FOREST HARVESTING DISTURBANCE AND SITE PREPARATION EFFECTS ON
SOIL PROCESSES AND VEGETATION IN A YOUNG PINE PLANTATION

by

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(ABSTRACT)

The favorable growth of young loblolly pines (*Pinus taeda* L.) in response to controlling non-crop vegetation is well documented. However, the beneficial effects of non-crop vegetation on soil quality, nutrient cycling, and biodiversity have not been thoroughly explored. A study was conducted to determine the effects of harvesting-induced soil disturbance, bedding and chemical vegetation control on soil processes and productivity, and to characterize the effects of silvicultural treatments on non-crop vegetation dynamics. Study plots were established on a wet pine flat on South Carolina's lower Coastal Plain. Treatments included a range of 5 disturbance classes (undisturbed, compression tracked, shallowly rutted, deeply rutted and churned), two site preparation treatments (flat planted and bedded) and a gradient of vegetation control (no vegetation control, operational-level weed control and complete weed control). Soil disturbances had relatively small effects on soil quality. Soil compaction reduced soil aeration, but this condition was fully ameliorated by bedding. Churning did not degrade the soil physical environment in any measureable way, largely because slash and litter were incorporated into the surface soil. Bedding and churning increase soil biological activity, which increased nitrogen mineralization in excess of pine demand. When non-crop vegetation was chemically controlled, mineralization rates increased due to increases in surface soil temperatures. With less vegetation on the site, the amount of nitrogen sequestered was less, furthering the potential for nitrogen loss by leaching or denitrification. Soil quality improved somewhat with increasing levels of non-crop vegetation biomass; however, these beneficial effects were marginal during two years of operational vegetation control. The majority of dominant species on undisturbed treatment areas were woody, and soil disturbance, including bedding, reduced the

proportions of these species. Silvicultural treatments had little effect on the prevalence of hydrophytic species on these wetland study sites. From a forest management point of view, for this site type, it appears that much is gained by reducing competition from non-crop vegetation; the benefits of controlling the density of non-crop vegetation for encouraging early pine growth are clear. While non-crop vegetation slightly improved system function by sequestering available nitrogen, increasing diversity and increasing soil quality, these improvements do not appear to be critical to forest function on these inherently high-quality sites.

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INTRODUCTION

The effects of non-crop vegetation on soil properties, processes and forest productivity have been debated for many years. In the 1950's, foresters in Europe experimented with interplanting leguminous species within forest stands. In the 1960's, with the rise of plantation forestry, understory vegetation management was again explored, this time via the use of herbicides. Questions concerning the importance of non-crop species were renewed when the use of herbicides to control competing vegetation became commonplace. The increased survival and growth of seedlings as a result of competition control is well documented (USDA Forest Service, 1984; Cain, 1991; Miller *et al.*, 1991). The consequences of herbaceous vegetation removal to long-term soil and forest productivity, however, have not been thoroughly explored.

With rising interest in sustainable forestry, more attention is being paid to the long-term and ecosystem-level effects of vegetation management (Perry, 1998). There is a movement to find alternative methods including an "integrated vegetation management" approach which advocates limiting herbicide usage and supports efforts to balance the beneficial and negative effects of non-crop vegetation (Wagner, 1993).

Although herbaceous vegetation is normally seen as competing with the crop-trees for moisture, light and nutrients, there is some evidence that the retention of non-crop herbaceous species may play a role in maintaining long-term productivity, especially in areas where soil has been disturbed by harvesting. For example, plant roots penetrate soil that has been churned and compacted, improving its structure, and increasing its permeability and aeration (Jastrow and Miller, 1991). Powers *et al.* (1990) cite management induced changes in macroporosity and organic matter as primary sources of long-term forest decline. Herbaceous root growth and dieback may create root channels that increase macroporosity and improve the soil structure and pore size distribution.

In the Southeastern Coastal Plain, herbaceous roots exploit fissures created by natural processes including the shrinking and swelling of smectite clays (Utomo and Dexter, 1982). This opportunistic exploitation of impermeable soil layers may provide a deeper and more favorable rooting environment for crop-species growth. In disturbed

areas, soil strength may also be reduced, and aggregate stability restored, by the active probing and sloughing of herbaceous plant roots.

Herbaceous plants can have a profound effect on nutrient cycling within forest systems (Wedin and Tilman 1990). The dynamics of nitrogen cycling are of particular interest in Southeastern Coastal Plain sites where nitrogen availability limits the productivity of southern pine plantations. Often during harvesting and site preparation activities, decomposition and mineralization processes are accelerated due to management-induced changes in soil temperature, moisture, and organic matter concentration (Burger and Pritchett, 1984, 1988). Nutrients, especially nitrogen, become available in larger quantities than is needed for early pine growth (Dougherty, 1996). Herbaceous vegetation has the potential to sequester critical amounts of excess nitrogen which may be lost from the early plantation system due to leaching or nitrification, and cycle it back into the soil for crop-tree use during periods of greater nutrient demand.

Despite the potential benefits of non-crop vegetation, it is operationally controlled in young pine plantation systems. The favorable growth response of pines to competition control is well documented; however, few scientists have attempted to quantify the beneficial effects a diverse herbaceous cover following disturbance, and the role non-crop vegetation plays in mitigating soil quality in plantation forest system.

In forested wetlands, native plant species are specially adapted to live in a reduced soil environment with limited aeration. Silvicultural activities may alter site properties that in turn affect the species composition and the successional trajectory of non-crop vegetation. In areas such as forested wetlands, there are both societal and legal concerns that intensive silvicultural treatments may alter site hydrology, soils, and vegetation to the point that wetland status and function are affected. A shift from predominantly obligate wetland species to facultative and upland species may undesirably change ecosystem function. Monitoring changes in naturally regenerating non-crop vegetation on wetland plantation sites will help determine how silvicultural disturbances affect wetland status and function.

Objectives

I hypothesized that direct and indirect effects of non-crop vegetation would significantly improve soil quality, nitrogen supply, and biodiversity after harvesting disturbance. Understanding the role of vegetation in the recovery of soil physical properties and nutrient cycling processes will benefit forest managers by allowing them to make more informed vegetation management decisions.

The overall objective of this study was to determine herbaceous vegetation effects on soil recovery and nutrient dynamics following disturbance. The specific project objectives were:

i. To determine if soil disturbance during harvesting operations affects soil properties and processes important for plant growth and productivity

ii. To evaluate the effectiveness of bedding and the role of non-crop vegetation in recovering soil processes and productivity following disturbance

iii. To identify differences in non-crop vegetation biomass and species dominance as a result of harvesting-induced soil disturbance, bedding site preparation, and chemical herbicide application

CHAPTER I

LITERATURE REVIEW

<u>Intensive Plantation Management and Sustainability</u>

Industrial forestry in the Southeastern United States has taken on added importance as the demand for wood products has increased over the past several decades. From the 1970's to the 1980's the production and consumption of wood in the United States increased by 28% (Salwasser *et al*., 1993). The United States consumes 33% of the global wood production (excluding fuel wood) and produces only 25% of the world's roundwood supply (Salwasser *et al*., 1993). Along with the growth in wood production and consumption has come a growing interest in sustainable forest resource use and the maintenance of long-term forest productivity.

Silviculturalists are concerned with the sustainability of site quality and thus productivity. These are controversial concepts, and their definitions have been the subject of much debate (e.g., Powers *et al.,* 1990; Noss, 1993; Kimmins, 1996). What is not of debate, however, is that the overall objective of sustainability is to meet the needs of society in the future. This objective was that of the Multiple Use-Sustained Yield Act of 1960 and parts of the National Forest Management Act of 1976, both of which charge the Department of Agriculture with monitoring and maintaining the productivity of federal land put to certain uses such as silviculture. On an international level, the United Nations Conference on Environment and Development (UNCED) developed criteria for the conservation and sustainable management of forests which included: the conservation of biological diversity, the maintenance of forest productivity, the maintenance of forest ecosystem health, the conservation and maintenance of soil and water resources, the maintenance of forest contribution to global nitrogen cycling, and the development of a legal, institutional and economic framework for sustainability (Coulombe, 1995).

Many indicators of forest sustainability and methods of maintaining forest sustainability have been proposed (Burger and Kelting, 1999, Kimmins, 1996, Noss,

1993, and Powers *et al.*, 1990). For example, Noss (1993) proposed a suite of quantitative measures by which to monitor sustainability, including age structure, spatial heterogeneity indices, fire regime, road density, and the demographics of sensitive species. Kimmins (1996), on the other hand, proposed a more qualitative approach to assessing forest health; he judged the health of a forest by its ability to provide landscape-level benefits even in the face of periodic disturbances. These values presumably include protection of air, water, and wildlife resources, as well as aesthetic benefits.

Determinants of soil quality, similar to those used in the agricultural paradigm of tilth, have been proposed for forest soils. Burger and Kelting (1999) developed a soil quality index model to monitor changes in key growth-determining attributes of forest soils. Ellert and Gregorich (1995) suggested a framework for monitoring changes in the cycling of soil organic matter, including laboratory and field incubations, litter decay studies, measurements of soil respiration and microbial biomass, root assessments, and analysis of soluble organic matter fractions.

Intensive silviculture can affect soil quality in many ways. Powers *et al.* (1990) cited several silvicultural treatments which can affect soil quality, including logging practices, biomass removal, and site preparation, all of which can lead to nutrient loss, organic matter removal, and the alteration of soil structure and site hydrology. Childs *et al.* (1989) cited compaction, surface soil mixing and displacement, fire, and soil removal as being serious threats to the physical quality of forest soils. Bormann and Likens (1979) reported the results of a watershed-scale study in which nutrient losses were dramatic in the first years following clearcutting and repeated herbicide application in a northern hardwood forest. For these reasons, it is recommended that the relationship between soil quality and intensive silviculture be investigated to a greater extent if our goal as a society is to maintain or improve the current level of environmental health.

Managed Forested Wetlands

Greater than 65% of nonfederal, forested wetlands in the United States are located in the South (including VA, WV, KT, TN, NC, SC, GA, FL, AL, MI, LA, AR, OK, TX) which totals approximately 29.3 million acres (Cubbage and Flather, 1993). Twenty-five percent of these non-forested wetlands are in southern pine or pine-hardwood forests

(Cubbage and Flather, 1993). Wetland types include peat and muck swamps, wet flats, red river bottoms, black river bottoms, branch bottoms, and bottomlands (Shepard *et al*., 1998). Many wet pine flats are productive pine plantations, which are intensively managed for wood production.

The effects of silvicultural activities on the wetland status and function of southeastern forested wetlands has been of much concern since the advent of several amendments to the Clean Water Act. For example, section 404 of the Clean Water Act defines criteria that farming and silviculture must meet in order to obtain exemptions from the permitting process. Examples of these criteria include the implementation of federal best management practices (BMP's), maintenance of the reach, flow and circulation of water, and the use of "normal" practices. "Normal" silvicultural activities are defined as those that:

> 1) are part of an ongoing operation
>
> 2) do not involve converting a wetland to an upland
>
> 3) do not require hydrological operations to reinitiate silvicultural activities
>
> 4) do not contain toxic pollutants
>
> 5) comply with federal BMP regulations.

In addition to federal regulations, there are several state ordinances and voluntary state BMP's that affect silvicultural activities in wetlands (South Carolina Forestry Commission, 1989; Siegel and Haines, 1990; Georgia Forestry Commission, 1993). Some Southern states, including Georgia, North Carolina and South Carolina have also developed BMP's specifically designed for forested wetland areas, the aims of which are to minimize the impacts of silvicultural activities in these areas (Aust, 1994).

The Soil Physical Environment

The physical condition of the soil is extremely important for optimal plant growth. Jastrow and Miller (1991) explain that soil structure controls the porosity of a soil and therefore affects infiltration, hydraulic conductivity and soil aeration. These specific soil properties are of critical concern on poorly drained Coastal Plain pine plantations where inadequate soil aeration can reduce pine growth. A soil's porosity also

influences the types and levels of activity of soil organisms, which in turn influences nutrient cycling through mineralization and immobilization processes. If the aggregates of a soil lack adequate stability, wetting of the soil may cause smaller aggregates to be produced from the slaking of larger aggregates. These smaller particles can clog soil pores and reduce infiltration and hydraulic conductivity. Therefore, the maintenance of good soil structure and stability is essential in order to sustain soil productivity.

Soil Disturbance Effects

Harvesting operations on poorly drained sites in the lower Coastal Plain can cause severe soil disturbance including compaction, rutting and churning (Gent *et al.*, 1983; Aust *et al.*, 1993; Aust *et al.*, 1998a). Soil compaction generally results in an increase in bulk density due to the consolidation of soil particles as air-filled voids are reduced. For this reason, bulk density is commonly used as an indirect measure of the degree of soil compaction. Soil compaction often causes increases in soil strength or mechanical resistance (Greacen and Sands, 1980). Maximum compaction generally occurs at soil water contents near field capacity (Akram and Kemper, 1979). Depending on the moisture content of the compacted soil, increases in soil strength can limit root growth and decrease site productivity.

Total soil porosity may or may not be affected by soil compaction; however; the proportion of larger pores ($\geq$ 0.06mm in diameter) generally decreases. These large voids or macropores are especially important for soil aeration. The volume of macropores, expressed as a percent, is called aeration porosity or macroporosity. A soil with a macroporosity of less than 10% is generally considered to have insufficient pores to promote gas exchange (Vomocil and Flocker, 1961). In addition to reducing average pore size, compaction may disrupt the connective nature of the pore structure, causing soil permeability to decrease (Greacen and Sands, 1980). Reductions in soil hydraulic conductivity may decrease drainage and cause soil aeration to be inadequate for optimal plant growth.

When trafficking occurs under near-saturated conditions and many pores are water-filled, soil may flow, resulting in rutting and churning of surface soil layers (Aust *et al.*, 1993). Severe soil churning may cause sufficient mixing to render a soil puddled.

A puddled soil is one that has been mechanically worked to the point where its specific volume is significantly reduced (Bodman and Rubin, 1948; Beacher and Strickling, 1955), or to where aggregates are reduced to individual particles at soil water contents near saturation (Sharma and De Datta, 1986). Puddling occurs when soils are subjected not only to normal stress, which is associated with soil compaction, but also to tangential or shear stress (Sharma and De Datta, 1986). The degree of puddling is a function of the soil moisture content, soil type, and cultural practice. Maximum puddling occurs at moisture contents between field capacity and saturation when the cohesion within soil aggregates is minimal, causing a greater number of shear planes (Koenigs, 1963). Soils with high clay contents, especially those containing smectite clays puddle more easily than coarser textured soils (Sharma and De Datta, 1986). The shrink-swell properties of smectite clays, however, often accelerate the process of natural amelioration and aggregate restoration following soil disturbance (Akram and Kemper, 1979; Utomo and Dexter, 1982)

The effects of churning and puddling are a destruction of natural soil structure, stability and aggregation (Beacher and Strickling, 1955). As with compaction, puddling generally reduces air-filled pore space and decreased soil permeability due to the destruction of macropores (Koenigs, 1963). The soil becomes uniform and massive, as well-aggregated porous soil changes to a plastic mud with a massive structure (Sharma and De Datta, 1986). Sharma and De Datta (1986) site some advantages of puddling soil for rice production; however, puddling can decrease the productivity of plants less adapted to a reduced soil environment where inadequate soil aeration may limit growth.

Several scientists have studied the changes in soil physical properties associated with compaction, rutting and churning. In the field of forestry, Aust *et al.*, (1995) found bulk density increases of 20% and decreases in average soil macroporosity (80%) and saturated hydraulic conductivity (12%) following harvesting disturbance on wet pine flats that had been compacted. Similarly, the results of a compaction study on a hardwood site in Wisconsin, showed greater than 80% increases in bulk density associated with logging disturbance and 20% decreases in porosity (Shetron *et al.*, 1988). Significant increases in bulk density and decreases in hydraulic conductivity were observed on the skid trails of a clearcut loblolly pine plantation (Gent *et al.*, 1983).

Compaction disturbance may limit plant growth by increasing the soil strength for root growth, or by limiting soil aeration due to a reduction in macropore space. Surface soil bulk density was 18% higher in skid trails than in adjacent undisturbed areas 16 years after logging in Oregon's Ochoco National Forest, which resulted in a 6 to 12% reduction in the growth of ponderosa pine in disturbed areas (Froehlich, 1979). In a study conducted in Washington State, Froehlich *et al*. (1986), observed a 20% reduction in volume growth of 10-year-old ponderosa pine (*Pinus ponderosa*) due to compaction caused by logging disturbance. Despite 27% increases in bulk density in the disturbed area of a lodgepole pine (*Pinus contorta*) plantation, however, there was no disturbance effect on lodgepole pine growth. Two years after harvest, loblolly pine planted in skid trails showed significant reductions in total height and diameter (DBH); however, after 4 years, the differences in height and diameter were not significant (Aust *et al*., 1998b).

Rutting and puddling of soils during harvesting operations has been shown to decrease macropore space by 40% and reduce hydraulic conductivity by 91% (Aust *et al*., 1995). Severe soil rutting can also interrupt subsurface drainage, causing further reductions in soil permeability (Aust *et al*., 1993). Soil porosity changes associated with puddling depend on the orientation of clay particles prior to and after disturbance. Generally, puddling reduces the number of macropores responsible for water movement, and increases residual pores associated with water storage; therefore, hydraulic conductivity is often reduced (Sharma and DeDatta, 1986).

The reported extent and spatial distribution of soil disturbance following harvesting varies greatly with terrain and harvesting method; however, in general, about 17 to 23% of a logged area is disturbed by logging equipment, and this disturbance is usually concentrated in skid trails (Koger *et al*., 1984). In the South Carolina Coastal Plain, the extent of soil disturbance in loblolly pine wet flats may be as high as 77% in areas harvested under wet conditions (Preston, 1996).

The effect of different agricultural practices on soil structure and stability has been a subject of recent concern, especially with the rising interest in no-till farming methods. The cultivation of soils and conventional tillage operations in agriculture, as well as the disturbance of soils by harvesting and site-preparation in forestry, has the potential to disrupt soil aggregates. Carter (1992) conducted a study to investigate the

influence of reduced tillage systems on macro-aggregate distribution and structural stability. The study showed that within a relatively short time period (3-5 years), reduced tillage systems improved soil structural stability. Similar results were found in research comparing a conventional tillage system to a no-tillage soil (Beare *et al.*,1994a). The water-stable aggregates were compared for soils that were under conventional and no-till systems for thirteen years. In the conventional-till system, the macro-aggregates were fewer and less stable than in the no-till system. Concerns over the potentially deleterious long-term effects of soil tillage in agriculture have been accompanied by questions about the sustainability of intensive site preparation methods in the field of forestry.

Site Preparation Effects

In intensively-managed forests, silvicultural treatments are imposed to mitigate the effects of harvesting disturbance including bedding, ripping, and disking; however, the effectiveness of these efforts in restoring favorable soil properties may be short-lived and counterproductive (Greacen and Sands, 1980). During the bedding process, surface soil from either side of the bed in mounded to create a raised row neighbored by depressed furrows. Good quality beds are sufficiently elevated to provide adequate aeration for seedling growth, and are structurally stable enough to maintain an elevational advantage during the establishment period. Bedding concentrates soil organic matter and generally controls non-crop competition. In soil that has been disturbed during harvesting, bedding may also help to mitigate the affects of disturbance by breaking up and aerating puddled and compacted soil. Gent *et al.* (1983) found that bedding successfully ameliorated physical damage in a sandy loam soil only in the surface 30 cm and outside the primary skid trail. They also concluded that the soil beneath the bed on primary skid trails might remain so severely compacted that root growth is inhibited.

Shoulders and Terry (1978) discuss the results of a study in the lower Coastal Plain of North Carolina where bedded areas with medium to fine textured soil had substantially greater macroporosity than adjacent non-bedded sites. Improvements were greater in areas that had been disturbed by wet weather logging. Schultz (1976), however, found that the improvements in bulk density and porosity observed after bedding a fine sand soil in Florida, were no longer significant only 2.5 years after the

bedding treatment. Shoulders and Terry (1978) concluded that soil texture may strongly influence the effectiveness of bedding in restoring physical soil damage and the duration of soil improvements due to bedding.

In poorly drained lower Coastal Plain sites, the benefits of bedding to crop tree survival and growth are well documented (McKee and Shoulders, 1974, McKee, 1989). Bedding creates an elevated, well-drained and aerated rooting zone for early pine growth. In mature slash pine (*Pinus elliottii* Engelm.) plantations on poorly drained soils in Louisiana, bedding treatments developed 30% more aboveground pine biomass than flat-planted treatments (McKee and Shoulders, 1974). Loblolly pine response to bedding was similar; 30 to 50% increases in aboveground growth to age 10 can be expected on wet flat sites where clay loam and sandy loam subsoils are present (McKee, 1989).

Influences of Plants and Other Biota

In addition to mechanical site preparation methods, natural processes also help to restore soil properties in the lower Coastal Plain following disturbance; these processes include weathering, the shrinking and swelling of 2:1 clays (McGowan *et al.*, 1983, Sarmah *et al.* 1996), the activity of soil fauna (Oades, 1993) and the active probing and sloughing of plant roots (Larson and Allmaras, 1971; Perfect *et al.*, 1990a). Of the natural recovery processes in the Southeastern U.S.A., root exploitation and the increased biological activity associated with the rhizosphere are believed to be the most important.

The influence of the soil biota in the creation and stabilization of soil aggregates is well documented. Soil biota in addition to climate, topography, parent material and time constitute the five soil forming factors as defined by Jenny in 1941. Especially in soil where organic matter is a major binding agent, plant roots and soil fauna contribute greatly to the formation and stability of soil aggregates (Jastrow and Miller, 1991). Structural pores are created by the active growth and sloughing of roots. Mycorrhizal hyphae and root mucigels enmesh soil particles, and contribute the formation and stabilization of macro-aggregates (Jastrow and Miller, 1991). Macro-fauna such as earthworms and burrowing larvae also contribute to the structure of the soil. Oades (1993) states that there is an increasing awareness within the scientific community of the important role that biology plays in the formation and stabilization of soil structure. He

goes on to say that there is great interest in managing soil biota to promote better soil structure. Lynch (1984) supports the management of soil biota, specifically microorganisms, and he states the possibility of manipulating the soil population balance towards beneficial organisms. Managing and manipulating soil microorganism populations under field conditions is a challenging prospect; however, plant and crop species composition can be easily altered by agricultural or forestry practices.

Much of the research involving the effects of vegetative species on soil structure comes from the field of agriculture, and there is limited information available from a forestry perspective. Chan and Heenan (1991) studied differences in soil aggregation under six different crop types. They found significant differences in the effects of certain crop species on the strength of aggregates, however no significant differences were found in aggregate stability in water. Chantigny *et al.* (1997) concluded that changes in soil aggregation associated with the shift from bare to vegetated soil were in the larger aggregate size fraction (>2mm). They found greater soil aggregation below perennial grasses than in bare soil and concluded that this was mainly due to the action of soil fungi associated with the root zone of the grasses. It is generally recognized that the impact of cultural soil manipulations is reflected to a greater degree in the macro-aggregates as opposed to the micro-aggregate fraction (Oades, 1984). Jastrow (1987) also found that perennial grasses were superior in their ability to form stable aggregates and attributed this superior ability to the development of a fine root system. Length of fine roots (0.2-1.0 mm diameter) has a very strong direct effect on the geometric mean diameter of water-stable aggregates (Miller and Jastrow, 1990).

Perfect *et al.* (1990a) investigated the changes in soil structural stability under forages and corn. They found no increases in structural stability under the corn treatment during the three-year study period; however, the forages all showed significantly higher levels of aggregate stability. The researchers also investigated the relationships between aggregate stability and root parameters. Significant correlations were found between mean root length and rates of structural stability. Mean root weight was also significantly correlated.

The effects of the forage treatments on aggregate stability may be due to indirect effects involving soil moisture. As already mentioned, wetting and drying cycles in soil

systems, especially where 2:1 clays are present, may contribute substantially to the formation of stable aggregates (Utomo and Dexter, 1982) and to the restoration of soil structure following disturbance. Oades (1993) stated that the wetting and drying cycle is the primary force involved in the formation of soil structure. The forage cover may significantly influence the moisture content of the soil during periods of high evapotranspiration. The resulting fluctuation in soil moisture associated with this drying and subsequent wetting after periods of precipitation may account for the greater structural stability under forages. Perfect *et al.* (1990b) further reported that soil moisture and microbial biomass were the most significant predictors of structural stability during the growing season.

It is evident that the question of how soil biota affects soil structure and quality is a timely one. Much research has been done in the field of agriculture to try to isolate the species-specific effects of vegetation and soil fauna on the formation and stability of aggregates; research of this type in the field of forestry, however, is limited.

Nitrogen Cycling Processes

Nitrogen is one of several macronutrients that is essential to plant survival and growth. It is supplied to the soil primarily by the decomposition of plant and animal residues. Despite relatively large quantities of organic nitrogen in soils (2,000 to more than 4,000 kg ha^{-1}) (Vitousek and Matson, 1985b), seldom more than 1% is in an available form at one time (Gosz, 1981). Organic nitrogen is made available to plants by microbially-mediated mineralization processes which convert organic nitrogen to ammonium (NH_4^+) (Figure 1.1). Ammonium is readily taken up by plants; however, it may also be converted by an oxidation process to the more mobile anion, nitrate (NO_3^-) in the presence of specialized nitrifying bacteria. Although nitrate is also readily available to plants, its mobility in soil solution causes it to be easily lost by leaching. On wet sites, nitrate may also be converted to gaseous nitrogen by denitrification, a process by which NO_3^- is reduced in a series of reactions to nitrous oxide or nitrogen gas ($NO_3^- \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2$) (Dowding, 1981). Nitrogen loss by denitrification following timber harvesting is likely, and is due in part to increased soil nitrogen

concentrations. Poorly drained, fine textured soils generally have higher rates of denitrification especially following harvest (Vitousek, 1981). DeLaune *et al*. (1996) quantified the denitrification rates in a bottomland hardwood wetland soil and found that over 40 days, NO3- in floodwater decreased by between 82% and 59% due to denitrification.

INPUTS   INTERNAL CYCLE   OUTPUTS

Decomposers

Harvest

Bulk
Precipitation

mineralization

immobilization

Litter production

Leaching

immobilization

uptake

Ammonia
Volatilization

Plants

NH_4^+

Denitrification

uptake

nitrification

N fixation

Erosion

NO_3^-
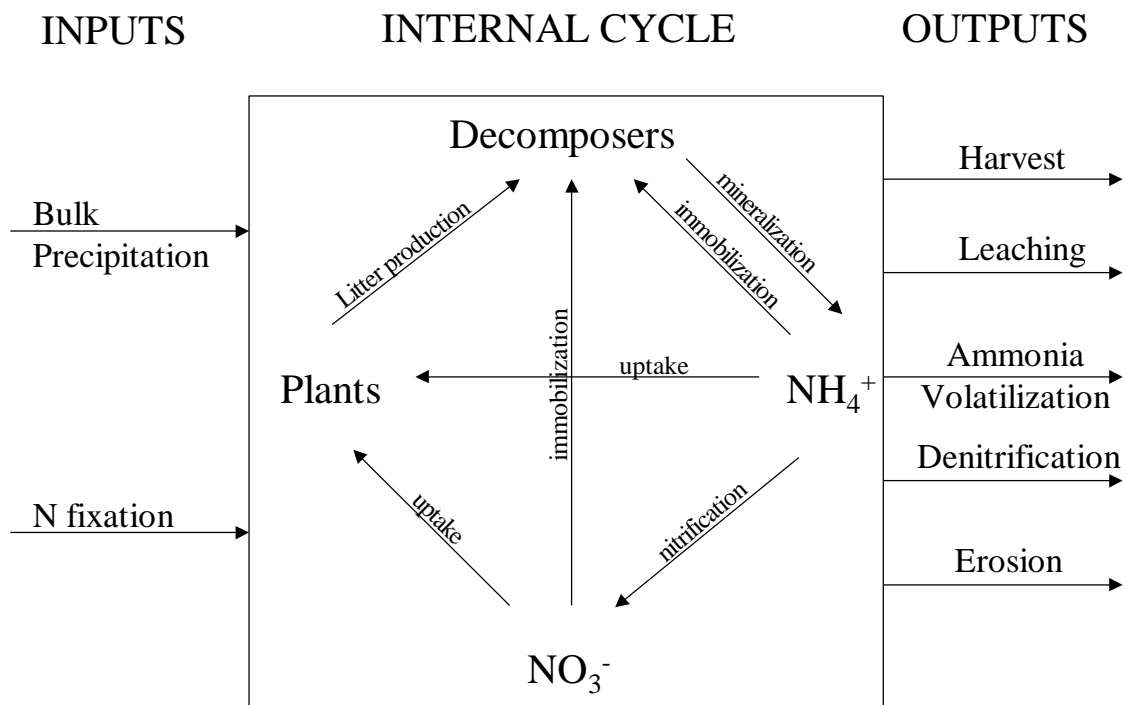
Figure 1.1. Conceptual model of nitrogen cycling in forests (adapted from Vitousek, 1981)

Only a portion of a soil's total nitrogen is reactive and has the potential to be mineralized. The nitrogen mineralization potential (N_o) of a soil is dependent on the quality and quantity of organic matter present. N_o is most frequently determined by incubating soil cores at optimal moisture and temperature conditions and using the cumulative inorganic nitrogen extracted throughout the incubation to estimate the amount of mineralizable nitrogen using first order kinetics (Stanford and Smith, 1972). N_o, and to a lesser extent the ratio of total soil carbon to nitrogen, have been used to predict nitrogen availability (Burger and Pritchett, 1984). Actual rates and net amounts of nitrogen mineralized in the field are dependent on environmental conditions including temperature, moisture, and the accessibility, quantity, and quality of organic matter (Waring and Schlesinger, 1985).

Nitrogen Supply and Demand in Pine Plantations

Low nitrogen availability often limits pine productivity in Southeastern Coastal Plain forest systems. Despite low levels of ecosystem nitrogen, undisturbed conifer ecosystems are extremely efficient at retaining nitrogen and limiting leaching losses (Gosz, 1981). This efficiency and balance between nitrogen supply and demand may, however, be lost in plantation forests, especially those receiving intensive site preparation and herbaceous weed control (Burger and Pritchett, 1984; Dougherty, 1996).

Several researchers have developed conceptual models of the dynamics of nitrogen supply and demand in intensively managed pine plantations (Burger and Kluender, 1982, Allen *et al.*, 1990). Models generally show a surplus of available nitrogen following harvest due to decreased plant uptake. The surplus may be compounded by increases in soil microbial activity and mineralization rates due to harvesting and site preparation-induced changes in soil temperature, moisture content, and organic matter concentration (Burger and Pritchett, 1984, Matson and Vitousek, 1981). Among the factors that control the rate of organic matter decomposition are moisture content, temperature, and juxtapositioning of organic matter and mineral soil (Waring and Schlesinger, 1985). Warmer and moister conditions following forest cutting can increase decomposition rates, causing more rapid conversion of organic nitrogen to

inorganic forms, thus increasing the available nitrogen pool (Binkley, 1984). When surface soils are disturbed and churned during harvesting or site preparation activities, logging slash may be mixed with mineral soil, causing decomposition processes to accelerate. Initially, nitrogen may be immobilized if the added organic substrate causes increases in microbial populations; however, net mineralization will occur once microbial demands for nitrogen are met and the carbon to nitrogen ratio narrows.

Surplus nitrogen, especially if in the highly mobile form of nitrate (NO_3), may be lost from forest plantation systems by leaching (Vitousek, 1981). This loss of nitrogen supplying potential may cause future nutrient deficiencies, and compromise overall site productivity. After planting, pine demand for nitrogen increases, and usually exceeds soil supply after stand closure. If the reactive pool of nitrogen is not conserved during the prior period of surplus, the productive potential of crop-pines will not be realized.

Disturbance Effects on Soil Nitrogen and Organic Matter

Several scientists have studied the effects of disturbance and cultural treatments on nitrogen dynamics. Vitousek and Matson (1985a) found that nitrogen mineralization was significantly affected by harvesting and site preparation operations. In the first year of their study, net nitrogen mineralization was significantly greater on harvested plots than on uncut reference plots, even with no residue removal. Nitrogen mineralization increased with increasing site preparation intensity from chop to shear, pile and disc treatments. Burger and Pritchett (1984) also predicted increases in nitrogen mineralization with increasing site preparation intensity based on their nitrogen mineralization potential data and laboratory simulations of treatment effects on soil moisture and temperature.

Soil microbes are responsible for mineralization processes, and these microbial populations are affected by changes in soil moisture and temperature that may occur following disturbance. Nitrogen mineralization rates have been shown to double with every 10°C increase in soil temperature due to greater microbial activity at higher temperatures (Powers, 1980; Kladivko and Keeney, 1987). Disturbances that change the amount of organic matter substrate can also affect microbial populations. Entry *et al.* (1986) found that microbial biomass was greatest in clearcut treatments where organic

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residues were left compared to clearcut sites where organic residue was removed or burned. If the residue left after clearcutting has a high C:N ratio, then the nitrogen needs of the larger microbial population may cause net nitrogen immobilization. This generally occurs when the C:N ratio is greater than 20 (Vitousek, 1981). Net immobilization may be desirable if plant demand for nitrogen is low. Immobilization of nitrogen in microbial populations may reduce nitrogen losses following disturbance (Vitousek and Matson, 1985a).

Like nitrogen, soil organic matter may also be lost by increases in decomposition due to soil disturbance. In addition to changing soil temperature and moisture regimes, disturbances such as tillage and churning often expose new aggregate surfaces (Dalal and Bridge, 1996). The activity of decomposer organisms may be increased and organic residues that have been incorporated into the soil at the time of disturbance may decompose more rapidly than under undisturbed conditions. This rapid decomposition may contribute to the long-term degradation of a site under intensive cultural treatment (Beare *et al.*, 1994a).

In addition to organic residues that may be subject to more rapid decomposition as a result of their tillage and burial, there is evidence for loss of stable organic matter *within* aggregates as a result of intensive tillage and soil disturbance (Beare *et al.*, 1994b). In undisturbed soil, organic matter may be guarded against microbial attack by being isolated in micropores or by being physically protected within stable macro-aggregates. The main mechanism of soil organic matter loss in areas under long-term, intensive cultivation appears to be by the degradation of soil aggregates (Jastrow, 1996). The results of a study conducted by Beare *et al.* (1994b) indicated that macro-aggregates provide an effective means of protection of soil organic matter in no-till systems compared to conventional-till soils in which macro-aggregate integrity may be compromised.

Similar studies that have been conducted to investigate the hypothesis that soil organic matter is stabilized and protected within aggregates are found in the field of forestry. Borchers and Perry (1992), studied the influence of soil aggregation on carbon and nitrogen dynamics in forested and clearcut areas. In this study, the effect of clearcutting and aggregate disruption on mineralizable nitrogen was used as an index of

organic matter protection. Aggregates were sonically disrupted and then incubated under anaerobic conditions for seven days. There were no significant differences between the clearcut and undisturbed forest with respect to the index of organic matter protection; however, significant differences were found among different soil textures. Soils with high clay and silt contents showed a greater likelihood of protecting and stabilizing soil organic matter following disturbance.

Vegetation Effects on Nutrient Cycling

Following silvicultural disturbances such as harvesting and site preparation, the growth of vegetation may help to capture a portion of the surplus mineralized nitrogen and cycle it into the soil where it may become available to pines during critical periods of higher nitrogen demand. Non-crop vegetation in pine plantation systems, however, is commonly controlled with herbicides due to the positive response of pines to competition control (USDA Forest Service, 1984; Cain, 1991; Miller *et al.*, 1991). Slay *et al.* (1987) reported significant nitrogen losses in treatment plots in which herbicide was applied. Similarly, Vitousek and Matson (1985a) found the greatest nitrogen losses by leaching, denitrification and erosion on treatment plots where organic residues were removed and herbicides were applied. Agriculturists have developed strategies to reduce the loss of nitrate by leaching. Winter and autumn cover crops have been successfully used to minimize nitrogen leaching during times when fields would otherwise be fallow (Powlson, 1993). Powlson (1993) discussed the need to study the time course of nitrogen released by these cover crops in order to better synchronize nitrogen supply with the demands of the subsequent crop.

In addition to providing a means of nitrogen sequestration, non-crop vegetation in pine plantations also affects nitrogen cycling processes by improving residue quality and affecting mineralization and nitrification rates. Polglase *et al.* (1992) found that specific nitrogen mineralization was inhibited by weed control and suggested that the residues from understory vegetation in his slash pine plantation study site were a better supply of available nitrogen than the pine organic residues. Plant litter and fine root production and exudation greatly affect carbon and nitrogen mineralization processes in forest soils. Hendrickson and Robinson (1984) found that without living roots, the available carbon

pool is significantly reduced, suggesting that much of the available carbon pool is comprised of fine roots, root exudates and the microbial biomass associated with the rhizosphere. Controlling vegetation with herbicides could, therefore, reduce the amount and quality of readily available substrate for mineralization processes.

Several studies suggest that individual species affect nitrogen mineralization and cycling processes differentially (Wedin and Tilman, 1990; Scott, 1998). As Wedin and Tilman (1990) explained, nitrogen supply rates influence plant communities by affecting species productivity, composition, and diversity. These supply rates, however, are directly influenced by the above- and below-ground litter quality, quantity and the timing of litter inputs, suggesting a feedback mechanism between plant processes and nitrogen and carbon cycling. Wedin and Tilman (1990) experimented with five different species of perennial grasses and found 10 fold differences in annual net mineralization among the species. Scott (1998) found that species-induced differences in soil aggregation did not explain species affects on nitrogen cycling.

Silvicultural Effects on Vegetation Communities

There has been much interest in the effects of silvicultural activities on vegetation communities. One reason for this is purely ecological; some silvicultural activities occur in areas such as wetlands which provide habitat for at least one-third of the threatened and endangered species of the United States (Murdock, 1994). There has also been increasing interest in the relationship between biodiversity, ecological stability, and disturbance (Hobbs and Huenneke, 1992; Tilman, 1996). In certain areas where invasive species have become abundant due to forest fragmentation and other human disturbances, there exists a danger that disturbance will stimulate the colonization of these weedy species at the expense of native species.

Silviculturists are concerned not only with the effects of disturbance on natural communities but also with how changes in plant communities affect plantation forests (Smith *et al.,* 1997). It has been well documented that herbaceous competition reduces the growth of southern pines (Nelson *et al.*, 1981; Lockaby *et al.,* 1988), and that vegetation control can improve early pine growth (McKee and Shoulders, 1974; McKee,

1989; Miller *et al.*, 1991; Cain, 1991). There is concern, however, that the complete control of herbaceous, non-crop vegetation in these systems will not only negatively impact the stability and diversity of the system as a whole, but also might lead to increased nutrient losses (Vitousek and Matson, 1985a) and increased susceptibility of pine damage by pathogens and herbivorous insects (Zutter *et al.*, 1987). For these reasons, land managers have studied the dynamics of vegetation communities in response to different silivicultural disturbances; examples of silvicultural disturbances include soil disturbance during harvest, site preparation, and chemical control of competing vegetation with herbicides.

One way that harvesting equipment can impact vegetation is by redistributing organic matter in the form of slash and logging debris. For example, Shelton (1995) found in a greenhouse study that increasing the weight of the forest floor resting on the dormant seed had negative effects on herbaceous seedling establishment. He also found that the placement of the seed (within the forest floor, or beneath, on the mineral soil surface) caused different rates of seedling germination and survival. These results indicate that processes which act to mound or increase the amount of organic material over the mineral soil might hamper the re-establishment of the vegetation community after such disturbances.

Other harvesting-induced soil disturbances include compaction, rutting, and churning of soils. Soil compaction can have a dramatic effect on soil bulk density and soil strength (Greacen and Sands, 1980), and thus root penetration. Rutting and churning can have differential effects on the plant community by creating a varied microtopography, and increasing the heterogeneity of the soil surface and thus the number of "safe" sites for seed germination. Harper *et al.* (1965) conducted a greenhouse study in which different types of soil surface disturbances were generated, and found that these differences affected the germination of seeds of plantain (*Plantago* spp.). Similarly, Zedler and Zedler (1969) found that differences in microtopography in a Wisconsin old field affected the plant community structure.

In addition to harvesting, site preparation methods such as plowing, discing, windrowing, burning and bedding can impact early succession in pine plantations. For example, Conde *et al.* (1983a and b) found that the rate of succession of vegetation

communities decreased as the intensity of post-harvest treatment increased. They did not, however, find any lasting effect on plant species richness or diversity. Swindel *et al.* (1989) and Conde *et al.* (1983a and b) reported that pre-harvest woody understory biomass was decreased to a greater extent with more intensive site preparation measures, and that the more intensive treatment favored pine growth. Herbaceous biomass dramatically increased after clearcutting and site preparation, but was not strongly affected by the intensity of site preparation. Locasio *et al.* (1991) also did not discover very strong, consistent differences in either plant species diversity or biomass of growth forms across a gradient of site preparation intensity in a Piedmont pine-hardwood forest. Stransky *et al.* (1986), however, reported that 10 years after treatment, the percentage of the pine-hardwood community biomass occupied by herbaceous species on non-site prepared plots was 100-400% greater than that for plots which had been subjected to varying degrees of mechanical site preparation. Similarly, Fredericksen *et al.* (1991) found that different intensities of site preparation of a Piedmont loblolly pine plantation differentially impacted the distribution of species with respect to growth forms; chopping tended to produce communities dominated by hardwoods, whereas discing created a more equitable distribution of grasses, forbs, and woody species.

Finally, herbicide application is a form of site preparation that has the potential to alter plant community composition. Fredericksen *et al.* (1991) concluded that herbicide treatments impacted plant composition at the species level by lowering the relative abundance of some woody species over others. However, Miller *et al.* (1995) did not find a very large difference in proportions of growth forms between plots subjected to intensive chemical vegetation control and those subjected to no chemical control. This would imply that although chemical site preparation has a dramatic effect on the biomass of the competing vegetation community, it has little effect on community structure. Results of other studies, however, suggest that certain herbicide formulations might have differential effects on species due to differences in the surface chemistry and physical structure of their leaves (e.g., Holloway 1970). Further study of the differential impacts of herbicides on plant community structure is needed.

Silvicultural Impacts on the Prevalence of Wetland Species

About 16% of the total timberland in the Southeastern United States grows in wetlands (Shepard *et al*., 1998). In South Carolina, 41% of the total forested wetland acreage are classified as wet pine flats (Harms *et al.,* 1998). Many of these areas are intensively managed for loblolly or slash pine production. In areas such as forested wetlands, there are both ethical and legal concerns that intensive silvicultural treatments may alter site hydrology, soils, and vegetation to the point that wetland status and function is affected. A shift from predominantly obligate wetland species to facultative and upland species might have legal consequences for silviculturists and would also threaten ecosystem function.

Wetlands are delineated based on site hydrology, soils and vegetation. According to the Federal Manual for Identifying and Delineating Jurisdictional Wetlands (Environmental Laboratory, 1987), an area is considered to meet the hydrophytic vegetation criterion if all of the dominant species are obligate (OBL), facultative wetland (FACW), or facultative (FAC) species according to the Nation List of Species found in wetlands (Reed, 1988). Dominant species are defined as any species whose total cover is 20% or greater, and a combination of the most abundant species whose total additive cover equals 50%, according to the 50/20 rule for wetland classification (Environmental Laboratory, 1987). Obligate and facultative wetland species often have certain adaptations that allow them to grow in low oxygen environments including: buttressed or multiple tree trunks, adventitious roots, shallow roots, air filled tissue in the roots and stem, and floating leaves (Environmental Laboratory, 1987)

Generally, following clearcutting operations in forested wetlands, water tables rise and soil water content increases (Aust, 1993). This is primarily due to significant decreases in evapotranspirational outputs. Site preparation measures such as bedding and mole plowing, which are designed to provide a more aerated soil volume for seedling establishment and growth, may decrease the prevalence of wetland species in these areas. Few studies have examined the effects of silvicultural treatments on the prevalence of wetland species. Gale *et al.* (1998), describe how bedding may create a "mosaic of patches across the wetland landscape" due to different rates of succession on wet (in the furrows) and dry (on top of beds) microsites. Although they did not directly measure the

effects of bedding and harvesting treatments on wetland species prevalence, their data suggested that harvesting operations may increase the prevalence of OBL and FACW species over uncut control plots, and that bedding did not affect wetland species prevalence. More research is needed in this area, especially if the intensity of harvesting operations in productive forested wetlands increases.

CHAPTER II

MATERIALS AND METHODS

Project History and Site Description

This study was part of a more extensive experiment designed to assess the long-term impacts of harvesting and site preparation operations on pine productivity. The project was initiated in 1992 with a pretreatment characterization of specific soil and hydrologic properties believed to influence wet-weather logging disturbance (Burger, 1994). Following clearcutting treatments, Preston (1996) completed his master's work studying the impacts of harvesting on site hydrology and soil properties related to drainage.

The study site was located in a wet pine flat on the Coastal Plain of South Carolina, in Colleton County (latitude 32°55', longitude 80°30') near Cottageville (Figure 2.1). Land in this area has been intensively managed for loblolly pine production by Westvaco Corporation. Two soil types dominate the study area: Argent loam and Santee loam which are classified as fine, mixed thermic Typic Ochraqualfs and fine, mixed, thermic, Typic Argiaquolls, respectively (Stuck, 1982). Both the Argent and the Santee soils are poorly drained with low permeabilities and are formed from marine and fluvial deposits. Water table levels during the growing season are often within 30 cm of the soil surface, and these soils are generally considered hydric (USDA-NRCS, 1991).
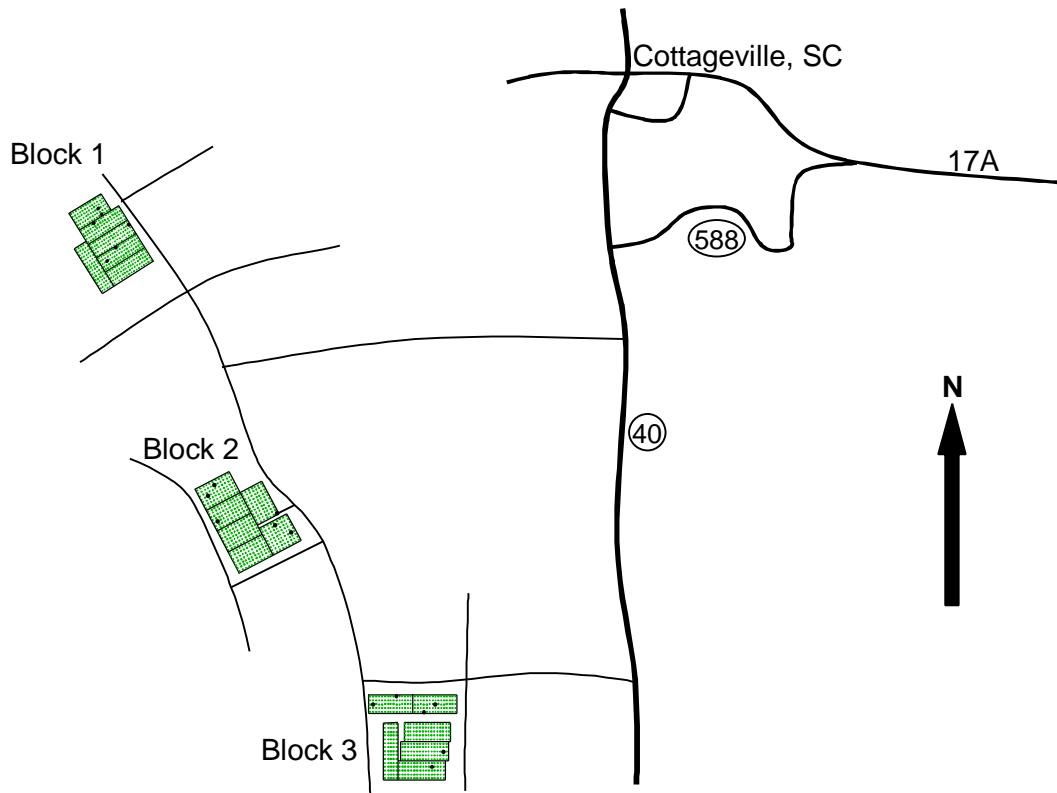
Figure 2.1 Study site location on Westvaco land in Colleton Co., SC.

Three 20 ha, 20-year-old loblolly pine plantations (blocks) were chosen based on differences in drainage ditches and soil types. Each block was subdivided into six 3 ha plots, one of which was left as an uncut control plot. The remaining five plots were treated as follows:

        wet harvested in the spring of 1994, no mechanical site preparation (WF)

        wet harvested in the spring of 1994, bedding site preparation (WB)

        wet harvested in the spring of 1994, mole-plow and bedding site prep (WM)

        dry harvested in the fall of 1993, no mechanical site preparation (DF)

        dry harvested in the fall of 1993, bedding site preparation (DB)

After harvest, all plots were chemically site prepared in July, 1995 with 454 g (16 oz.) of Arsenal (53.1% imazapyr) and 2.3 L (2 qts) of Accord (41.5% glyphosate) per acre. Wet conditions at the time of harvest in the spring of 1994 resulted in severe disturbance, including the compaction, rutting and churning of soil material. The dry-harvest

operation caused only soil compaction. A survey crew mapped the soil disturbance on each plot within each block into 5 classes: undisturbed, compression track, shallow rut, deep rut, churned (Preston, 1996). The undisturbed class was assigned to areas that had no visual signs of soil disturbance, the compression track class was for those areas where soil was visually compacted without plastic or liquid soil movement, the shallow rut class was assigned to areas where ruts were $\leq$ 20 cm, the deep rut class was for ruts > 20 cm, and the churned class was for those areas where soil disturbance resulted in a mixing of surface and some subsurface soil, rendering it massive (Figure 2.2). Preston (1996) reported that on average, 77% of the wet harvested area was disturbed, with 22% showing compression tracks, 31% shallow ruts, 20% deep ruts, and 4% churning. The dry-harvest operation caused only soil compaction, which covered 8% of the total dry-harvested area leaving the remaining land visually undisturbed.

For the purposes of this study, vegetation treatment sites were established across all disturbance classes, but only within the WF, WB, DF and DB treatment plots, across all three blocks (Figure 2.3).
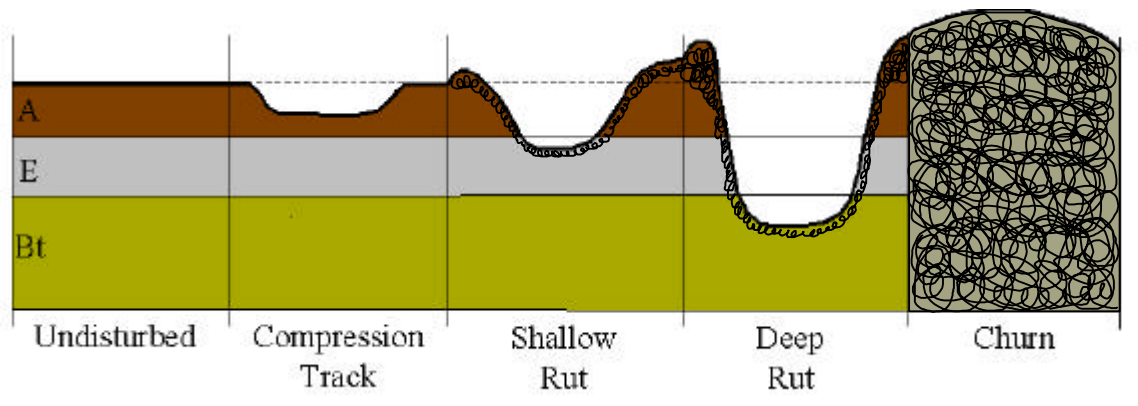
Figure 2.2 Diagram of soil disturbance classes used to characterize the post-harvest disturbance, showing effects on soil horizons.
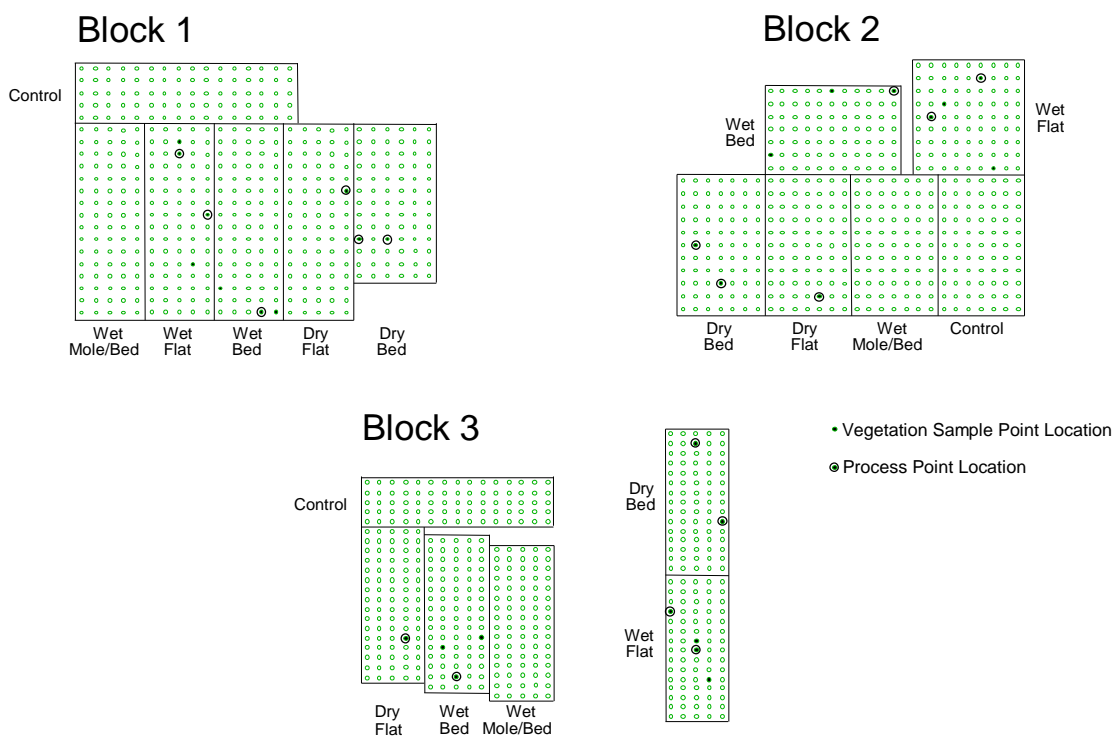
Figure 2.3 Diagram of vegetation treatment plots within overall study design plots in Colleton Co., SC.

Plot Layout and Experimental Design

In order to determine the role of herbaceous vegetation in the recovery of soil properties and processes, treatment plots consisting of a gradient of three different vegetation intensities were established within each of the five disturbance types, on both bedded and flat-planted sites. The vegetation control treatment gradient was composed of three levels: the vegetated control, operational control and complete vegetation control. The vegetated control sub-plots were protected from the initial herbicide application using plastic tarps. Prior to seedling planting, operational sub-plots were sprayed aerially with 113 g (4 oz.) of Oust (75% sulfometuron-methyl) and 14 g (0.5 oz.) of Escort (60% metsulfuron-methyl) per acre. Vegetation-free sub-plots were treated as needed to maintain nearly-complete non-crop weed control throughout the first two growing seasons. In general, a low volume directed spray of 5% (by volume) Accord (41.5% glyphosate) plus surfactant was applied with a backpack sprayer to achieve

partial coverage of individual target plants. The three sub-plot vegetation levels occurred randomly within each treatment plot (Figure 2.3)

Data were analyzed using analysis of variance and regression with SAS PROC MIXED and PROC REG procedures, respectively (SAS Institutes, 1985). Analysis of variance was performed using the split plot, factorial model within a randomized complete block design (Tables 2.1, 2.2, and 2.3). Statistical differences ($\alpha \leq 0.10$) were calculated using Tukey's mean separation.

Table 2.1. Statistical model with 2 levels of site preparation treatments crossed with 5 levels of soil disturbance, split with 3 levels of vegetation control, within 3 blocks.

Source of Variation	Degrees of Freedom
Block	(b-1)=2
Site Prep	(s-1)=1
Soil Dist.	(d-1)=4
Site Prep*Soil Dist.	(s-1)*(d-1)=4
Error A	
Block*Site Prep*Soil Dist.	(b-1)*(s-1)*(d-1)=8
Block*Site Prep	(b-1)*(s-1)=2
Block*Soil Dist.	(b-1)*(d-1)=8
	18
Veg	(v-1)=2
Veg*Site Prep	(v-1)*(s-1)=2
Veg*Dist. Class	(v-1)*(d-1)=8
Veg*Site Prep*Soil Dist.	(v-1)*(s-1)*(d-1)=8
Error C	
Block*Veg*Site Prep*Soil Dist.	(b-1)*(v-1)*(s-1)*(d-1)=16
Block*Veg*Soil Dist.	(b-1)*(v-1)*(d-1)=16
Block*Veg*Site Prep	(b-1)*(v-1)*(s-1)=4
Block*Veg	(b-1)*(v-1)=4
	40
Total	(b*s*d*v)-1=89

Table 2.2. Statistical model with 2 levels of site preparation treatments crossed with 3 levels of soil disturbance, split with 3 levels of vegetation control, within 3 blocks.

Source of Variation	Degrees of Freedom
Block	(b-1)=2
Site Prep	(s-1)=1
Soil Dist.	(d-1)=2
Site Prep*Soil Dist.	(s-1)*(d-1)=2
Error A	
Block*Site Prep*Soil Dist.	(b-1)*(s-1)*(d-1)=4
Block*Site Prep	(b-1)*(s-1)=2
Block*Soil Dist.	<u>(b-1)*(d-1)=4</u>
	10
Veg	(v-1)=2
Veg*Site Prep	(v-1)*(s-1)=2
Veg*Dist. Class	(v-1)*(d-1)=4
Veg*Site Prep*Soil Dist.	(v-1)*(s-1)*(d-1)=4
Error C	
Block*Veg*Site Prep*Soil Dist.	(b-1)*(v-1)*(s-1)*(d-1)=8
Block*Veg*Soil Dist.	(b-1)*(v-1)*(d-1)=8
Block*Veg*Site Prep	(b-1)*(v-1)*(s-1)=4
Block*Veg	<u>(b-1)*(v-1)=4</u>
	24
Total	(b*s*d*v)-1=53

Table 2.3. Statistical model with 2 levels of site preparation treatments crossed with 5 levels of soil disturbance, split with 2 levels of vegetation control, within 3 blocks.

Source of Variation	Degrees of Freedom
Block	(b-1)=2
Site Prep	(s-1)=1
Soil Dist.	(d-1)=4
Site Prep*Soil Dist.	(s-1)*(d-1)=4
Error A	
Block*Site Prep*Soil Dist.	(b-1)*(s-1)*(d-1)=8
Block*Site Prep	(b-1)*(s-1)=2
Block*Soil Dist.	<u>(b-1)*(d-1)=8</u>
	18
Veg	(v-1)=1
Veg*Site Prep	(v-1)*(s-1)=1
Veg*Dist. Class	(v-1)*(d-1)=4
Veg*Site Prep*Soil Dist.	(v-1)*(s-1)*(d-1)=4
Error C	
Block*Veg*Site Prep*Soil Dist.	(b-1)*(v-1)*(s-1)*(d-1)=8
Block*Veg*Soil Dist.	(b-1)*(v-1)*(d-1)=8
Block*Veg*Site Prep	(b-1)*(v-1)*(s-1)=2
Block*Veg	<u>(b-1)*(v-1)=2</u>
	20
Total	(b*s*d*v)-1=59

CHAPTER III

Role of Vegetation in Mitigating Soil Quality in a
Two-Year-Old Loblolly Pine Plantation

INTRODUCTION

Concern over the effect of harvesting disturbance on sustained forest and soil productivity has raised questions about the role of roots and soil flora and fauna in natural soil amelioration. Competitive non-crop vegetation is commonly controlled during site preparation in intensively managed plantation forests because of the growth response of southern pine seedlings to weed control; however, the benefits of a diverse herbaceous cover following disturbance and the role non-crop vegetation plays in mitigating soil quality are not well known.

Harvesting operations on poorly drained sites in the lower Coastal Plain can cause severe soil disturbance including compaction, rutting and churning (Aust *et al.*, 1993, Gent *et al.*, 1983). Soil compaction generally results in an increase in bulk density due to the consolidation of soil particles as air-filled voids are reduced. This results in increases in bulk density and soil strength, and decreases in macroporosity and saturated hydraulic conductivity (Greacen and Sands, 1980). Consequently, crop tree growth may be reduced due to poor soil aeration and a restricted, unfavorable rooting environment.

When trafficking occurs under saturated conditions and pores are water-filled, soil may flow, resulting in rutting and churning of surface soil layers (Aust *et al.*, 1993). The characteristics of this churning and puddling are a destruction of natural soil structure, stability and aggregation (Koenigs, 1963). The soil becomes uniform and massive, which may limit crop tree growth and reduce long-term site productivity.

Many silvicultural treatments, including bedding, ripping and disking are imposed to mitigate the effects of harvesting disturbance; however, these efforts to restore favorable soil properties may be short-lived or may be counterproductive (Greacen and Sands, 1980). In poorly drained lower Coastal Plain sites, the benefits of bedding to crop

tree survival and growth are well-documented (McKee and Shoulders, 1974, McKee, 1989). Bedding creates an elevated, well-drained and aerated rooting zone for early pine growth. The effectiveness of bedding in restoring the soil physical environment for crop tree growth following disturbance, however, is not well known.

Natural processes such as weathering, the shrinking and swelling of 2:1 clays (McGowan *et al.*, 1983, Sarmah *et al.* 1996), soil biological activity (Oades, 1993) and the active probing and sloughing of plant roots (Larson and Allmaras, 1971, Perfect *et al.*, 1990a), also help to restore soil properties in the lower Coastal Plain following disturbance. Of the natural recovery processes in this area, we hypothesized that root exploitation and the increased biological activity associated with the rhizosphere are the most important. The influence of the soil biota in the creation and stabilization of soil aggregates is well documented. Especially in soil where organic matter is a major binding agent, plant roots and soil fauna contribute greatly to the formation and stability of soil aggregates (Jastrow and Miller, 1991). Structural pores are created and soil strength is reduced by the active growth and sloughing of roots. Mycorrhizal hyphae and root mucigels have been observed to enmesh soil particles, and to contribute the formation and stabilization of macro-aggregates (Jastrow and Miller, 1991). The presence of a dense and diverse below-ground root system promotes soil biological processes including decomposition and nitrogen mineralization. Symbiotic plant-microbe associations may improve the soil environment and increase crop species productivity.

Non-crop vegetation in pine plantation systems, however, is commonly controlled with herbicides due to the positive response of pines to competition control. The increased survival and growth of seedlings as a result of competition control is well documented (Morris *et al.*, 1993, USDA Forest Service, 1984, Miller *et al.*, 1991, and Cain, 1991). The consequences of herbaceous vegetation removal for soil recovery and soil and forest productivity, however, have not been thoroughly explored.

Accordingly, the objectives of this study were:
1. To determine if soil disturbance during harvesting operations affects soil properties important for plant growth and productivity.

2. To evaluate the effectiveness of bedding site preparation in recovering soil processes and productivity following disturbance.

3. To determine if different levels of vegetation control have differential effects on soil processes which aid in the recovery and maintenance of soil productivity.

MATERIAL AND METHODS

Site Description and Research Design

The research site was established in a wet pine flat, intensively managed for loblolly pine production and located on the Coastal Plain of South Carolina, in Colleton County. The poorly drained soils on the study site, which were derived from marine and fluvial deposits, are dominated by two soil types, Argent loam (Ochraqualf) and Santee loam (Argiaquoll) (Stuck, 1982). The average annual rainfall in this warm temperate region is 132 cm with 82 cm falling between March and October. The average temperature between March and October is 31°C and between November and February is 18°C (Stuck, 1982).

The experiment was 2 x 3 factorial split plot with a randomized complete block design, where blocks were chosen based on differences in drainage ditches and soil types (Figure 3.1). Factorial treatments included three levels of harvesting disturbance (none, compression track, and churn) and two types of site preparation (none or flat planted, and bedded). Each disturbance/site preparation combination was split into three 3.05 m by 6.10 m plots which received different levels of herbaceous weed control (none, operational control and complete control). The soil disturbance gradient was achieved as a result of operational scale harvesting under both dry and wet conditions in the fall of 1993 and spring of 1994. Following clearcutting, soil disturbance was classified as described by Preston (1996). On average, 77% of the wet harvested area was disturbed, with 22% showing compression tracks, 31% shallow ruts, 20% deep ruts, and 4% churning. The dry-harvest operation caused only soil compaction, which covered 8% of the total dry-harvested area leaving the remaining land visually undisturbed Preston,

1996). In 1995, site preparation treatments were installed (see Kelting *et al.* 1999 for a detailed description of silvicultural methods and equipment used) and the sites were planted with one-year-old loblolly pine bare-root seedlings from genetically-improved seed stock.

The vegetation control treatment gradient was composed of three levels: the vegetated control, operational control and complete vegetation control. The vegetated control sub-plots were protected from the initial herbicide application using plastic tarps. Prior to seedling planting, operational sub-plots were sprayed aerially with 113 g (4 oz.) of Oust (75% sulfometuron-methyl) and 14 g (0.5 oz.) of Escort (60% metsulfuron-methyl) per acre. Vegetation-free sub-plots were treated as needed to maintain nearly complete non-crop weed control throughout the first two growing seasons. In general, a low volume directed spray of 5% (by volume) Accord (41.5% glyphosate) plus surfactant was applied with a backpack sprayer to achieve partial coverage of individual target plants.

Figure 3.1. Schematic of research plots showing soil disturbance, site preparation and vegetation treatments for the 2x3 factorial with split, randomized complete block study design, Colleton Co., South Carolina.

Field and Laboratory Methods

In order to characterize soil processes within vegetation, disturbance class, and site preparation treatments, a series of in situ measurements was taken bimonthly for one year beginning in June 1997. A single, representative measurement point was chosen within each of the three vegetation treatment plots. For non-bedded sites, the process point was located in a micro-site area that corresponded to the broader scale disturbance classification (no disturbance, compression track and churn), and in bedded sites the process point location was located on top of the bed.

Volumetric soil moisture, nitrogen mineralization and aerated soil volume data were collected at each soil process point (Figure 3.2). Time Domain Reflectometry (TDR) was used to measure the soil volumetric moisture content (TRASE System, Soil Moisture Equipment Corp., Goleta, CA). A set of TDR wave guide rods was vertically inserted into the upper 30 cm of soil at each sample point. In addition, the volume of aerated soil was determined by measuring the depth to a reduced zone on a buried iron rod (Carnell and Anderson, 1986; Bridgham *et al.*, 1991).

Nitrogen mineralization was determined using a standard buried bag technique (Eno, 1960). A portion of a composite loose soil sample from the surface 30 cm at each point was air dried to a workable moisture content, sieved (2 mm mesh) and analyzed for available inorganic nitrogen (NO_3-N and NH_4-N). The other portion was buried for two months in a sealed polyethylene bag, 5 cm beneath the soil surface, prior to the available nitrogen extraction. Inorganic soil nitrogen was extracted from ~5 g (dry mass) of soil using 100 ml of 2M KCl. After shaking for 1 hour, samples were filtered (Whatman No. 1) and filtrate was analyzed colorometrically using a Technicon Autoanalyzer II (Technicon, 1973). Data were converted to kg/ha using bulk density measurements.

Four core samples (5 cm long, 4.8 cm diameter) were collected from the mineral soil between a depth of 5 and 10 cm in each treatment plot in June 1997 and 1998. For each year, two cores were used to determine bulk density (Blake and Hartge, 1986), total porosity, capillary porosity (Danielson and Sutherland, 1986), saturated hydraulic conductivity (Ksat) (Klute and Dirksen, 1986), and air permeability (Corey, 1986). The remaining two cores were air dried and broken on planes of weakness. Aggregates

>1mm and <2mm were analyzed for percent stable aggregate determination using a standard wet sieve method (Kemper and Rosenau, 1986).
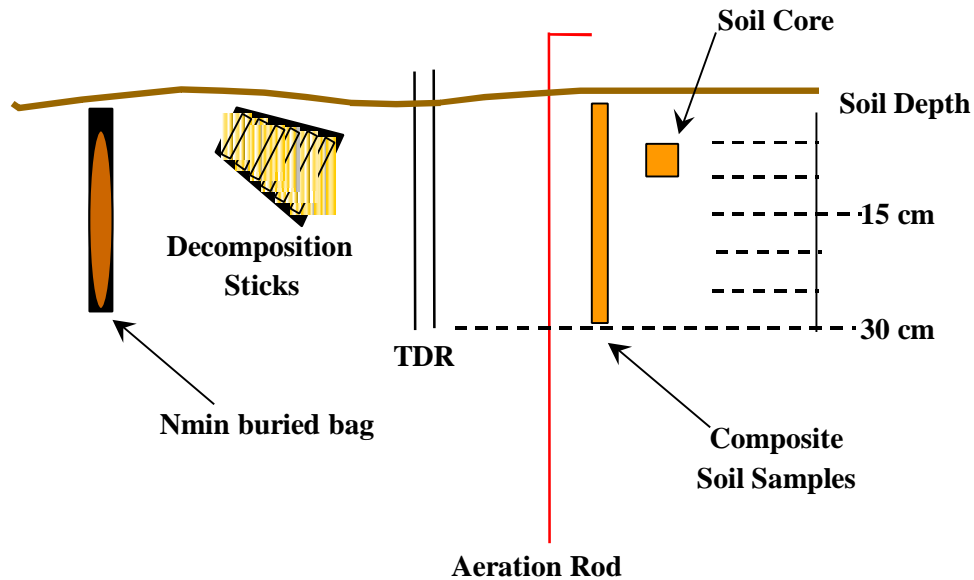
Figure 3.2. Diagram of soil sampling depths on process point locations within each treatment plot.

During the April and June 1998 sampling periods, a composite loose soil sample was collected and analyzed for soil microbial biomass carbon (SMBC) analysis using a chloroform fumigation and carbon extraction procedure (Vance *et al.*, 1987, Wu *et al.*, 1990). For SMBC determination, fresh soil was sieved (0.6 cm mesh) and thoroughly mixed. Duplicate subsamples of approximately 25 g (dry weight basis) of soil were weighed in separate 50-ml beakers and placed in a vacuum desiccator along with a beaker of 25 ml of ethanol-free chloroform ($CHCl_3$) and 100 ml of deionized water. A vacuum was drawn, allowing the chloroform to boil for 5 minutes. The vacuum was slowly released and then drawn three more times for 5 minutes. The desiccator was left under vacuum pressure in a darkened fume hood for 24 hours. Fumigated soils and duplicate samples of unfumigated soil were then extracted with 100ml of 0.5 M K_2SO_4 and filtered (Whatman No. 42) prior to organic carbon analysis by UV-persulfate oxidation using a Dohrman DC 80 automatic analyzer. SMBC was calculated using the following equation:

SMBC = [extractable C (fumigated)-extractable C (unfumigated)] kec

Where Kec is the rate constant (the fraction of SMBC extracted), in this case 0.39. (Sparling and West, 1988)

As an indicator of soil biological activity, the degree and characteristics of wood decomposition were evaluated. Two strips (2 cm by 10 cm by 0.32 cm) of southern yellow pine wood were arranged within a flat mesh (0.32 cm hole openings) bag. Duplicate bags were buried at each treatment point, such that the top of each strip was approximately 5 cm below the soil surface. One decomposition bag was co-located with the bimonthly process-point and the other was buried in an area representative of the treatment plot. To bury the decomposition bags with minimal soil and vegetation disturbance, a spade was driven into the ground at approximately a 30° angle with the soil surface, and was lifted gently to allow room to insert the bag. After insertion, the upper soil block was packed down slightly to ensure good soil-wood contact. Decomposition bags were buried for one year in July 1998. Initial weight of dry (65°C) wood strips were compared to an ash corrected (muffle furnace 500°C) post harvest dry weight for percent weight loss determination.

In the fall of 1997 and 1998, measurements of height and base diameter were recorded for crop-pines falling within each treatment plot. Non-crop vegetation aboveground biomass was sampled every three months for one year, starting in May 1997. All aboveground vegetation within a 30.5 cm by 305 cm belt-transect, oriented lengthwise and reaching half-way across each vegetation sub-plot, was collected for dry mass determination. The sampling period with the largest biomass was considered the peak production period, and the foliage from this sampling period was used as an estimate of aboveground net primary production.

Data were analyzed using analysis of variance (ANOVA) with SAS PROC MIXED procedures (SAS Institutes, 1985). Statistical differences were calculated using Tukey's mean separation ($p \leq 0.10$). A one-way ANOVA was used to test soil disturbance effects for each of the two site preparation treatments (flat-planted and bedded). When no significant interactions were found between soil disturbance and site preparation, the main effect of site preparation was presented as a pooled, main-effect value across soil disturbance and vegetation treatments. A single averaged value of the

1997 and 1998 soil core measurements (bulk density, porosity, Ksat, air permeability) and aggregate stability was used in analysis of all treatment effects because no significant differences were found between years. The results from two sample periods for SMBC data were also averaged prior to statistical analysis.

RESULTS AND DISCUSSION

Soil Disturbance Effect

In order to evaluate the effect of soil disturbance without the confounding effects and added soil disturbance associated with bedding, disturbance treatment were evaluated for flat-planted plots only in this section. Compacted soil samples in compression tracks tended to have lower macroporosity and lower saturated hydraulic conductivity compared to undisturbed soil; however these differences were not significant (Table 3.1). High spatial variability and inadequate sample replication may explain why statistically significant relationships were not found in the data presented here. In addition, soils for this study were collected three years following harvesting disturbance, and differences among disturbance treatments may be less pronounced due to natural soil recovery processes since disturbance occurred.

Several recent studies show that harvesting operations resulting in compression tracks cause soil compaction as indicated by increases in bulk density and soil strength (Gent *et al.*, 1983, Incerti *et al.*, 1987, Shetron *et al.*, 1988; Aust *et al.* 1995). Results reported by Aust *et al.* (1995) are typical; they found 20% increases in bulk density and 80% and 20% decreases in average soil macroporosity and saturated hydraulic conductivity, respectively, following harvesting disturbance on wet pine flats that had been compacted. These results are consistent with those found in this study; bulk density increased by 4%, and macroporosity and saturated hydraulic conductivity decreased by 25 and 68%, respectively, suggesting that adequate soil aeration may be compromised by the compaction disturbance.

In this study, percent water stable aggregates and a stability index were determined to test for treatment effects on soil structure. When well-aggregated soils are

subjected to compactive forces, soil structure changes as aggregates are crushed and soil particles fill pore spaces (Lull, 1959). These changes may be reflected in the stability of soil aggregation and structure. A stability index based on the work of Reeve (1953) and modified by Whelan *et al.* (1995) was determined by comparing the relative permeabilities of soil to water and air. Based on this theory, a soil with poor structure would be less permeable to water (a ratio of air to water permeability less than unity) due to the instability of the soil when subjected to the wetting and slaking action of water. In this study, compacted soil aggregates appeared to be less stable than undisturbed soil aggregates (Table 3.1), but again, these average values across blocks were not significant.

In spite of severe soil mixing, churning, and rearrangement of surface soils by logging machinery, measured soil physical properties in the churned treatment were not different from the undisturbed (non-trafficked) treatment. These findings differ from the results of most previous studies where churning caused soils to become puddled, generally resulting in increased bulk density, and decreased macroporosity and hydraulic conductivity (Koenigs, 1963, Bodman and Rubin, 1948, Aust *et al.*, 1995). However, on this site, large amounts of litter, slash, and other coarse woody debris were incorporated into the surface 30 cm of the soil profile. The soil was kneaded and churned, but net changes in hydraulic properties, aeration and soil density were not observed due to the presence of coarse organic debris.

Table 3.1. Disturbance and site preparation effect on soil properties. Flat planted and bedded treatments analyzed separately, then pooled when no significant interactions were found between site preparation and soil disturbance treatments. (Unlike letters within treatments represent significant differences at $p < 0.1$.)

	Bulk Density (g/cm^3)	Total Porosity (%)	Aeration Porosity (%)	Ksat (cm/hr)	Stability Index x10^-13	Aggregate Stability (%)	Aeration Depth (cm)	Y. Pine Wt. Loss (%)	SMBC (ug/g soil)	Nmin (kg/ha/yr)
Flat Planted										
None	1.42	48.1	10.6	13.2	1.32	77.4	23	35.0	457	46.9b
Comp. Track	1.47	47.0	7.9	4.2	1.19	63.5	24	39.6	537	56.8ab
Churned	1.40	48.7	10.1	12.2	1.35	73.5	23	46.6	511	101a
Bedded										
None	1.20	57.5	11.1	16.6	1.19	77.3	23	59.4	707	109a
Comp. Track	1.10	59.6	13.0	35.8	1.65	76.4	23	43.4	710	43.2b
Churned	1.28	54.2	11.7	13.5	1.45	71.1	24	29.5	528	69.3ab
Pooled										
Flat Planted	1.43a	48.0b	9.6b	----	1.29	71.5	21	40.4	502b	----
Bedded	1.19b	57.1a	11.9a	----	1.43	74.9	23	44.1	648a	----

Biological activity, measured by rate of wood decomposition, microbial biomass, and nitrogen mineralization was enhanced by the disturbance (Table 3.1). Soil churning caused the rate of nitrogen mineralization to double from 47 to 101 kg ha^{-1} yr^{-1}. This higher level of biological activity soon after harvesting is consistent with the literature (e.g., Burger and Pritchett, 1988). Slash that was mixed into the soil profile on the churned sites is more accessible because of its proximity to mineral soil, and populations of soil organisms may grow in response to a larger substrate pool. Accelerated decomposition and mineralization may not, however, be desirable in young forest systems if the increased supply of nutrients greatly exceeds the seedling demand, and nutrient pools for future use are diminished by leaching (Burger and Pritchett, 1984, Vitousek and Matson, 1985a).

Neither soil compaction nor soil churning had a negative effect on two-year pine growth and aboveground net primary production (ANPP) (Figures 3.3 and 3.4). The trend of increasing production with increasing soil disturbance in flat-planted sites, suggests that planted pines and herbaceous pioneer species may temporarily benefit from disturbance-induced increases in micro-topography and nutrient supply. These results differ from most of the literature which generally reports negative effects of increasing disturbance on plant production (Skinner *et al.*, 1989). However, it remains to be seen how these disturbances will affect tree growth with time as the trees are forced to exploit larger soil volumes.
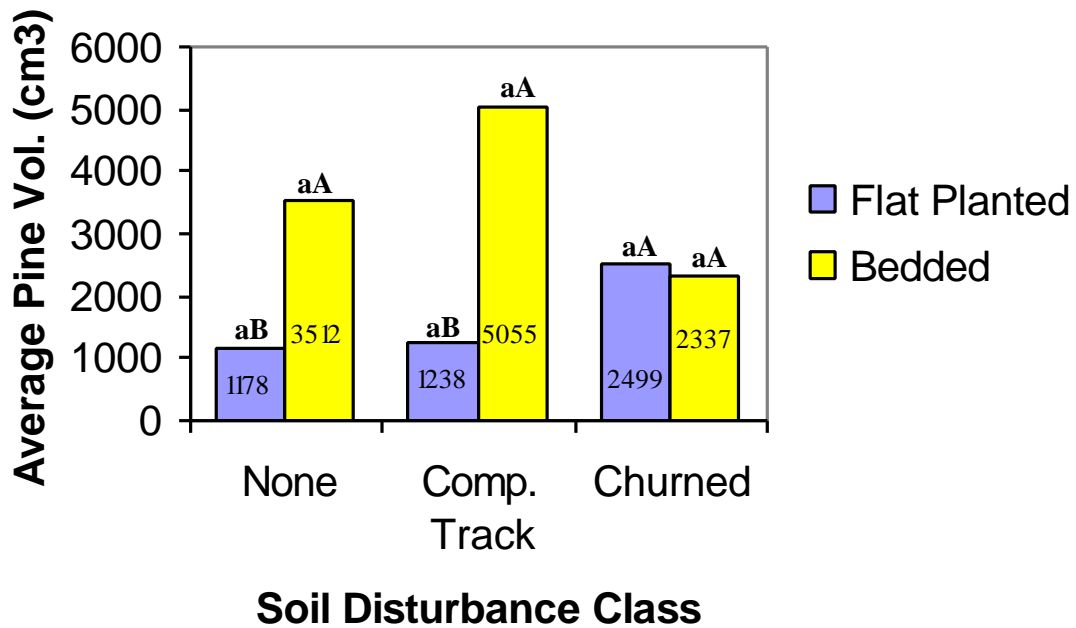
Figure 3.3. Disturbance effect on early pine productivity. (Within site preparation, differing lower case letters represent significant differences at p<0.1; within disturbance class, differing capital letters denote significance.)
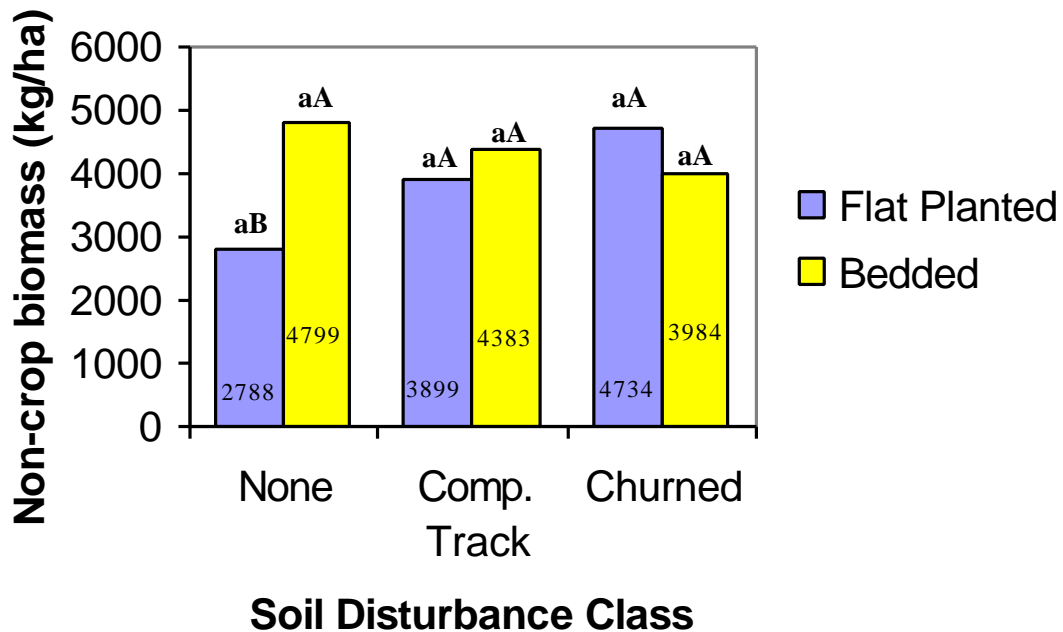
Figure 3.4. Non-crop vegetation biomass as a bioassay of site productivity. (Within site preparation, differing lower case letters represent significant differences at p<0.1; within disturbance class, differing capital letters denote significance.)

Bedding Effect

Bedding improves the appearance of severely disturbed clear-cut sites, however the effectiveness of bedding in restoring soil productivity has been questioned, especially in areas where soil disturbance extends below surface soil horizons (Gent *et al.*, 1983). In this study, bedding generally improved the soil physical properties of compacted and churned soil, and based on the properties we measured, soils appear to be fully ameliorated. When data from all disturbance classes were pooled, bedding reduced bulk density values by 17 % and total porosity and macroporosity were increased by 19 and 24%, respectively (Table 3.1). There was significantly more SMBC on bedded sites compared to flat-planted sites, and although not statistically significant, aggregate stability, aeration depth, and the degree of wood decomposition were greater with bedding. Overall soil biological activity is higher due to the mixing of surface soil and the creation of a more aerated soil environment.

Bedding on undisturbed and compacted treatments significantly increased pine volume, however no increase was observed on the churned sites (Figure 3.3). Churned areas on non-bedded sites have the advantage of being slightly elevated above undisturbed and compacted areas. In wet flats, subtle changes in elevation greatly influence seedling survival and growth due to characteristically high water tables and poor soil aeration. If bedding and churning both serve to create a more aerated rooting environment, then it is logical that further improvements in seedling productivity would not be observed when churned areas are bedded. In fact, pine productivity was lower on bedded-churned areas than on bedded-undisturbed and compression tracked sites. Bed quality may have been reduced by severe soil disturbance.

Vegetation Effect

As expected, pine growth increased significantly with increasing vegetation control (Figure 3.5). These results are consistent with the findings of other studies (USDA Forest Service, 1984; Cain, 1991; Miller *et al.*, 1991). There were, however, only small gains in pine production achieved with the operational level of control

because, on average, operational levels of vegetation control decreased non-crop vegetation biomass by only 17 % (Figure 3.6). Pine response between fully vegetated and operationally-controlled plots were significant when sites were bedded, due to an interaction between site preparation and vegetation treatments (Figure 3.5). Complete control of herbaceous vegetation on bedded sites caused a dramatic increase in pine volume. Bedding and vegetation control acted synergistically to double and more than quadruple the average pine volume on the operational and total vegetation control plots respectively. Controlling non-crop vegetation gives planted pines a competitive advantage, but this early pine response must be weighed against suppressing the growth of vegetation that may enhance soil quality.
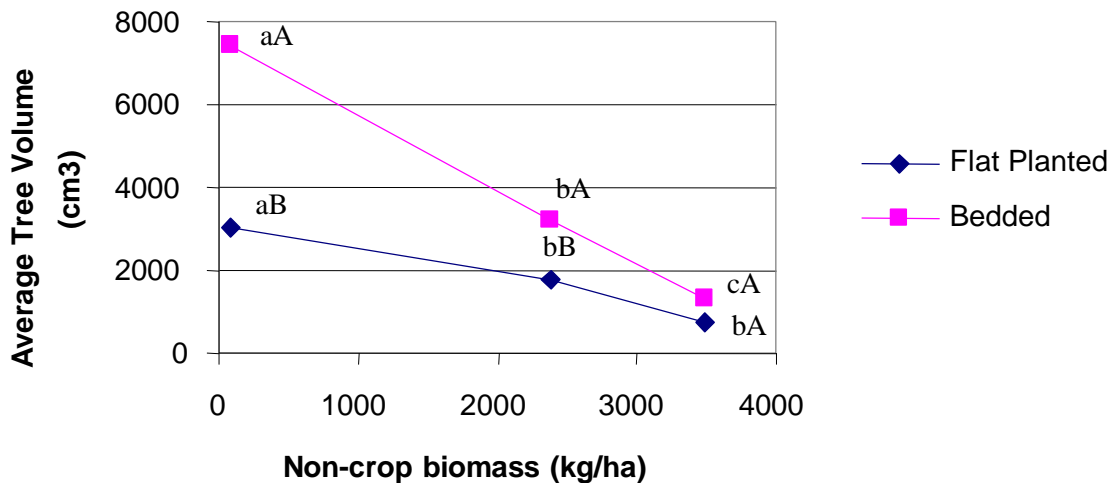
Figure 3.5. Pine volume response to vegetation control treatments which have been converted to aboveground biomass data based on average dry weight data for each treatment. (Within site preparation, differing lower case letters represent significant differences at $p<0.1$; within vegetation level (biomass), differing capital letters denote significance.)
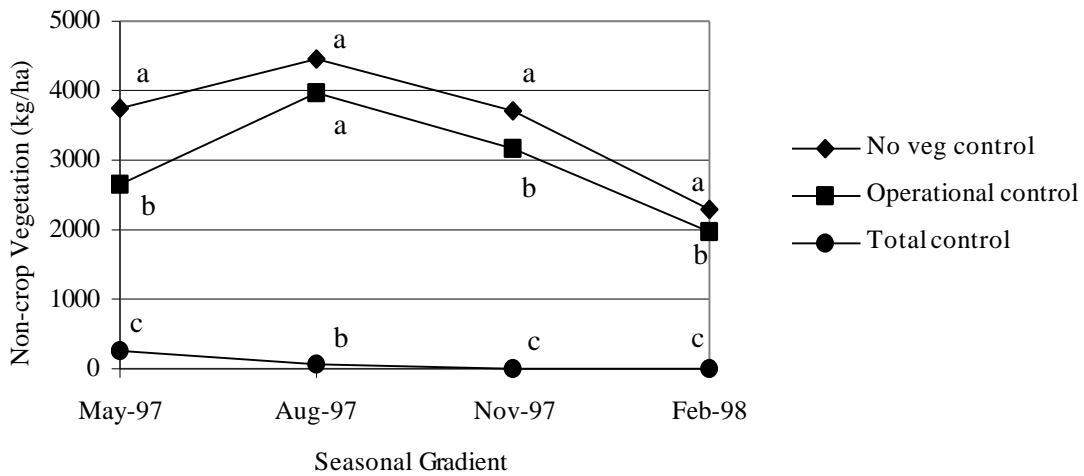
Figure 3.6. Seasonal dynamics of non-crop vegetation showing peak production in August and significant differences among vegetation within each season when letters are dissimilar.

Soil quality may be described as the ability of a soil to fulfill certain functions. One such function is maintaining tree productivity, and key attributes of this function include: promoting root growth, providing for optimum gas exchange and promoting soil biological activity (Kelting *et al.*, 1999). We hypothesized that increasing amounts of herbaceous vegetation could have a positive influence on these soil quality attributes. In order to better visualize the effect of different levels of vegetation control on soil quality, data are presented in the context of sufficiency curves, where a value of one denotes sufficiency for the given soil property (Figure 3.7).
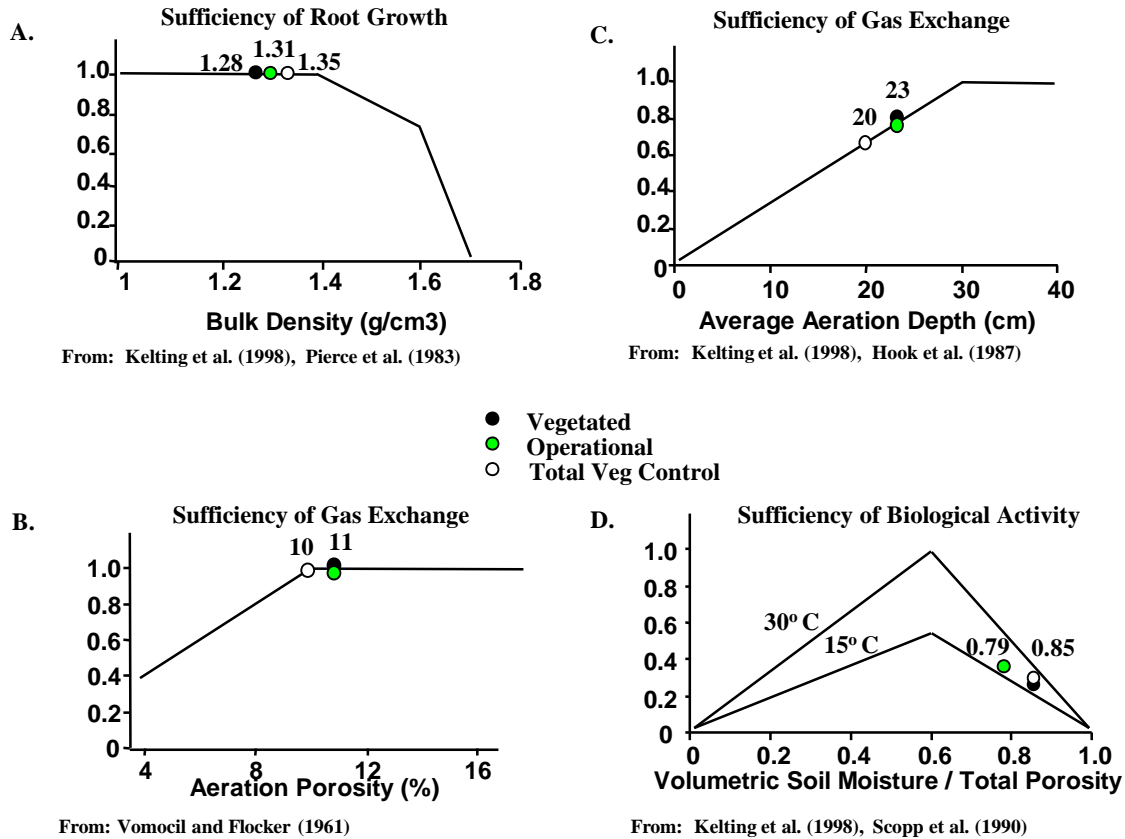
Figure 3.7. Sufficiency curves for vegetation treatment effect on the soil rooting environment (A), aeration (B and C), and soil biological activity (D). (No significant treatment effects were found for any of the soil quality attributes.)

Root growth has been found to be restricted in fine, silty soils having bulk densities above 1.4 g/cm^3 (Pierce *et al.*, 1983). The average bulk density values for all our vegetation treatments fall within this threshold for sufficient root growth (Figure 3.7A); however, there is a trend of increasing soil bulk density with increasing vegetation control. Soil structure and stability are additional indicators of the quality of the soil environment for root growth. On flat-planted plots, percent water stable aggregates increased with decreasing vegetation control intensity (Figure 3.8). This relationship, however, does not hold on the bedded sites where differences among vegetation treatments are not significant. Depending on the species of vegetation present, plant roots may or may not improve soil structure and stability, however, cultural

activities such as bedding generally decrease soil aggregate stability (Lynch, 1984). Miller and Jastrow (1990) concluded that nearly all below-ground biota contribute to the formation and stabilization of soil aggregates, and root activity is especially important in soils such as those at our study site where organic matter is a major binding agent.
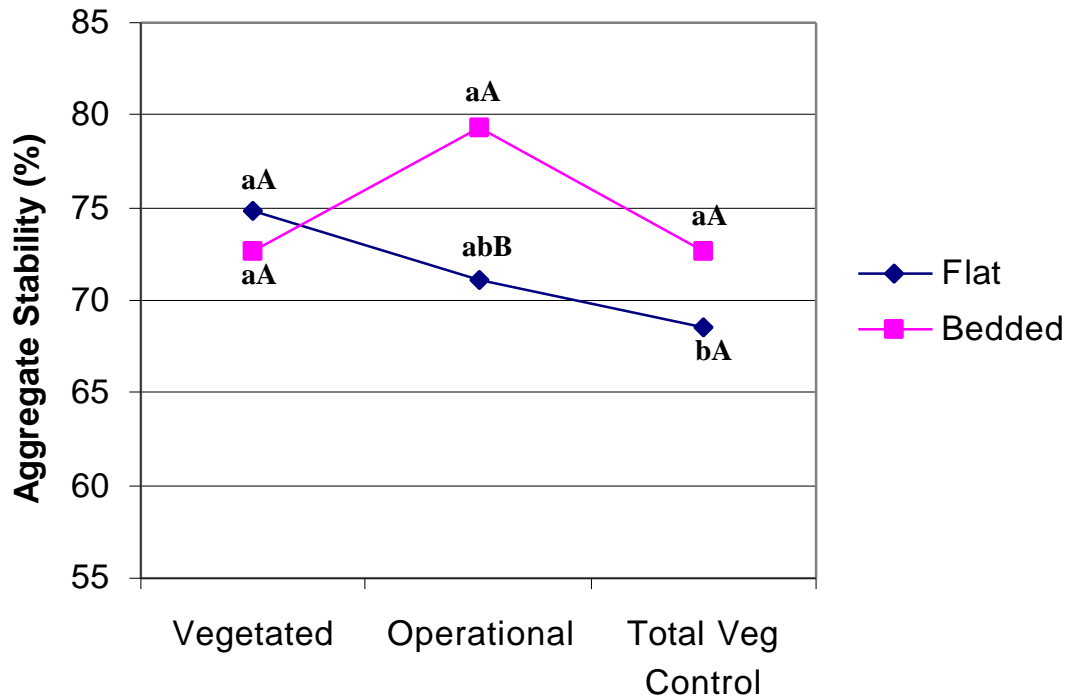
Figure 3.8. Interaction between vegetation treatment and site preparation. (Within site preparation, differing lower case letters represent significant differences at p<0.1; within vegetation treatment level, differing capital letters denote significance.)

Soils in the total vegetation control treatment have slightly lower average values for macroporosity; however, in all plots, macroporosity was > 10% which is considered sufficient (Figure 3.7B). Overall, aeration depth was inadequate and herbaceous vegetation improved it slightly. Total porosity was also 4% higher on the vegetated plots than on the total vegetation control treatment (Table 3.2). In the total vegetation control treatment, there were probably fewer root channels which typically provide a connective matrix of soil pores for improved drainage and aeration. Saturated hydraulic conductivity, however, appears to be unaffected by the differing vegetation treatment

levels, suggesting that the presence of non-crop vegetation did not significantly affect soil permeability (Table 3.2).

Table 3.2. Vegetation treatment effect on soil properties. (Treatments that differ significantly (p<0.1) are followed by dissimilar letters.)

	Total Porosity (%)	Ksat (cm/hr)	Stability Index x10^-13	Y. Pine Wt. Loss (%)	SMBC (ug/g soil)	Nmin (kg/ha/yr)	Avg. Soil Temp (kg/ha/yr)
Pooled							
Vegetated	54.3a	14.6	1.50	45.8	608a	61.6	18b
Operational	52.8ab	18.2	1.31	41.3	602a	74.6	18b
Total Veg Control	50.4b	14.9	1.26	39.6	516b	77.0	20a

A curve developed by Kelting *et al.* (1999) was used to present differences in the sufficiency of biological activity for pine growth. The model was created based on the work of Skopp *et al.* (1990) who studied the relationship between soil moisture and total porosity and found that soil biological activity was maximized at a moisture content of 60% of total porosity. No statistical differences or consistent trends were found among our vegetation treatments based on the soil water/porosity sufficiency function (Figure 3.7D); however, consistent trends were found for other indicators of soil biological activity. SMBC was 15% lower on the total vegetation control treatment plots than on the vegetated treatment plots (Table 3.2), which may offer support for our hypothesis that the presence of roots promotes soil biological activity. The results from a study conducted by Busse *et al.* (1996) where understory vegetation was suppressed in a ponderosa pine forest also showed higher SMBC when vegetation was present.

The trend in wood decomposition rate further supports our hypothesis that soil biological activity is reduced as a result of controlling vegetation (Table 3.2); however, the coefficients of variation for the three variables were all greater than 50 percent. Bimonthly measurements of net nitrogen mineralization were also extremely variable within vegetation treatments. The trend suggests that greater nitrogen immobilization occurs with more microbial biomass.

CONCLUSIONS

Soil disturbance during harvesting operations had relatively small effects on soil quality. Compaction disturbance may compromise adequate soil aeration as indicated by increases in bulk density and decreases in macroporosity and hydraulic conductivity. Soil churning, however, did not degrade the soil physical environment, largely because slash and litter were incorporated into surface soil horizons. Disturbance enhanced soil biological activity as measured by decomposition rates, microbial biomass and nitrogen mineralization. Accordingly, a trend of increasing pine and non-crop vegetation production was observed with increasing disturbance suggesting that plants may temporarily benefit from disturbance-induced improvements in microtopography and nutrient supply. Therefore, this may be positive in the short term, but long-term effects of accelerated soil biological activity are uncertain. Bedding fully ameliorated the effects of soil compaction based on the physical properties measured, however, bed quality may be compromised on churned sites as indicated by lower pine productivity on the churned bedded treatment.

Trends suggest some improvements in soil quality with increasing levels of non-crop vegetation biomass; however, during two years of operational vegetation control, the beneficial effects of the non-crop vegetation were marginal. Vegetated treatment plots were generally more aerated, had lower bulk densities and higher aggregate stabilities. The most dramatic improvement in plant growth was seen when the effects of bedding and vegetation control were combined; pine growth increased by nearly 800%. I am concerned, however, that a combination of bedding and vegetation control, which typically increases nitrogen mineralization, might increase nitrogen leaching losses early in plantation development, and lead to productivity declines at stand closure and beyond due to depleted nitrogen reserves.

CHAPTER IV

Silvicultural Effects of Soil Nitrogen in a Two-Year-Old
Loblolly Pine Plantation

INTRODUCTION

Low nitrogen availability often limits pine productivity in Southeastern Coastal Plain forest systems. Despite low levels of ecosystem nitrogen, undisturbed conifer ecosystems are extremely efficient at retaining nitrogen and limiting leaching losses (Gosz, 1981). This efficiency and balance between nitrogen supply and demand may, however, be lost in plantation forests, especially those receiving intensive site preparation and herbaceous weed control (Burger and Pritchett, 1984; Dougherty,1996). Managing plantation forests to better synchronize nitrogen supply and demand may minimize deficiencies and improve long-term forest productivity.

Several researchers have developed conceptual models of the dynamics of nitrogen supply and demand in intensively managed pine plantations (Burger and Kluender, 1982; Allen *et al.*, 1990). Models generally show a surplus of available nitrogen following harvest due to decreased plant uptake (Figure 4.1). The surplus may be compounded by increases in soil microbial activity and mineralization rates due to harvesting and site preparation-induced changes in soil temperature, moisture content, and organic matter concentration (Matson and Vitousek, 1981; Burger and Pritchett, 1984). Among the factors that control the rate of organic matter decomposition are moisture content, temperature, and juxtapositioning of organic matter and mineral soil (Waring and Schlesinger, 1985). Warmer and moister conditions following forest cutting can increase decomposition rates, causing more rapid conversion of organic nitrogen to inorganic forms, thus increasing the available nitrogen pool (Binkley, 1984). In addition, when surface soils are disturbed and churned during harvesting or site preparation activities, logging slash may be mixed with mineral soil, causing decomposition processes to accelerate provided soils are not water-logged. Initially, nitrogen may be

immobilized if the added organic substrate causes increases in microbial populations; however, net mineralization will occur once microbial demands for nitrogen are met and the carbon to nitrogen ratio narrows.

Surplus nitrogen, especially if in the highly mobile form of nitrate (NO_3^-), may be lost from forest plantation systems by leaching or by denitrification. This loss of nitrogen supplying potential may cause future nutrient deficiencies, and compromise overall site productivity. After planting, pine demand for nitrogen increases, and usually exceeds soil supply after stand closure (Figure 4.1). If the reactive pool of nitrogen is not conserved during the prior period of surplus, the productive potential of crop-pines will not be realized.
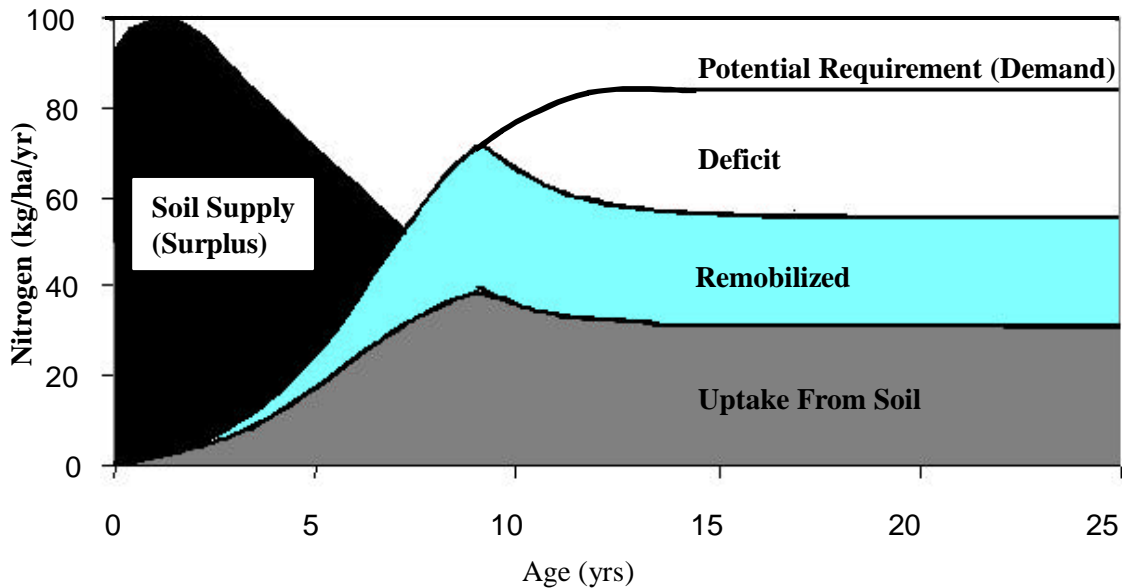
Figure 4.1. Conceptual model of nitrogen supply and demand during a single rotation in a site-prepared loblolly pine plantation. (Adapted from Burger and Kluender, 1982; Allen et al., 1990)

The presence of herbaceous vegetation may help immobilize this surplus pool of nitrogen by cycling it into the soil where it may become available to pines during critical periods of higher nitrogen demand. Burch *et al.* (1997) studied root development and soil nitrogen concentrations in a pine-hardwood forest following harvesting, and found that root density was inversely correlated with nitrate concentration. In their study,

herbaceous vegetation had the highest belowground growth rates and therefore, may be critical for retaining nitrogen following harvest. Non-crop vegetation in pine plantation systems, however, is commonly controlled with herbicides due to the positive response of pines to competition control. The increased survival and growth of seedlings as a result of competition control is well documented (Morris *et al.*, 1993, USDA Forest Service, 1984, Cain, 1991; Miller *et al.*, 1991). The longevity of this period of higher productivity might be diminished, however, by the early loss of non-sequestered nitrogen. The role non-crop vegetation plays in synchronizing nutrient supply and demand after harvesting and site preparation-induced disturbances has not been thoroughly explored.

In order to address these issues, the objectives of this study were (i) to determine the effects of harvesting disturbance, bedding, and vegetation control on nitrogen reserves and mineralization, and to (ii) evaluate the importance of non-crop vegetation for nitrogen sequestration.

MATERIAL AND METHODS

Site Description and Research Design

The research site was established in a wet pine flat, intensively managed for loblolly pine production and located on the Coastal Plain of South Carolina, in Colleton County. The poorly drained soils on the study site, which were derived from marine and fluvial deposits, are dominated by two soil types, Argent loam (Ochraqualf) and Santee loam (Argiaquoll) (Stuck, 1982). The average annual rainfall in this warm temperate region is 132 cm with 82 cm falling between March and October. The average temperature between March and October is 31°C and between November and February is 18°C (Stuck, 1982).

The experiment was a split plot in a 2 x 5 factorial within a randomized complete block design, where blocks were chosen based on differences in drainage ditches and soil types (Figure 4.2). Factorial treatments included five levels of harvesting disturbance (none, compression track, shallow rut, deep rut, and churn) and two types of site preparation (none or flat planted, and bedded). Each disturbance/site preparation combination was split into three 3.05 m by 6.10 m plots which received different levels

of herbaceous weed control (none, operational control, and complete control). The soil disturbance gradient was achieved as a result of operational scale harvesting under both dry and wet conditions in the Fall of 1993 and Spring of 1994.

Following clearcutting, soil disturbance was classified as described by Preston (1996). The undisturbed class was assigned to areas that had no visual signs of soil disturbance, the compression track class was for those areas where soil was visually compacted without plastic or liquid soil movement, the shallow rut class was assigned to areas where ruts were $\leq$ 20 cm, the deep rut class was for ruts > 20 cm, and the churned class was for those areas where soil disturbance resulted in a mixing of surface and some subsurface soil, rendering it massive (Figure 2.2). Preston (1996) reported that on average, 77% of the wet harvested area was disturbed, with 22% showing compression tracks, 31% shallow ruts, 20% deep ruts, and 4% churning. The dry-harvest operation caused only soil compaction, which covered 8% of the total dry-harvested area leaving the remaining land visually undisturbed. In 1995, site preparation treatments were installed (see Kelting *et al.* 1999 for a detailed description of silvicultural methods and equipment used) and the sites were planted with one-year-old loblolly pine bare-root seedlings from genetically-improved seed stock.

The vegetation control treatment gradient was composed of three levels: the vegetated control, operational control and complete vegetation control. The vegetated control sub-plots were protected from the initial herbicide application using plastic tarps. Prior to seedling planting, operational sub-plots were sprayed aerially with 113 g (4 oz.) of Oust (75% sulfometuron-methyl) and 14 g (0.5 oz.) of Escort (60% metsulfuron-methyl) per acre. Vegetation-free sub-plots were treated as needed to maintain nearly complete non-crop weed control throughout the first two growing seasons. In general, a low volume directed spray of 5% (by volume) Accord (41.5% glyphosate) plus surfactant was applied with a backpack sprayer to achieve partial coverage of individual target plants.

Soil Disturbance Gradient

Figure 4.2. Schematic representation of study design showing vegetation split plots within a randomized complete block, 2x5 factorial design.

Field and Laboratory Methods

Soil Analysis

In order to obtain representative composite soil samples following harvesting and site preparation treatments, the soil disturbances within each vegetation sub-plot were characterized on a smaller scale (30.5 cm ^{2} grid) in June of 1996. In treatment areas that were flat planted, the micro-site soil disturbance classes were identical to those used to classify the broad scale disturbance (none, compression track, shallow rut, deep rut, and churn). Harvesting disturbance on the bedded sub-plots was masked by subsequent bedding; therefore, these sub-plots were mapped using the following micro-topological classes: top of bed, side of bed, furrow, and inter-bed. A volume-weighted composite soil sample, which reflected the proportions of each micro-site class represented, was collected from each sub-plot. Soil was sampled to a depth of 30.5 cm and air dried to a workable moisture content before sieving (2 mm mesh).

An incubation method described by Burger and Pritchett (1984) and modified from Stanford and Smith (1972) was used to determine nitrogen mineralization potential. For each treatment, a sand/soil mixture of approximately 3:1 was uniformly packed in incubation tubes (3 cm diameter, 15 cm length PVC pipe). Every two weeks, soil in the tubes was flushed with 250 ml of 0.1 M $CaCl_2$, followed by 100 ml of a nitrogen-free nutrient solution. Soil water content was maintained at approximately field capacity, and temperature at $35^{\circ}C$ during the 16-week incubation. Filtrate from the $CaCl_2$ flush (with the exception of the initial flushing) was analyzed for available inorganic nitrogen (NO_3-N and NH_4-N) using a Technicon Autoanalyzer II (Technicon, 1973). Inorganic nitrogen concentrations through time (N_t) were calculated to estimate nitrogen mineralization potential (N_0) and the mineralization rate constant (k) by first order kinetics using the following model (Stanford and Smith, 1972):

$$N_t = N_o(1 - e^{-kt})$$

Initial volume-weighted composite samples were also analyzed for total nitrogen using a standard Kjeldahl block digest procedure (Bremmer and Mulvaney, 1982). Liquid samples from the digestion were analyzed for NH_4^+ colorimetrically using a Technicon Autoanalyzer II (Technicon, 1973). Total carbon was determined by dry combustion and infrared analysis of CO_2 evolved using a LECO CR 12 carbon analyzer.

In situ nitrogen mineralization, volumetric soil moisture, and soil temperature were determined bimonthly for one year beginning in June 1997 for each level of soil disturbance, site preparation, and vegetation-control treatment with the exception of the shallow- and deep-rut soil disturbance levels. Time Domain Reflectometry (TDR) was used to measure the soil volumetric moisture content (TRASE System, Soil Moisture Equipment Corp., Goleta, CA). A set of TDR wave guide rods was vertically inserted into the upper 30 cm of soil at each sample point.

Nitrogen mineralization was determined using a standard buried bag technique (Eno, 1960). A composite loose soil sample from the surface 30 cm at each point was air dried to a workable moisture content, sieved (2 mm mesh), and analyzed for available inorganic nitrogen (NO_3-N and NH_4-N). The other portion was buried for two months in a sealed polyethylene bag, 5 cm beneath the soil surface, prior to the available nitrogen extraction. Inorganic soil nitrogen was extracted from ~5 g (dry mass) of soil using 100

ml of 2M KCl. After shaking for 1 hour, samples were filtered (Whatman No. 1) and filtrate was analyzed colorometrically using a Technicon Autoanalyzer II (Technicon, 1973). Data were converted to kg/ha using bulk density measurements. Four core samples (5 cm long, 4.8 cm diameter) were collected from the mineral soil between a depth of 5 and 10 cm in each treatment plot in June 1997 and 1998. For each year, two cores were used to determine bulk density (Blake and Hartge, 1986).

Vegetation Analysis

In the fall of 1997 and 1998, measurements of height and base diameter were recorded for crop-pines falling within each treatment plot. Aboveground non-crop vegetation biomass was sampled every three months for one year, starting in May 1997. All aboveground vegetation within a 30.5 cm by 305 cm strip-transect, oriented lengthwise and reaching half-way across each vegetation sub-plot, was collected for dry mass determination. The sampling period with the largest biomass was considered the peak production period. The aboveground biomass from this sampling period was used as an estimate of aboveground net primary production and was analyzed for total nitrogen using a standard Kjeldahl block digest procedure (Bremmer and Mulvaney, 1982).

In order to determine the amount of nitrogen sequestered in the aboveground crop-pines, the pine volume data were converted to stem and foliar biomass based on a site-specific regression relationship developed by Kelting (1999). Estimates of stem and foliar nitrogen concentrations were determined based on the literature (Bengtson, 1981) and average pine nitrogen content was determined for each vegetation treatment.

Belowground biomass and nitrogen concentrations for both non-crop vegetation and pines were not determined experimentally, but were estimated based on root to shoot ratios and root nitrogen concentrations reported in previous studies. There are characteristic root:shoot ratios for individual species at different stages of development; however, these ratios and the nitrogen concentration of belowground plant tissues are known to be influenced by environmental conditions such as light, nutrient availability, temperature, and water supply. To the extent possible, data were selected from studies involving similar species and site conditions. For the non-crop species, a generalized root:shoot of 0.6 was selected (Dumortier, 1991; Figiel *et al.*, 1995; Wardle *et al.*, 1998)

and the concentration of nitrogen in root tissue was assumed to be 1% (Nordin and Nasholm, 1997; Pregitzer *et al.* 1997).

Extensive data are available for loblolly pine growth and nutrition. Root:shoot ratios in the literature ranged from 0.16 to 0.46 (Bengtson, 1981; Bongarten and Teskey, 1987; Fredericksen *et al.*, 1993a; Fredericksen *et al.*, 1993b; Schultz, 1997); however the average for young loblolly pines was approximately 0.20, and this was the ratio selected for these calculations. The nitrogen concentration of loblolly pine roots was estimated from the literature to be 0.2% (Bengtson, 1981; Shultz, 1997).

Total nitrogen sequestered was then calculated by summing the aboveground data and belowground estimates of nitrogen content for both crop pine and non-crop vegetation on a per hectare basis.

Statistical Methods

Data were analyzed using analysis of variance (ANOVA) and regression procedures with SAS PROC MIXED and PROC REG procedures, respectively (SAS Institutes, 1985). Statistical differences were calculated using Tukey's mean separation ($p \leq 0.10$). A single averaged value of the 1997 and 1998 soil bulk density measurements was used for conversion purposes because no significant differences were found between years. Estimates of N_o and k were made using a nonlinear approximation procedure with SAS PROC NLIN (SAS Institutes, 1985).

RESULTS AND DISCUSSION

Nitrogen mineralization potentials (N_o) across all disturbance treatments averaged 63 ug g^{-1}, which amounts to 167 kg ha^{-1} in the surface 20 cm (Figure 4.3). Harvesting-induced disturbance had no effect on N_o; however, bedding increased N_o by 63% on the non-trafficked treatment. Relative to nitrogen mineralization potentials estimated in other pine plantations (Powers, 1980; Burger and Pritchett, 1984), the levels observed in this study were high, suggesting that our study site may be more resistant to nitrogen

deficiencies than other less fertile sites, providing that soil moisture and temperature are properly controlled.
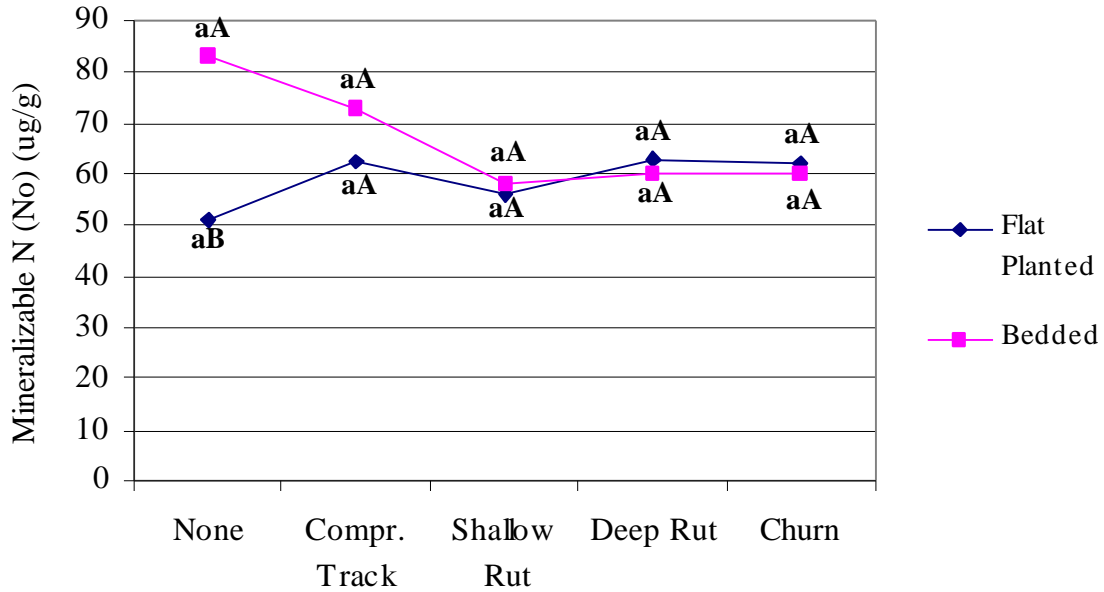
Figure 4.3. Mineralizable nitrogen across a gradient of harvesting-induced disturbance in a loblolly pine plantation, Colleton County, SC. (Dissimilar lowercase letters within site preparation treatments and dissimilar   captial letters within soil disturbance treatments represent significant differences at $p < 0.1$.)

Several studies address the effects of harvesting-induced soil disturbance on mineralizable nitrogen. For example, Burger and Pritchett (1984) found that N_o decreased by 29% on sites where soil had been disturbed by blading, discing and bedding over that of an uncut control site; however, they did not examine the effects of harvesting-induced disturbance, nor did they include a non-site prepared treatment in their study. Furthermore, the spatial distribution of soil organic matter due to site preparation was much greater than that in this study. The soils in the work of Burger and Pritchett (1984) were sandy Spodosols which differ greatly from the fertile and finer textured Alfisols and Mollisols of our lower Coastal Plain study site. The effect of nitrogen loss on long-term productivity may be site-specific and may not be as great a concern on our sites as on less fertile areas.

The significant increase in N_o due to bedding on undisturbed treatment areas (Figure 4.3) may be caused by the shallow mixing of vegetation, slash and coarse organic debris with the A horizon of the mineral soil. On rutted and churned sites, however, harvesting mixed surface soil with less nutrient-rich, clayey subsurface horizons prior to bedding. This may have caused the organic substrate quantity in the upper 30 cm sampling depth to be lower than in the undisturbed sites.

The ratio of total carbon to nitrogen has also been used as an index of nitrogen availability. In this study, different levels of harvesting disturbance had no significant effect on total nitrogen and carbon pools or the carbon to nitrogen ratio (Table 4.1). The observed C:N ratios of greater than 20:1 across all disturbance treatments indicate that net nitrogen immobilization in microbial populations was probably occurring at the time of sampling, two years after clearcutting and one year after site preparation treatments (Vitousek, 1981). In a similar study, Vitousek and Matson (1985a) concluded that the most important process for retaining nitrogen within disturbed sites was microbial immobilization. The large amounts of slash and organic substrate left on the study site following harvest may limit net nitrogen mineralization and help to conserve the pool of reactive nitrogen during a period of low plant demand. As these C:N ratios drop below the critical level (20:1), net mineralization will occur and nitrogen losses will be possible. In less productive sites or in areas where organic slash is removed by harvesting and site preparation, C:N ratios may be narrower and microbial immobilization may not be occurring to the same extent. Higher rates of net nitrogen mineralization may deplete the limited pool of reactive nitrogen on these less fertile sites.

Table 4.1. Treatment effects on soil chemical and physical properties in a one-year-old loblolly pine plantation, Colleton County, SC. (Dissimilar letters within each of the three main treatments (Soil Disturbance, Site Preparation, and Vegetation) represent significant differences at p< 0.1)

	Total C (g/kg)	Total N (g/kg)	Total N (kg/ha)	C:N ratio	Avg. Soil Temp (C)	Avg. Soil Vol. Moist (%)
None	22.5	1.03	2704	22.5	18.6	38.8
Compr. Track	25.3	1.11	2834	23.1	18.4	41.6
Shallow Rut	22.3	0.947	2556	24.0	---	---
Deep Rut	23.7	1.05	2846	23.0	---	---
Churn	20.9	0.93	2493	23.0	19.2	39.4
Flat	22.1	0.956	2551	23.6	19.2a	39.4
Bedded	23.8	1.07	2734	22.7	18.3b	40.4
Vegetated	---	---	---	---	18.2b	40.9
Operational	---	---	---	---	18.5b	38.5
Total Veg Control	---	---	---	---	19.6a	40.3

As expected, both total nitrogen ($r^2 = 0.58$) and carbon ($r^2 = 0.51$) were positively correlated with No (p< 0.001) (Figure 4.4). There was no correlation, however, between C:N and N_o; the C:N ratio may not reflect differences in organic matter quality due to different proportions of reactive and recalcitrant nitrogen pools. These results are consistent with those of other studies (Lea and Ballard, 1982, Maimone *et al.*, 1991). The slope of the linear regression relationship between total nitrogen and mineralizable nitrogen indicates the proportion of total nitrogen that is mineralizable, in this case, 5%. A higher proportion of reactive nitrogen would indicate greater quality of organic substrate. The proportion of mineralizable nitrogen observed in this study is the same as those observed by Burger and Pritchett (1984) across their site preparation treatments located in a slash pine (*Pinus elliotii* Engl.) plantation forest.
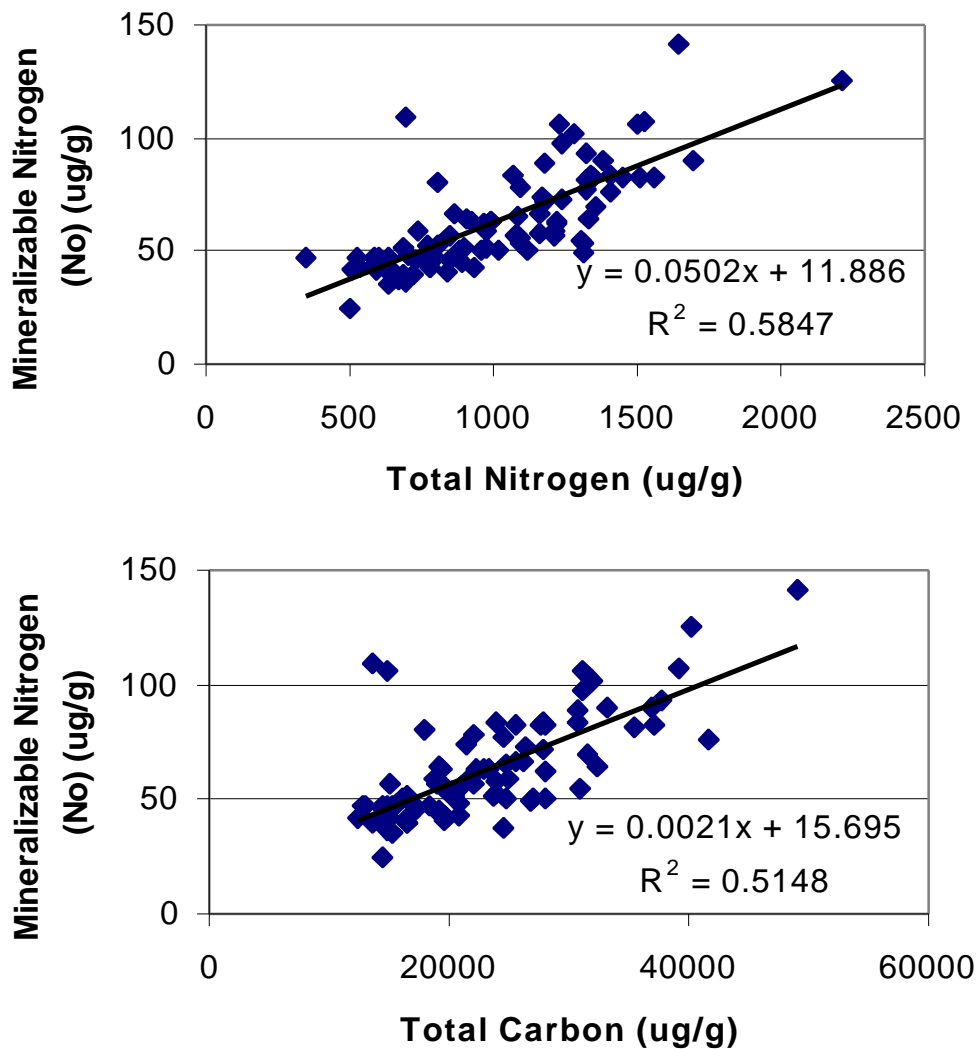
Figure 4.4. Linear regression relationship between mineralizable nitrogen (No) and total nitrogen and carbon in a one-year-old loblolly pine plantation, Colleton Co., SC.

N_o provides an index of mineralizable nitrogen under optimal moisture and temperature conditions and gives a basis for comparing the potential of a site to provide plant available nitrogen. Disturbance treatments, however, often alter environmental factors including moisture and temperature regimes that affect the amount of nitrogen mineralized in the field. In this study, there was a significant nitrogen mineralization interaction effect between site preparation and soil disturbance treatments (Figure 4.5). It appeared that nitrogen mineralization increased with increasing harvesting-induced soil disturbance. Net nitrogen mineralization on the flat-planted churned treatment was more

than double that of the undisturbed treatment. This may be partially due to increases in soil moisture and temperature on disturbed sites. Nitrogen mineralization doubles with every 10°C increase (Powers, 1980). The average soil temperature and water content were about 5 % higher on the churned treatment (Table 4.1). In addition, litter and slash mixed into the soil profile by churning decompose faster than organic matter laying on the soil surface because of its proximity to the mineral soil and its accessibility to soil organisms. Therefore, silvicultural treatments and disturbances such as churning and bedding that mix slash and organic litter with mineral soil will generally accelerate decomposition and nitrogen mineralization rates early in plantation development, when pine demand for nitrogen is low. This may result in a temporary increase in pine productivity, but nitrogen reserves for future periods of higher nitrogen demand may be depleted.

Bedding increased net nitrogen mineralization (by 130%) on the undisturbed treatment (Figure 4.5) because, in addition to incorporating slash and other organic debris into the soil profile, bedding created a well aerated, favorable microsite for mineralization processes. Poor bed quality due to severe soil disturbance may explain why bedding did not increase mineralization rates on the compression track and churn treatments.

Average annual nitrogen mineralization across all treatments was greater than 70 kg ha $^{-1}$yr^{-1} (Figure 4.5), about 3 to 4 times the requirement for trees of this age. According to the conceptual model of Allen *et al.* (1990) (Figure 4.1), the nitrogen requirement for a two-year-old loblolly pine plantation is less than 20 kg ha $^{-1}$ yr^{-1}. If the surplus nitrogen is not sequestered, its loss due to leaching or denitrification may result in a nitrogen deficiency at a later plantation age.
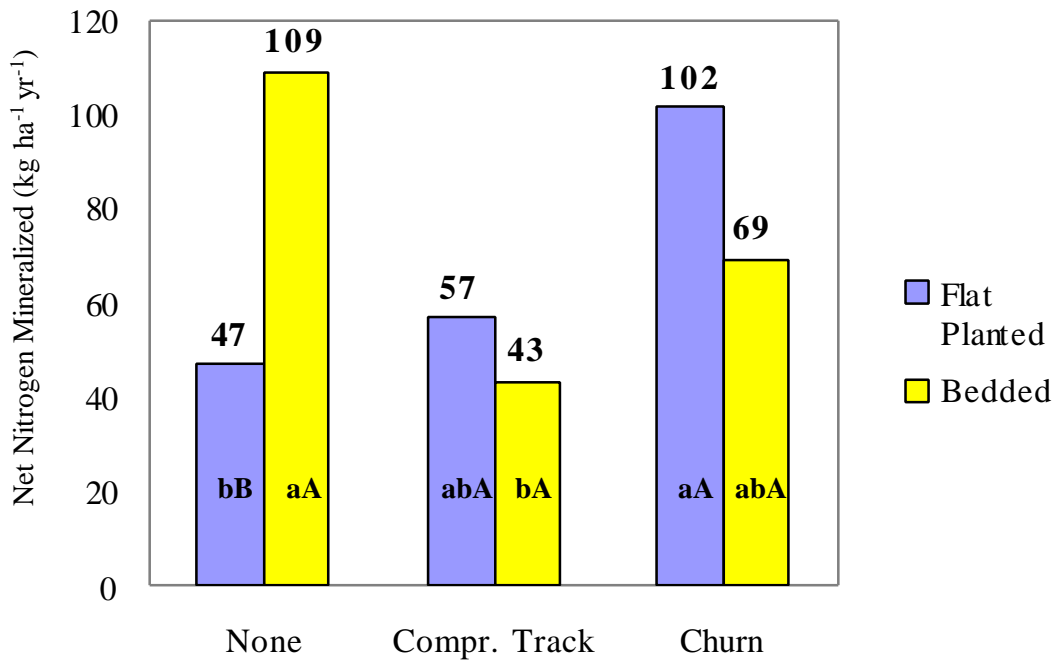
Figure 4.5. Interaction plot of annual nitrogen mineralization across disturbance class and site preparation treatments. (Dissimilar lowercase letters within site preparation treatments and dissimilar capital letters within soil disturbance treatments represent significant differences at $p < 0.1$)

Nitrogen sequestration by non-crop vegetation may help limit the potential loss of nitrogen from young plantation systems. Conserving nitrogen supplies early on may improve pine productivity after stand closure when the demand for nitrogen is greater. The early growth of young pines, however, is greatly improved by non-crop vegetation control.

In this study, pine growth increased significantly with increasing vegetation control (Figure 4.6). These results are consistent with the findings of other studies (USDA Forest Service, 1984; Cain, 1991; Miller *et al.*, 1991). Complete control of herbaceous vegetation on bedded sites caused a dramatic increase in pine volume. Bedding and vegetation control acted synergistically to double and more than quadruple the average pine volume on the operational and total vegetation control plots, respectively. Controlling non-crop vegetation gives planted pines a competitive

advantage, but this early pine response must be weighed against the potential pine productivity that may be lost in the long term, if the pines become nitrogen deficient.
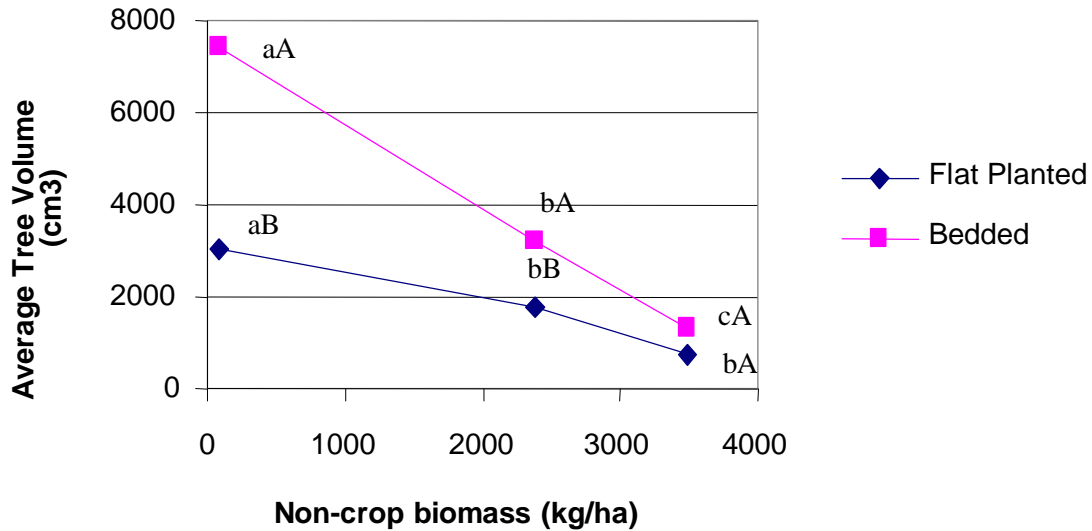
Figure 4.6. Pine volume response to vegetation control treatments which have been converted to aboveground biomass data based on average dry weight data for each treatment. Within site preparation, differing lowercase letters represent significant differences at $p<0.1$; within vegetation level (biomass), differing capital letters denote significance.

Although not significant in this study, net nitrogen mineralization may be accelerated by total-vegetation-control (Figure 4.7) due to significant increases in surface soil temperatures (Table 4.1). Nitrogen mineralization rates have been shown to double with every 10°C increase in soil temperature due to greater microbial activity at higher temperatures (Powers, 1980; Kladivko and Keeney, 1987). In a similar study, Burch *et al.* (1997) found slightly higher surface soil temperatures in treatment plots where herbaceous and hardwood competition was controlled. In their study, these pine-only plots also had significantly greater soil water nitrate concentrations during the first growing season which might be attributed to higher mineralization rates and reduced nitrogen uptake by vegetation.

In this study, the amount of nitrogen sequestered by aboveground vegetation was determined based on field measurements of biomass and plant nitrogen concentrations.

Nitrogen sequestered in belowground plant tissue was estimated using root:shoot ratios and root nitrogen concentrations from the literature. Root:shoot ratios, even within a single species are known to vary with changing environmental conditions; therefore, a ratio was selected that matched the study site environment. Figiel *et al*. (1995) found that the root:shoot ratios of both Japanese millet (*Echinochloa crusgalli*) and reed canary grass (*Phalaris arundinacea*) decreased with increasing nutrient supply; however, soil water content had no effect on the root:shoot relationship. Other studies, however, have shown that under wetter conditions, a greater proportion of biomass is allocated to shoot than to roots (Ledig, *et al.*, 1970; Dumortier, 1991). The root:shoot of 0.6 was selected for the non-crop vegetation species based on the wetness of the study site and its high fertility. This value represents an average of the root:shoot ratios of several species grown in a high nutrient, moist environment (Dumortier, 1991; Figiel *et al*., 1995; Wardle *et al.*, 1998). The selected root: shoot relationship for loblolly pine (0.2) was derived from the work of Fredericksen *et al.* (1993b) and Bongarten and Teskey (1987) who studied the growth of young loblolly pines on sites in the Piedmont of Virginia and the Coastal Plain of South Carolina, respectively.

Less than 16% of the nitrogen mineralized was sequestered by vegetation (above and belowground) in the total-vegetation-control treatment (Figure 4.7). This was significantly less than the amount of nitrogen sequestered in the operation control and vegetated plots. The estimated data for belowground nitrogen sequestration combined with the nitrogen content of aboveground biomass exceeded net nitrogen mineralization in the surface 20cm soil layer for the vegetated treatment plots, indicating that plants may be acquiring additional nitrogen from below the surface soil layer. This shows that there is a very low potential for nitrogen loss on the fully vegetated sites; in the absence of herbaceous weed control, non-crop and pine vegetation are able to capture most of the nitrogen mineralized following clearcutting. At the operational level of vegetation control, 92% of the nitrogen mineralized in the surface soil layer was sequestered, suggesting that nitrogen loss due to denitrification or leaching from this treatment would also be minimal.

The data indicate that in plantations where vegetation is completely controlled, annual losses in excess of 65 kg ha $^{-1}$yr^{-1} are possible. When vegetation was controlled

operationally, the amount of unused nitrogen was minimized and there were no significant differences between the amount of nitrogen mineralized in operationally-controlled and vegetated plots.
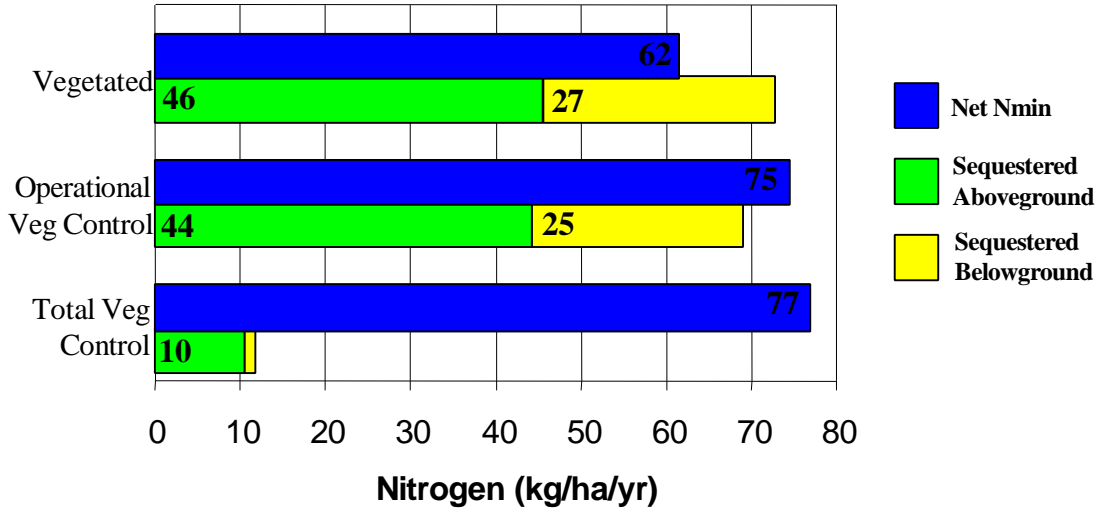
Figure 4.7. Effect of vegetation control on net nitrogen mineralization (Net Nmin) in the surface 20-cm soil layer and on estimated proportions of nitrogen sequestered in above- and below-ground vegetation on treatment plots in Colleton County, SC.

CONCLUSIONS

Soil disturbance due to harvesting did not affect mineralizable nitrogen pools on these study plots. Bedding of undisturbed sites, however, significantly increased the pool of potentially mineralizable nitrogen above that found on unbedded sites. The data indicate that the productivity of extremely fertile sites might not be compromised by harvesting-induced soil disturbance if available nitrogen is conserved.

Rates of nitrogen mineralization, however, were generally higher on more disturbed sites. Bedding also showed the potential to increase nitrogen mineralization rates. Since the annual nitrogen requirements in young pine plantations are less than the annual amounts mineralized, nitrogen may be lost from the site if it is not sequestered.

Nitrogen amounts sequestered on operationally-sprayed sites (69 kg ha^{-1}yr^{-1}) were the same as on unsprayed (73 kg ha^{-1}yr^{-1}) sites. On sites where all non-crop vegetation was controlled, pines alone sequestered only 12 kg ha^{-1}yr^{-1} of the 77 kg mineralized.

Continuous vegetation control could cause nitrogen deficiencies at a later age. The results of this study suggest that the beneficial effects of bedding and vegetation control on short term site productivity must be balanced with potential nitrogen deficiencies in the long term, and potential adverse effects on water quality.

CHAPTER V

Silvicultural Effects on Non-crop Vegetation in a Two-Year-Old Loblolly Pine Plantation on a Wet Forest Site

INTRODUCTION

The effects of silvicultural activities on the wetland status and function of Southeastern forested wetlands has been of much concern since the advent of several amendments to the Clean Water Act. For example, section 404 of the Clean Water Act defines criteria that farming and silviculture must meet in order to obtain exemptions from the permitting process. Examples of these criteria include the implementation of federal best management practices (BMP's), maintenance of the reach, flow and circulation of water, and the use of "normal" practices. "Normal" silvicultural activities are defined as those that: 1) are part of an ongoing operation, 2) do not involve converting a wetland to an upland, 3) do not require hydrological operations to reinitiate silvicultural activities, 4) do not contain toxic pollutants, and 5) comply with federal BMP regulations.

In addition to federal regulations, there are several state ordinances and voluntary state BMP's that affect silvicultural activities in wetlands (South Carolina Forestry Commission, 1989; Siegel and Haines, 1990; Georgia Forestry Commission, 1993). Some Southern states, including Georgia, North Carolina and South Carolina have also developed BMP's specifically designed for forested wetland areas, the aims of which are to minimize the impacts of silvicultural activities in these areas (Aust, 1994). Forested wetland BMP's generally recommend avoiding excessive soil compaction, maintaining soil tilth, and maintaining the natural site topography to ensure that activities do not convert wetlands to a non-wetlands. In order to avoid costly litigation, companies and individuals have made a concerted effort to monitor the effects their actions have on wetlands in the context of these rules.

Not only are legal concerns an issue, but much has been written about the importance of maintaining species diversity and richness in wetland areas (Murdock, 1994). Silvicultural activities can have long-term impacts on the composition of vegetation communities. For example, Meier *et al.* (1995) reported that populations of rare species were reduced by logging in Eastern deciduous forests, and that changes in the forest floor microclimate tended to promote the spread of invasive species, which are more tolerant of the extremes in environmental conditions found in disturbed areas. Similarly, Wright (1997) found that the importance values and coverage of several species were significantly different from pre-harvest conditions 17 years after harvest of an Appalachian hardwood forest. Finally, Duffy and Meier (1992) showed that the recovery of herbaceous understory communities after logging in Appalachian mixed mesophytic forests might take several centuries. The results of these and other studies suggest that activities related to silviculture, e.g., logging, site preparation, and competition control, might have serious long-term effects on the composition and successional trajectories of wetland systems.

The objectives of the current study were to 1) determine the effects of harvesting-induced soil disturbance, bedding and vegetation control on non-crop vegetation biomass, and on the relative proportions of growth forms of dominant species; and 2) to determine whether soil disturbance, bedding, and vegetation control affect the prevalence of wetland species. The results of this study may help guide forest managers in controlling the course of plant succession and maintaining dominance of wetland-adapted species on wetland sites.

MATERIAL AND METHODS

Site Description and Research Design

The research site was established in a wet pine flat, intensively managed for loblolly pine production and located on the Coastal Plain of South Carolina, in Colleton County. The poorly and very poorly drained soils on the study site, which were derived from marine and fluvial deposits, are dominated by two soil types, Argent loam (Ochraqualf) and Santee loam (Argiaquoll) (Stuck, 1982). Water table levels during the

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growing season are often within 30 cm of the soil surface, and therefore these soils are generally considered hydric (USDA-NRCS, 1991). The average annual rainfall in this warm temperate region is 132 cm with 82 cm falling between March and October. The average temperature between March and October is 31°C and between November and February is 18°C (Stuck, 1982).

The experiment was a split plot in a 2 x 5 factorial experiment within a randomized complete block design, where blocks were forest plantations that were chosen based on differences in drainage ditches and soil types. Treatments included five levels of harvesting disturbance (none, compression track, shallow rut, deep rut, and churn) and two types of site preparation (none or flat planted, and bedded). Each disturbance/site preparation combination was split into three 3.05 m by 6.10 m plots which received different levels of herbaceous weed control (none, operational control, and complete control) (Figure 5.1).

The soil disturbance gradient was achieved as a result of operational scale harvesting under both dry and wet conditions in the Fall of 1993 and Spring of 1994. Following clearcutting, soil disturbance was classified as described by Preston (1996). The undisturbed class was assigned to areas that had no visual signs of soil disturbance, the compression track class was for those areas where soil was visually compacted without plastic or liquid soil movement, the shallow rut class was assigned to areas where ruts were ≤ 20 cm, the deep rut class was for ruts > 20 cm, and the churned class was for those areas where soil disturbance resulted in a mixing of surface and some subsurface soil, rendering it massive (Figure 2.2). Preston (1996) reported that on average, 77% of the wet harvested area was disturbed, with 22% showing compression tracks, 31% shallow ruts, 20% deep ruts, and 4% churning. The dry-harvest operation caused only soil compaction, which covered 8% of the total dry-harvested area leaving the remaining land visually undisturbed. In 1995, site preparation treatments were installed (see Kelting *et al.* 1999 for a detailed description of silvicultural methods and equipment used) and the sites were planted with one-year-old loblolly pine bare-root seedlings from genetically-improved seed stock.

The vegetation control treatment gradient was composed of three levels: the vegetated control, operational control and complete vegetation control. The vegetated

control sub-plots were protected from the initial herbicide application using plastic tarps. Prior to seedling planting, operational sub-plots were sprayed aerially with 113 g (4 oz.) of Oust (75% sulfometuron-methyl) and 14 g (0.5 oz.) of Escort (60% metsulfuron-methyl) per acre. Vegetation-free sub-plots were treated as needed to maintain nearly complete non-crop weed control throughout the first two growing seasons. In general, a low volume directed spray of 5% (by volume) Accord (41.5% glyphosate) plus surfactant was applied with a backpack sprayer to achieve partial coverage of individual target plants.

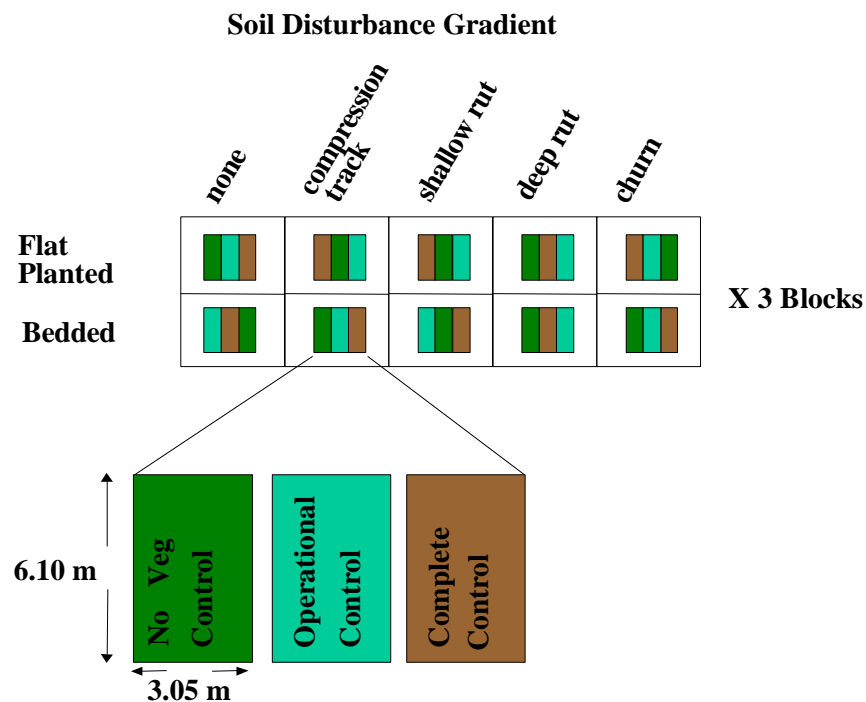Figure 5.1. Schematic representation of study design showing vegetation split plots within a randomized complete block, 2x5 factorial design.

Field and Laboratory Methods

Non-crop vegetation biomass was sampled every three months for one year, starting in May 1997. All aboveground vegetation within a 30.5 cm by 305 cm strip-transect, oriented lengthwise and reaching half-way across each of the 90 vegetation sub-

plots, was clipped at the soil surface and collected for dry mass determination. Care was taken to avoid sampling adjacent to previously cut areas and along the plot edge. Species that were estimated to occupy greater than 10% cover were collected separately, and all other vegetation was pooled. After drying to an equilibrium weight at 65 $^{\circ}$C, dominant species were identified based on the dry weight data. Species dominance was determined based on the "50/20 rule" used in wetland delineation; dominant species were the most abundant species whose cumulative biomass immediately exceeded 50% of the total plot biomass, and any additional species whose aboveground biomass was greater than or equal to 20% of the total plot biomass (Environmental Laboratory, 1987).

Each dominant species group was then assigned an appropriate plant growth form. Grass-like species and grasses were grouped into one category (hereafter referred to as "grass"), herbs were composited into the "forbs" group, and any woody species, including woody vines, were grouped as "woody". A wetland classification group was also assigned to each dominant species based on the National List of Plant Species That Occur in Wetlands (Reed, 1988). These included obligate wetland species (OBL) which are almost always found in wetlands (estimated probability >99%), facultative wetland species (FACW) which usually occur in wetlands (67-98% probability), facultative species (FAC) which are equally likely to occur in wetlands and nonwetlands (34-66% estimated probability), and facultative upland species (FACU) which usually occur in nonwetlands, but occasionally are found in wetlands (1-33% probability) (Table 5.1). For each sample plot, the relative percentages of each plant-form type and wetland classification group were calculated by dividing the dry weight for each category by the total plot weight of all dominant species.

A wetland species prevalence index was calculated for each sample plot according to standard methods (Environmental Laboratory, 1987). Each wetland classification group corresponds to a prevalence ranking from 1 (OBL) to 4 (FACU) and prevalence values were averaged within each sample plot.

Statistical Methods

Data were analyzed using analysis of variance (ANOVA) with SAS PROC MIXED based on the randomized complete block design model with a 2x5 factorial and

split plots (SAS Institutes, 1985). Statistical differences were calculated using Tukey's mean separation ($p \leq 0.10$). For plant growth form and wetland classification group comparisons, the model was used to test for significant differences only within an individual growth form or wetland group.

RESULTS AND DISCUSSION

Non-crop Biomass

Churned soil tended to support greater aboveground non-crop vegetation biomass, especially at the peak of production in August of 1997 (Figure 5.2). Biomass differences among soil disturbance levels for non-bedded (flat-planted) treatments, however, were not significant. When disturbed sites were bedded, undisturbed and compression track treatments had the highest aboveground biomass (1.5 times the biomass on the severely disturbed sites) in nearly every season. Differences were significant during the May sampling period (Figure 5.2). In churned and deeply rutted sites, bedding operations were less successful at creating good quality beds. Poor bed quality may account for the lower productivity observed on these sites.
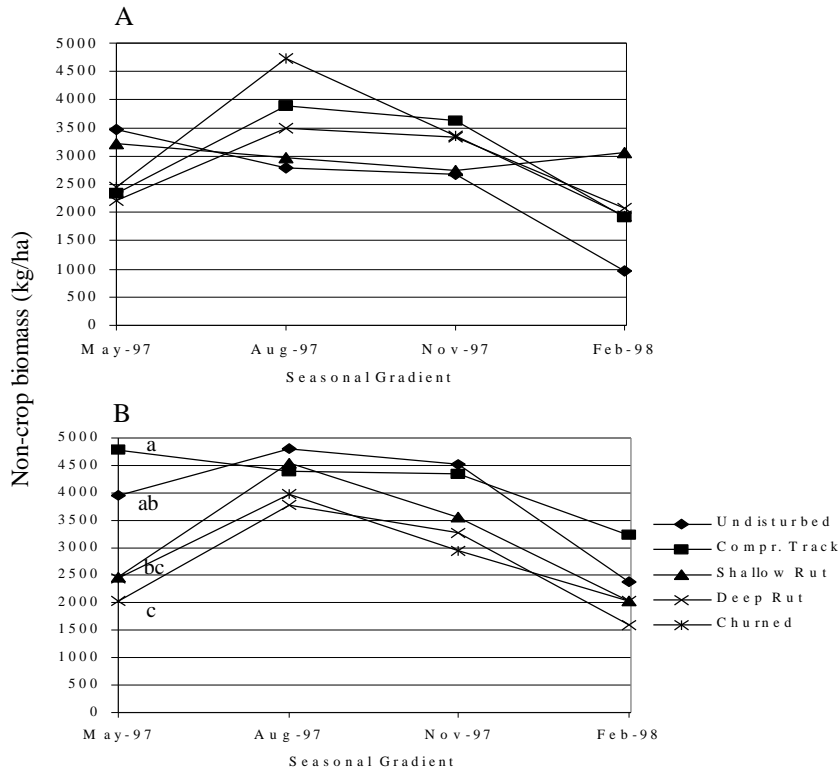
Figure 5.2. Soil disturbance effect on non-crop biomass for both flat-planted (A) and bedded (B) sites across a seasonal gradient in a young loblolly pine plantation, Colleton Co., SC. (Statistical differences among the disturbance treatments are denoted by dissimilar letters (p< 0.1).)

In general, bedding increased the aboveground biomass production across all seasons, although differences between bedded and flat-planted plots were not statistically significant (Figure 5.3). In these poorly drained soils where perched water limits soil aeration for much of the year, bedding creates an elevated, well-aerated environment for root growth. Overall gains in productivity with bedding were observed despite the adjacent, less productive furrows between beds. Bedding also increases surface microtopography, which may create a greater number of favorable microsites for plant germination and growth (Harper *et al.*, 1965; Zedler and Zedler, 1969). Furthermore, wind dispersed seeds may have been more easily captured by the raised bed topography. Schultz and Wilhite (1974) found grass species to be stratified by the micro-relief created by bedding, suggesting that microtopography might strongly influence species composition.

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Figure 5.3. Pooled main effect of site preparation on non-crop biomass across a seasonal gradient in a young loblolly pine plantation, Colleton Co., SC. (There were no significant differences between flat and bedded treatments.)

On average, the operational level of vegetation control reduced non-crop biomass by 17% (Figure 5.4). Biomass differences between the vegetated and operational control treatment were significant throughout all seasons, except during peak production in August. Nearly all vegetation was eliminated on the total vegetation control plot. In addition to reducing overall biomass, competition control treatments often change the composition of dominant competitor species (Morris *et al.*, 1993). Altering plant community structure may have long-term, ecosystem level effects (Perry, 1998).
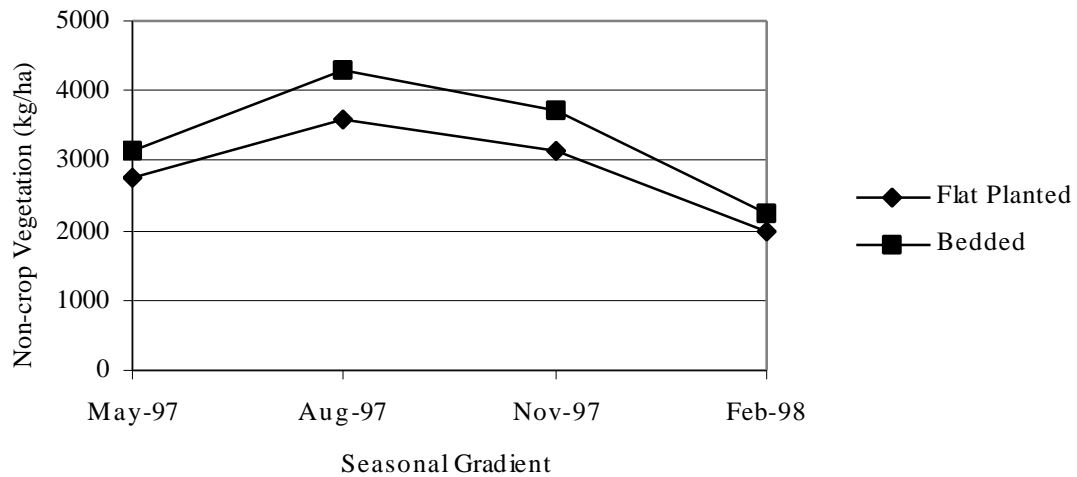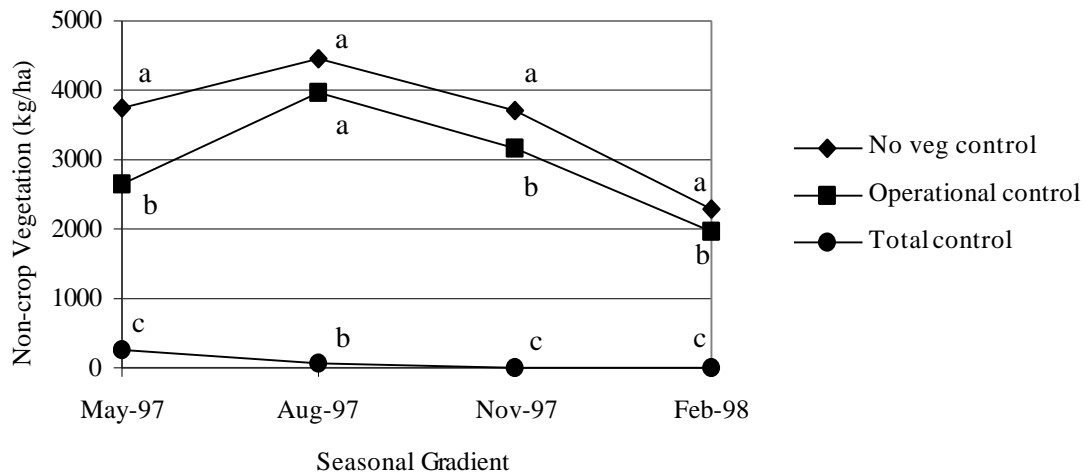
Figure 5.4. Effect of herbicide application on non-crop biomass across a seasonal gradient in a young loblolly pine plantation, Colleton Co., SC. (Dissimilar letters among the vegetation treatment within a single sampling period represent significant differences (p<0.1).)

Vegetation Growth Forms

Grass and grass-like species generally prevailed among the dominant species (Figures 5.5, 5.6 and 5.7). In this growth form category, soft rush (*Juncus effusus* L.) predominated, along with panic grass (*Panicum* spp.). The most prevalent forb species was dog fennel (*Eupatorium capilifolium* Lam.), followed by Goldenrod (*Solidago spp.*). Overall, blackberry (*Rubus* spp.) and southern bayberry (*Myrica cerifera* L.) were the most abundant woody species (Table 5.1). These are some of the more common non-crop plant species on young loblolly pine plantations in the Southeast. On sandy loam soils in loblolly and slash pine plantations in Alabama, dog fennel, panic grass, southern bayberry, and blackberry were identified among the major interfering species (Zutter *et al.*, 1986). Only a few of these dominant species encountered on the research site are likely to persist to rotation age. In a survey conducted by Hauser (1992) in a 23 year old loblolly pine plantation on a similar site, southern bayberry, switch cane (*Arundinaria gigantea*), and virginia creeper (*Parthenocisus quinquefolia*) were found in the midstory, shrub and grass layer, but none of the other dominant species observed on our study plots were present in his study at rotation age.

Table 5.1. Dominant taxa encountered in May and August 1997 on research plots in Colleton Co. SC. Hydrophytic wetland classes were assigned according to Reed (1988). When plants were identified to the genus level, best approximations of the wetland class were made based on distribution maps and field observations.

Scientific Name	Author	Common Name	Code	Form	Wetland Class region 2
Ampelopsis arborea	(L.) Koehne	Pepper-vine	AMAR	W	FAC+
Andropogon sp.	------	Blue stem	ANDRO	G	FAC
Arundinaria gigantea	Walter	Giant cane	ARGI	S	FACW
Baccharis halimifolia	L.	Grounsel tree	BAHA	S	FAC
Cirsium sp.	------	Thistle	CIRSI	F	FAC
Campsis radicans	(L.) Seem	Trumpet-creeper	CARA	G	FAC
Carex sp.	------	Sedge	CAREX	G	FACW
Cyperus virens	Michx.	Green flatsedge	CYVI	G	FACW
Cyperus sp.	------	Flatsedge	CYPER	G	FACW
Dicanthelium aciculare	Gould and C.A. Clark	Needle leaf witchgrass	DIAC	G	FACU
Dicanthelium scoparium	(Lam.) Gould	Broom grass	DISC	G	FACW
Dichanthelium consanguineum	Gould and C.A. Clark	Blood witchgrass	DICO	G	FAC
Erechtites hieracifolia	L.	American burn	ERHI	F	FAC-
Eupatorium capilifolium	(Lam.) Small	Dog-fennel	EUCA	F	FACU
Eupatorium perfoliatum	L.	Common boneset	EUPE	F	FACW+
Foeniculum vulgare	Mill.	Sweet fennel	FOVU	F	FAC-
Galium tinctorium	L.	Stiff marsh bedstraw	GATI	F	FACW
Gnaphalium obtusifolium	L.	Rabbit tobacco	GNOB	F	FAC-
Hypericum mutilum	L.	St. John's wort	HYMU	F	FACW
Juncus diffusissimus	Buckley	Slim-pod rush	JUDI	G	FACW
Juncus effusus	L.	Soft rush	JUEF	G	FACW+
Juncus sp.	------	rush	JUNCU	G	FAC
Myrica cerifera	L.	Southern bayberry	MYCE	S	FAC+
Parthenocissus quinquefolia	L. Planch	Virginia creeper	PAQU	W	FAC
Paspalum urvillei	Steud.	Vasey grass	PAUR	G	FAC
Panicum sp.	------	Panic grass	PANIC	G	FAC
Penthorum sedoides	L.	Ditch-Stonecrop	PESE	F	OBL
Polygonum pensylvanicum	L.	Pennsylvania smartweed	POPE	F	FACW
Rhynchospera caduca	Elliot	Falling beakrush	RHCA	G	OBL
Rubus sp.	------	Blackberry	RUBUS	S	FAC
Serenoa repens	(W. Bartram) Small	Saw palmetto	SERE	S	FACU
Solidago rugosa	Mill.	Wrinkled golden-rod	SORU	F	FAC
Solidago sp.	------	golden-rod	SOLID	F	FAC

Over half of the dominant species on undisturbed sites in the flat-planted treatment were woody in their growth form (Figure 5.5a). Soil disturbance significantly (p<0.1) reduced the proportion of woody forms among the dominant species by 64%. Soil disturbance during clearcutting may break up the root masses of small shrubs and woody perennials. Small stumps may be mixed in with mineral soil, retarding their ability to sprout. Other researchers have observed similar decreases in the numbers of woody species with increasing disturbance (Conde *et al.*, 1983a; Stransky *et al.*, 1986; Gale *et al.*, 1998).
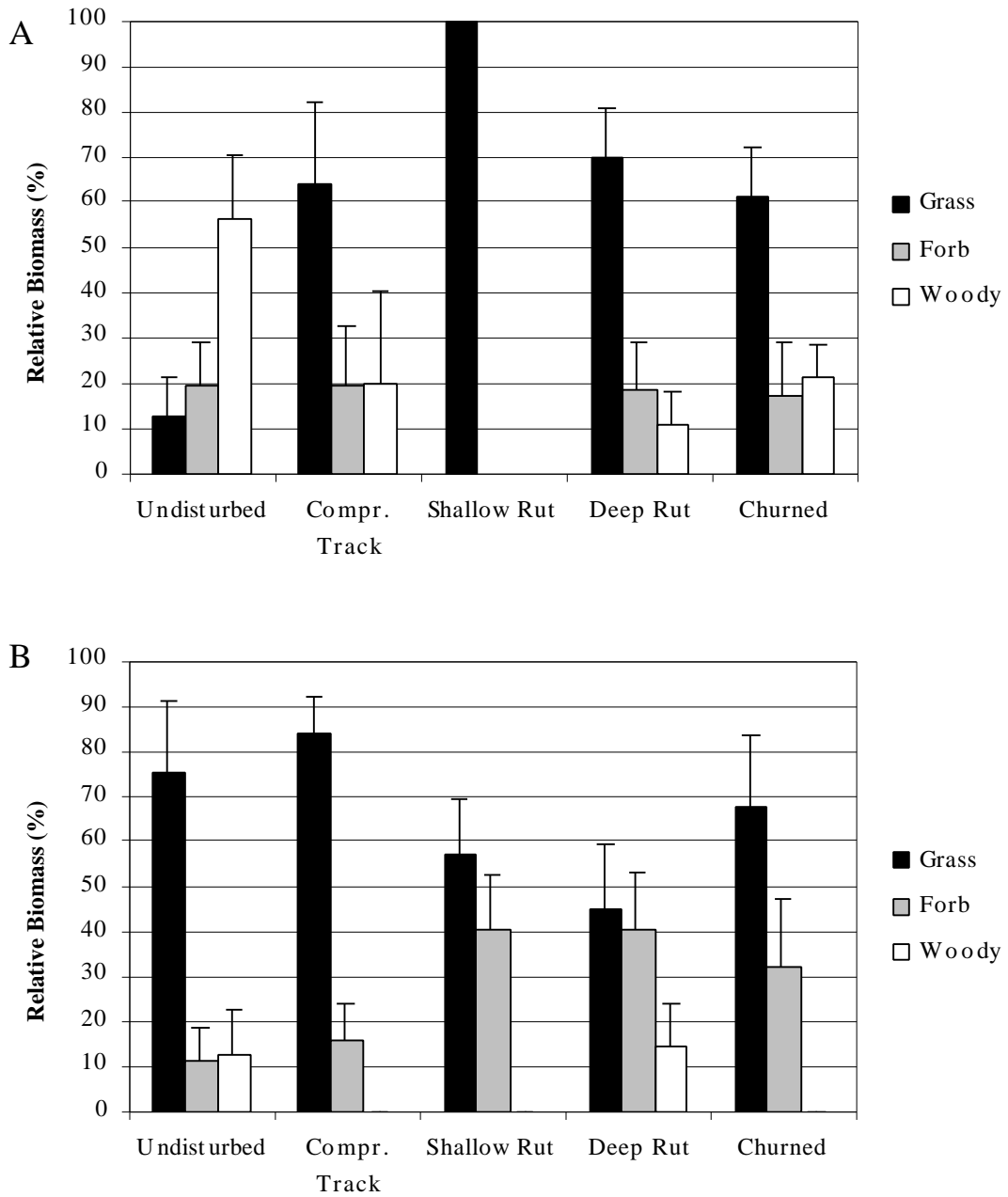
Figure 5.5. Effect of harvesting-induced soil disturbance on non-crop vegetation growth form for dominant species on both flat-planted (a) and bedded (b) sites on a young loblolly pine plantation, Colleton Co., SC. (Error bars are $\pm$ one standard error of the mean (n=6).)

In addition to disturbance, the timing of harvesting may have resulted in higher proportions of woody growth forms on the undisturbed treatment. Undisturbed treatment

areas were harvested in the fall of 1993, while more severely disturbed sites were harvested in the spring of 1994. Undisturbed treatments, therefore, might be at a more advanced level of succession; sprouting stumps and roots may have gained a slight competitive advantage over herbaceous species in the late fall and winter following clearcutting. On the disturbed sites, harvesting occurred at an opportune time for herbaceous species invasion in late spring and early summer.

As expected, bedding also caused a significant ($p < 0.1$) reduction in woody growth of naturally regenerated species. Bedding on the undisturbed treatment areas decreased the proportion of woody forms by 78%. Similar reductions in woody biomass with site preparation are reported in the literature (Hebb, 1971; Conde *et al.*, 1983a; Stransky *et al.*, 1986; Swindel *et al.*, 1989). Bedding is a form of soil disturbance, so it is not surprising that in this study, the effects of bedding are similar to the effects observed when soil was disturbed during harvesting operations. In fact, one of the purposes of bedding is to reduce competition of non-crop species (Swindel *et al.*, 1989). In a 23-year old loblolly pine plantation on a similar wet flat site, Hauser (1992) found that early reductions in shrub and hardwood species competition as a result of bedding persisted through rotation age. He observed lower productivity in the shrub layer and greater overstory biomass on bedded sites.

Overall, however, bedding increased the proportion of forbs among the dominant species (Figure 5.6). Increases in herbaceous competition as a result of bedding have been reported in other studies (Hebb, 1971; Schultz and Wilhite, 1974, and Swindel *et al.*, 1989). Swindel *et al.* (1989) explained that increases in herbaceous competition, at the expense of woody species, as a result of mechanical site preparation treatments are a favorable tradeoff if crop pine growth is a priority. This is because long-term pine growth is closely related to the proportion of woody species in the stand, and woody species, especially hardwoods, tend to persist if not controlled in the early stages of plantation establishment.
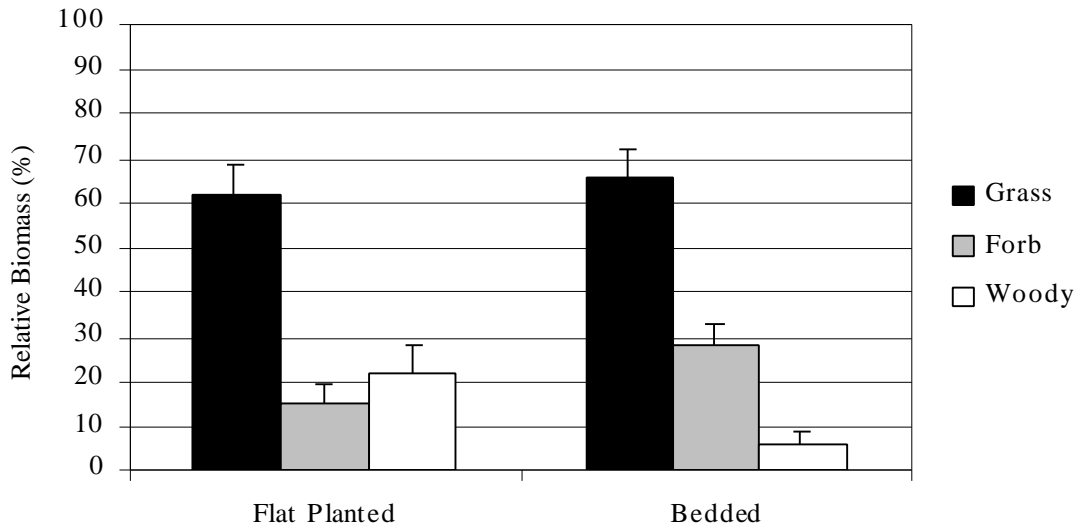
Figure 5.6. Effect of bedding site preparation on non-crop vegetation growth form for dominant species on a young loblolly pine plantation, Colleton Co., SC. (Error bars are $\pm$ one standard error of the mean (n=30).)

Although these shifts in proportions of growth forms following mechanical site preparation are favorable for crop pine growth and productivity, changing the community structure may compromise ecosystem diversity. Hauser (1992) observed an overall reduction in shrub layer diversity as a result of bedding as measured by both Shannon-Wiener and Simpsons diversity indices. Meier *et al.* (1995) explained how silvicultural treatments, especially clearcutting in eastern deciduous forests, resulted in a decrease in the diversity of vernal herb species. One proposed mechanism for this loss in diversity included the inability of sensitive herb species to compete with more aggressive invasive species that generally have wind dispersed seeds and are more tolerant to increased radiation and water stresses. Duffy and Meier (1992) indicated that certain herbaceous species in the Appalachian region may never recover from proposed logging cycles, and that future losses in herbaceous species diversity may be imminent.

Other silvicultural treatments such as chemical vegetation control also have the potential to change the proportions of different plant types. The results from this study show a general increase in the proportion of woody species following operational chemical vegetation control measures (Figure 5.7). Treatment plots (excluding a

vegetated control) were sprayed with a mixture of Oust and Escort herbicides, which plants absorb by foliar and root uptake. Herbicide was applied in April during a time when the woody species were just beginning to leaf out, possibly making them less susceptible to herbicide-induced mortality. Furthermore, it has been shown that the surface chemistry of certain plant species affects their susceptibility to herbicides (Holloway, 1970). The observed increase in the proportion of woody plant types among the dominant species in this study may be a result of the inability of the herbicides to control woody species to the extent that herbaceous and grassy species were controlled.
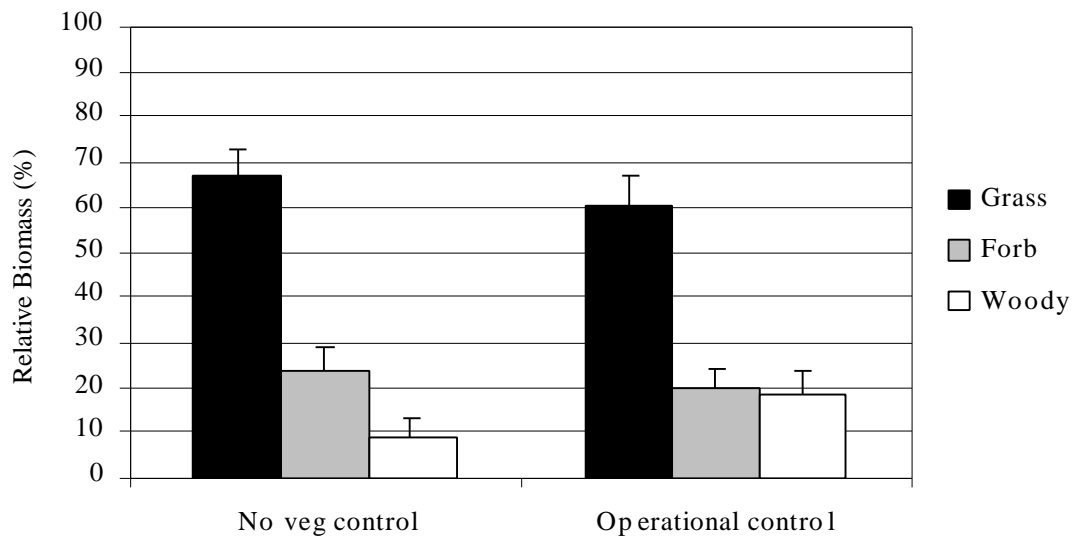
Figure 5.7. Effect of operational level of vegetation control on non-crop vegetation growth form for dominant species on a young loblolly pine plantation, Colleton Co., SC. (Error bars are $\pm$ one standard error of the mean (n=30).)

Operational levels of competition control generally result in a reduction in non-crop biomass and a shift in species composition (Nambiar and Zed, 1980). Although the intent may be to favor species that are more problematic for crop-tree growth, the opposite may occur. For example, coffeeweed (*Sesbania exaltata* Raf.), a leguminous plant, has been known to dominate on certain sites during the early stages of pine establishment. In many cases coffeeweed takes over the site, out-competing pine

seedlings, and potentially compromising pine productivity (Morris *et al.*, 1993). Although not tested in this study, field observations indicated that coffeeweed was more abundant on the plots where non-crop vegetation was operationally controlled than on the plots that received no vegetation control. Herbaceous cover may limit the opportunistic proliferation and dominance of problem species.

Wetland Species Prevalence

In forest plantations that have been identified as jurisdictional wetlands, there is a great deal of concern about the effects of silvicultural treatments on wetland status and function. A shift from wetland dominated plant communities to more facultative species following silvicultural treatments might indicate that the forestry practices interfered with wetland function, and that wetland regulations had been violated.

Facultative wetland species were the most prevalent among the dominant species for all treatments (Figures 5.8, 5.9, and 5.10). In general, obligate species were found only on the more severely disturbed areas (Figure 5.8a). Rutted and churned treatments created wet microsites where species adapted to anaerobic rooting environments predominated. The churned treatment in flat-planted areas had the most even distribution of proportions of all wetland species types (Figure 5.8a). This again is probably due to varied microtopography typical of disturbed sites. A wide range of microsite conditions was created which favored different wetland species types.
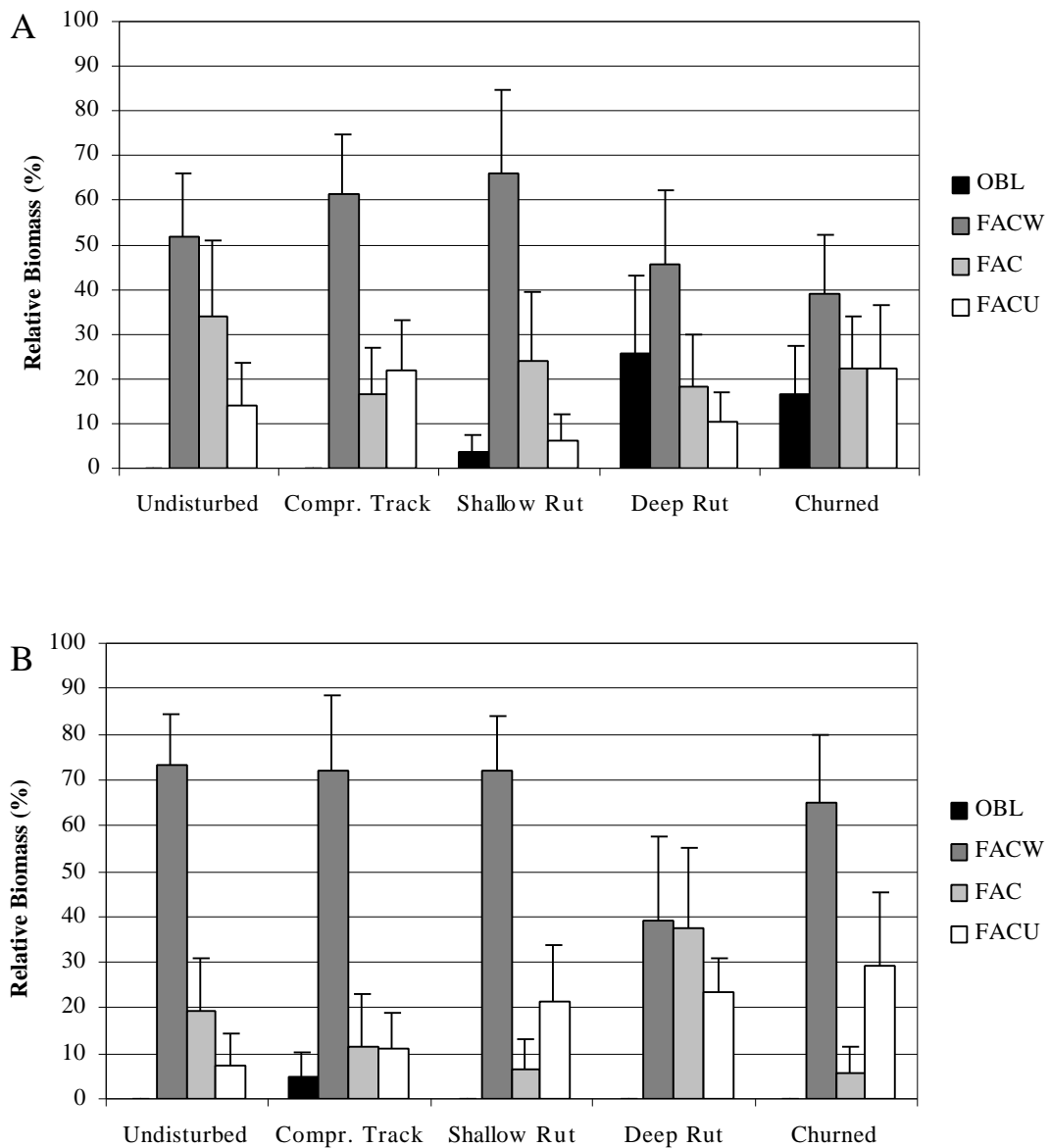
Figure 5.8. Effect of harvesting-induced soil disturbance on wetland classification groups for dominant species on both flat-planted (A) and bedded (B) sites on a young loblolly pine plantation, Colleton Co., SC. (Error bars are $\pm$ one standard error of the mean (n=6).)

In general, bedding decreased the proportion of obligate wetland species found among the dominant vegetation across all disturbance classes by 80% (Figures 5.8b and 5.9). However, there were no obligate species among the dominant plants on the undisturbed (non-trafficked) treatment, so this reduction is reflective of only disturbed

treatments. Bedding creates an elevated, more aerated rooting environment for plant growth. Although vegetation was also collected from the furrow and interbed region, these contributions to the total biomass collected on each site were probably small.
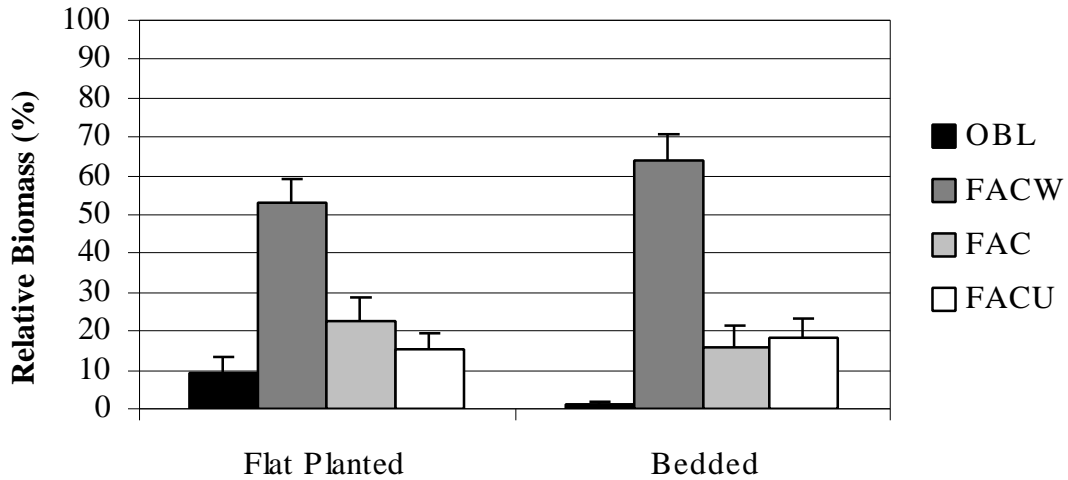
Figure 5.9. Effect of bedding site preparation on wetland classification groups for dominant species on a young loblolly pine plantation, Colleton Co., SC. (Error bars are $\pm$ one standard error of the mean (n=30).)

Operational chemical control of the vegetation had no effect on the proportions of different wetland species classes among the dominant vegetation (Figure 5.10). It might have been possible for the herbicide treatment to more effectively control either predominantly wetland or non-wetland species depending on the herbicide's mode of action and differences between the root and leaf morphology among the wetland groups. According to these results, however, there was no differential herbicide effect.
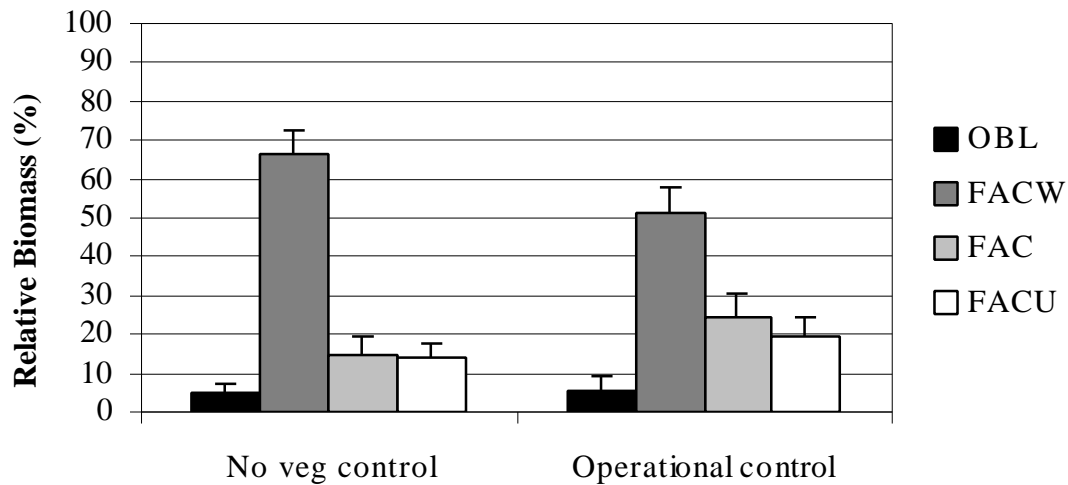
Figure 5.10. Effect of operational level of vegetation control on wetland classification groups for dominant species on a young loblolly pine plantation, Colleton Co., SC. (Error bars are $\pm$ one standard error of the mean (n=30).)

The study site fell within the definition of a jurisdictional wetland prior to the most recent harvest. Data collected in this study were analyzed to determine if the hydrophytic vegetation criterion for wetland delineation was affected by harvesting-induced disturbances, bedding and vegetation control. According to the Corps of Engineers Wetlands Delineation Manual (1987), a site meets the hydrophytic vegetation criterion if the weighted average prevalence index is 3 or less. The data indicate that none of the silvicultural treatments changed the site's legal status as a wetland according to the vegetation criterion (Figure 5.11).

Silvicultural treatment effects on wetland status may not be detectable in the year directly following harvesting operations. After clearcutting, large reductions in transpiration generally cause water tables to rise and soil moisture content to increase (Aust *et al.*, 1993). Temporarily-wetter conditions may obscure the longer-term effects of forestry operations on wetland status. Subsequent surveys, therefore, may be necessary to track possible changes in the classification of this area as a wetland.
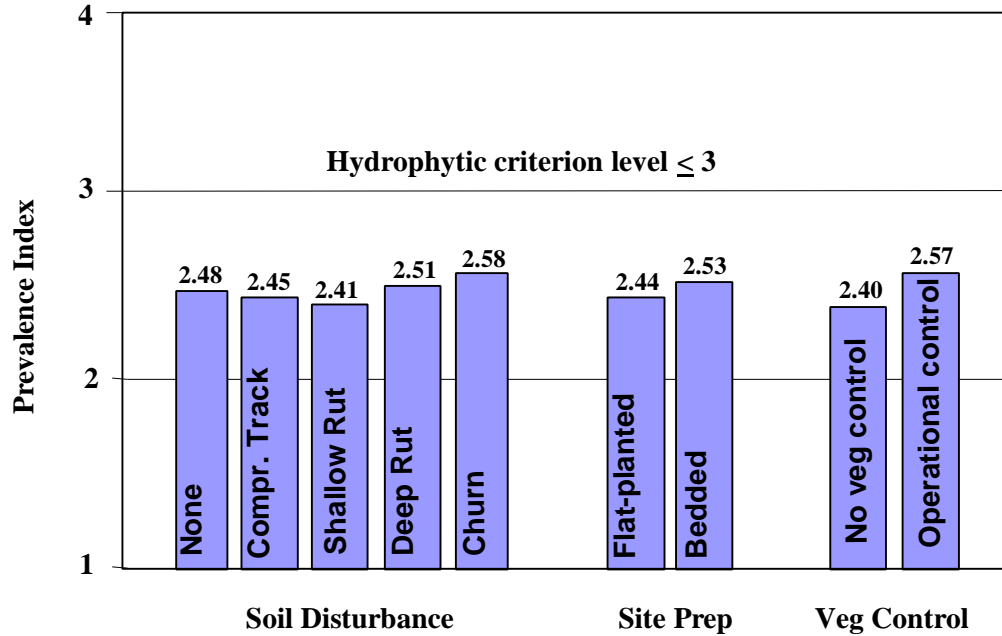
Figure 5.11. Soil disturbance, site preparation and herbicide treatment effects on the prevalence of wetland species in a young loblolly pine plantation, Colleton County, SC. (No significant differences were found within the three main treatments (soil disturbance, site preparation, and vegetation control).)

CONCLUSIONS

Vegetation biomass tended to be higher on churned areas due to the creation of elevated microsites. When severely disturbed soils were bedded, however, plant biomass was less than on bedded undisturbed sites because bed quality was reduced. In general, bedding increased vegetation productivity by 17%, possibly due to improved soil aeration and increased surface microtopography, which favored seed germination and growth.

The majority of dominant species on undisturbed treatment areas were woody (56%). Soil disturbance and bedding reduced the proportions of woody forms by 64 and 78%, respectively. Bedding caused the proportion of forbs to increase over that on non-bedded sites.

Soil rutting and churning increased the proportions of obligate wetland species by creating saturated microsites that favored their growth. Bedding, however, decreased the

dominance of obligate species because an elevated and well-aerated rooting environment was created. Herbicide treatment had no effect on the proportions of wetland species classes.

Although this study indicates no significant effect of silvicultural treatments on the prevalence of hydrophytic species, long-term monitoring and more extensive research is probably needed to determine if forestry operations affect wetland function.

SUMMARY

With rising interest in sustainable forestry, more attention is being paid to the long-term and ecosystem-level effects of vegetation management. In intensively managed southern pine plantations, non-crop vegetation is operationally controlled both mechanically and chemically. The consequences of this vegetation removal for long-term forest productivity are not well known. A study was conducted to evaluate the effects of soil disturbance, bedding site preparation and chemical vegetation control on soil and forest productivity. The importance of non-crop vegetation for maintaining and improving soil quality was evaluated, as well as the effects of silvicultural treatments on non-crop vegetation dynamics. Furthermore, the study site was located in a wet pine flat which was classified as a jurisdictional wetland, allowing us to determine the effects of silvicultural treatments on the prevalence and dominance of hydrophytic plant species.

The effects of harvesting-induced soil disturbance on soil quality and 2-year pine productivity were minimal. On flat-planted sites, soil compaction tended to increase soil bulk density and decrease macroporosity and hydraulic conductivity, which might limit adequate soil aeration on these poorly drained sites. Bedding, however mitigated the effects of soil compaction, based on the soil physical properties measured. I hypothesized that soil churning would degrade the soil physical environment, but it did not, largely because slash and coarse litter were mixed into surface soil horizons. This created a surface soil with favorably-low bulk density and improved soil macroporosity and hydraulic conductivity. Churning also created an increased number of elevated microsites where pine productivity was improved. The long-term effects of soil churning on pine productivity on these sites are still largely unknown, because the crop pines are just beginning to exploit the lower soil horizons, which may have been degraded by the churning treatment. On other forest sites where slash and litter are not abundant and are not mixed with surface soil horizons during wet weather harvesting, soil churning may cause soil degradation and limit the survival and early growth of crop pines. There were consistent trends of improved soil quality with increasing levels of non-crop vegetation

biomass; however, these beneficial effects were marginal during two years of operational vegetation control.

Soils on the study site are very fertile, and have high nitrogen mineralization potentials relative to other Coastal Plain pine plantations. This pool of reactive nitrogen, however, has the potential to be mineralized in greater quantities than is needed by young pine plantations, especially on sites where intensive silvicultural treatments are used. On this study site, soil disturbance and bedding generally enhanced soil biological activity and increased nitrogen mineralization rates. Nitrogen mineralization increased with increased vegetation control due to higher surface soil temperatures. Since the annual nitrogen requirements in young pine plantations are less than the annual amounts mineralized, nitrogen may be lost from the site by leaching or denitrification if it is not sequestered.

On the fully vegetated and operational vegetation control treatments, the majority of nitrogen mineralized in the surface 20 cm of soil was sequestered by non-crop vegetation; however, in the total vegetation control treatment only 16% was sequestered. Accelerated mineralization caused by continuous vegetation control may cause nitrogen deficiencies later in pine development, especially on those treatment areas where soil was disturbed by harvesting or site preparation. On this fertile site, where there are high levels of mineralizable nitrogen, and where leaching losses may be limited by poor drainage, nitrogen losses due to the operational level of vegetation control may be minimal. From a pine productivity perspective, the benefits of operationally-controlling vegetation during the first two years after planting may outweigh the potential losses in productivity at stand closure and beyond. However, on less fertile sites with coarser-textured soil, operational levels of non-crop vegetation control may substantially reduce mineralizable nitrogen pools and lower long-term pine productivity.

Gains in pine productivity with various silvicultural treatments must also be weighed against the potential effects of these treatments on the composition and successional trajectory of the non-crop plant community. Both bedding and churning tended to increase overall plant biomass on the study site. This may be due to the creation of elevated microsites. Increases in micro-relief of the soil surface may have also favored the germination and growth of invasive, wind dispersed seeds, which may

outcompete more sensitive native wetland species. Undisturbed treatments tended to have a greater percentage of woody species among the dominant plants, and as expected, soil disturbance, including bedding, reduced the proportion of this growth form. In fact, one of the purposes of bedding is to mechanically control the growth of woody competitor species. Although a shift from woody to herbaceous competitors may favor pine productivity, there are often important ecological consequences associated with a shift in species composition.

The scope of this study did not include a thorough evaluation of the effects of silvicultural treatments on the site's ecology and biological integrity. Future studies might include complete spatial vegetation surveys before and after harvesting and site preparation treatments to detect both micro-scale and community-level changes in species composition, richness and diversity. Soil invertebrate and vertebrate populations might also be studied to evaluate treatment-induced changes in habitat quality and the effects of species of soil fauna on soil quality.

There were no significant effects of soil disturbance, bedding or chemical vegetation control on the prevalence of hydrophytic plant species, and these silvicultural treatments did not affect the site's status as a jurisdictional wetland. Longer-term monitoring of wetland plant communities, however, is necessary to properly evaluate silvicultural effects on wetland status and function.

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