------------		
None	0.50 a‡	0.61 a	0.55 b
Compression Track	0.28 b	0.33 b	0.33 c
Shallow Rut (<20cm)	0.46 a	0.61 a	0.57 ab
Deep Rut (>20cm)	0.31 b	0.40 b	0.39 c
Churned	0.51 a	0.68 a	0.62 a

† SQI = 0.3 (Promote Root Growth) + 0.6 (Air / Water Balance) + 0.1 (Soil Fertility).
‡ Values within columns followed by different letters are significantly different at alpha = 0.05.

The sufficiency of the 'promote root growth' soil quality attribute increases with the addition of coarse woody debris (light slash and up; Table VII.4). The organic debris is incorporated into the soil, which decreases the bulk density and increases the aeration porosity (Greacen and Sands, 1980), with these changes increasing the LLWR (Chapter IV). Thus, retention and incorporation of logging slash is a good method for improving the quality of the soil physical environment for root growth.

Table VII.3. Simple effects of soil disturbance on the sufficiency of the 'soil fertility' soil quality attribute at each level of organic debris.

Soil Disturbance Level	Organic Debris Level Bare Soil	O Horizon	Light Slash + O Horizon	Heavy Slash + O Horizon	Slash Piles
	------------------------ Sufficiency, 0 to 1 ------------------------				
None	0.67 a†	0.45 b	0.24 c	0.26 c	0.29 b
Compression Track	0.73 a	0.58 ab	0.43 c	0.37 c	0.31 b
Shallow Rut (<20cm)	0.71 a	0.69 a	0.73 ab	0.55 b	0.33 b
Deep Rut (>20cm)	0.57 ab	0.67 ab	0.64 b	0.54 b	0.48 ab
Churned	0.35 b	0.62 ab	0.88 a	0.76 a	0.60 a

† Values within columns followed by different letters are significantly different at alpha = 0.05.

Table VII.4. Main effects of organic debris removal on the sufficiency of the 'promote root growth' soil quality attribute.

Organic Debris Level	Promote Root Growth
	--------- Sufficiency, 0 to 1 ---------
Slash Pile	0.45 a†
Heavy Slash + O Horizon	0.46 a
Light Slash + O Horizon	0.48 a
O Horizon	0.35 b
Bare Soil	0.31 b

† Values followed by different letters are significantly different at alpha = 0.05.

Site Preparation Effects on Indicators and SQI

The site preparation treatments had significant effects on all three soil quality attributes and the SQI (Table VII.5). Soil disturbance did have some effects on the sufficiency's of the 'promote root growth' and 'air / water balance' attributes of soil quality and the SQI.

The sufficiency of the 'soil fertility' attribute of soil quality was not affected by soil disturbance.

The sufficiency's of the soil quality attributes and SQI were plotted by site preparation treatment across the soil disturbance gradient (Fig. VII.2). The gray band on each plot delineates +/- one standard error of the mean for the dry-harvest / bedded treatment response on the undisturbed soil. This treatment serves as a minimum impact baseline against which to compare the other treatment effects. The interpretation is that if the standard error bar for other site preparation / soil disturbance combinations falls within the gray band, then the disturbance effect on the variable has been mitigated.

Table VII.5. Significance levels from ANOVAs testing the effects of soil disturbance and site preparation on the sufficiency's of 'promote root growth', 'air / water balance', and 'soil fertility', and the Soil Quality Index (SQI).†

Factor	Soil Quality Attributes			SQI
	Promote Root Growth	Air / Water Balance	Soil Fertility	
	------------------------------- P values		-------------------------------	
Site Preparation Treatment	0.016‡	0.000	0.023	0.000
Soil Disturbance within Treatment (5 levels)	0.050	0.047	0.514	0.008

† SQI = 0.3 (Promote Root Growth) + 0.6 (Air / Water Balance) + 0.1 (Soil Fertility).
‡ P-values computed from ANOVAs for an unbalanced RCB with soil disturbance nested within site preparation treatment. N = 51. Analysis done at organic debris level 2 (light slash + O horizon).

The dry-harvest / bedding treatment mitigated the effects of compression tracks on the 'promote root growth' attribute (LLWR; Fig. VII.2.A); however, the wet-harvest and mole-plow / bedded treatments did not mitigate the effects of compression tracks on the

LLWR. Also, the wet-harvest / bedded treatment was not successful in mitigating the effects of deep rutting on the LLWR. The mole-plow / bedding treatment was borderline effective. The LLWR is a measure of soil physical quality that is largely driven by bulk density, with LLWR increasing with decreasing bulk density (da Silva and Kay, 1994). Thus, the low sufficiency's indicate that bedding and mole-plow / bedding did not decrease the surface soil bulk density enough to ameliorate the LLWR for the compacted and deeply-rutted soils. Others have also concluded that bedding may not be effective in ameliorating soil physical conditions on trafficked soils (Gent et al., 1983).

All of the site preparation treatments were successful in mitigating the effects of compression tracks and deep rutting on the sufficiency of 'air / water balance' (Fig. VII.2B). However, the trends of lower sufficiency's with compression tracks and deep ruts are still evident even after site preparation. The sufficiency's range from 0.7 to 1.0 after bedding, showing that the 'air / water balance' attribute of soil quality is nearing its maximum with site preparation, but there is still some opportunity for improvement.

The variation in the sufficiency of 'soil fertility' was too high to detect any significant soil disturbance effects (Fig. VII.2C). But, the sufficiency baseline shows that 'soil fertility' was not mitigated for the wet-harvest / bedded treatment for compression tracks, and shallow and deep ruts. This effect may be explained by inhibited soil microbial activity for bedded / disturbed soils, as was reported by Doluhery et al. (1996). They linked lower activity with decreased air-filled porosity. There was a trend of lower air-filled porosity for bedded disturbed soils (Chapter V; Fig. V.4C), which may explain the lower sufficiency of 'soil fertility' with wet-harvest / bedding the compacted and rutted soils. The 'soil fertility' sufficiency's with wet-harvest / bedding also follow the low sufficiency's for 'promote root growth' (Fig. VII.2.A), which may be thought of as a surrogate for air-filled porosity, to some extent.

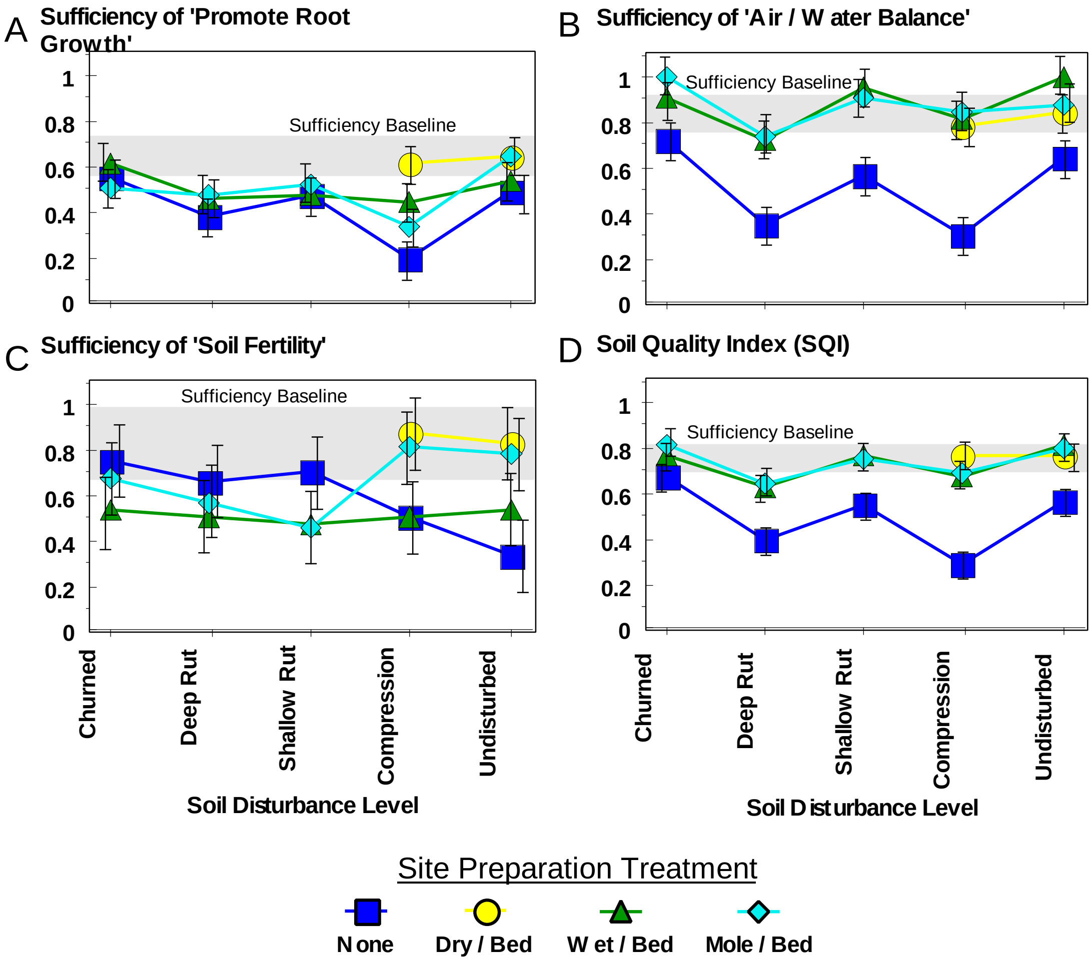


Figure VII.2. Site preparation effects on the sufficiency's of 'promote root growth' (A), 'air / water balance' (B), 'soil fertility' (C), and the SQI (D), across the soil disturbance gradient. Bars are +/- one standard error of the mean (n = 3). SQI = 0.3(LLWR) + 0.6(Oxidation Depth) + 0.1(N mineralization).

Because of the high relative weight assigned to the 'air / water balance' soil quality attribute in the soil quality index model, most of the sufficiency's for the SQI were mitigated by site preparation (Fig. VII.2.D). The exception is the sufficiency of SQI for the wet-harvest / bedded treatment for deep ruts, which is just under the baseline. The combination of low sufficiency's for 'promote root growth' and 'soil fertility' resulted in the low SQI. This result indicates that extensive deep rutting should be avoided on these sites, as bedding does not mitigate the damage to soil quality caused by deep rutting.

Table VII.6. Site preparation treatment effects on the sufficiency's of 'promote root growth', 'air / water balance', and 'soil fertility', and the Soil Quality Index (SQI).†

	Soil Quality Attributes			
Site Preparation Treatment	Promote Root Growth	Air / Water Balance	Soil Fertility	SQI
	----------------------------- Sufficiency, 0 to 1 -----------------------------			
None	0.42 c‡	0.52 b	0.59 b	0.49 b
Dry / Bed	0.63 a	0.81 a	0.85 a	0.76 a
Wet / Bed	0.51 b	0.87 a	0.51 b	0.73 a
Mole / Bed	0.50 bc	0.88 a	0.66 ab	0.74 a

† SQI = 0.3 (Promote Root Growth) + 0.6 (Air / Water Balance) + 0.1 (Soil Fertility).
‡ Values within columns followed by different letters are significantly different at alpha = 0.05. Analysis done at organic debris level 2 (light slash + O horizon).

The overall site preparation treatment effects on the attributes of soil quality and the SQI demonstrate the overriding importance of the 'air / water balance' attribute (Table VII.6). The dry-harvest / bedding treatment resulted in the highest sufficiency's for the 'promote root growth' and 'soil fertility' attributes, but there was no significant difference between the SQIs for the bedding treatments. The slightly higher sufficiency's of 'air /

water balance' for the wet-harvest and mole-plow / bedding treatments were enough to offset the lower sufficiency's for the other two attributes, resulting in SQIs of 0.76, 0.73, and 0.74 for the dry-harvest / bedded, wet-harvest / bedded, and mole-plow / bedded treatments, respectively.

Harvesting and Site Preparation Effects on Bioassay Response

The SQI is a measure of the sufficiency of the soil environment for tree growth that is based on generalized relationships between soil quality attributes and tree growth, but the real test of soil disturbance, organic debris removal, and site preparation effects on the soil environment is a direct measurement of biomass production.

Table VII.7. Significance levels from ANOVA for testing the effects of soil disturbance and organic debris removal on total aboveground biomass.†

Source	Aboveground Biomass
	--------------- P - value ------------
Organic Debris (3 levels)	0.677‡
Soil Disturbance (3 levels)	0.021
Interactions	0.464

† Aboveground biomass computed using regression equations that predicted oven-dried foliage + stem weight as a function of groundline diameter^2 times total height.

‡ P-values computed from ANOVA for an RCB complete factorial design. N = 21.

Aboveground (foliage + stem) biomass production was measured at 3 levels of organic debris (slash piles, light slash + O horizon, and bare soil) and 3 levels of soil disturbance (none, shallow ruts, and churned) on the non-site prepared plots. Organic debris had no effect on biomass production, and there were no interactive effects of organic debris and soil disturbance on above ground biomass (Table VII.7). Soil disturbance did have a significant effect on aboveground biomass production.

The data for the non-site prepared plots was combined with the biomass measurements from the site prepared plots to examine the overall treatment and soil disturbance effects on aboveground biomass production (Table VII.8). Site preparation doubled the aboveground biomass production on the wet-harvest / bedded treatment (1.29 kg m^{-2}), tripled aboveground biomass production on the mole-plow / bedded treatment (1.57 kg m^{-2}), and dry-harvest / bedding response was intermediate. The SQIs for the dry-harvest, wet-harvest, and mole-plow / bedded treatments were 0.76, 0.73, and 0.74, respectively, which does not correspond to the trend measured in aboveground biomass. The trend is probably explained by the higher sufficiency's of 'soil fertility' for the dry-harvest and mole-plow / bedded treatments (Table VII.6). As was discussed previously in Chapter VI, higher fertility has been shown to decrease carbon allocation belowground with a commensurate increase in aboveground production (Albaugh et al., 1998).

All three site preparation treatments improved aboveground biomass production on the undisturbed and shallow rutted soil (Table VII.8). The mole-plow / bedding treatment also improved aboveground biomass production on the churned soil. The biomass response to the mole-plow / bedding treatment, along with the SQIs for this treatment (Fig. VII.2D), show that the mole-plow / bedding treatment mitigated the effects of soil disturbance on soil quality. The biomass response to the mole-plow / bedding treatment also shows that this treatment improved soil quality over the dry-harvest / bedding baseline.

The wet-harvest / bedding treatment did not improve aboveground biomass production over the non-site prepared treatment for the churned soil (Table VII.8); however, looking within the non-site prepared treatment, the churned soil had significantly greater aboveground biomass production than the undisturbed and shallow rutted soils. So, the lack of a wet-harvesting / bedding effect on a churned soil which has all ready been improved is probably not cause for concern. This combined with no significant differences between the dry- and wet-harvest / bedding treatment effects on aboveground biomass production suggest that wet-harvest / bedding improved soil quality at these 3 soil disturbance levels. The concern with wet-harvest / bedding is for deeply rutted soils which had a significantly lower SQI than the sufficiency baseline set by dry-harvest / bedded soil (Fig. VII.2D). Lower aboveground biomass is expected for these soils at this time in the rotation.

Table VII.8. Soil disturbance and site preparation effects on aboveground biomass.†

		Soil Disturbance		
Site Preparation Treatment	Combined	Undisturbed	Shallow Rut (<20cm)	Churned
	-------	-------	kg m^{-2}	-------
None	0.49 c‡	0.47 bB¶	0.21 bB	0.78 bA
Dry / Bed	1.29 ab	1.29 a	--	--
Wet / Bed	1.09 b	1.03 a	1.03 a	0.91 ab
Mole / Bed	1.57 a	1.78 a	1.78 a	1.59 a

† Aboveground biomass computed using regression equations that predicted oven-dried foliage + stem weight as a function of groundline $diameter^2$ times total height.

‡ Values within a column followed by different *lower case* letters are significantly different at alpha = 0.05. ANOVA for an unbalanced RCB with soil disturbance nested within site preparation treatment. N = 30.

¶ Values within a row followed by different *upper case* letters are significantly different at alpha = 0.05. ANOVA for an unbalanced RCB with soil disturbance nested within site preparation treatment. N = 30.

Given the naturally high variation in field studies, and hence the possibilities of making Type II errors, I relaxed the P-value for the aboveground biomass response to shallow rutting which had a mean value 0.21 kg m^{-2} (Table VII.8). Shallow rutting significantly reduced aboveground biomass production at an alpha level of 0.109. Unfortunately, there were no bioassay plots located on the compression tracks and deeply rutted disturbance classes.

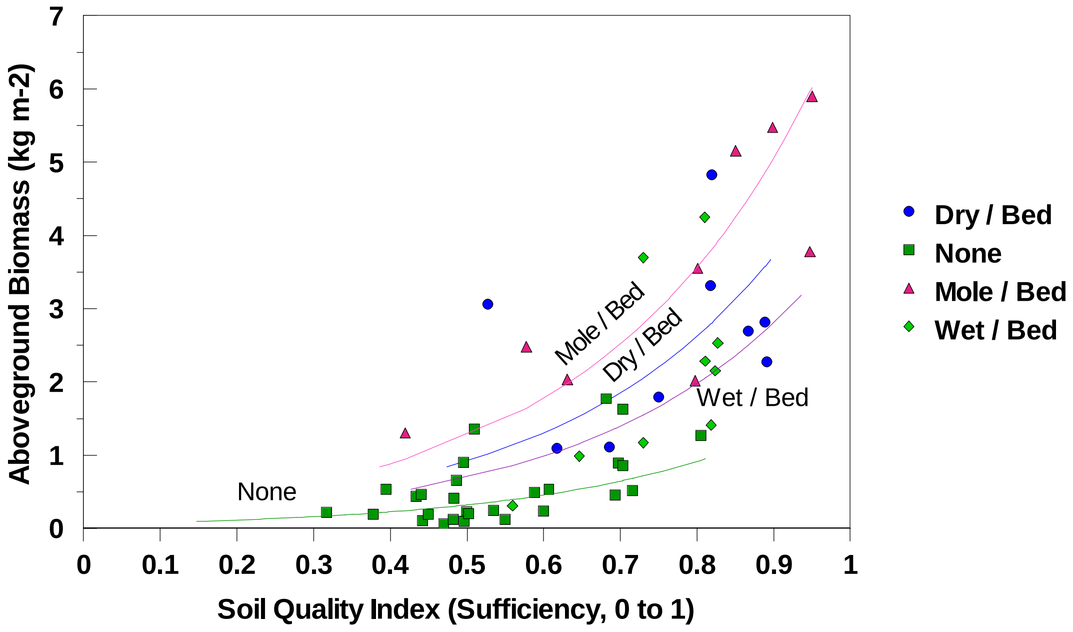
Aboveground biomass had a strong, positive, relationship with SQI (Fig. VII.3). This analysis shows that the SQI, which was derived from a combination of weighted soil quality attributes based on their statistically-determined relative importance to tree growth, and sufficiency curves obtained from the literature and this study (Chapter VI), is a useful measure of soil quality for tree growth. Because aboveground biomass was not measured for compression tracks and deep ruts, I used the relationships in Fig. VII.3 to predict aboveground biomass production across all disturbance levels (Table VII.9). The 90 % confidence intervals show that compression tracks and deep rutting are predicted to significantly reduced aboveground biomass production.

It is important to consider that the bioassay plots were designed to simulate the soil environmental stresses a loblolly pine tree would experience at around stand closure. The fact that detrimental effects on aboveground biomass production were observed for shallow rutting and predicted for compression tracks and deep rutting would then suggest that we may see detrimental effects of soil disturbance on tree growth in the future. This interpretation assumes that soil quality will not change through time, when in fact it will most likely improve beyond its current state through natural recovery processes such as

Table VII.9. Predicted soil disturbance effects on aboveground biomass production using SQI equations in Fig. VII.3.

Soil Disturbance Class	Predicted Aboveground Biomass (kg m^{-2})	90 % Confidence Intervals
Undisturbed Soil	0.40	0.34 - 0.51
Compression Tracks	0.18	0.15 - 0.25
Shallow Ruts	0.26†	0.22 - 0.32
Deep Ruts	0.15†	0.13 - 0.18
Churned	0.54	0.40 - 0.74

† Predicted values adjusted to account for % of bioassay plot in ruts where survival = 0.



Treatment	Model
None	log (Biomass) = -2.89 + 3.495 (SQI)
Wet / Bed	log (Biomass) = -2.11 + 3.495 (SQI)
Dry / Bed	log (Biomass) = -1.83 + 3.495 (SQI)
Mole / Bed	log (Biomass) = -1.53 + 3.495 (SQI)

R - Square = 0.73; P = 0.0001; N = 54

Figure VII.3. The relationship between 2-yr-old loblolly pine aboveground biomass and the SQI.

shrink / swell and aggregation by root exploitation (Fanning and Fanning, 1989). Thus, the lower aboveground biomass responses reported for some treatments in the bioassay plots is a "worst-case-scenario" in my opinion, leading me to conclude that these disturbances probably will not have any long-term negative effects on soil quality and / or site productivity. Also, whether or not the mole-plow / bedding treatment will continue to outperform the other site preparation treatments will partly depend on natural recovery and improvements in soil quality over time. I hypothesize that all of the site preparation treatments will slowly converge to a common level of productivity, as the trees' influence on water table dynamics increases over time and net N mineralization decreases to a common level driven by more homogenous soil temperature dynamics after stand closure.

A final interpretation of the aboveground biomass response to soil disturbance and site preparation was to examine microsite differences in productivity within the bedded plots. The bioassay plots on the bedded sites were divided into four microsites: (i) top of bed, (ii) side of bed, (iii) furrow, and (iv) interbed. The reason for examining the data this way was that the ameliorative effects of bedding on soil physical properties decrease moving down the side of the bed, with the soil between the beds being largely unaffected by the bedding treatment (Gent et al., 1983). Therefore, if soil disturbance or the site preparation treatment had a negative effect on soil quality for tree growth then the effect should be seen in the furrow and interbed areas.

Microsite had a significant effect on aboveground biomass production (Table VII.10). But there was no soil disturbance effect, and aboveground biomass production was similar within microsites across the site preparation treatments (Table VII.11). Thus, this more in depth analysis of tree growth response to soil disturbance indicates further that disturbance had no negative effects on soil quality for the shallow rutted and churned soils.

Table VII.10. Significance levels from ANOVA testing the aboveground biomass response to site preparation and soil disturbance across the bed microsites.†

Source	Aboveground Biomass
	----------- P value -----------
Site Preparation Treatment (3 levels)	0.048‡
Soil Disturbance within Treatment (3 levels)	0.887
Bed Microsite¶ (4 levels)	0.000
Treatment x Microsite Interactions	0.168

† Aboveground biomass computed using regression equations that predicted oven-dried foliage + stem weight as a function of groundline diameter^2 times total height.

‡ P-values computed from ANOVA for an unbalanced RCB for a crossed-nested design. N = 84.

¶ Bedded plots divided into four microsites: (i) top, (ii) side, (iii) furrow, and (iv) interbed.

The treatment x microsite interaction was not significant (Table VII.10). I had hypothesized that an interaction would exist if the extra pass over the site with the mole-plow / bedding treatment caused some additional compaction. The consistently higher productivity with the mole-plow / bedding treatment is underscored by the large increase in aboveground biomass production on the top of the bed compared with the other site preparation treatments (Table VII.11). The mole-plow / bedding treatment produced 1.5 kg m^{-2} more aboveground biomass on top of the bed than the wet-harvest / bedding treatment. This difference magnifies to a 14.3 Mg ha^{-1} difference in aboveground production. With a stem to biomass ratio of 0.64 (computed from the biomass data), and a specific gravity of 0.48 g cm^{-3} (Shultz, 1997), this equates to an increase of about 19 m^3 ha^{-1} of stem biomass. The mole-plow / bedding treatment produced about 14 m^3 ha^{-1} more stem biomass than the dry-harvest / bedding treatment. These large increases in productivity highlight the beneficial effect the mole-plow / bedding treatment has on site productivity for loblolly pine at this early age.

Table VII.11. Site preparation effects on aboveground biomass across bed microsites.†

	Bed Microsite			
Site Preparation Treatment	Top	Side	Furrow	Interbed
	---------------------------- kg m^{-2} ---------------------------			
Dry / Bed	2.48 bA¶	1.27 B	0.26 C	0.97 C
Wet / Bed	2.09 bA	1.16 B	0.15 C	0.20 C
Mole / Bed	3.52 aA	1.59 B	0.16 C	0.30 C

† Aboveground biomass computed using regression equations that predicted oven-dried foliage + stem weight as a function of groundline $diameter^2$ times total height.

‡ Values within columns followed by different *lower case* letters are significantly different at alpha = 0.05.

¶ Values within rows followed by different *upper case* letters are significantly different at alpha = 0.05.

Spatial Extrapolation of SQI

The SQI response to soil disturbance showed that compression tracks and deep rutting decreased the Soil Quality Index. However, this assessment was made on a point-level basis. To understand the significance of changes in soil quality at the stand-level, the SQI needs to be extrapolated across each plot to account for the percent area within each soil disturbance and organic debris class. Stand-level SQIs were calculated for each treatment using the 20 by 20 m soil disturbance and organic debris maps created by Preston (1996). The LLWR and net N mineralization values were extrapolated to the same levels of organic debris and soil disturbance within each plot. Oxidation depth was predicted spatially based on plot-specific regression equations that predicted oxidation depth as a function of the average water table depth during the winter, with adjustments for disturbance effects with dummy variables (model R^2's ranged from 0.75 to 0.95). The average water table depth during the winter was calculated for each point on the 20 by 20 m grid using monthly water table data collected by Miwa (1999).

The spatially-extrapolated SQIs are shown by block and plot (Fig. VII.4a-c). The 20 by 20 m grids cells are coded with gray-scale which indicates the predicted SQI for each location. The site preparation effects on SQI are readily apparent from these plots, with the site-prepared plots showing overall higher SQIs than the non-site prepared plots. The SQIs are uniformly low within the non-site prepared plots, while there is considerable spatial variation in SQI within the site prepared plots. With large areas of low soil quality still occurring within the site prepared plots.

The relatively uniform distribution of SQIs across the wet- and dry-harvested plots is probably due to the overwhelming effect site hydrology has on water table dynamics and air / water balance. Preston (1996) showed that water table depth in winter was not affected by soil disturbance, with the exception of churning which had a lower water table depth. When the transpiration pump is basically shut off during the dormant season, the water table rises across the watershed. Since the disturbed area is an insignificant percentage of the watershed, the dormant season hydrology of the watershed overwhelms the disturbance effect on water table depth. So the dormant season water table is uniformly high across both the wet- and dry-harvested / non-site prepared treatments, with some variation due to changes in elevation.

Spatial variation in elevation within the site prepared treatments accounts for a significant percentage of the observed variation in SQI within the site-prepared plots. Elevation, which is a surrogate for water table depth (and air / water balance), explained from 30 to 70 % of the variation in SQI within the site prepared plots (Kelting et al., 1999a). A 4 cm difference in elevation translates to roughly a 0.1 change in the Soil Quality Index; thus, a large part of the within treatment variation in SQI seen on the

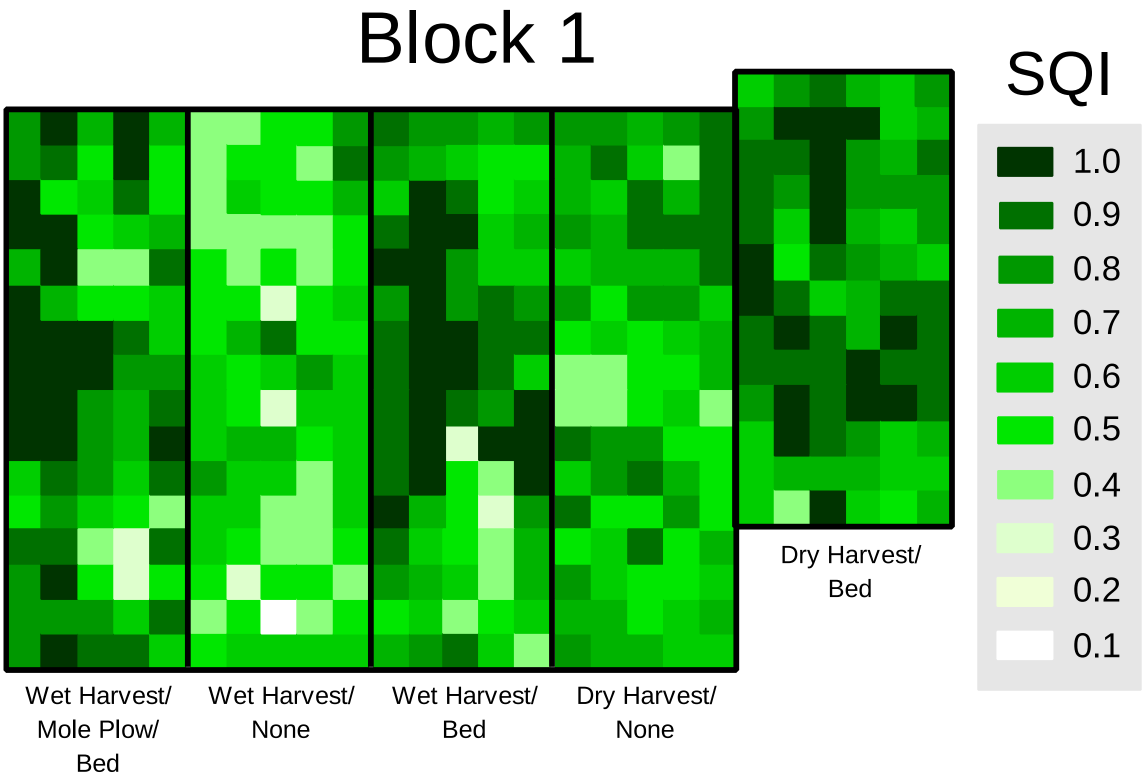


Figure VII.4a. Spatial extrapolations of SQI across the study design for Block One.

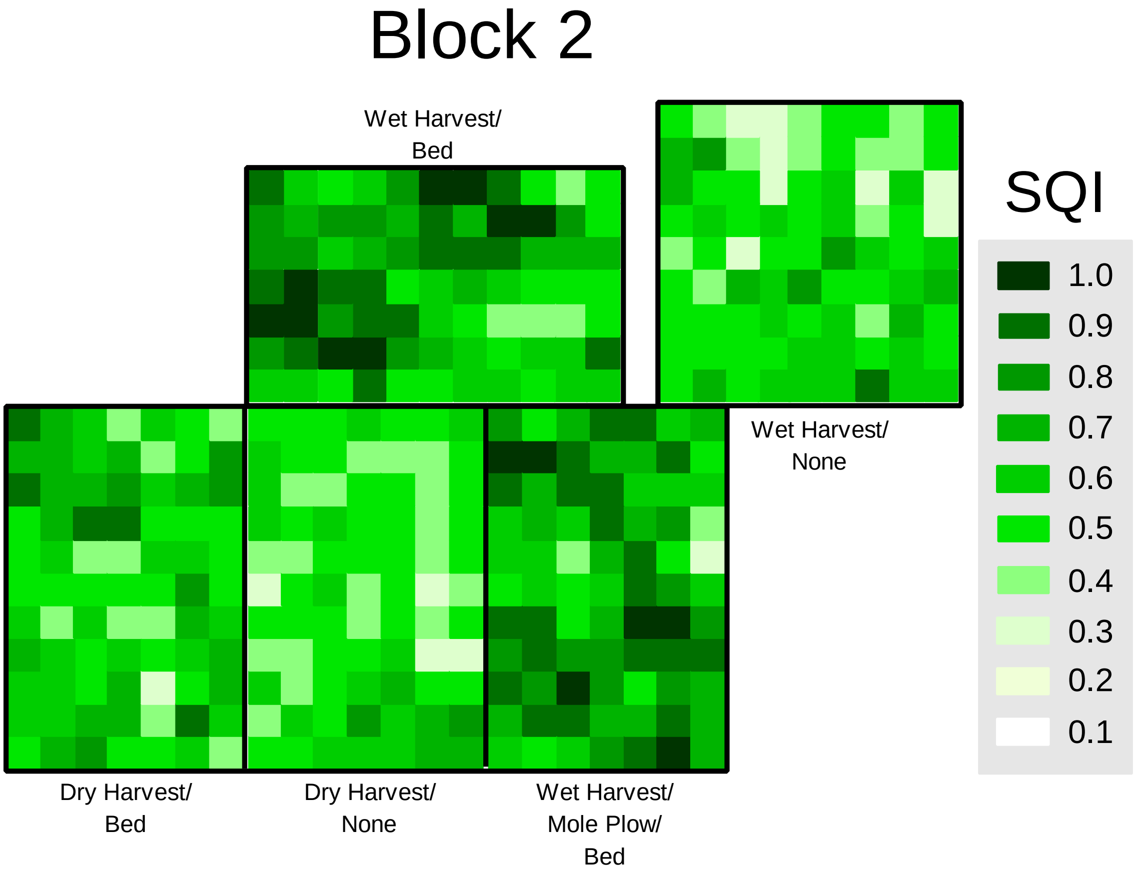


Figure VII.4b. Spatial extrapolations of SQI across the study design for Block Two.

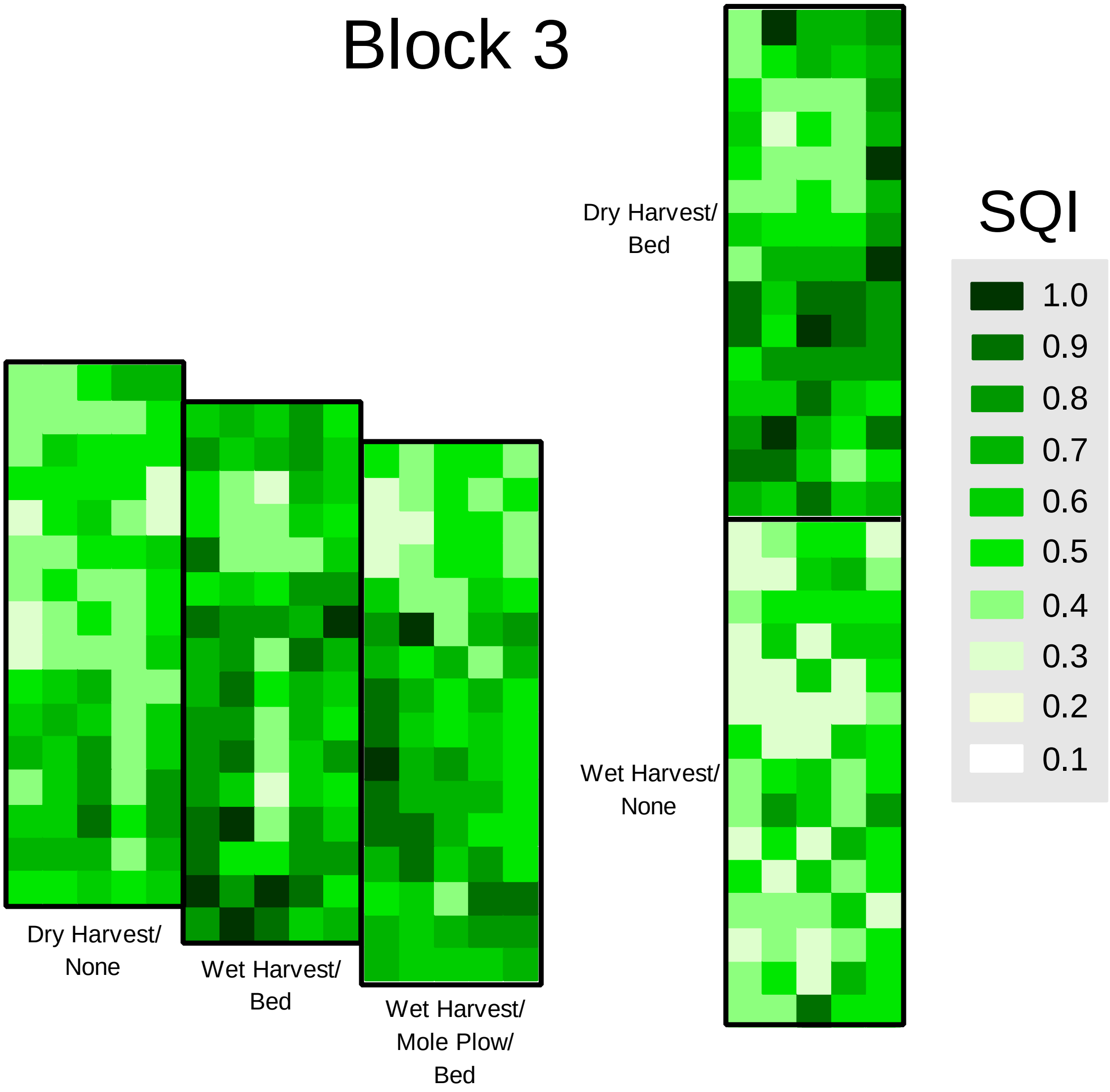


Figure VII.4c. Spatial extrapolations of SQI across the study design for Block Three.

maps can be attributed to elevation. With elevation basically overriding the disturbance effect on SQI for the same reason as in the non-site prepared plots.

A final interpretation of management impacts on SQI and tree growth was made by using the spatially-extrapolated SQIs (Fig. VII.4abc) combined with the regression equations in Fig. VII.3 to predict plot-level aboveground biomass and SQIs (Table VII.12). The stand-level response shows no differences in SQI between the dry- and wet-harvested / non-site prepared treatments (Table VII.12), suggesting that wet-harvesting had no detrimental effects on soil quality. The sufficiency of air / water balance (oxidation depth), the most important attribute in the SQI model, was only decreased significantly by compression tracks and deep ruts (Table VII.2). Based on this result, a lower SQI would have been expected for the wet-harvested / non-site prepared treatment given the distribution of soil disturbance classes (Table VII.13).

Twenty-seven and 18 % of the wet-harvested / non-site prepared area was in compression tracks and deep ruts, respectively, versus only 5 % of the dry-harvested / non-site prepared area being classified as disturbed (compression tracks). The watershed-level hydrology effects discussed earlier probably explain the lack of treatment effects.

Another possible explanation is that we may have underestimated the percent area disturbed (compacted) in the dry-harvested / non-site prepared treatment. Based on the wet-harvested treatments, we know that between 73 and 82 % of the harvested-area was trafficked (Table VII.13). There is little reason to suspect that less than this % area would have been trafficked on the dry-harvested plots. Therefore, it is likely that upwards of 75 % of the dry-harvested / non-site prepared treatment was actually trafficked, and surface soil compaction was probably more extensive than we've estimated.

The wet- and dry-harvested / bedding treatments increased the SQI by the same amount, with a commensurate large increase in predicted 2-yr-old tree aboveground biomass from about 0.25 to 1.25 kg m^{-2}, on average (Table VII.12). I think the previous explanations for the wet- and dry-harvested / non-site prepared treatments extend to the wet- and dry-harvested / bedded treatments. As long as the bedding plow is able to pull the soil up into a planting bed uniformly across the site, and thus create a well aerated soil volume above the non-bedded soil surface, then the effects of soil disturbance on air / water balance are mitigated (Fig. VII.4).

Table VII.12. Stand level wet- and dry-site timber harvesting and site preparation effects on the Soil Quality Index (SQI) and predicted 2-yr-old tree aboveground biomass.†

Site Preparation Treatment	Soil Quality Index‡	Predicted Aboveground Biomass¶
	---- Sufficiency, 0 to 1 ----	(kg m^{-2})
Dry / None	0.42	0.24 c§
Wet / None	0.44	0.26 c
Dry / Bed	0.61	1.35 b
Wet / Bed	0.64	1.14 b
Mole / Bed	0.70	2.50 a

† Analyzed with and RCB design. N = 15.
‡ SQI = 0.3 (Promote Root Growth) + 0.6 (Air / Water Balance) + 0.1 (Soil Fertility).
¶ Aboveground biomass predicted using regression equations (see Fig. VII.3).
§ Significant differences based on 90 % confidence intervals from regression equations in Fig. VII.3.

The mole-plow / bedding treatment resulted in the highest SQI, 0.70, and a predicted 2-yr-old tree aboveground biomass of 2.50 kg m^{-2} (Table VII.12). The mole-plow / bedding treatment also had consistently greater aboveground biomass than the other site preparation treatments (Table VII.8). We had hypothesized that the network of channels in the surface of the Bt horizon created by the mole-plow would enable surface water to move down and out of the rooting zone, creating a more aerated soil volume for early tree growth. The mole-plow treatment did result in the lowest water table depth on average (Miwa, 1999). This, combined with the higher SQI and biomass with the mole-plow / bedding treatment, indicates that the mole-plow / bedding treatment was effective in improving the quality of the soil environment for tree growth.

Table VII.13. Distribution of soil disturbance classes within each site preparation treatment.†

	Soil Disturbance Class				
Site Preparation Treatment	Undisturbed	Compression Track	Shallow Rut (<20 cm)	Deep Rut (>20 cm)	Churned
	------------------------------- % -----------------------------				
Dry / None	95	5	--	--	--
Wet / None	18	27	33	18	4
Dry / Bed	91	9	--	--	--
Wet / Bed	24	17	27	23	9
Mole / Bed	27	17	33	20	3

† Adapted from Preston (1996).

CONCLUSIONS

Surface soil compaction and deep rutting reduced the SQI, mainly through their effects on air / water balance. The wet-harvest and mole-plow / bedding site preparation treatments mitigated the effects of compaction and deep rutting on 'air / water balance', but not 'promote root growth'. However, the higher relative importance of 'air / water balance' in the SQI model resulted in SQI being mitigated across all levels of soil disturbance for the mole-plow / bedding treatment. Soil disturbance reduced aboveground biomass production of 2-yr-old loblolly pine. Whether or not this reduction continues through time will depend on the ability of soil quality to recover naturally. The site preparation treatments significantly improved aboveground biomass production across soil disturbance classes. The mole-plow / bedding treatment consistently had the highest levels of soil quality resulting in significantly more aboveground biomass production with this treatment.

SUMMARY

All of the indicators of soil physical condition and aeration showed that compression tracks and deep ruts reduced soil aeration status during the winter. This indicated that anaerobic soil conditions should have occurred. However, though soil disturbance negatively impacted the soil physical environment, this did not translate to negative effects on the soil chemical or biological environment. None of the redox-induced changes typically seen in soil pH, ECEC, or available P with poor aeration were observed. Site preparation did change the soil chemical environment, but the changes were associated with tillage effects on organic matter and clay content; that is, soil disturbance appeared to play no role in the changes in soil chemistry.

The sites had very high base saturation for forest soils, with commensurate high levels of exchangeable calcium. Calcium saturation appeared to control the soil pH on these sites, thus buffering any redox-effects on soil chemical properties.

Net nitrification, a sensitive biological indicator, was not affected by soil disturbance or organic matter removal. Bedding increased net N mineralization above the rate required for a 2-yr-old pine plantation, but a combination of a large quantity of N on-site and probable high inputs during the first few years makes these sites very resistant to negative changes in N availability. These results demonstrate the important role of high fertility in buffering potentially-negative effects of forest management practices on the soil nutritional environment.

A multilinear regression analysis showed that early loblolly pine growth was largely controlled by oxidation depth, the LLWR, and to a lesser extent, N availability. Oxidation depth was the most important soil property in the model, followed by the LLWR. The modeling results showed that trees grew well on soils with very low LLWRs if the oxidation depth was high. However, with deeper oxidation depths and higher LLWRs, oxidation depth had a negative effect on tree growth. This result showed that these sites could be both aeration and available water limiting. High fertility offset the negative effects on high oxidation depths, probably through reduced carbon allocation belowground for root production.

Least Limiting Water Range, oxidation depth, and net N mineralization were used successfully as surrogate indicators of the three attributes of soil quality for tree growth in the SQI model. The SQI had a strong relationship with tree growth, explaining about 73 % of the variation in aboveground biomass production of 2-yr-old loblolly pine. The SQI was also sensitive to management, as the index showed that compression tracks and deep ruts reduced soil quality. The SQI also showed that the site preparation treatments were generally successful in mitigating soil quality. This result was confirmed by a bioassay which showed no differences in aboveground biomass production between the soil disturbance classes after bedding. The bioassay also showed that soil disturbance reduced productivity on the non-bedded sites.

Several important management implications are evident from the results of this study. Bedding is not employed after harvesting on the majority of sites. Because soil compaction and rutting were shown to reduce soil quality and early loblolly pine growth, these disturbances should be avoided on similar sites if bedding is not employed. This recommendation assumes that natural soil recovery processes will not ameliorate soil quality sufficiently to overcome the early reductions in loblolly pine productivity. Bedding appears to be an effective tool for ameliorating certain soils disturbed during logging; however, it should be noted that the soils used in this study are among the most inherently productive in the southeast, and thus are not representative of all soils under management. In similar soils with a high clay content in the subsurface, the mole-plow / bedding treatment may be an effective means for enhancing soil quality for loblolly pine production, but this treatment needs to be further evaluated in additional studies before it can be recommended for operational deployment.

APPENDIX

This appendix shows the location for each of the soil process measurement points by block and treatment.

Treatment codes for maps on following pages.

Block	Plot	Harvest	Site Preparation
1	1	Wet	Mole-Plow / Bed
1	2	Wet	Flat (none)
1	3	Wet	Bed
1	4	Dry	Flat (none)
1	5	Dry	Bed
1	6	Reference	--
2	1	Dry	Bed
2	2	Dry	Flat (none)
2	3	Wet	Mole-Plow / Bed
2	4	Reference	--
2	5	Wet	Flat (none)
2	6	Wet	Bed
3	1	Dry	Bed
3	2	Wet	Flat (none)
3	3	Dry	Flat (none)
3	4	Wet	Bed
3	5	Wet	Mole-Plow / Bed
3	6	Reference	--

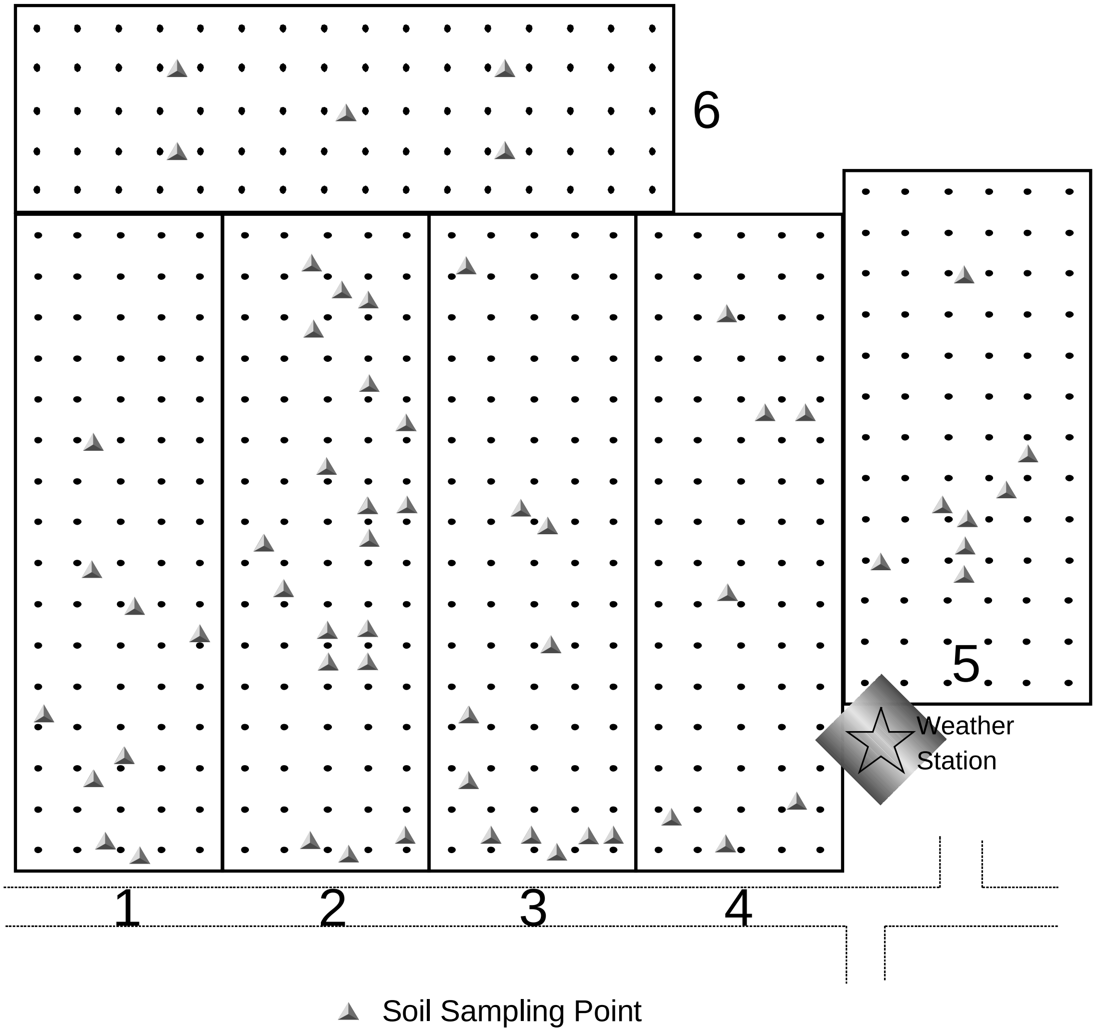


Figure Appendix.1. Soil sampling point locations for Block 1.

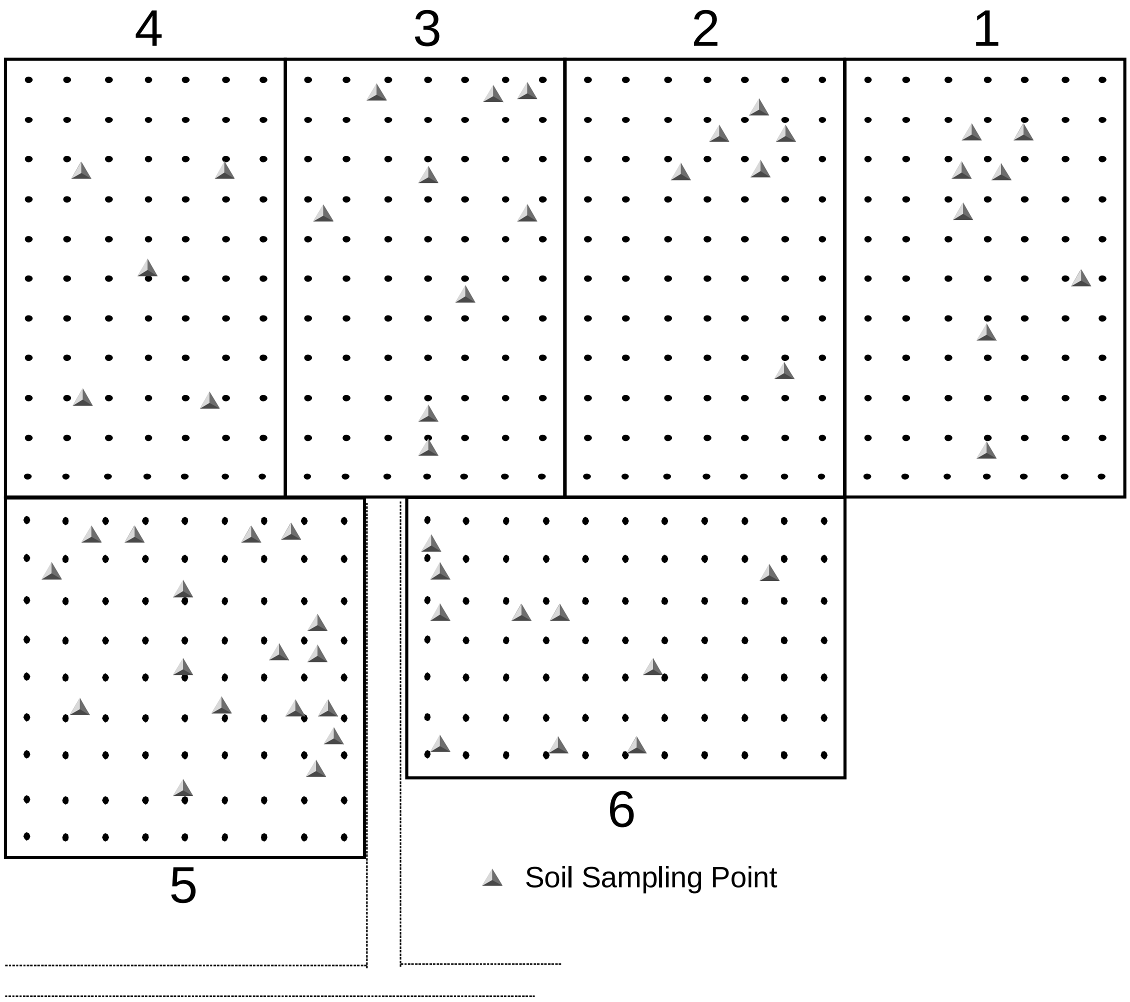


Figure Appendix.2. Soil sampling point locations for Block 2.

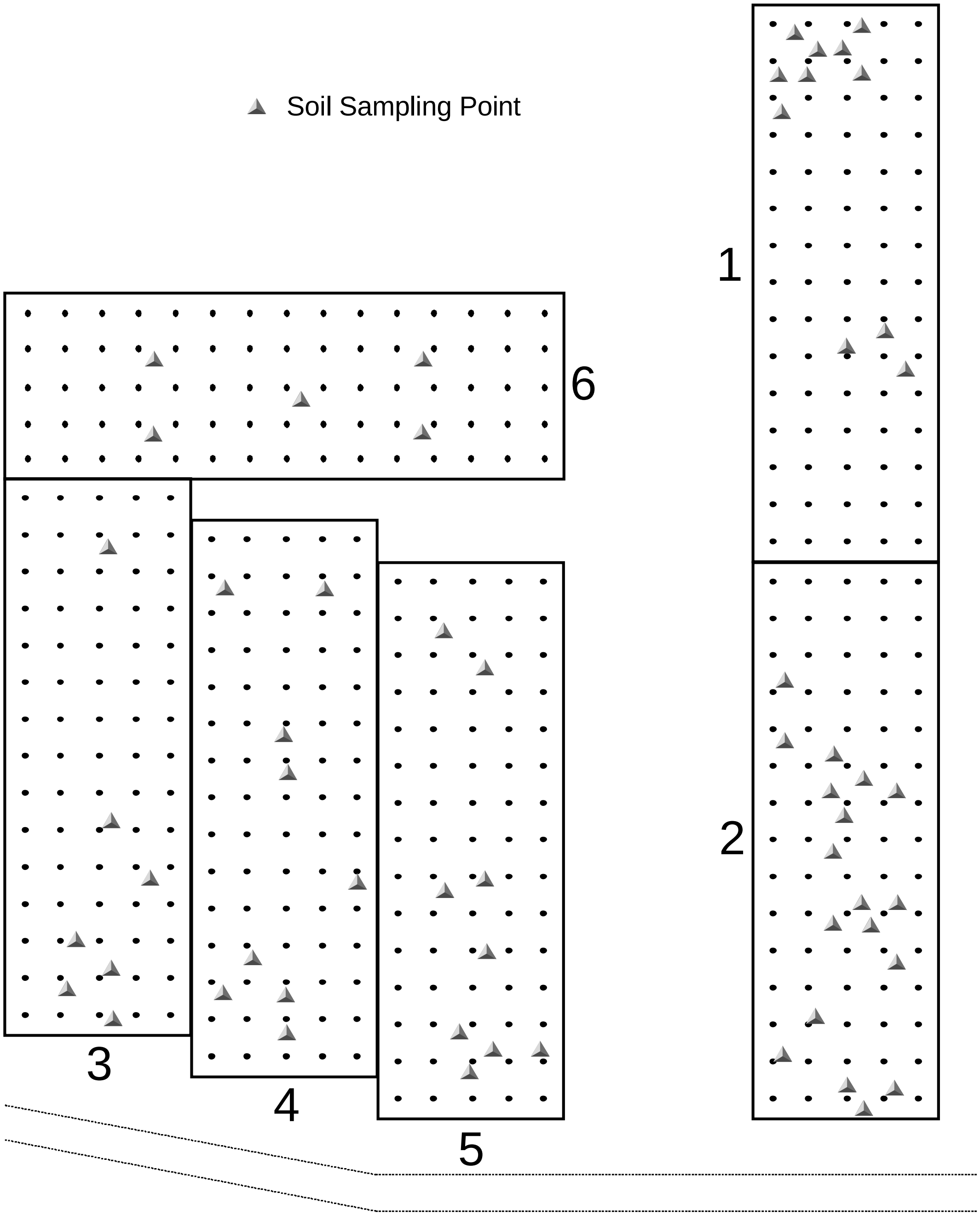


Figure Appendix.3. Soil sampling point locations for Block 3.

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VITA

Daniel L. Kelting was born November 5, 1965 in Plainfield, New Jersey to Jane and William Kelting. He received a A.A.S. in Forest Technology in 1987 from the New York State Ranger School, a B.S. in Resource Management in 1990 from S.U.N.Y. College of Environmental Science and Forestry, and a M.S. in Forestry in 1995 from Virginia Polytechnic Institute and State University. He is presently an Assistant Professor of Forest Soils in the College of Forest Resources, North Carolina State University. He was previously employed by Virginia Tech, the National Marine Fisheries Service, N.Y.S. Dept. of Environmental Conservation, Diamond Occidental Forests Inc., and International Paper Company.