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CHAPTER 1

Introduction

1.1. Justification

Southern pine plantations are among the most intensively managed forests in the United States (Allen and Campbell, 1988). The cultural practices employed on southern industrial forestland are within Stone's (1975) definition of "domesticated" forests. The process of domestication of forests has manifested itself in the southeast through the conversion of native forests to pine plantations, and the decreased rotation lengths as a result of intensive management practices. Contemporary forest managers actively control site factors in order to maximize biomass production over a series of rotations. By contrast, "regulated" forests (Stone, 1975) are extensively managed by manipulating only their composition and density.

By their very nature domesticated forests require a much higher level of activity compared to regulated forests. Increasing inputs and cultural activity, along with shortened rotations, will lead to increased stand trafficking resulting in increased forest disturbance (Burger et al., 1988; Rachel and Karr, 1989; Gao and Karr, 1989). There is a great deal of scientific and public concern that the productivity of intensively managed forest soils may be in decline (Powers et al., 1990; Johnson, 1994; Nambiar, 1996; Kimmins, 1996a; Kimmins, 1996b). The effects of trafficking disturbance on soil physical properties, soil movement, nutrient loss, and organic matter loss are the mechanisms by which productivity is reduced (Powers et al., 1990; Sheriff and Nambiar, 1995; Kozlowski, 1999). In a sustainable system, the pressures placed on the forest by management operations should not exceed its capacity to recover via natural processes (Worrell and Hampson, 1997) or by management activities.

The importance of maintaining or improving site quality and productivity on intensively managed forests is unmistakable as population demands for forest products increase (USDA, 2001a), while production is concentrated on a smaller and smaller forested land base (Wallinger, 1978; Fox 2000). Two-thirds of softwood timber harvests are expected to come from plantations by 2050 (USDA, 2001a). Furthermore, the contributions of domesticated forests toward environmental quality are included in international proposals that will account for national and industrial responsibilities toward energy use, pollution, and global climate change (Gessel, 1981; USDA, 2001b; Liski et al. 2001).

Southern forest timber industries and timber investment management organizations (TIMOs) are primarily concerned with selling wood fiber to timber mills while sustaining productivity and maintaining site quality on lands that form the central pillar of its wood supply. Although landowners have sovereign rights to manage their land as they wish, managers and foresters have an ethical responsibility (Ford, 1983, Worrell and Hampson, 1997; Society of American Foresters, 2000) as well as a practical interest to avoid the permanent degradation of forest sites (Gessel, 1981; Worrell and Hampson, 1997). The passage of the Sarbanes-Oxley Act of 2002 (HR-3763) has implications for land managers because companies are required to protect stockholder interests. According to Bob Shaffer, professor of forestry at Virginia Tech, some companies have interpreted this law to mean that logging operations must be physically inspected to ensure they conform to industry standards (personal communication, June 2004). The forest industry is being increasingly scrutinized due to the focus of public, government, and special interests on forest management practices (McCullough, 1999). The development and use of best management practices (BMPs) and the implementation of the Sustainable Forestry Initiative (SFI) (AFPA, 2002) are examples of steps the forestry community has taken to ensure the long-term sustainability.

BMPs designed to protect long-term productivity primarily seek to reduce the amount of rutting and churning incurred during harvest trafficking. During dry-weather harvesting trafficking is generally less of a problem; however, during the wet-season trafficking results in a great deal of soil physical disturbance. The fundamental conflict lies in the fact that the demand for wood fiber remains higher than the costs associated with stockpiling raw materials for the duration of the wet seasons in the Southern United

States; this in turn forces harvesting to occur during times of the year when heavy soil disturbance due to trafficking is a high probability. Wetland sites could be at even more risk because of their moisture regimes. Approximately 16 percent of intensively managed plantations, or one million hectares, reside in wetland areas (Aust et al., 1993; Shepard et al., 1998).

Soil physical disturbance diminishes certain soil physical and chemical properties that are tied to soil-site quality (Powers et al., 1990). It is feared that the reduction in soil-site quality reflects a non-sustainable condition. However, many uncertainties remain regarding the effect of these disturbances on site productivity. Forest managers are uncertain as to which sites are most vulnerable, how long disturbance effects may last, and how effective certain mitigative practices work. The growth rate of trees in response to different site preparation techniques can change over time (Burger and Kelting, 1999) therefore certain sustainability questions can only be answered after a full rotation. Operational practices that cause initial differences may not be manifested over the entire rotation (Burger 1994a; Cerchiaro, 2003). Harvesting BMPs that are intended to offset or prevent disturbance, are sometimes based as much on professional inference and assumptions as scientific fact (Aust and Blinn, 2004).

Although many studies have shown the impact of harvesting disturbance within limited temporal and spatial scales, few studies have been able to explain the long-term effects of BMPs, harvesting, and soil disturbances at an operational level commensurate with common forest industry practices. Although there are many studies that have been initiated within the past 15 years (Smith et al., 1994a; Aust, 1998; Jones et al., 1999; Proe et al., 1999; Terry et al., 2001; Powers, 2002), no studies as of yet have tracked site quality parameters over the course of an entire rotation. Although these studies will certainly be important additions to the body of science, they will be at a disadvantage due to the limitations of standard bioassays and the lack of an effective field method for tracking changes in productivity (Morris and Miller, 1994; Burger, 1994a) Understanding how the land (soil) resists, responds, and recovers following disturbances associated with forestry management practices remain the key objective toward developing effective management strategies for sustaining long-term productivity.

1.2. Research objectives

This dissertation encompasses one phase of a 20-year study designed to address two central questions: (1) do logging disturbances affect soil quality, hydrologic function, and loblolly pine (*Pinus taeda* L.) productivity on wet pine flats, and (2) can forestry practices mitigate disturbance effects if they exist? The specific objectives of this dissertation will be to:

(1) Evaluate whether logging disturbance diminishes productivity, and whether forest practices mitigate disturbance using a standard bioassay approach at stand closure.

(2) Develop a new diagnostic that allows comparisons between rotations to be made that is less affected by the limitations associated with traditional bioassays.

(3) Evaluate the effect of soil physical disturbance and harvesting residue disturbance on changes in soil and site quality.

(4) Determine which stand and landscape-scale factors influence changes in soil-site productivity, and

(5) Track changes in key soil physical and chemical properties through pre-harvest conditions, harvesting, and stand closure.

CHAPTER 2

Literature Review

2.1. Southern forestry

Southern forests have long been referred to as the timber belt of the Eastern United States and are an important part of its economy (Prestemon and Abt, 2002). In 1999, 89 million hectares were forested, and approximately 20 million hectares are used for the production of commercial southern yellow pine species on the Coastal Plain and Piedmont extending from East Texas to Virginia (Conner and Hartsell, 2002). Non-industrial private landowners own approximately 70 percent of the timberland, while industry and the public own the remaining 20 and 10 percent respectively (AFPA, 2001; USDA Forest Service, 2001a). Approximately 16 percent of intensively managed plantations, or one million hectares, reside in wetland areas (Aust et al., 1993; Shepard et al., 1998), and 90 percent of forests grown on wet pine flats consist of loblolly pine (Boyer and South, 1984; Conner, 1994). Plantation forests produce 10 m^3 ha^{-1} yr^{-1} and up to 28 m^3 ha^{-1} yr^{-1} of wood fiber annually depending on the intensity of management (Borders and Bailey, 2001).

2.2. The soil resource

2.2.1. Soil properties

Soil is the medium that supplies and maintains the nutrient and water resources necessary for tree growth. It is the key resource that must be maintained to sustain the system (Powers et al., 1990). Soil has other functions as well. Soil is the shared medium for the growth of non-crop species. Nutrient cycling and other biogeochemical processes are controlled by soil chemistry. It serves to buffer the system by acting a sink for carbon and other atmospheric products. Soil properties are affected by and also affect near-surface hydrology. Additionally, micro and macro organisms utilize soil as habitat and nutrient source (Worrell and Hampson, 1997).

To maximize productivity, soil attributes must (1) promote root growth, (2) store, supply, and cycle nutrients, (3) accept, hold, and supply water, (4) promote gas exchange, and (5) promote soil biological activity (Kelting et al., 1999). Many people view soil as a static resource, but managers and scientists recognize soil ecosystems as a dynamic living entity. Soils are a nexus of many important chemical and biological processes that can change dramatically in minutes, days, or even years (Fisher and Binkley, 2000) yet many important soil properties are a result of natural processes that have developed them over thousands of years (Stone, 1975). Management practices have the capacity to alter these properties in very short time frames. Managers must, at a minimum, be aware that soils are not static and manage them within the context of our best understanding of the internal and external processes that alter their properties. The presence of tree litter, tree roots, and certain soil organisms in a forest system further distinguish forest soil management from its agricultural counterpart.

2.2.2. Exploitation of the soil resources

Natural systems generally maintain and improve their soil resources because they have evolved to constantly have trends that approach maximum production (Reichle et al., 1975). Plants capture resources and bring them into the local biogeochemical cycle. Natural systems are always approaching equilibrium with the soil environment (Worrell and Hampson, 1997). However, the equilibrium the system approaches is not actually constant because the system is not closed, and because species distributions are not continuous. Species that are better adapted to compete for resources displace pioneer species. Plants exploit soils differently depending on which stage of forest succession is currently taking place. Tolerance of competition may be due to different rooting strategies (Walstad and Kuch, 1987; Persson, 2000), tolerance of shading or through greater retention of nutrients within plant tissues (Waring and Schlesinger, 1985; Ellert and Gregorich, 1995).

Carrying capacity and environmental resistance are two limits that dictate the amount of biomass accumulated by a forest ecosystem over time (Switzer, 1978). Carrying capacity is the ultimate productive potential of a site and is not static (Ford, 1983; Kimmins, 1996a; Worrell and Hampson, 1997). Environmental resistance encompasses the environmental pressures that control the rate with which the ecosystem achieves its carrying capacity. Each is strongly influenced by abiotic site factors, biotic factors, and cultural practices (Switzer, 1978, Burger 1994a). Site factors include topography, climate, drainage, soil physical properties, and organic matter. Biological factors include genetics, competition, density, and vegetative structure. Cultural practices include site preparation and manipulation, genetic tree improvement, and silvicultural technology. Ultimately these factors combine to control the supply of air, water, and nutrients to the plants growing on the site. The main focus of most site preparation treatments are to enhance regeneration, stand density, and volume production by controlling critical soil properties; in particular, bulk density, drainage, soil fertility, and organic matter because these are the factors on which we have found to have the most direct control (Powers et al., 1990; Kimmins, 1996a; Worrell and Hampson, 1997).

2.2.3. Tree roots

Roots are the means by which trees exploit the soil environment (Smit et al., 2000). The rooting patterns of various tree species and genotypes are known to follow several distinctive spatial (Fitter, 1996, Persson, 2000) and temporal (Idol et al., 2000) patterns. Roots are opportunistic at the scale in which soil properties begin to play a role in resource allocation, and resource availability also plays a part in the allocation of above and belowground biomass (Aber and Melillo, 1991). The presence of mycorrhizal fungi can greatly enhance the ability of a tree to take up nutrients and water. In order for trees to make the most of the resources present in the soil, conditions that favor root system development should be maintained or improved. However, due to their transient nature and the experimental difficulty associated with root studies, very little basic information exists with regard to the amount of roots or their distribution in many crop systems (Smit et al., 2000).

Assuming the density of the root system is sufficient, roots do several things to their local environment to cause the movement of water and nutrients into the plant (Barber, 1977). The flux of nutrients to tree roots occurs via mass flow and diffusion gradients. The active transport of dissolved nutrient anions and cations, as the plant uptakes water, is the primary means of absorption of certain nutrients. These nutrients pass through the root wall via the exchange of H^+ and OH^- ions with the soil solution. Trees release additional amounts of H^+ and OH^- into the soil solution, which establish diffusion gradients by which nutrients move toward the roots in an effort to maintain equilibrium. The importance of diffusion increases as the mobility and availability of a specific nutrient decreases (Bowen, 1984) and is affected by pH. Phosphate and ammonium are the two most significant of these less-mobile nutrients. Thus, the flux of nutrients toward the roots depends on the local moisture conditions, and the extent of the root system.

2.2.4. Loblolly pine roots

Loblolly pine is the most important tree species in commercial plantation forestry in the southern United States (Baker and Langdon, 1990). Its selection is due mainly to its responsiveness to silvicultural treatments (Borders and Bailey, 2001), rapid early growth, and a degree of tolerance to both drought and periodic flooding (Baker and Langdon, 1990). Young loblolly seedlings develop deep taproots in sandier soils; however, the rooting strategy commonly takes the form of extensive lateral rooting when root-limiting layers are encountered. Roots of neighboring trees commonly graft as the systems extend well beyond the crown. In young loblolly stands the ratio of live to dead roots ranges between 1:4 to 1:26 (Frederickson and Zedaker, 1995), which is higher than other, similarly aged, pine species (Persson, 2000). However, heavy fine root turnover contributes to the fertility of loblolly stands (King et al., 1997), which is indicative of the high resource nutrient capture rates normally associated with competitive pioneer species (Smit et al., 2000). Small size classes (<10mm) lose up to 60% of their mass in just two months (King et al., 1997). Through 15 years of age, decomposing loblolly pine roots can act as a net source for important nutrients such as N, P, K, Ca, and Mg in those stands. In addition, decomposing root channels have been shown to act as preferential pathways for further root development (Van Lear et al., 2000) and for air and water movement.

2.3. Forest Productivity

Forest productivity must be defined in order to discuss the sustainability of management. Trees species are adapted to specific site types and exploit specific site conditions (Switzer, 1978). Productivity typically refers to the rate of biomass accumulation with time although it is commonly used to refer to actual production as well, which refers to the total biomass produced. Net primary productivity (NPP) or net primary production is considered the gold standard of productivity or production measures (Powers et al., 1990). In the context of forestry management practices, the production of crop tree biomass is the most common means of comparison when evaluating combinations of species, site, and silviculture (Haines and Gooding, 1983; Morris and Miller, 1994).

Forest productivity is alternatively defined as the combination of biological (biotic), environmental (abiotic), and cultural factors that determine the rate at which the forest overcomes environmental resistance and achieves a site's productivity potential (carrying capacity) (Switzer, 1978). Site productivity is a subordinate component of forest productivity (Morris and Miller, 1994, Burger 1994a). It is the inherent capacity of a site to produce vegetation and is a function of intrinsic site properties such as physiography, climate, and soil quality.

The economic goal of most forest owners and managers is to grow more wood for a lower cost. Intensive silviculture is the mechanism used to increase forest productivity through the application of technologies that decrease environmental resistance or increase the carrying capacity (Burger 1994a). Some components of forest productivity are essentially fixed, or certainly are beyond our ability to manipulate them appreciably. These include physiography, climate, and other relatively static features of the environment (Powers et al., 1990; Kimmins, 1996a). Instead, forest managers attempt to affect forest productivity through soil manipulation, competition control, and species or genotype selection (Terry and Campbell, 1981; Stanturf et al., 2003). These practices can range from simple to the technologically sophisticated, and their adoption is ideally subject to matching practices with site conditions and performed within the context of a cost-benefit analysis.

2.4. Measuring site productivity

2.4.1. Approaches for measuring site productivity

Site productivity essentially relates to the response of plants, particularly the crop species, to the combination of chemical, physical, biological, and environmental process and attributes in the soil and forest floor (Van Miegroet et al., 1994). The growth environment controls the rates of processes that ultimately affect a plants ability to convert inputs into biomass (Worrell and Hampson, 1997). Our best information on productivity is based on rotation length changes. NPP is considered the gold standard for defining the productivity of a given site (Morris and Miller, 1994). However, not only is NPP probably not constant, it is exceedingly difficult to accurately measure. As a result metrics of the crops species are more commonly used, such as site index (Carmean, 1975), and crop yield (Vance, 1999). Because of the long rotation lengths used in forestry, foresters are often unable to make meaningful comparisons of production across rotations. Bioassays are further limited because they may only be used on sites where the desired crop already exists; bioassays are not possible when reclaiming disturbed sites or making site conversions (Burger, 1996). Furthermore, evaluating site productivity by comparing bioassays across time is not possible because forest industries continue to make silvicultural advances that increase production.

Given the limitations of bioassay assessments, there have been efforts to develop methods that evaluate site quality based on inherent site properties or growth potential that are the determinants of tree growth (Van Miegroet et al., 1994; Kimmins, 1996a; Burger and Kelting, 1999; Kelting et al., 1999, Vance, 2000). Evaluating the quality of sites using inherent soil-site properties remains an ongoing art and science. Liebig's law of the minimum (Brady, 1984) implies that on any given site there are specific site factors that will control growth. There is a vast array of soil and site properties that can potentially affect tree growth (Van Miegroet et al., 1994; Vance, 2000). Indirect site quality measures include soil properties, soil biological activity, conservation of mass, nutrient budgets, or indirect indicators of environmental quality such as water quality. Examples of growth potential measurements include leaf area index, foliar nutrient analysis, carbon allocation, and water stress (Van Miegroet et al., 1994). The effect of management on site productivity will depend on the interaction between the limiting environmental factors and the changes imposed by management disturbance.

2.4.2. Comparing productivity between rotations

Comparing productivity between rotations is a difficult challenge (Morris and Miller, 1994; Burger, 1996; Richardson et al., 1999). There are a large number of confounding factors that prevent direct comparisons of forest production between rotations (Dyck and Cole, 1994). Climate (Boardman, 1978; Shoulders and Tiarks, 1980; Valentine et al., 1999; Kirschbaum, 2000), intensive silviculture (Hasenauer et al., 1994), the use of genetically improved trees (Schultz, 1997; Stanturf et al., 2003), physiography and drainage class (Carmean et al., 1989), even the specific productivity model selected (Carmean, 1975) render direct comparisons between two distributions (e.g. NPP, biomass, site index) inappropriate for answering questions about changes in productivity between rotations, or long term productivity questions for that matter. Many contemporary studies have been initiated in the past 15 years that aspire to address the long-term productivity issues associated with intensive management (Smith et al., 1994a; Aust, 1998; Jones et al., 1999; Proe et al., 1999; Terry et al., 2001; Powers, 2002); however, they have not yet matured into true long-term studies (Dyck and Cole, 1994).

Efforts have also been made to use computer modeling to address long-term productivity, but modeling approaches are imperfect and sometimes unsatisfying because of scaling issues (Proe et al., 1994). Model output is also only as good as the data used to create it, and models are subject to the limitations of their inference space (Moore and McCabe, 1993). Models are based on approximations, and if the derivative database is not representative or does not account for the heterogeneity, then model bias becomes a problem. As a model is scaled these biases are propagated and lead to inaccuracies.

We currently lack good methods for direct field evaluations of changes in productivity (Morris and Miller, 1994; Richardson et al., 1999). While modeling approaches can account for some of the sources of variation, we still require some direct way to evaluate these systems. One technique that has been proposed involves using stand growth rates as an indicator of the sustainability of site resources (Richardson et al., 1999) based on the hypothesis that stands either have parallel growth trends to prior rotations or divergent trends. Evaluating this hypothesis could be done using state-space models (Garcia, 1994; Richardson et al., 1999), which utilize height, basal area, and stem density as state variables for the stand. The disadvantage of this approach is the necessity of including all state variables in order to avoid errors that may mask soil-site productivity trends.

2.4.3. Heterogeneity and scale

One of the most difficult problems associated with applied silvicultural research and most ecological and biological sciences is the issue of pattern and scale (Levin, 1992, Waring and Running, 1998). Forests develop over time on landscapes made up of a heterogeneous mosaic of vegetation, soils, landforms, climate, land use and disturbance, which all change through time (Urban et al., 1987; Pickett and Cadenasso, 1995). Spatial scales range from the microscopic arrangement of soil particles to whole ecosystems (Robertson et al., 1988; Jackson and Caldwell, 1993; Gross et al., 1995; Miller, et al., 1995; Robertson et al., 1997; Pachepsky et al., 2003). Temporal scales range from seconds to hundreds of thousands of years (Urban et al., 1987; Boul et al., 1989).

Although the importance of system heterogeneity is apparent, it has remained difficult to define (Dutilleul and Legendre, 1993; Li and Reynolds, 1995). Statistical heterogeneity, or heteroscedasticity, describes the inequality of variances, and is a particular type of heterogeneity that may not always be ecologically meaningful or interpretable because it is a description of the mathematical combination of the observations but does not provide insight into their structure (Dutilleul and Legendre, 1993). From an ecological standpoint, heterogeneity is a description of the complexity of a system; however, it is not strictly a quantitative property, but also a qualitative one.

Therefore it is difficult to put it in terms that are easy to recognize, or neatly quantify (Li and Reynolds, 1995, Wiens, 2000).

The science of environmental heterogeneity and scale is rooted primarily in complex mathematical theory. It has largely been the realm of landscape ecologists and environmental modelers (Weins, 2000). Field scientists in forestry and soil science use the scientific method and experiments that are designed to test very specific hypothesis. Through experimental design we attempt to control the effects of site heterogeneity (Pickett and Cadenasso, 1995). The challenge is that our perceptions are dictated by our expertise and experience, and an individual observer sets the scale based on that expertise (Allen and Hoekstra, 1992). Studies cannot be limited to arbitrary scales, and experiments conceived at different scales may yield conflicting results and interpretations (Addicott et al., 1987). In addition, the ability to extend conclusions based on one scale onto others can be very limited (Addicott et al., 1987; Proe et al., 1994). Therefore, matching scale to the hypothesis becomes a fundamental challenge to field scientists.

It is a common approach to divide natural systems into discrete functional components operating at different scales using some hierarchical paradigm (Urban et al., 1987; Hoosbeek and Bryant, 1992). Heterogeneity will manifest itself differently at each of these scales because environmental gradients are manifested as patchy mosaics (Addicott et al., 1987; Ehrenfeld et al., 1997). Creating robust statistical and process based models that will reliably characterize a system requires multiple levels of organization and observation that include components from scales above and below the scale of interest (Allen and Hoekstra, 1992; Ryan et al., 2000). Beyond that, we would also argue that experiments must be conducted, and models constructed, at multiple scales in order to provide insight into the system and phenomena that are transparent at certain scales (Allen and Hoekstra, 1992).

2.4.4. Spatial analysis in forestry

Geographic information systems (GIS) are a potentially powerful tool for evaluating long-term productivity in forestry, and they have been in development for forest industries for over 30 years. Initially their primary use for foresters had been as a tool to overlay multiple resource data layers as part of decision support to inventory the resource and schedule harvest applications (Bell and Atterbury, 1983; Honea et al., 1991). These functions remain the dominant GIS application in resource management (Klemas, 2001; Gustafson and Crow, 1998; Loh and Rykiel, 1992). Improvements in computer hardware and software over the past decade, as well as the increased ease of data acquisition, have spurred the application of GIS tools toward answering specific research questions and environmental monitoring (Hess and Cheshire, 2002).

Forestry and forest science have utilized GIS in recent years as a tool to evaluate growth and yield (Proe et al., 1997), long-term harvest planning (Proe et al., 1997; Mlandenoff et al., 1994), fire-management (Plant and Vayssieres, 2000), wildlife habitat (Plant and Vayssieres, 2000, Rickers et al., 1995) or BMPs in the control of non-point pollution (Plant and Vayssieres, 2000, Cox and Madramotoo, 1998, Liah and Tim, 1994, Sun et al., 2001). Much of this work uses computer modeling at the landscape or regional scale and remotely sensed data (Mankin et al., 2002) or site classification (Louw and Scholes, 2002). Little of the work has occurred at a stand scale that includes soils information or discrete harvesting impacts. Payn et al. (1999) attempted to use soil and vegetation parameters along with GIS to predict changes in forest productivity in radiata pine (*Pinus radiata*) stands in New Zealand, but concluded that current methods of monitoring site quality were not sufficient for such a use with their data.

Crop and soil science also use modeling algorithms in conjunction with GIS software. However, they have also made efforts to use GIS software as a management tool at smaller scales than forestry science (Mallawaarachchi et al., 1996). The main difficulty lies with compiling data from multiple scales into a useful management product. Priya and Shibasaki (2001) used soils information to model site-specific crop simulations. In addition, applying GIS tools to precision agriculture is an active area of agronomy research (Bullock et al., 2002; Blackmer and White, 1998; McKinion et al., 2001; Earl et al., 2000).

The importance of having soils information at larger scales than provided by standard soil surveys is recognized by both forest and soil science practitioners (Karlen and Fenton, 1991; Indorante et al., 1996; Priya and Shibasaki, 2001). The main limitation in applying GIS to these scales appears to do with the persistent gap in understanding the cause and effect relationships that exists between landscape function and production, as well as the inherent variability that occurs at these scales (Boyle et al., 1997; Bettinger et al., 1998). Successfully linking the stand-level information to a landscape or regional scale will not be achieved from high-resolution remote sensing alone (Ryan et al, 2000). Information must also be gathered at the stand scale to complement high-resolution remotely sensed data.

2.4.5. Site quality mapping

An explicit goal of intensive forestry is determining the quality of a given site, and providing a means to incorporate site classification and site evaluations into management planning (Jones, 1994; Louw and Scholes, 2002). Forest science has developed a wealth of technology to enhance production, and the most benefit is gained when these technologies are applied to the highest quality sites (Carmean, 1975). Good sites in general produce higher yields and higher quality products, and are preferred by the more valuable crop species. In addition these sites are generally more responsive to intensive management and therefore the returns on investments are usually higher.

Tracking direct measurements of soil-site properties is an important means for evaluating long-term changes in soil-site quality (Burger, 1996, Kelting et al., 1999). Soil is a dynamic and very complex and heterogeneous biological system; therefore, choosing the specific indicators of soil quality can be difficult (Jones, 1994). The approach in agricultural research is to define soil functions as they relate to productivity, and then single out soil attributes that reflect key functions (Carmean, 1975; Doran and Parkin, 1994; Karlen and Stott, 1994; Larson and Pierce, 1994). The strongest models are those that reflect multiple levels of organization and observation and include components from scales above and below the scale of interest (Allen and Hoekstra, 1992; Ryan et al., 2000). The best indicators are those that are able to express soil physical parameters in some sort of integrative biological context such as the least limiting water range (LLWR) (DaSilva et al., 1994), which models moisture conditions that are most favorable for root growth using bulk density, soil strength, organic matter, and texture. Another approach to soil quality modeling includes scoring model components based on the sufficiency for the desired function such as tree growth (Kelting et al, 1999), or erosion resistance (Pierce et al., 1983).

One-time measurements of soil properties are not necessarily sufficient for establishing disturbance effects on long-term productivity. Important soil properties such as bulk density, pore distribution, and hydraulic conductivity are prone to change and can all be improved due to natural process and management practices (Voorhees, 1983; Cairns, 1989). Soil organisms alter soil structure (Jastrow and Miller, 1991; Oades, 1993), plant roots constantly probe the soil matrix and die off (Larson and Allmaras, 1971; Perfect et al., 1990; Lister et al., 2004), and the shrink-swell properties of 2:1 clays lower bulk density and increase macroporosity (McGowan et al., 1983; Sarmah et al., 1996).

As there are many approaches to evaluating productivity, there are also many approaches to tie productive capacity to indirect measures of site quality (Jones, 1994). The goal of most site classifcation approaches is to link the productive capacity of forests to indirect measures, but mappable units (Carmean, 1975). Sites types are natural units that can be described and mapped, but generally not further subdivided in a broad sense (Louw and Scholes, 2002). The goal of site evaluation is to establish the connection between specific site types and biotic and abiotic factors such as climate, topography, parent material, cover types, and time (Bailey et al., 1978). No single classification or evaluation system is universally accepted, however, they all provide a framework from which land managers can base their decisions (Jones, 1994). The main limitation when choosing or developing a site classification system is the inference space for any given model. Small-scale systems while very precise and informative are limited by the wider availability of key model components. Large-scale systems while incorporating widely available and easily mapped data may be very imprecise for areas outside of a reasonable inference space for the data (Jones, 1994; Ramsey and Schafer, 1997). Large-scale approaches can be very useful as long as several key conventions are adhered to (Carmean, 1975). (1) The precision of these models depends greatly in the care taken defining the areas in question. The classifier must carefully consider the nature of the stands and the ability to observe, measure, and define important site features. (2) "Soil-site results apply only to the area studied, and further only to the particular soil and topographic conditions sampled within the study area." (Carmean, 1975). (3) The types of areas studied should include a wide variety of site quality. (4) Models should be validated against check plots. Following these guidelines should protect against model bias and inaccurate predictions.

2.5. Productivity decline

2.5.1. Scientific and societal concerns

Scientific concerns about the decline of forest productivity have been present for at least 100 years (Powers et al., 1990; Johnson, 1994). Evidence of productivity decline is mixed, and many recent reviews note that direct links between forest management and forest decline have not yet been established (Powers, 1990; Morris and Miller, 1994; Kimmins, 1996a). In addition, public anxiety over perceived problems with large monoculture tree farms has become more acute (Nambiar, 1996).

Indeed, ample literature is available that demonstrates there are potentially negative effects of forest trafficking and management on soil properties that could affect long-term productivity (Moehring and Rawls, 1970; Hatchell et al., 1970; Shoulders and Terry, 1978; Gent et al., 1983; Burger et al., 1988; Rachel and Karr, 1989; Guo and Karr, 1989). Repeated trafficking that causes reduced soil physical quality, erosion, nutrient loss, and organic matter loss; all of which are tied to soil quality and have an effect on potential productivity (Powers et al., 1990; Sheriff and Nambiar, 1995; Worrell and Hampson, 1997; Kozlowski, 1999). A persistent criticism of contemporary forest management is that it is not sustainable because of disturbances associated with management (Nambiar, 1996; Burger and Kelting, 1999).

2.5.2. Evidence of forest productivity decline

There is considerable evidence in the literature concerning potential declines in productivity associated with intensive forestry, although there are deferring opinions about the actual interpretation of this evidence (Gessel, 1981; Childs et al., 1986; Powers et al., 1990; Johnson, 1994; Morris and Miller, 1994; Kimmins, 1996b; Worrell and Hampson, 1997). Cole and Compton (1994) observed 26 percent reductions in Douglas fir (*Pseudotsuga menziesii*) production after bole-only harvesting in Washington. Smith et al. (1994b) reported similar declines for radiata pine (*Pinus radiata* D. Don.) plantations in New Zealand. Both studies mention that these declines could be corrected with fertilization, which can be a routine practice for intensive management of more productive sites. Tiarks and Haywood (1996) provide one of the few examples of the effects of intensive management over multiple rotations on the Lower Coastal Plain. They observed an average 20 percent decline in volume production between rotations.

Harvesting practices

Studies on the effects of trafficking associated with wet-weather harvesting in the United States (Youngberg, 1959; Perry, 1964; Moehring and Rawls, 1970; Hatchell et al., 1970; Simmons and Ezell, 1983; Lockaby and Vidrine, 1984; Scheerer et al., 1994; Aust et al., 1995; Heninger et al., 2002) have shown that disturbances, especially associated with skid trails, reduces seedling survival and reduces the height and diameter growth of young trees. Some of the more recent reviews have noted that while ample evidence exists that improper forest practices can negatively affect soil physical and chemical properties, the direct link with the exception of erosion (Childs et al, 1986 Worrell and Hampson, 1997) between disturbance and actual long-term productivity declines remains elusive (Morris and Miller, 1994; Kimmins, 1996a). Soil physical disturbance associated with wet-weather harvesting was observed to diminish the productivity of quaking aspen (*Populus tremuloides* Michx.) stands (Bates et al., 1993); however there was no effort to recover these stands using some sort of site preparation. Considering that the exact potential productivity of a site is impossible or exceedingly difficult to determine, researchers are at a disadvantage to establish this link (Powers et al., 1990; Morris and

Miller, 1994; Kimmins, 1996a). The ability to make a compelling field evaluation of treatment and disturbance effects on long-term site productivity would be a significant achievement (Comerford et al., 1994).

Soils

Powers et al. (1990) stated that air, water, and soil are the three fundamental resources necessary for tree growth. Soil is perhaps even more important because soil chemical and physical properties control the supply of air, water, and nutrients to the trees (Switzer, 1978; Childs et al., 1986; Worrell and Hampson, 1997). Most losses in site quality can be attributed to reductions of soil function (Kimmins, 1996a), particularly the rates of soil processes (Worrell and Hampson, 1997). In general, less fertile sites are the most sensitive to disturbance, and most at risk for productivity decline because they lack the attributes that allow higher quality sites to rebound from disturbance (Burger and Kelting, 1999). Intensive forestry practices potentially impact soil quality, and therefore sustainability, by changing soil properties in negative ways (Greacen and Sands, 1980; Childs et al. 1986; Worrell and Hampson, 1997). Soil is the least renewable resource influencing site productivity, but also the resource over which managers have the most control, so the majority of studies have focused on the effects of harvesting and forest management on soil properties like organic matter and compaction (Kimmins, 1996a).

Logging practices

Perhaps the most thorough discussion to date on the effects of logging practices on site productivity and sustainability has been made by Worrell and Hampson (1997). There are six main modes that forest management operations affect site and soil productivity: 1) increasing erosion, 2) compaction, 3) organic matter quality and quantity, 4) water availability and aeration, 5) change in soil structure and horizonation, and 6) altering nutrient status/cycling. Most other reviews emphasize erosion, compaction, and soil organic matter (Greacen and Sands, 1980; Childs et al, 1986, Powers et al., 1990; Morris and Miller, 1994), however these three factors strongly influence the last three modes mentioned by Worrell and Hampson (1997).

Erosion

Erosion is potentially the worst harvesting effect regarding long-term productivity on sites where it is an issue. Soil forms at rates between 20 and 1900 kg ha^{-1} yr^{-1} (Alexander, 1988), which amounts to an annual maximum of only 0.02 cm yr^{-1} assuming a bulk density of 1 g cm^{-3}. If the rate of soil loss exceeds the rate of soil formation, we must assume that this condition is not sustainable (Childs et al., 1986; Worrell and Hampson, 1997). For forestry, the period of greatest risk is during harvesting and site preparation because of the installation and use of roads and skid trails (Aust and Blinn, 2004). There is frequently a spike in sedimentation at this time; therefore, ensuring that erosion does not continue into stand development is important. In most cases, forestry practices in the United States falls within acceptable limits (Powers et al., 1990) particularly since BMP's have become widely adopted by industrial forest managers and non-industrial landowners (Ellefson et al., 2001; Edwards and Stuart, 2002; Kilgore and Blinn, 2004).

Soil Compaction

Soil compaction occurs as a result of trafficking of machinery during forestry operations. While compaction can be beneficial in some cases (Kozlowski, 1999), it normally is not (Greacen and Sands, 1980; Kozlowski, 1999). Compaction can increase bulk density on poorly drained loblolly pine plantations by 10 to 20 percent, and decrease macroporosity by half (Moehring and Rawls, 1970; Dickerson, 1976; Simmons and Ezell, 1983). When soils are trafficked, three types of physical disturbances can occur: non-deforming, hardening, and plastic flow (Koolen, 1994). The principal effects of compaction on soil are the loss of porosity, structure, stability, aggregation and increased soil strength, which can have several consequences (Greacen and Sands, 1980). The growth of tree roots is strongly influenced by the balance of air and water (Greacen and Sands, 1980; Childs et al., 1986; Da Silva et al., 1994). Root growth, and therefore tree growth, is optimized when water content falls within a root growth window. Compaction can also inhibit the uptake of nutrients by plants such as nitrogen, phosphorus, and potassium (Kozlowski, 1999). The susceptibility of a given soil to compaction depends on several factors: texture structure, roots, pH, cation exchange capacity, clay particle morphology, and water content. When sites are sufficiently wet they are particularly susceptible.

Organic Matter

The loss of surface organic matter (litter) is an important productivity concern because it affects many soil properties and influences several important soil functions (Childs et al., 1986). Twenty-six percent reductions in tree growth were observed after whole tree harvesting, or whole-tree harvesting with forest floor removal (Smith, 1995). Organic matter acts as a source of soil nutrients, acts as an exchange site for nutrient cations, improves soil structure and tilth, lowers soil strength, improves soil water relations, insulates soil from temperature fluctuations, and acts as an energy source for soil organisms (Childs et al., 1986).

Organic matter has many forms ranging from the harvesting residues, the forest floor, old root channels, and organic compounds in the mineral horizons (Prichett and Fisher, 1987; Scott and Martin, 1990, Van Lear et al., 2000). Certain types of organic matter are more important to environmental quality than others. Organic matter varies in its chemical make up, age, and resistance to decomposition (Connell et al., 1995). Microorganisms are the primary means by which nutrients in organic matter are mineralized for use by plants. In addition, the byproducts of this biological activity contribute to the formation and stability of soil aggregates (Jastrow and Miller, 1991). Forest operations can change the soil environment and lead to organic matter loss either through direct removal or accelerated decomposition (Ellert and Gregorich, 1995). In addition, operations can influence the type of organic matter and its distribution on a site after harvesting, as well as exposing bare soil (Neary et al., 1984; Eisenbies et al., 2002).

Other modes of decline

Foresters have less direct control over the other modes affecting long-term productivity. While compaction and organic matter affect water availability, it is also affected by site drainage (Conner, 1994), soil texture (Vance, 2000), and effective rooting depth (Pearson, 1974). Soil mixing due to trafficking can alter soil structure, texture, and horizonation (Kelting, 1999; Miwa, 1999). Clay particles lifted from argillic horizons can lead to reduced water availability, as well as increased soil strength (Da Silva and Kay, 1997). Lastly, nutrient cycles can be disrupted after whole tree harvesting, soil loss due to erosion, fire, or disrupted nutrient cycles (Neary et al., 1984; Childs et al., 1986; Vitousek, et al., 1992; Kimmins, 1996a)

2.5.3. Productivity decline caused by non-forestry operations

Logging and forestry operations are not the only contemporary threat to long-term site productivity. Several studies have examined the effect of climate change on forest productivity. Acid rain has been linked to loss of base cations in forest soils (Johnson, 1992; Drohan and Sharpe, 1997; Adams, 1999). Forest soils are naturally buffered against changes in pH, however the capacity is not unlimited. Once this capacity is met, fertility will likely decline. Some agricultural and forest systems have already suffered declines from acidification and associated loss of nutrient availability and increased aluminum toxicity (Adams, 1999).

A second mode of climate change is the increased concentrations of carbon dioxide in the atmosphere, and the accompanying increases in temperature (Alley, 2000). Carbon dioxide content in the atmosphere is on the rise, increasing from about 300 ppm in 1900 to 315 ppm in 1950 and 370 ppm in 2000 (Lomborg, 2001). While some studies indicate that carbon dioxide increases could boost tree growth (Kirschbaum, 2000), others have reached an opposite conclusion because nutrient supplies are not increasing in tandem (Comins and McMutrie, 1993). The Earth's climate through geologic history has been chaotic (Alley, 2000). There remains a great deal of uncertainty as to how elevated carbon dioxide contents will affect specific geographic regions.

There remains a great deal of debate as to the degree of influence human society has on climate change (Lomborg, 2001). There is certainly less debate about humans' ability to substantially influence climate in a way that improves site productivity. Acid rain may be the most serious problem associated with climate change because these changes are more insidious (Galloway, 1989; Adams, 2001). It could be many years before the problems associated with acid rain manifest themselves. Although there are means to lessen the effects of acidification of soils through liming, the expense of liming less productive land may be prohibitive.

2.5.4. Evidence of decline using ecosystem models

A third branch of sustainability research includes ecosystem-modeling approaches through computer simulations. The complexity of the forest system and the length of time required in order to observe some phenomena makes standard field trials impractical (Morris and Miller, 1994; Rastetter, 1996). In addition, some problems may be far more difficult to correct if action is delayed until an ecosystem response is measurable. Simulation models allow scientists to compare a variety of productivity scenarios over time periods that are far longer than would be reasonable for a field trial. With the advances in computing power over the past decade, ecosystem models have become increasingly sophisticated.

There is a wide variety of modeling techniques that are available to researchers (Morris and Miller, 1994; Ryan et al., 2000). Process-based models appear to be the most desirable because of the ability to model key environmental processes and link them to productivity or environmental indicators (Smith, 1995; Kimmins, 1996a). Many models have already been developed that predict sustainability or productivity based on soil fertility and site productivity under different regimes of management, climate, and disturbance: FORCYTE, FORECAST, FORCEE (Kimmins, 1996a), LINKAGES (Pastor and Post, 1985), FOREST-BGC (Running and Gower, 1991; Waring and Running, 1998), G'DAY (Comins and McMurtrie, 1993) LEEMATH (Li et al., 2000), and many others (Proe et al., 1994). Models can also be modular, such that important ecosystem components are modeled independently and then linked together in a full model (Waring and Running, 1998; Li et al., 2000).

There are a number of examples of models that have predicted productivity declines, or the potential for decline, both from intensive management as well as climate change. King (1995) used the G'DAY model to predict late rotation declines in radiata pine stands in New Zealand associated with nitrogen release and organic matter pools. Morris et al. (1997) used FORCAST to simulate productivity declines associated with whole tree harvesting on Douglas fir stands on both a fertile unmanaged site, and a depleted site. They concluded that heavily impacted sites could improve under less demanding management, specifically longer rotations.

The downside of models is that they are only generalizations. Good models are difficult to construct (Morris and Miller, 1994). Ecosystems are exceedingly complex systems. Errors in predictions can result from leaving out critical components, scaling errors, and violation of model assumptions. While they may provide useful insights into the behavior of a system, and they may predict trends, it must also be emphasized that there may be a fair amount of error with the absolute values predicted (Morris and Miller, 1994; Rastetter, 1996; Morris et al., 1997; Ryan et al., 2000). Therefore models are most useful as a guide for which factors are most important to long-term productivity. As a tool for implementing specific policy, models become limited because they are so difficult to validate (Comerford et al., 1994; Rastetter, 1996).

2.5.5. Sustainability as a management paradigm

In response to the body of evidence implicating intensive management as a potential cause of forest decline and the corresponding increase in societal concerns, there have been calls for sustainability to become the new paradigm (Powers et al., 1990; Kimmins, 1996a; Burger and Kelting, 1999). Sustainability, in the context of intensive management, is "the ability of [a managed ecosystem] to maintain production through time, in the face of long-term ecological constraints and socioeconomic pressures" (Altieri, 1987). In southern forestry, species selection ranges from allowing natural regeneration to planting genetically improved stock acquired from tree-improvement programs (Schultz, 1997). Cultural practices include harvesting methods that favor the desired species, site preparation such as bed preparation, organic residue manipulation, burning, altering site drainage, chemical weed control, or fertilization. The signature of effective management is that site resources are efficiently improved or utilized without exceeding the lands capacity to recover from the various disturbances (Maini, 1992; Worrell and Hampson, 1997). While the goal of most forest managers is to maintain or increase productivity, the execution of a silvicultural plan can result in significant site disturbance as well.

Opinions vary on what constitutes sustainable forest management (Comerford et al., 1994; Kimmins, 1996a; Vance, 2000). Some may argue, that as long as we maintain forest productivity that sustainability is achieved (Burger 1994a). However, forest productivity can be buoyed by technology and mask the degraded productive capacity of the site (Burger 1994a; Vance 2000). There is no guarantee that technology will necessarily maintain pace with environmental changes. This is complicated by the fact that we in fact do not really know the true carrying capacity of the systems we manage (Powers et al., 1990).

An additional level of complexity is that carrying capacity, or "achieved NPP", varies for different management regimes (Ford, 1983; Kimmins, 1996a). Given that forest management represents a change in ecosystem structure and composition, it is probably unreasonable to expect forest conditions will be identical to a preceding management condition (Worrell and Hampson, 1997). Worrell and Hampson (1997) present four questions that should be used to evaluate whether an operation may be deemed sustainable. (1) What is the magnitude and scale of the impact, and is it desirable or undesirable? (2) What is the significance and permanence of the impact? (3) How reversible is the impact? (4) What are the long-term benefits or costs associated with the impact or with corrective action?

Included in the recent sustainability discourse are arguments where biodiversity, ecosystem structure, and ecosystem health are emphasized (Swanson and Franklin, 1992; Kimmins, 1996a; Perry, 1998). Biodiversity issues were first raised in tropical systems and the same questions have been raised regarding temperate climates (Hansen et al., 1991; Franklin, 1993; Freedman et al., 1994; Simberloff, 1999). Ecosystem structure issues include managing forests so that attributes of old growth structure, such as snag and coarse woody debris, are maintained or mimicked (Vanha-Majamaa and Jalonen, 1991; Emmingham, 2002; Ferguson and Archibald, 2002). Ecosystem integrity and health are broad concepts that involve maintaining forest function (Costanza et al., 1992). Kimmins (1996a) notes that the expansion of issues and values society places on the forest was bound to expand. Foresters must now consider aspects of the forest beyond wood production and consider these other sustainability concepts. However, Fox (2000) counters that intensively managed industrial forests, although not explicitly managed for these functions and values, still contribute to the overall goal by reducing production pressures on the surrounding landscape.

2.5.6. Important forest productivity sustainability considerations

There are a number of important considerations when evaluating the sustainability of forest systems. First, ecosystems are very complex (Kelting et al., 1999). Second, what is true for some sites will not be true for all sites (Tiarks and Haywood, 1996). Third, the site productivity is not fixed (Powers et al, 1990; Worrell and Hampson, 1997), and the productive potential of a site may not be achieved in any given rotation (Kimmins, 1996a). Fourth, the true effect of disturbance on productivity may never be known because of the time periods required to establish a true test of change (Morris and Miller, 1994; Vance, 2000). Fifth there are many factors, such as non-crop competition, that can have as great of an impact on forest productivity as soil quality (Allen, 1990; Kimmins, 1996a; Lister, 1999; Xu et al., 2002; Lister et al., 2004).

As a final consideration, ecosystems are constantly moving toward equilibrium (Reichle et al., 1975; Worrell and Hampson, 1997), but progression through succession does not necessarily coincide with increasing site productivity (Powers et al., 1990). In cases where we significantly alter the composition and structure of an ecosystem, it may take many rotations to establish what the true productivity change has been. This is the main reason most long-term productivity research has concentrated on the maintenance of natural paradigms (Kimmins; 1996a). However, disturbance is a natural component of many ecosystems, and there are very few ecosystems that have not been disturbed by human activity (Cairns, 1989; Kimmins, 1996a). Moreover, there are examples where managed systems are more productive than their natural counterparts (Powers et al., 1990). The assumption is that as long as we preserve or restore critical natural function, then our practices may be deemed sustainable. However, what constitutes a "critical" function? Lastly, any system humans adopt will only mimic natural ecosystems, and in only certain cases can we hope to exceed natural primary productivity (Reichle et al., 1975; Stone, 1975; Worrell and Hampson, 1997). In most cases it is unreasonable to expect our managed systems to be equally productive as natural systems (Cairns, 1989; Worrell and Hampson, 1997; Vance, 2000).

Despite the varying positions on what constitutes sustainability, the main point is that land stewards must manage systems ethically utilizing the best combination of technology and scientific knowledge at our disposal. Society must also resist the urge to declare management and sustainability as mutually exclusive. Cairns (1989) outlines four management options once a site has been disturbed: (1) we can completely restore the system to its predisturbance condition, (2) we can restore selected ecosystem attributes, (3) we can move toward an alternate ecosystem paradigm, or (4) we can do little or nothing and accept whatever system develops. Option one may be economically and ecologically unattainable. Option four is not acceptable in light of the ethical and practical constraints of intensive management, but there is a fine line between it and option three; option three, however, at least implies a plan and a vision.

2.6. Site remediation

There are several proactive and rehabilitative means foresters can use to remediate sites with reduced productivity. Proactive steps are preferred because the costs associated with restoring degradation can be quite large compared to the costs that maintain or enhance soil or site productivity (Gessel, 1981). Rehabilitative steps are applied during site preparation using treatments that commonly include bedding, nutrient management, and weed control. The primary proactive steps that can be taken include (1) selecting sites that are able to naturally auto-remediate (Greacen and Sands, 1980; McGowan et al., 1983; Sarmah et al., 1996; Worrell and Hampson, 1997; Aust and Blinn, 2004; Lister et al., 2004), (2) adjusting harvest scheduling so that trafficking occurs when the risk to soil disturbance is minimized, and adjust rotation lengths in order to allow natural processes to effect positive changes both physically and nutritionally (Larson and Allmaras, 1971; McGowan et al., 1983; Raison and Crain, 1986; Perfect et al., 1990; Oades, 1993; Kimmins, 1996a; Sarmah et al., 1996), (3) avoiding treatments that may do more harm than good, such as intense burning (Neary et al., 1984) and (4) compliance with forest BMPs.

2.6.1. Auto-remediation of sites

Site remediation can occur both naturally and artificially (Voorhees, 1983; Cairns, 1989). The presence of shrink swell clays can allow compacted soils to achieve lower bulk densities after multiple cycles of wetting and drying (McGowan et al., 1983; Sarmah et al., 1996). Soil biological activity can benefit soil properties by contributing to the formation and stabilization of soil aggregates, alter soil structure, incorporate organic matter, and decrease bulk density by means of actively probing root systems (Larson and Allmaras, 1971; Perfect et al., 1990), or through the activity of soil organisms (Jastrow and Miller, 1991; Oades, 1993)

2.6.2. Best management practices

BMP programs developed by individual states are designed to protect natural resources for the long and short term and promote the use of preferred forest practices (Kilgore et al, 2004). The principal focus of BMP recommendations includes the protection of water resources by reducing erosion, controlling non-point pollution, and protecting stream water quality (Aust, 1994; Aust and Blinn, 2004). Most BMPs entail the establishment of vegetated buffers along waterways and drainages that filter sediments and nutrients. Many states, such as South Carolina, have also adopted harvesting BMPs to further augment water protection by preventing erosion and minimizing the impact to natural site drainage (Kilgore et al., 2004). Some recommendations were originally developed with little research information. In other cases, sites may prove to be resistant to disturbance, and some sites may naturally recover from disturbance (Morris and Miller, 1994; Scheerer, 1994; Aust et al., 1997; Maul et al., 1999; Kelting et al., 1999). However, the efficacy of these practices in this regard has since been well established and several states have modified their BMPs as additional information was collected (Aust, 1994).

A secondary goal of harvesting BMPs is to protect site productivity (Aust and Blinn, 2004); these types of BMP's may also be referred to as Sustainable Forestry Practices (SFPs) (Burger and Kelting, 1999). The SFP concept is currently a formative one and is not well developed separately of BMP programs. The timing of forestry operations relative to weather conditions is a critical element of harvesting BMPs (Aust 1994). Wet-weather harvesting increases the amount and degree of physical disturbance. About one quarter of the states that implement BMPs include soil productivity as a protection area (Kilgore et al., 2004). In the case of South Carolina, state foresters look for evidence of compaction and rutting when evaluating harvesting sites. According to Darrel Jones, Coordinator of BMP Inspectors (Personal Communication, August, 2002), South Carolina Forestry Commission inspectors look for harvesting sites that suffer deep rutting (>30 cm) over 20 percent of the site. Since compaction and rutting reduce macroporosity and increase bulk density, these impacts might reduce long-term site productivity; a number of prior studies have concentrated on harvesting impacts of soil physical properties (Greacen and Sands, 1980; Worrell and Hampson, 1997). However, certain sites may prove to be resistant to disturbance, and the connection hasn't necessarily been made between actual stand productivity and site disturbance (Morris and Miller, 1994; Aust and Blinn, 2004). In this regard, the actual efficacy, efficiency, or even necessity of some BMPs as a way to preserve long-term site productivity has not been fully substantiated because of site-specific management requirements (Reisinger et al., 1988; Burger and Kelting, 1999; Aust and Blinn, 2004). Given the expense of implementing some BMPs (Lickwar, 1992; Shaffer et al., 1998; Cubbage, 2004) care should be taken that the recommendations being made are well conceived, effective, and communicated to loggers and landowners alike (Kilgore and Blinn, 2004).

2.6.3. Site preparation

There are five goals associated with site preparation in pine plantations (Walstad and Kuch, 1987). First, site preparation creates uniform conditions with microsites favorable to pine such that the physical condition of the soil allows the best access to air, water, and nutrients. Second, the crop trees are able to gain an advantage over competing vegetation in a favorable setting. Third, undesirable species are removed or controlled by mechanical or chemical means. Forth, slash is managed to prevent fire and evenly distribute the nutritional benefit of the organic residues. Last, site access is improved. Ultimately, in terms of practical forestry, site preparation is primarily for the purpose of competition control, equipment access, and resource allocation (Prichett and Fisher, 1987).

Bedding and other tillage methods

Bedding is a very common site preparation on poorly drained sites, and its benefits are well established (Coile, 1952; Schultz and Wilhite, 1974; Gent et al., 1983; McKee et al., 1985; Prichett and Fisher, 1987; Morris and Lowery, 1988; Aust et al., 1995). In general bedding concentrates topsoil, litter, and debris near the seedlings to promote early growth (Prichett and Fisher, 1987). On wet pine flats bedding enhances microsite drainage and restores physical properties (Schultz and Wilhite, 1974; Gent et al., 1983; McKee et al., 1985; Prichett and Fisher, 1987; Morris and Lowery, 1988; Tippett, 1992; Aust et al., 1995), which enhance survival and growth of loblolly pine seedlings (Baker and Langdon, 1990; Shultz, 1997). The benefits of bedding diminish once trees begin to fully exploit the soil environment unless flooding is persistent (Terry and Hughes, 1975). In spite of the benefits of site preparation, care must be taken in their application. It is possible that while focusing on one facet of site productivity, others might inadvertently be diminished (Dulohery et al., 1996; Harrison et al., 1996). Furthermore, the gains in growth may not offset the expense associated with more intensive site preparation (Burger and Kluender, 1982; Cerchiaro, 2003).

There are many other types of mechanical site preparation: chopping, harrowing, discing, shearing, etc. (Smith, 1986). The primary goals of these treatments are to expose mineral soil and control competing vegetation. Secondary goals might include improving site drainage, as with mole-plowing (Spoor et al., 1982; Spoor and Fry, 1983; Weil et al., 1991), or loosening compacted soils, as with ripping. The main limitations of mechanical site preparation methods include the expense and potential impacts of repeated trafficking (Walstad and Kuch, 1987).

Fire

Fire is an important component of southern pine ecology and an important management tool (Smith, 1986; Walstad and Kuch, 1987). Prescribed fire is a very common silvicultural practice in southern pine plantations because it is can be more economical than its chemical and mechanical counterparts (Wade and Lunsford, 1988), although due to environmental conditions can make its overall cost highly variable (Walstad and Kuch, 1987). Fire is most often used to reduce fuel loads, but it is also used to prepare seed beds, control competing vegetation, and control forest pests (Smith, 1986). Along with the benefits of prescribed fire come some potential negative effects. Fire can lead to an increase in runoff and erosion, it can decrease air quality, and it can be a nuisance to neighboring landowners (Wade and Lunsford, 1988). Intense fire can affect soil productivity by decreasing infiltration, altering structure, and texture, increasing soil temperatures by solar radiation, and volatilize important soil nutrients and organic matter (Childs et al. 1986).

Nutrient management and fertilization

While nutrient loss has been shown to be an important sustainability issue, nutrient management is an integral part of intensive forest management. In most cases when people think of nutrient management they think of fertilization. Fertilization can have both sustainable and non-sustainable connotations (Lockeretz, 1998). Compared to agriculture, fertilizer use in forestry is fairly nominal and is generally used to enhance growth at critical stages in stand development by addressing site nutrient limitations

(Neary et al., 1984; Jokela et al., 1991). However, fertilization can also result in nutrient imbalances and deficiencies in non-targeted nutrients (Harrison et al., 1996). Fertilization has also been used for the purpose of replenishing site fertility after direct nutrient removal, such as by whole tree harvesting (Merino and Edeso, 1999). This form of remediation does not fit within more stringent definitions of sustainability because the system is technically not balanced (Lockeretz, 1998)

Organic matter conservation and management is a second type of nutrient management (Ellert and Gregorich, 1995). Organic matter influences fertility both by contributing to cation exchange and retention in the soil, but also by acting as a source for important nutrients such as nitrogen. In infertile sandy soils, the contribution to cation exchange may be quite substantial. The actively cycling components of organic matter are more important from a nutritional standpoint (Ellert and Gregorich, 1995). Organic matter is also inexorably linked to nutrient transformations in soil (Gressel et al., 1996; Harrison et al., 1996).

Herbicide application

The application of herbicides is an important tool for silviculturalists to influence stand development and enhance growth. Competition has as much of an effect on productivity as site properties (Kimmins, 1996a). Like any of the site preparations treatments mentioned above, herbicide treatments also have sustainable and non-sustainable connotations. Foresters use herbicides to retard undesirable species within the stand so that it follows a desired successional track. The obvious benefits of herbicides are that they increase survival and allow site resources to be directed to the crop species. However, herbicide use can also affect nutrient transformations (Vitousek et al., 1992), and some non-crop vegetation may be desirable for improving soil physical and chemical properties after disturbance (Lister, 1999).

2.7. Summary

The sustainability of intensive forest management practices remains a key issue in forest industry. The development of BMPs have been the primary means by which forest industries have tried to protect site and soil productivity, primarily by restricting the amount of heavy soil physical disturbances. There are many soil and site properties that are affected by trafficking; however, many questions remain about the ability of sites to resist and recover from site disturbance. Furthermore, the ameliorative effects of site preparation are not considered by most BMP guidelines (Burger and Xu, 2001). This dissertation will address the effects of trafficking across a wide gradient of soil physical and organic matter disturbance for some intensively managed loblolly pine plantations located on wet pine flats.

CHAPTER 3

General Materials and Methods

3.1. Site description

The study site is located in Colleton County, South Carolina, near Cottageville on marine terraces in the coastal plain approximately 100 km west of Charleston (Figure 3.1). The topography is flat to gently rolling. These sites are classified as Palustrine, forested, needle leaved evergreen wetlands (Cowardin et al., 1979), commonly referred to as "wet pine flats" (Hallbick, 1976; Messina and Conner, 1998). Regionally, these types of sites are very productive, and many have been managed as loblolly pine plantations for the past 50 years. These specific sites are very productive, with an average loblolly pine site index of 25 m (base age 25), ranging between 13 m and 33 m (Chapter 5), and an average volume of 371 m^3 ha^{-1} (Burger and Xu, 2001). , The hardwood understory and midstory consists of sweetgum (*Liquidambar styraciflua* L.), elms (*Ilmus spp.*), oaks (*Quercus spp.*), green ash (*Fraxinus pennsylvanica* Marsh.), red maple (*Acer rubrum* L.), and iron wood (*Carpinus caroliniana* Walt.)(Burger and Xu, 2001). The sites receive an average precipitation of 1200 mm annually, most of it falling between June and September (Stuck, 1982). The mean annual temperature is 19 ºC, and ranges from 10.1 ºC in January to 27.6 ºC in July.

Soil parent material consists of marine and fluvial sediments deposited during the Oligocene and Pleistocene eras (Stuck, 1982). Four soil series are represented on these study sites, although for the purposes of the current managers they are all mapped as a single soil type All soils are poorly to somewhat poorly drained and have aquic moisture regimes (Soil Survey Staff, 2003). The Argent loam (fine, mixed, thermic Typic Ochraqualfs) was found in each treatment block and comprised almost 60 percent of soils in the study area plots (Table 3.1). The Hobcaw fine sandy loam (fine-loamy siliceous, thermic, Typic Umbraquults), Santee loam (fine, mixed, thermic Typic Argiaquolls), and Yemassee loamy fine sand (fine-loamy, siliceous, thermic Aeric Ochraquults) represented 15, 13, and 14 percent of the rest of the area, respectively.

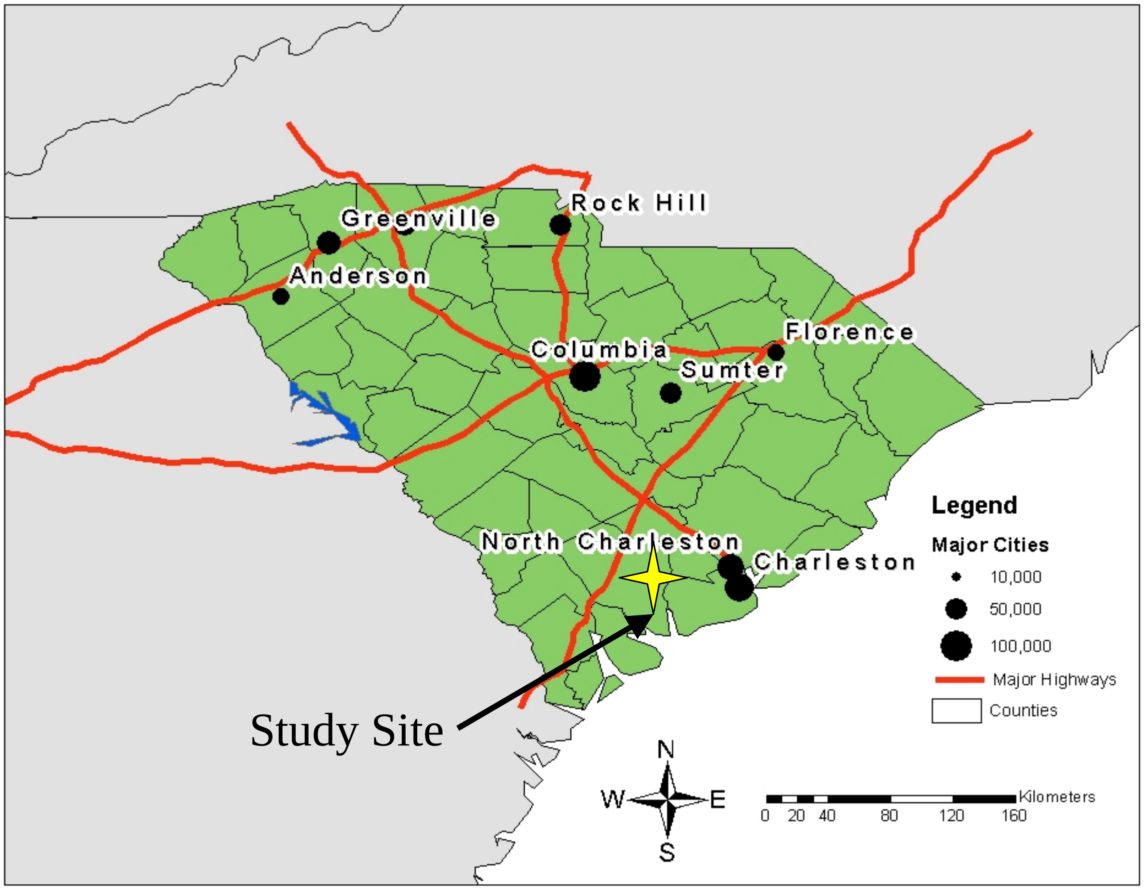


Figure 3.1. The study site is located on the lower coastal plain of South Carolina, approximately 100 km west of Charleston.

Table 3.1. The distribution of the four soil series across the study site.

	Block 1	Block 2	Block 3	Total
	----------	---------- %	----------	----------
Argent loam	85	14	75	57
Hobcaw fine sandy loam	0	45	0	15
Santee loam	15	0	25	13
Yemassee loamy fine sand	0	41	0	14

Prior studies have also identified Nemours fine sandy loam (clayey, mixed, thermic Aquic Hapludults) in the study plots, (Burger, 1994b; Kelting et al., 1999), representing a minor component of the area. Each soil consists of sandy loam textured A and incipient E horizons over a thick, clayier argillic horizon. The argillic horizon is typically very strong when moisture contents are low, and due to their very low hydraulic conductivities remain strong enough to support vehicle traffic even in very wet conditions. The average combined depth of the surface horizons is approximately 30 cm (Burger and Xu, 2001). These soils are very fertile compared to most other poorly drained, Coastal Plain wetland soils, primarily due to an underlying phosphate marl (Siple, 1957; Ellerbe and Smith, 1966). The mixed mineralogy includes shrink-swell clays that help restore physical properties during wetting/drying cycles. When drained, these soils can be very productive.

3.2. Operational treatment design

In 1992, three 20-ha loblolly pine plantations were selected based on similar age, soil, and hydrologic conditions. At the time of treatment installation, the tracts were 20 (block 1), 23 (block 2), and 25 (block 3) years of age. Each plantation was subsequently divided into six 3.3 ha treatment plots (Figure 3.2). Treatments were randomly assigned and included a control, dry harvests with and without conventional bedding, and wet harvests with and without bedding. A fifth treatment was an experimental mole-plow and bedding combination designed to equilibrate the water table after surface drainage had been disrupted. Operationally, the treatments were designed to directly address these basic research questions: (1) do logging disturbances affect soil quality, hydrologic function, and forest productivity?, and (2) If so, how, and do forestry practices mitigate disturbance effects? At the substand scale (0.04 ha), the treatments provided a wide gradient of soil physical disturbance, organic matter manipulation, and site preparation in which specific soil-site conditions were studied under realistic operating conditions.

Each treatment plot was subsequently overlain with a 20 x 20 meter grid, offset 10 m from the mole plow grid (Figure 3.3). At the intersection of the gridlines, a 0.008-ha plot center was established and a 1-meter deep water well installed. The gridpoints comprised the basic observational units for all experimental designs applied to the study site through all phases of the study.

Harvesting was conducted using conventional commercial logging operations using feller buncher/grapple skidder systems (Kelting, 1999). Despite being contiguous within each block, each plot was laid out as a separate harvest operation and had separate decks and skid trails. In the fall of 1993, two plots on each block received a dry-weather harvesting treatment. In the spring of 1994, the remaining three plots on each block were harvested during wet conditions in order to maximize soil disturbance. Bedded sites were sheared and chopped by a Caterpillar D-8 tractor with V-blade and drum chopper in 1995. In late July 1995, a chemical weed control in the form of Imazapyr (1.2 L ha^{-1}) and Glyphosate (5.6 L ha^{-1}) was applied to each block. Mole plowing was done in October 1995, and bedding in November 1995. For the mole plow treatment, a 10 cm channel, 80 cm below the surface, was created on a 20 x 20-m grid by drawing a mole shank below a modified bedding plow behind a Caterpillar D-8 tractor. The sites were hand planted in February 1996 with genetically improved loblolly pine provided by the Mead-Westvaco (formerly Westvaco) nursery. Double planting was utilized in order to emphasize productivity as a result of site quality over stocking and survival effects.

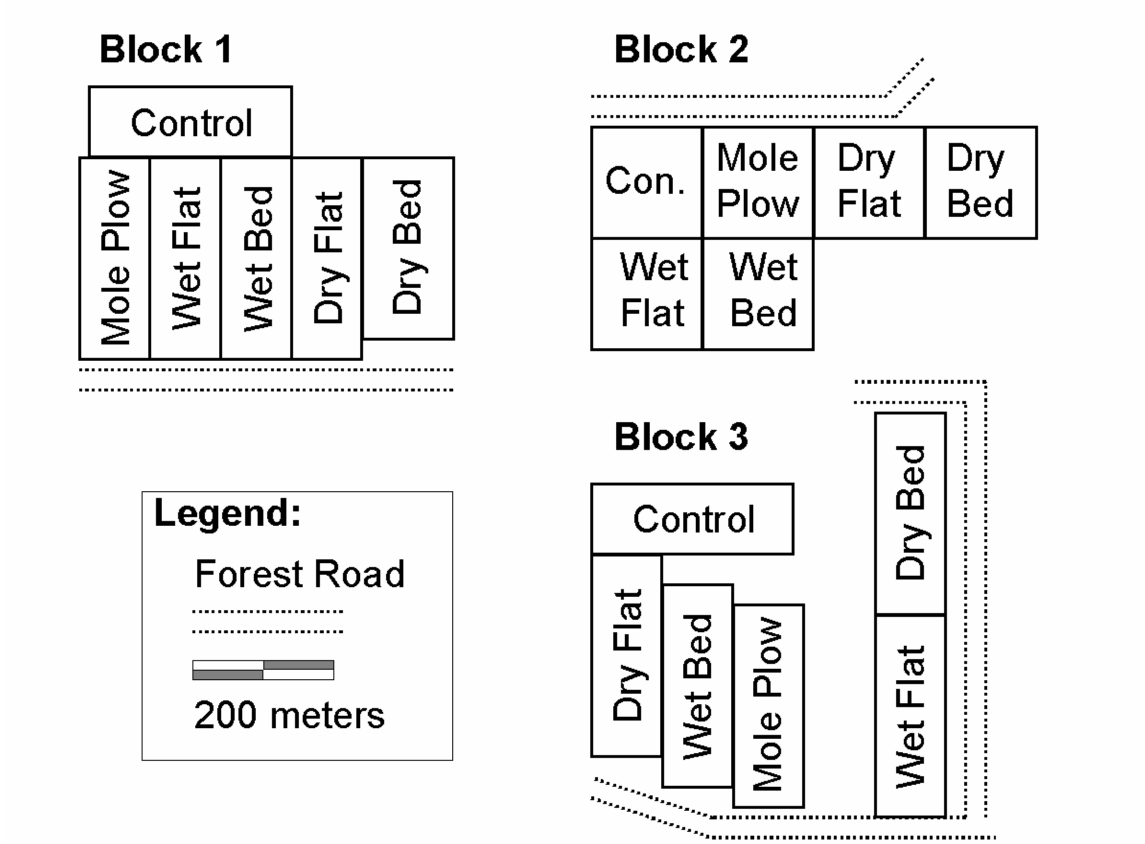


Figure 3.2. Division of each 20-ha block into individual 3.3-ha treatment plots, comprising the basic study design.

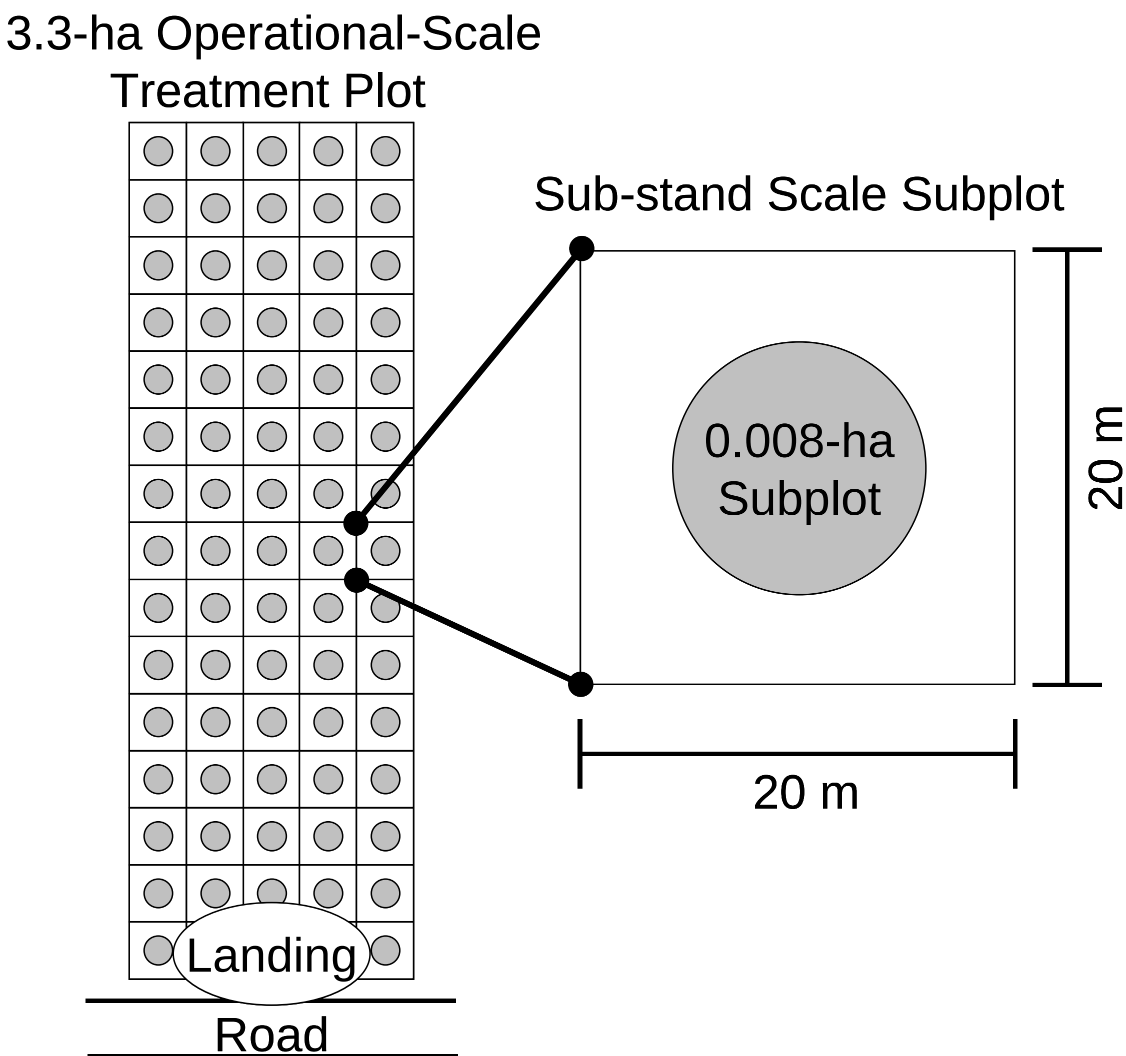


Figure 3.3. Schematic of the 20x20 meter subplots on each 3.3-ha harvesting unit and placement of the measurement plot.

3.3. Experimental designs

3.3.1. Operational scale

Analysis of site responses at the operational scale was conducted within the framework of a randomized complete block design (Table 3.2). Each response was analyzed using the general linear model at the alpha = 0.10 level (SAS Institute Inc. 2001) and means separations determined by Fisher's protected least significant difference. Contrasts were used to address the specific research questions regarding the response of tree growth to the effects of wet-weather harvesting and the mitigative effects of bedding and mole-plowing.

Table 3.2. General ANOVA table used to test the harvesting/site preparation treatment differences in productivity, stocking, and site index at the operational scale.

Source	Degrees of Freedom		Denominator MS
Block	b-1	2	
Treatment	t-1	4	$MS_{blk*trt}$
Block*Treatment (error term)	(b-1)(t-1)	8	
Total	bt-1	14	

3.3.2. Sub-stand scale factorial design

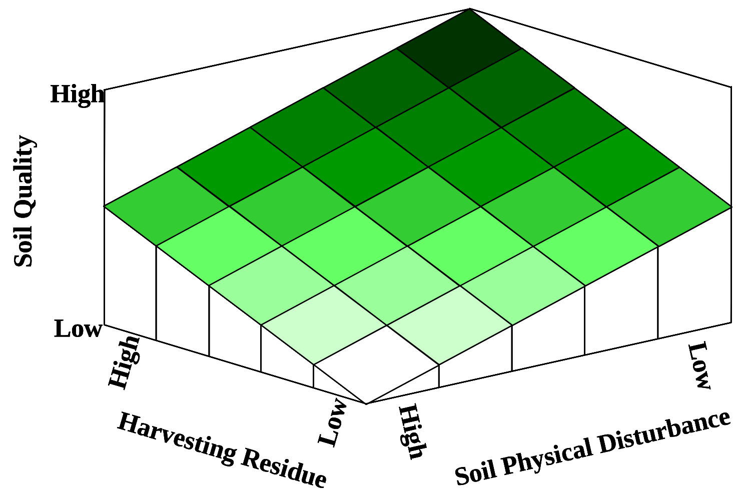
The inherent ability of sites to resist or recover from disturbances associated with wet-weather harvesting may affect the productivity on intensively managed stands. Soil physical disturbances such as the displacement of surface organic matter can diminish site productivity. Site preparation may be used to partially restore lost productivity. At the sub-stand scale, soil physical disturbances included a mosaic of undisturbed soil, compacted soil, ruts, and churning, which are disturbances not directly reflected at the operational (whole plot) scale.

Based on our understanding of the effects of disturbance we might hypothesize that the greater degree of physical disturbance the more soil quality may be diminished. Harvesting residues comprised of branches, bark, needles and other material are distributed differently across sites, and may maintain soil nutrition, or a favorable soil physical environment. Site preparation is meant to mitigate disturbances. Therefore, an experiment is necessary to address how the interaction between soil physical disturbance, harvesting residues, and site preparation affect stand level productivity, and the effect of bedding and site preparation on the overall system productivity.

Expanding the original hypothesis

Previous studies based their hypotheses on a 5x5 matrix of increasing soil physical disturbance and increasing organic matter (Figure 3.4) (Kelting, 1999). Five categories of increasing physical disturbance and lower levels of organic residues were used. It was hypothesized that a level increase along either axis would result in a measurable decrease in biomass production. In those initial studies, the 5x5 matrix was sufficient because small research plots could be completely contained within a given cell of the matrix.

After harvest, site disturbances associated with logging were characterized for the 20-m grid by visually estimating (Terry and Chilingar, 1955) the percent coverage of five physical disturbance classes (undisturbed, compressed, shallow rutting (< 30 cm deep), deep rutting (> 30 cm deep), and churning) (Figure 3.5), and five harvesting residue classes (bare soil exposed by logging, litter, light slash (< 2.5 cm diameter), heavy slash (> 2.5 cm diameter), and slash piles greater than 30 cm deep) (Figure 3.6). At the 20-m scale logging these disturbances occur as a mosaic; therefore, a physical disturbance index (PDI) was necessary to classify disturbance for the individual sub-stand scale (0.008 ha) subplots. The PDI was determined by calculating a weighted average based on percent coverage and the ordinal score for each level of increased disturbance: undisturbed (1), compacted (2), shallow rutted (3), deep rutted (4), and churned (5). Similarly, a harvesting residue index (HRI) was determined by calculating a weighted average based on the percent coverage and ordinal scores for decreasing amounts of harvesting residue: piles (1), heavy slash (2), light slash (3), litter only (4), and bare soil (5).



- Soil Physical Disturbance
  - Undisturbed
  - Compressed
  - Shallow Rutted
  - Deep Rutted
  - Churned
- Harvest Residue
  - Piles
  - Heavy Slash
  - Light Slash
  - Litter
  - Bare Soil

Figure 3.4. Theoretical matrix of harvesting disturbances and their hypothesized relationship to soil productivity.

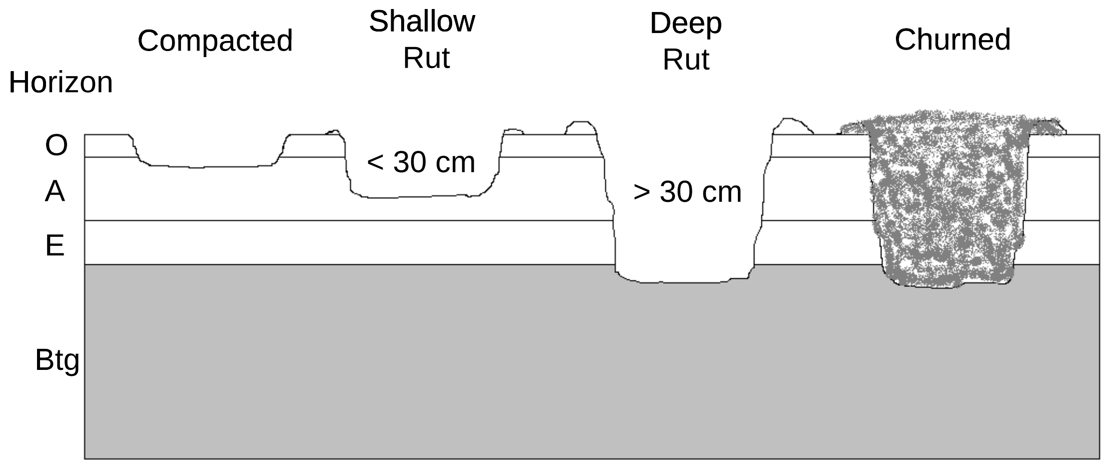


Figure 3.5. Diagram illustrating the typical levels of soil physical disturbance after harvesting classes of a poorly drained soil on a wet pine flat.

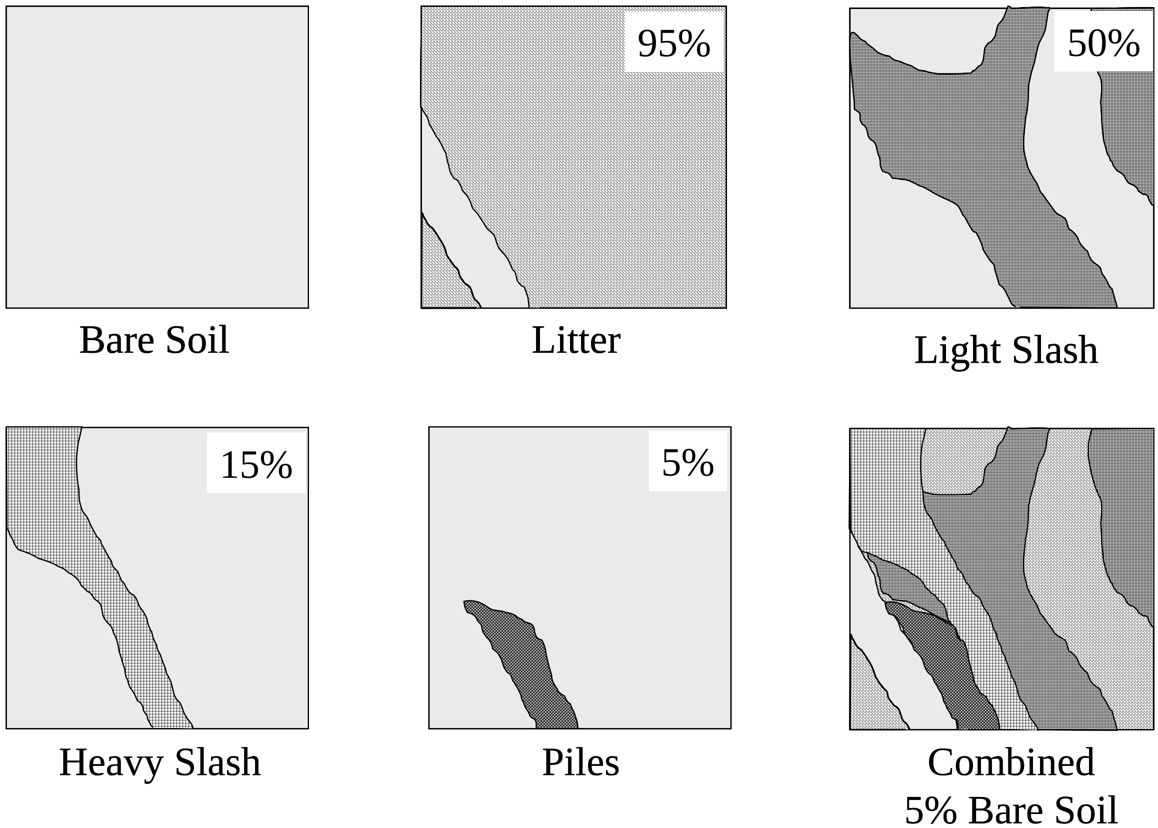


Figure 3.6. Representation illustrating how residue types were visually quantified (percent) on the site of a 20 x 20 m subplot fitting a Class II harvesting residue category.

Observational units are 0.008-ha subplots now that the loblolly stands are entering stand closure. The 0.008-ha subplots occupy larger areas and are in fixed locations; thus, each grid location contains a mosaic of disturbance that is not easily constrained to the central concepts of disturbance classes as defined by the 5x5 matrix. Additionally, only 15 of the 25 cells have representative subplots using the 5x5 matrix based on Preston's (1996) categories. In addition, there is an inherent inability of the 5x5 matrix design to make direct statements about the mitigating processes of site preparation as they relate to disturbance.

To address the new scale an alternative design that compares two levels of site preparation (bedded and non-bedded), three levels of soil physical disturbance (minimal, moderate, and heavy), and three levels of harvesting residue (Class I, Class II, and Class III) will be applied (Figure 3.7). This design sacrifices some detail in characterizing the disturbance gradients of the 5x5 matrix, but offers two major improvements: (1) all cells in this matrix are represented by subplots, and (2) the mitigating processes related to site preparation for specific levels of disturbance can now be analyzed. In addition, the new soil disturbance and harvesting residue classes can still be related to disturbance concepts that are linked to the original 5x5 matrix via decision factors.

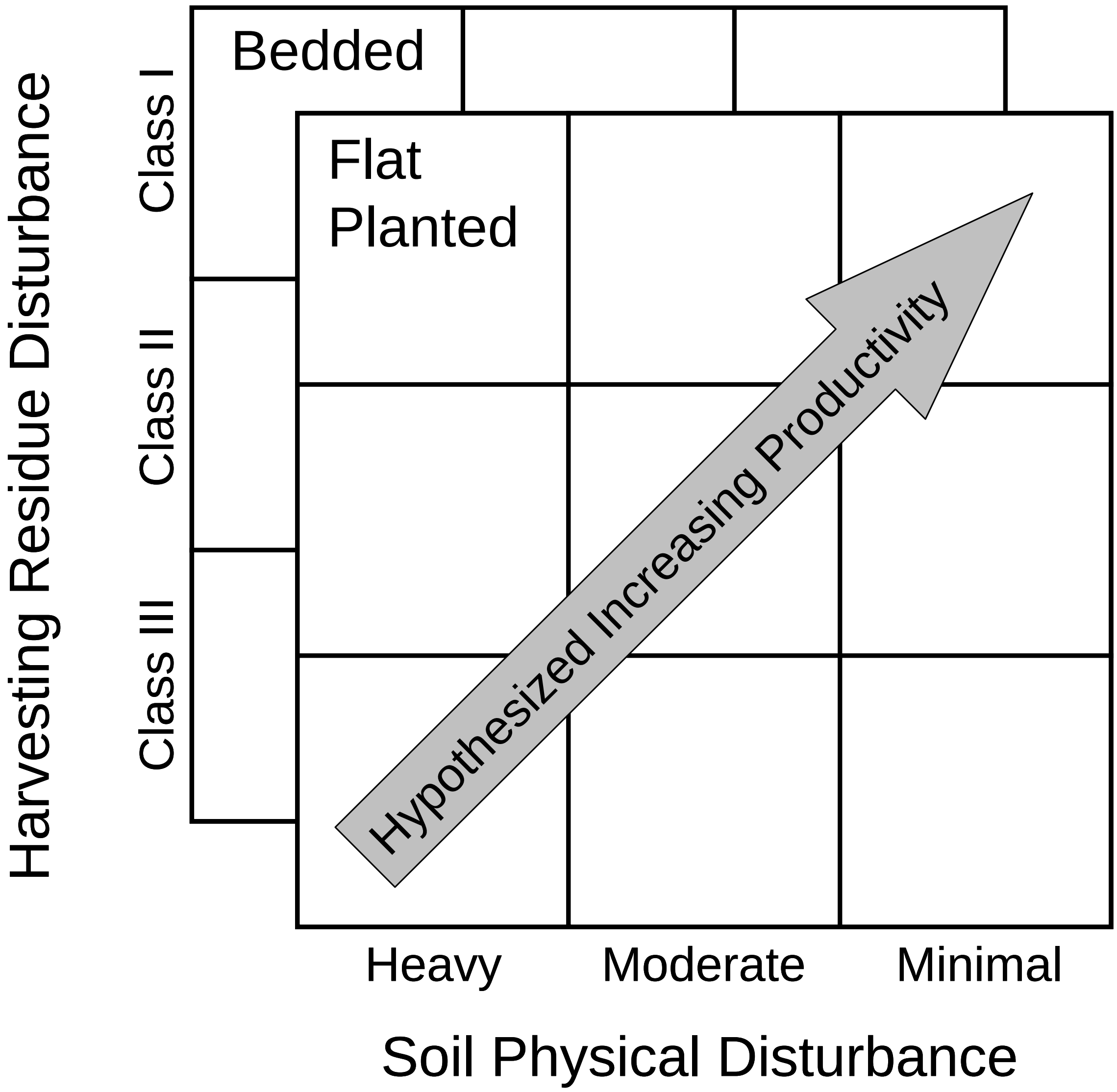


Figure 3.7. Revised matrix of harvesting disturbance and site preparation. Soil physical disturbance is divided into 3 levels of increasing disturbance, and harvesting residues are divided into 3 levels of decreasing biomass.

Disturbance category decision factors

The soil physical disturbance of each 20-m grid cell was categorized minimal if the PDI was exactly 1, light disturbance if the PDI was greater than 1 and less than or equal to 2.5, and heavy disturbance if the PDI was between 2.5 and 5; reflecting the combination of the heavier disturbance classes as suggested by Aust et al. (1998). The harvesting residues of each 20-m grid cell was categorized as Class I if the HRI was less than or equal to 3.3 and there was less than 25 percent bare soil after harvesting. They were categorized as Class II if the HRI was 3.3 or higher, and there was less than 25 percent bare soil. They were categorized as Class III if there was more than 25 percent bare soil regardless of the HRI. The total dry weight biomass of the residues in the 20-m cell was obtained using regressions that estimate biomass from the percent coverage of each of the five residue categories (Eisenbies et al., 2002). For site preparation, we did not distinguish the mole plow treatment from the other bedded treatments for the two levels of site preparation due to the similarity of the response of these treatments in other analyses (Eisenbies et al., 2004), and to ensure all cells in the factorial were represented.

General ANOVA

The experiment investigating disturbances at the sub-stand scale will be analyzed as a 3 x 3 x 2 factorial (Table 3.3), which includes 2 levels of site preparation (bed, flat), three levels of soil disturbance (minimal, moderate, and heavy) and three levels of harvesting residue (Class I, Class II, and Class III).

Table 3.3. General ANOVA table used to test the 3x3x2 factorial on productivity and site index at the operational scale.

Source	Degrees of freedom		Denominator MS
Block	b-1	2	
Site Preparation (p)	p-1	1	error
Harvesting Residue (h)	h-1	2	error
Soil Disturbance (d)	d-1	2	error
p*h	(p-1)(h-1)	2	error
p*d	(p-1)(d-1)	2	error
h*d	(h-1)(d-1)	4	error
p*h*d	(p-1)(h-1)(d-1)	4	error
error (all block components)	(b-1)(phd-1)	34	
Total	bphd-1	53	

3.3.3. Sub-stand scale regression analysis

Regression analysis is used to evaluate response variables in terms of site specific properties measured at the sub-stand scale. Two sets of subplots are used for the regression analyses depending on the level of detail required. The primary regression dataset consists of 203 randomly selected plots from three sources 1) permanently established legacy plots, 2) a set of 10 representative plots from each treatment plot in the block design at the operational scale, and 3) a set of plots representing specific soil physical disturbance and harvest residue categories.

A secondary subset from the 203 primary plots consists of 71 subplots for the purpose of intensive soil measurements. A minimum of three subplots were randomly selected from each of the 18 disturbance categories in the 3 x 3 x 2 factorial design to account for the fact that heavier disturbance categories less common (Table 3.4). Furthermore, due to the limited number of observations for each cell, the thresholds based on the PDI and HRI used in section 3.3.2. were used to select subplots that best represented the central concepts of these ratings to avoid selecting borderline plots with ambiguous disturbance characteristics (Tables 3.5 and 3.6). Seventeen additional plots were subsequently selected from the borderline plots in order to fully represent the range of soil physical disturbance and harvesting residues.

Table 3.4. Quartile distribution of soil disturbance and harvesting residue composite score for use in decision rules for categorization.

Quartile	Physical Disturbance Index	Harvesting Residue Index
100 Maximum	4.65	4.69
99	4.50	4.43
95	4.09	4.06
90	3.70	3.79
75	2.93	3.50
50 Median	1.48	3.32
25	1.00	3.11
10	1.00	2.94
5	1.00	2.85
1	1.00	2.71
0 Minimum	1.00	2.00

Table 3.5. Constrained decision criteria for the central concept of the physical disturbance categories.

Physical Disturbance Category	Physical Disturbance Index
Minimal	= 1.0
Moderate	1.6 - 2.2
Heavy	3.4 - 4.5

Table 3.6. Constrained decision criteria for the central concept of the harvesting residue categories.

Category	Decision Criteria	Average Percent Coverage		
		Bare	Light Slash	Heavy Slash
Class I	If bare soil is less than 15 percent and the HRI† is less than 3.1	3	73	40
Class II	If bare soil is less than 15 percent and the HRI is greater than 3.4	7	45	11
Class III	If bare soil is greater or equal to 25 percent	48	35	12

†Harvesting Residue Index

CHAPTER 4

Loblolly Pine Response to Wet-Weather Harvesting on Wet Flats after 5 Years

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4.1. Introduction

This research is the first of four sub-studies that evaluate the effects of wet- and dry-weather harvesting on forest productivity and site quality. There are four specific research questions this paper will address. (1) How does the occurrence of soil physical disturbance and harvesting residue differ between dry- and wet-harvested sites? (2) Does wet-weather harvesting reduce stand production? (3) If so, can conventional bedding restore production? (4) If conventional bedding is not effective on wet-harvested sites, can production be restored by the addition of mole-plowing and bedding? This research employs a more conventional approach for evaluating production using standard bioassays, and evaluates site disturbances using a visual survey.

4.2. Methods

4.2.1. Data collection

Prior to harvest a 10 percent stand inventory was conducted on the 0.008-ha subplots. After harvest, and before site preparation, a visually calibrated inventory (Terry and Chilingar, 1955) of site physical disturbance and harvesting residue was made with 100 percent coverage of the entire study site. Soil physical disturbance was characterized by the percent coverage of five classes: undisturbed soil, compressed soil, shallow rutting (< 30 cm), deep rutting (> 30 cm), and churning. Organic residue was categorized by percent bare soil, and percent coverage by litter, light slash (< 2.5-cm diameter), heavy slash (> 2.5-cm diameter), and slash piles greater than 30 cm in depth. At age two and five a 20 percent inventory of height and diameter of the entire study site was conducted at the 0.008-ha subplots.

4.2.2. Statistical analysis

Site disturbance associated with each treatment was characterized by the percent coverage of the five harvesting residue classes, and the five physical disturbance classes. These data were summarized as population statistics because they entailed a 100 percent site survey. Harvesting residue biomass was calculated from percent coverage by regression (Eisenbies et al., 2002).

Green-weight tree biomass (GWB) prior to harvest was calculated as a function of height, diameter, and age (Baldwin, 1987). GWB after planting was calculated using yield equations for young, coastal-plain loblolly pine as a function of height and diameter (Phillips and McNab, 1982). Mean, individual-tree biomass for each treatment was determined using the unweighted (by stem density) subplot means. We used this estimate rather than a weighted mean because each subplot was subjected to different degrees of disturbance depending on their location within the overall treatment. Therefore, even though the growth response at the subplot level may be a result of the whole-plot treatment, a weighted mean would be biased against areas that have low biomass and fewer trees. Thus, the unweighted mean is a response variable that is more representative of the disturbances associated with the treatments, and also independent of tree density. Unweighted individual biomass was analyzed using the general linear model at the α=0.05 level (SAS Institute Inc., 2001) and means separations were determined by Fisher's protected least significant difference. Contrasts were used to address our specific research questions regarding the response of tree growth to the effects of wet weather harvesting and the mitigative effects of bedding and mole-plowing.

Total productivity was expressed as the mean Mg ha^{-1} of each treatment plot, and stocking was expressed as mean basal area (m^2 ha^{-1}). At age five, tree density was no longer uniform between treatments; therefore, trees per hectare were used as a covariate in the analysis of variance for both productivity and basal area. Statistical analysis was performed by the general linear model at the α=0.05 level (SAS Institute Inc., 2001), and means separations by Fisher's protected least significant difference. Contrasts were used to address the specific research questions regarding the response of tree growth to the effects of wet weather harvesting and the mitigative effects of bedding and mole-plowing.

4.3. Results

4.3.1. Summary of stand disturbance

Wet weather harvesting resulted in a higher degree of soil physical disturbance (Table 4.1). Only nine percent of dry-harvested sites sustained any disturbance (all compressed). Wet-weather sites were 41 percent undisturbed, and the remaining levels of disturbance were between 13 and 18 percent (compressed, shallow rutted, deep rutted, and churned). Soil physical disturbance was concentrated toward the logging deck where trafficking was greatest and almost non-existent at the periphery of the stand boundaries. Conversely, dry weather harvesting resulted in a greater incidence of bare soil exposure (Table 4.2). Heavy and light slash biomass was significantly lower on the dry-harvested stands (alpha = 0.05).

Table 4.1. Inventory of soil physical disturbance associated with wet and dry-weather harvesting.

Class	Dry Harvest	Wet Harvest
	--------Percent--------	
Undisturbed	91	41
Compressed	9	14
Shallow Rutted	0	14
Deep Rutted	0	13
Churned	0	18

Table 4.2. Harvesting residue biomass and percent bare soil associated with wet and dry-weather harvesting. Numbers followed by an * indicate a significant difference between wet and dry-harvesting conditions. Multiply by 10 to get Mg ha^{-1}.

Class	Dry Harvest	Wet Harvest
	--------kg m^{-2}--------	
Piles (Heavy Slash > 30-cm deep)	0.16	0.16
Heavy Slash (> 2.54-cm diameter)	1.89*	2.49
Light Slash (< 2.54-cm diameter)	1.99*	2.47
Litter	2.36	2.50
Total Harvest Residue Biomass	6.40	7.62
	-------- % --------	
Percent Bare Soil	16	9

4.3.2. Individual tree biomass

The treatment differences in the unweighted individual GWB between ages two and five became more distinct although their relative ranking remained the same: WMP > WB > DB > D > W. At age two, individual tree biomass ranged between 0.2 and 0.7 kg $tree^{-1}$. Analysis of variance indicated the bedded sites had significantly higher individual tree biomass than the non-bedded sites (Table 4.3), and the model explained 49 percent of the variation in biomass. The contrast specifically testing the differences between wet harvesting and dry harvesting ($P = 0.1185$), WMP and WWB treatments ($P = 0.3321$), and the interaction of harvesting conditions and bedding ($P = 0.4262$) were not significant. The contrast of bedding versus flat planting, however, was significant ($P = 0.0008$).

At age five, individual tree GWB among the treatments increased to a range of 12.6 and 24.6 kg $tree^{-1}$ (Table 4.3). Biomass on the WB and WMP stands became significantly higher than the DB stands. The D and W stands remained statistically the same; however, at age five, the W sites had closed the relative gap with the D sites. Analysis of variance revealed differences between individual observations that were also more prevalent. The correlation coefficient was 0.44, which was less than at age two. However, the coefficient of variation between age two and age five also dropped from 54 to 41 percent. Contrasts specifically comparing wet harvesting versus dry harvesting ($P = 0.0021$), bedding versus flat planting ($P < 0.0001$), and the interaction of harvesting conditions and bedding ($P = 0.0311$) were significant at this age at the alpha = 0.05 level. As with the mean separation, the contrast of mole plowing versus the wet bed treatment indicated there was still no difference between the two treatments ($P = 0.2388$).

Table 4.3: Comparison of the unweighted individual tree GWB associated with each treatment combination. Letters indicate significant differences within age class only.

	Green Weight Biomass†	
Treatment	Year 2	Year 5
	------------------------------kg tree^{-1}------------------------	
Wet Harvested - Mole Plow	0.703 a	24.6 a
Wet Harvested - Bedded	0.609 a	22.8 a
Dry Harvested - Bedded	0.548 a	18.6 b
Dry Harvested - Flat Planted	0.263 b	13.3 c
Wet Harvested - Flat Planted	0.215 b	12.6 c

4.3.3. Total Productivity

The treatment differences in the covariate analysis of total GWB had the same patterns and interpretation as the unweighted individual GWB at both age two and five. Contrasts specifically comparing wet harvesting versus dry harvesting ($P = 0.0030$), bedding versus flat planting ($P < 0.0001$), and the interaction of harvesting conditions and bedding ($P = 0.0164$) were significant at this age at the $\alpha = 0.05$ level. As with the mean separation, the contrast of mole plowing versus the wet bed treatment indicated there was still no difference between the two treatments ($P = 0.3081$). Total biomass at age two ranged between 0.036 and 0.199 Mg ha^{-1}, and at age five ranged between 3.64 and 7.36 Mg ha^{-1} (Table 4.4). The covariate models explained 49 percent of the variability both at age two and five. The coefficient of variation dropped substantially from 72 percent at age two to 41 percent at age five.

Table 4.4. Comparison of total green weight biomass per hectare associated with each treatment combination. Letters indicate significant differences within age class only.

Treatment	Total Green Weight Biomass† Year 2	Year 5
	----Mg ha^{-1}----	
Wet Harvested - Mole Plow	1.21 a	45.1 a
Wet Harvested - Bedded	0.951 a	40.6 a
Dry Harvested - Bedded	0.797 a	33.8 b
Dry Harvested - Flat Planted	0.300 b	24.5 c
Wet Harvested - Flat Planted	0.221 b	22.3 c

† Correction of errata in table IV of the Water Air and Soil Poll. paper.

4.3.4. Basal Area

The relative ranking of basal area between the treatments was similar to that of biomass except with respect to the flat-planted stands at age five, although there were fewer significant differences. Analysis of covariance at age two had a correlation coefficient of 51 percent, and a coefficient of variation of 47 percent. Basal area ranged between 0.034 and 0.101 m^2 ha^{-1} (Table 4.5). Basal area ranged between 0.406 and 0.507 m^2 ha^{-1} at age five. The correlation coefficient increased to 62 percent, and the coefficient of variation decreased to 19%. There were fewer significant differences than found in biomass and the contrasts of wet harvesting versus dry harvesting (P = 0.0822), and the interaction between site preparation and harvesting condition (P = 0.1184) was no longer significant at the α=0.05 level.

Table 4.5. Comparison of basal area (m^2 ha^{-1}) associated with each treatment combination. Letters indicate significant differences within age class only.

Treatment	Basal Area† Year 2	Year 5
	----m^2 ha^{-1}----	
Wet Harvested - Mole Plow	1.56 a	3.10 a
Wet Harvested - Bedded	1.31 ab	2.87 ab
Dry Harvested - Bedded	1.14 b	2.71 bc
Dry Harvested - Flat Planted	0.61 c	2.47 d
Wet Harvested - Flat Planted	0.52 c	2.05 c

† Correction of errata in table V of the Water Air and Soil Poll. paper.

4.3.5. Rainfall

Between stand establishment and the first two years of stand growth the sites received close to normal rainfall (Figure 4.1). During the third growing season, rainfall decreased from the 20-year average by about 25 percent, and dropped by 40 % through the fourth and fifth growing seasons. In the first four months of the growing season, when moisture is especially important to loblolly pine growth (Baker and Langdon, 1990), two out of four months had above average precipitation. However, from ages 3 to 5, precipitation was only 50 to 75 percent of the 20-year average for three out of the first four months of the growing season.

4.4. Discussion

4.4.1. Wet versus dry harvesting

There is no indication that wet weather harvesting negatively impacted growth at the stand level despite the increased level of soil physical disturbance. The negative effects of soil disturbance on soil physical properties are well established (Greacen and Sands, 1980; Childs, et al., 1989; Worrell and Hampson, 1997; Kozlowski, 1999). Kelting et al. (1999) reported at age 2 on these same sites consistent results that rutting and churning lowered soil quality in terms of its air water balance and its ability to promote root growth. Lister (2004) reported decreased porosity and increased bulk density on the wet-weather harvested sites. However, the damage associated with wet-weather harvesting seemed to have no negative effect on biomass accumulation at age two at an operational scale, and better growth by age five on the bedded sites. In another study, Aust, et al. (1998) saw little impact on tree growth on trees planted directly in skid trails that would be the equivalent of our deep rutting and churned soil disturbance levels.

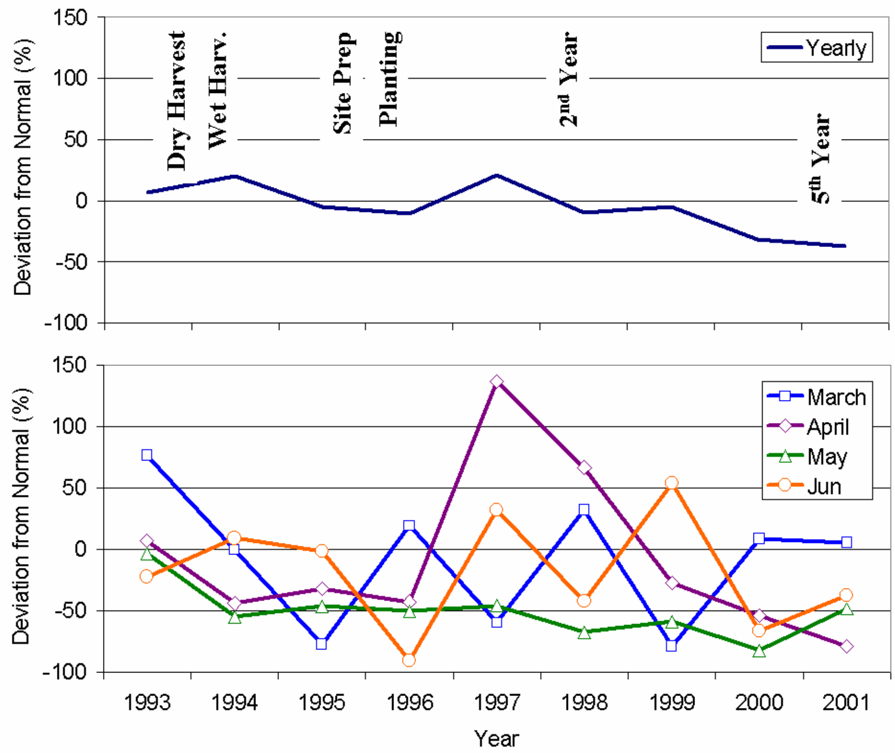

Figure 4.1. Deviation of yearly precipitation from normal between 1993 and 2001 (above) and the first four months of the growing season (below) based on the 20-year average (NOAA, 2002). Timing of harvesting, site preparation, planting, and stand measurements are also indicated.

This result is counter-intuitive compared to results reported by Kelting et al. (1999), but the difference may simply be a function of observational scale. Kelting (1999) used 0.001-ha bioassay plots that were placed in locations that were exact representatives of each level of disturbance. In contrast, this study used a 0.008-ha observational subplot that contained a mosaic of soil physical disturbance. While a specific disturbance level might negatively impact soil quality at a specific location, the mosaic of disturbance resulted in either no effect, or more favorable tree growth.

4.4.2. Bedding versus flat planting

Bedding has traditionally been shown to provide many benefits for initial tree growth. Bedding certainly improves the air-water balance near the seedlings by increasing aeration and elevation above the water table. Loblolly pine, while tolerant of wet sites, is intolerant of prolonged flooding (Baker and Langdon, 1990). In addition bedding helps control competing vegetation (Terry and Hughes, 1975; Pritchett and Fisher, 1987).

Bedding increased tree growth on these sites, and there was a stronger bedding response on the wet harvested stands. While bedding helps control competing vegetation, Lister (2004) showed that non-crop biomass decreases with increased soil disturbance on bedded sites, but increases on flat-planted sites. In addition, the drought between the third and fifth growing season may also explain the success of the WB and WMP treatments over the DB treatment. Compaction can increase plant-available water (Gomez et al., 2002). Increased soil physical disturbance will lower water-holding capacity due to the loss of macroporosity but the increase in microporosity will increase water retention (Childs et al., 1989; Aust et al., 1998; Startsev and McNabb, 2001). Therefore, the wet-harvest disturbance could have resulted in increased drought tolerance.

4.4.3. Interaction of site preparation and harvesting conditions

We detected an interaction between site preparation and wet weather harvesting in which the difference between WB and W was greater than the difference between DB and D. This suggests that the disturbance associated with wet-weather harvesting was mitigated or enhanced by the bedding treatment. Kelting (1999) reported that soil quality on these same sites improved after bedding. Lister (1999) reported that bulk density decreased by 17 percent and macroporosity increased by 24 percent on bedded sites.

Lister (1999) and Miwa (1999) observed that the rutting and churning associated with wet weather harvesting resulted in harvesting residues being incorporated into the soil. Wet-weather harvested sites retained over 1 kg m^{-2} greater harvest residue distributed across the site. This difference was because the operational loggers topped the trees out on the site in wet-weather conditions to increase traction and reduce drag during skidding. Conversely, trees harvested in dry weather were delimbed near the landing causing a displacement of harvest residue toward the deck. Skidding the trees with the limbs attached functioned to sweep, rake and otherwise further displace slash as well as increased the incidence of bare soil.

4.4.4. Mole-plow treatment

The WMP treatment did not appear to improve growth over the WB treatment. The WMP treatment was intended to enhance the equilibration of the water table and to minimize disruption of natural drainage patterns. The drought effectively rendered the response to treatments equivalent, although the WMP treatment received an additional tractor pass.

4.4.5. Implications

It is entirely possible that if the climate had been normal or wetter over the first five years of growth that these results would have been different. We feel the drought period between the third and fifth year of growth was the most important factor in explaining the treatment differences (Terry and Hughes, 1975). Soil water availability is particularly important for young loblolly pine, especially in the early growing season (Baker and Langdon, 1990). The same wet-harvested sites were observed to respond to changes in hydrologic condition much more slowly than the dry harvested sites (Xu et al., 2002). Loss of macroporosity decreases the capacity of water to move out of the soil (Wilson and Luxmoore, 1988). However, we are still 15 years from the end of the rotation, so it is difficult to say if the differences today will still be manifested by age 20. Burger and Kluender (1982) hypothesized that some forest practices that initially stimulate growth can converge with non-treated sites and may have a negative effect by rotation age. The same convergence may yet happen on these sites as the trees increasingly utilize the site resources and approach the carrying capacity. Thus the questions of whether wet-weather harvesting affects long-term productivity remains to be answered.

These fertile sites are very productive; other sites and soils might be more susceptible to loss of productivity due to this kind of disturbance. Sensitive sites that are less tolerant of disturbance are more likely to be degraded because they may be less productive, less resilient, or important biogeochemical cycles are less buffered (Burger and Kelting, 1999). By this definition, our sites are not very sensitive, and some disturbance (i.e. scarification, and imperfect or poor drainage without waterlogging) seems to favor loblolly pine (Baker and Langdon, 1990). They have high clay content, and therefore hold water well. Their mixed mineralogy gives them ample exchange sites for ion exchange, and the presence of 2:1 clays causes enough shrink-swell action to help remediate physical disturbance (Aust et al., 1997).

We expect moderate to little effect on tree growth caused by our levels of harvesting residue at the stand level. Pritchett and Fisher (1987) reported that Haines et al., (1975) saw little improvement in tree growth by residue levels more than 7 kg m^{-2}. Dry-weather harvesting yielded slightly less than 7 kg m^{-2} of harvesting residue. Given the productivity of these sites, we are unlikely to see an effect except from differences in the amount of bare soil, which were similar between wet and dry-harvested sites.

4.5. Conclusions

The implications of this study are considerable. Examples of the damage that occurs to the soil physical environment as a result of wet-weather harvesting have been in the literature for many years. Although some studies have shown no negative effects (Aust et al., 1998), none have suggested that these disturbances may actually benefit tree growth. Soils trafficked during wet weather were disturbed over 60 percent of their entire area, whereas only 9 percent of dry-harvested sites were disturbed. Wet-weather disturbance was nearly evenly distributed between compression, shallow rutting, deep rutting, and churning. Dry weather disturbance was limited to compression. However, dry harvesting resulted in almost double the bare soil, and about 1 kg ha^{-1} less harvesting residue.

It remains to be seen what the long-term effect of wet-weather harvesting will have on these sites. Therefore we offer several caveats to our results. These sites are not what we would consider to be very sensitive to harvesting disturbance. More sensitive sites will probably respond differently to similar disturbances. Lower than average precipitation during a portion of the study may have resulted in disturbed sites having more favorable water holding characteristics (drought tolerance). Lastly, our results only represent the first five years of growth in a twenty-year study. These stands are in the midst of stand closure, and therefore may not be fully utilizing the soil volume. Once the whole soil volume is utilized, any damage associated with wet-weather harvesting may begin to limit stand growth and decrease vigor in the long-term.

CHAPTER 5

Assessing Change in Soil-Site Productivity of Intensively Managed Loblolly Pine Plantations

5.1. Introduction

This research is the second of four sub-studies that evaluates the effects of wet- and dry-weather harvesting on forest productivity and site quality. The objectives of this chapter are to address five questions. (1) Does wet-weather harvesting reduce long-term soil-site productivity? (2) If so, does conventional bedding restore productivity? (3) If conventional bedding does not restore the reduced productivity of wet-harvested sites, will an experimental mole-plow treatment succeed? (4) Can a model be developed that indicates which soil-site factors maintain or diminish site productivity after harvesting disturbance? (5) Can this information be used to identify areas of risk associated with harvesting disturbance at a larger spatial scale? Although some of the objectives are the same as those employed in chapter four, this research outlines a new method using a rank diagnostic that allows changes in soil-site productivity to be evaluated rather than simply production.

5.2. Materials and methods

5.2.1. Data collection

Prior to harvest each treatment plot was overlain with a 20 x 20-meter grid (Figure 3.3). At each cell, a 0.008-ha measurement subplot was permanently established. A total of 1170 subplots were installed and all subsequent stand measurements were collected at these "sub-stand scale" subplots. Height and diameter of all trees within the 0.008-ha subplots were measured prior to treatment installation. The sampling intensity was 20 percent of the entire study area.

After harvest, site disturbances associated with each treatment were characterized by the percent coverage of five harvesting residue classes, and five physical disturbance classes preceding site preparation (Eisenbies et al., 2004). An index of soil physical disturbance was determined by assigning an integer value to successively increased levels of soil disturbance (undisturbed, compacted, shallow rutted, deep rutted, churned) and calculating a weighted average based on percent coverage. Harvesting residue biomass was calculated from percent coverage by regression (Eisenbies et al., 2002). A second inventory of height and diameter was conducted at age five at the 0.008-ha subplots across the study.

ARCGIS (ESRI Coporation, Redlands, CA) was used to assign spatial and soils information to each of the 1170 sub-stand scale subplots. The fixed 20 x 20 m treatment plot grids were georeferenced to other data layers using aerial photography and global positioning to locate the block corners (Magellan Inc., Santa Clara, CA). Five soil attributes were obtained from the NRCS Soil Survey Geographic (SSURGO) database: soil order, soil series, depth to the argillic horizon, depth to gleying, and the Universal Soil Loss Equation constant K which is a function of organic matter and texture (Wischmeier and Smith, 1978; Stuck, 1982).

Elevation data were obtained from a United States Geological Survey 30-m grid digital elevation model (DEM). Landscape position was quantified by calculating relative elevation and flow accumulation layers. Relative elevations for each 0.008-ha subplot were determined from the DEM for surrounding square neighborhoods ranging in size between 4 ha (7 x 7 cells) and 40 ha (21 x 21 cells). Relative elevations were calculated by subtracting the minimum elevation within each neighborhood from the elevation of the subplot using the neighborhood statistics function in ARCGIS. The hydrology module in ARCGIS was used to calculate a flow accumulation layer, which represents the total number of cells in an elevation model that hypothetically flow to a given cell. Mean flow accumulations were also calculated for square neighborhoods ranging between 4 and 40 hectares using the neighborhood statistics function in ARCGIS. Data were assigned to the subplots using the spatial join function in ARCGIS.

5.2.2. Evaluating changes in soil-site productivity using rank

Many conceptual models exist for defining the biotic, abiotic, and cultural practices that influence forest productivity (Switzer, 1978; Burger 1994, Morris and Miller, 1994). Morris and Miller (1994) described forest productivity as a function of plant potential, climate, soil-site quality, and catastrophe. This definition is useful because it separates soil-site quality from the major confounding factors associated with comparing productivity between rotations (e.g., genetics, silvicultural technology, climate). We can further hypothesize that the change in site-soil quality will be a function of silvicultural treatments, inherent site factors, and harvesting disturbance.

Evaluating the treatment effects on changes in soil-site productivity using standard bioassays or by taking the difference of standard productivity measures (NPP, biomass, site index) from one rotation to the next is generally not possible. Normal distributions of NPP, volume, biomass, and site index are all stretched or shifted, relative to prior rotations, by using genetically improved trees, changing silvicultural treatments, climate change, and stand age. Production at the end of the second rotation may even be higher than the prior rotation only because the technological improvements mask site degradation (Burger, 1994a). Therefore, in order to evaluate the treatment effects on soil-site productivity change between rotations we need to utilize a distribution that is independent of the confounding factors that limit our ability to make these comparisons.

The confounding factors associated with standard productivity measures can be partially alleviated by making the assumption that regardless of an uniformly applied treatment, the rank of soil-site quality (as signified by site index or tree biomass) for a specific location will remain relatively constant within a designated neighborhood at any point across time (i.e. the best sites will always be the best, etc.). For our particular data analysis, the rank distribution is especially attractive because it always has the same range and mean, and has no outliers; therefore, it appears to be more immune from the confounding factors. Change in rank will consequently be a meaningful diagnostic to elucidate changes in soil-site quality due to different treatments. Change in rank has the further advantage in that an observation that might experience a large-magnitude change in variable of interest would have the same change in rank as a relatively small-magnitude change near the median. Thus, the influence of outliers in the untransformed dataset should also be suppressed.

The ranking procedure has four basic steps as explained below. First, determine the growth metric for each observational unit. Second, rank observational units within relevant neighborhood. Third, determine the change in rank between time periods. Fourth, conduct a standard parametric analysis.

(1) Site index (base age 25) was calculated to the nearest 0.1 meter for each sub-stand scale subplot (0.008-ha) from the average tree height at the end of the prior rotation and from the third quartile height at age 5 (Carmean et al., 1989). The equations used were developed for loblolly pine in all but very poorly drained soils on the North and South Carolina Coastal Plain (Pienaar and Shiver, 1980). Green-weight biomass was calculated as a function of height and diameter for the end of the prior rotation (Bullock and Burkhart, 2003), and at age five for the new rotation (Phillips and McNabb, 1982) to three significant digits.

(2) The ascending rank of all 1170 subplots was determined based on site index and biomass within three neighborhoods (blocks) for years 1993 and 2001 (SAS Institute Inc, 2001). The estimation of post-harvest site index at a young age is typically too young to be used as a standard bioassay; however, it may be used in the ranking method because the rank distributions of height and site index are identical and fully interchangeable when the same site index model is used throughout. The blocks were designated as the neighborhoods because they encompass all treatments and were different ages at the time of harvest (ages 20, 23 and 25 for blocks 1, 2, and 3 respectively). Rank values therefore ranged between 1 (best sites) and 390 (worst sites). Ties were assigned the average rank for that set of observations.

(3) Change in rank was finally calculated by the rank in 2001 subtracted from the rank in 1993. Change in rank was normally distributed, and could therefore be modeled using standard parametric procedures.

(4) Change in rank based on site index (RCSI), individual tree biomass (RCTB), and plot biomass (RCSB) was evaluated at the operational scale (3.3 ha) using the general linear model at the alpha = 0.05 level using prior rank as a covariate (SAS Institute, 2001). Means separations were determined by Fisher's protected least significant difference. To interpret the change in site productivity we used a reference treatment that was most similar to the treatment previously applied and the one that is considered the most desirable from a disturbance standpoint (in this case the DB treatment). If change in rank was greater than or equal to the reference treatment we concluded productivity was maintained or improved. If change in rank was less than the reference we concluded productivity was diminished.

Change in rank was evaluated at the sub-stand scale (0.008-ha subplots) as a function of silviculture, site factors, and harvesting disturbance using multiple linear regression (SAS Institute, 2001). A subset of 198 observations was used to construct the model. The candidate regressors were selected based on their availability for all 1170 sub-stand scale subplots (Table 5.1). The regressors represent our hypothesized model; the change in soil-site quality is a function of silviculture, inherent site factors, and harvesting disturbance. Three models were constructed: change in rank based on site index (RCSI), individual tree biomass (RCTB), and plot biomass (RCSB). Final model selection was based on the Mallows' Cp statistic (Mallows, 1973; Mallows, 1995). Outliers were evaluated using the studentized residuals, diagonal elements (Montgomory et al., 2001), and DFITTS deletion influence (Belsley et al. 1980). Change in rank was interpreted relative to zero at the sub-stand scale (0.008-ha) as opposed to the reference treatment used at the operational scale (3.3-ha).

Table 5.1. Candidate regressors representing the hypothesis that the change in site-soil quality will be a function of silvicultural treatments, inherent site factors, and harvesting disturbance.

Category	Candidate Regressors
----------*Silviculture*----------	
Treatments	Bedding
	Wet-harvesting
	Interaction of Bedding and Wet-harvesting
----------*Inherent Site Factors*----------	
Productivity	Prior Site Index
	Prior Individual Tree Biomass†
	Prior Plot Biomass‡
Stand Density	Trees per Hectare‡
Topography-Drainage	Elevation§
	Relative Elevation (4-40 ha)§
	Flow Accumulation (4-40 ha)§
Soils (NRCS Soil Survey Geodatabase¶)	Soil Order
	Soil Series
	Depth to Bt
	Depth to Gleying
	USLE erosion factor (k)#
----------*Harvesting Disturbance*----------	
Soil Physical Disturbance	Distance to Landing
	Disturbance Index
	Percent Rutting
	Percent Undisturbed
Organic Matter Disturbance	Percent Bare Soil after Harvest
	Total Residue Biomass
	Litter Biomass
	Slash Biomass

† Prior individual tree biomass was only included in the regression where the change in rank was based on individual tree biomass.
‡ Prior plot biomass was only included in the regression where the change in rank was based on plot biomass.
§ 30-m grid digital elevation model (USGS)
¶ NRCS Soil Survey Geodatabase (SSURGO)
# Universal Soil Loss Equation (Wischmeier and Smith, 1978; Stuck, 1982)

5.3. Results

5.3.1. Site index and biomass comparisons

Pre-harvest site indexes (base age 25) of the 0.008-ha subplots ranged between 13 and 33 meters based on the average tree height. The interquartile range ranged between 23.2 and 25.6 meters. Post harvest site indexes ranged between 8 and 33 meters. The interquartile range was between 19.9 and 26.7 meters.

Pre-harvest, green weight, individual tree biomass of the 0.008-ha subplots ranged between 10 and 195 kg tree^{-1}. The interquartile range ranged between 40 and 64 kg tree^{-1}. Post harvest individual tree biomass ranged between 1 and 48 kg tree^{-1} at age 5. The interquartile range was between 10 and 25 kg tree^{-1}.

Pre-harvest, green weight, plot biomass of the 0.008-ha subplots ranged between 2 and 71 Mg ha^{-1}. The interquartile range ranged between 25 and 41 Mg ha^{-1}. Post harvest plot biomass ranged between 0.5 and 95 Mg ha^{-1} at age 5. The interquartile range was between 18 and 47 Mg ha^{-1}.

5.3.2. Operational scale treatment effects

The treatment effects on RCSI at the operational scale were WMB = WB = DB > D > W (Figure 5.1). The global analysis of covariance (ANCOVA) was significant (P = 0.0013), and the r-square was 93 percent. Prior rank was significant as a covariate (P = 0.0006). The treatment effects on RCTB were WMB = DB = WB > D = W (Figure 5.1). The global ANCOVA was significant (P = 0.0012), and the r-square was 95 percent. Prior rank was significant as a covariate (P = 0.0039). The treatment effects on RCSB were ordered the same as the RCTB result. The global ANCOVA was significant (P = 0.0085), and the r-square was 88 percent. Prior rank was marginally significant as a covariate (P = 0.0808).

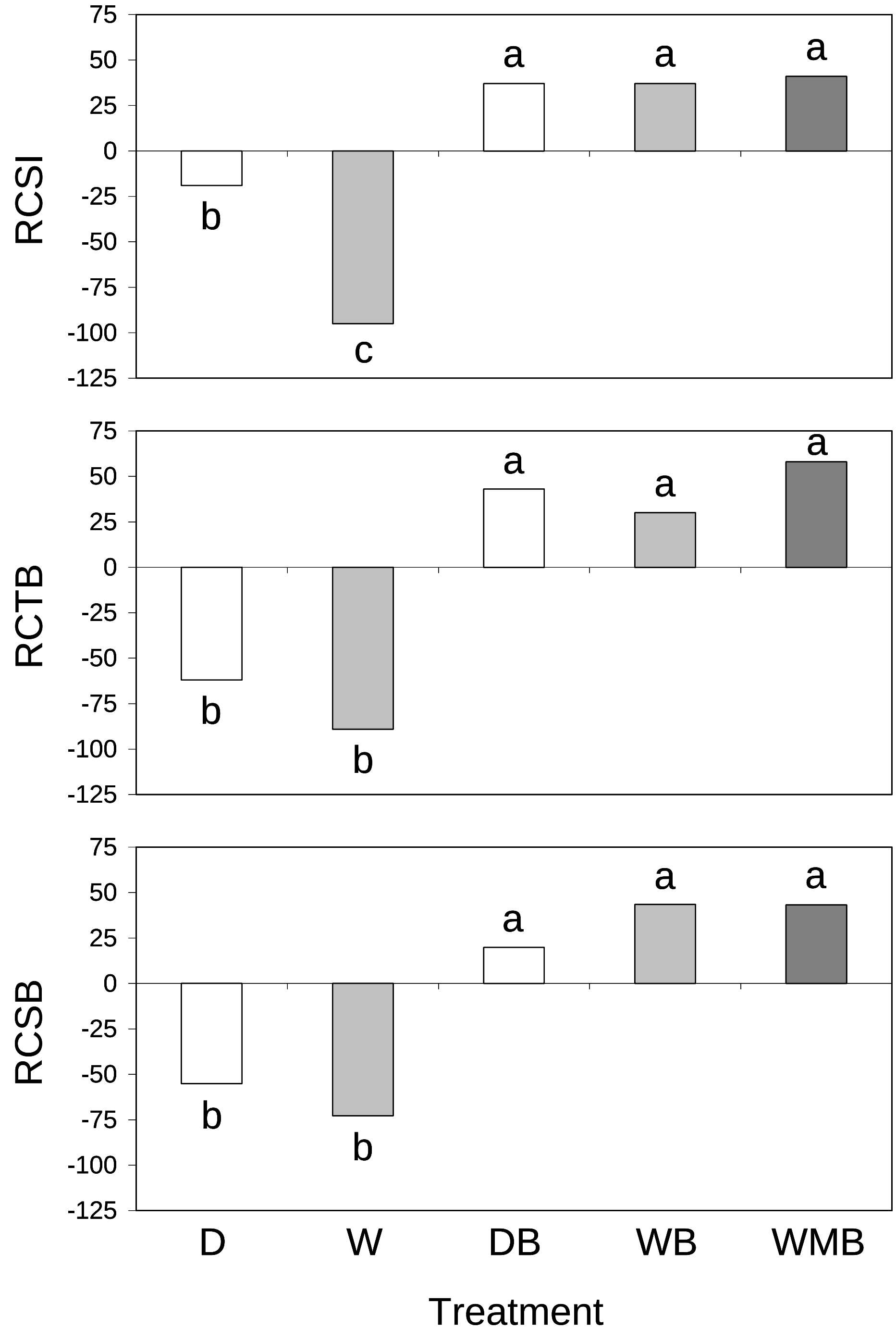

Figure 5.1. Relative change in soil-site productivity between rotations for five combinations of harvesting and site preparation treatments as reflected by the change in rank based on site index (RCSI) and biomass (RCTB and RCSB). Letters indicate Fisher's least significant differences for each series at the alpha = 0.05 level, and using prior rank as a covariate.

In all three rank analyses, the WMB treatment had an extremely low variance compared to the other treatments, which violated the constant variance assumption of ANCOVA (Table 5.2). However, although repeating the entire procedure with WMB removed from the analysis sufficiently restored compliance with the constant variance assumption, it did not change the basic relationship or conclusions among the other treatments.

Table 5.2. Within-treatment variance of change in rank based on site index (RCSI), individual tree biomass (RCTB), and plot biomass (RCSB).

Treatment	RCSI	RCTB	RCSB
	------------------------- Variance ------------------------		
Mole Plow-Bedded (WMB)	31	398	150
Dry Harvested-Bedded (DB)	3589	1127	1409
Wet Harvested-Bedded (WB)	6270	3102	1640
Dry Harvested-Flat Planted (D)	2846	1620	896
Wet Harvested-Flat Planted (F)	1240	1316	403

As the D and W treatments lost rank, the bedded treatments gained rank relative to zero. There was no difference between the WB and WMB treatments and the DB reference treatment. In the analysis of RCSI the D treatment lost approximately 60 places relative to the bedded plots, or about a 0.6-quartile loss in the post-harvest SI distribution. The decrease in RCSI between the W and all bedded plots was approximately 140 places, which represents approximately a 1.4-quartile shift. In the analysis of RCTB and RCSB the D and W sites lost about 100 places relative to the bedded sites, which represents a shift in the biomass distribution of about one quartile.

In contrast to the rank analysis, the bioassay approaches using height, individual tree biomass and plot biomass indicate that the wet-harvested, bedded sites are outperforming the dry-harvested, bedded sites (Table 5.3). Pre-harvest site index, tree biomass, and plot biomass were not significant as covariates. Stem density was marginally significant as a covariate to plot biomass ($P = 0.0769$).

Table 5.3. Comparison of treatments using standard bioassays and significance of prior site condition as a covariate.

Treatment	Height	Tree Biomass	Stand Biomass	Stem Density
	m	kg $tree^{-1}$	Mg ha^{-1}	trees ha^{-1}
Wet Harvested -Mole Plow (WMB)	5.7 a	24.6 a	45.1 a	1860 b
Wet Harvested - Bedded (WB)	5.4 ab	22.9 a	40.6 a	1750 c
Dry Harvested - Bedded (DB)	5.1 b	18.5 b	33.8 b	1850 b
Dry Harvested - Flat Planted (D)	4.3 c	13.3 c	24.5 c	1680 c
Wet Harvested - Flat Planted (W)	4.4 c	12.5 c	22.3 c	1990 a
Significance				
	------------------------ P-value ------------------------			
Global ANOVA	0.0009	< 0.0001	0.0004	0.0002
Stem Density as Covariate	0.4948	0.1613	0.0769	
Prior Site Index as Covariate	0.4891			0.6953
Prior Tree Biomass as Covariate		0.1466		
Prior Plot Biomass as Covariate			0.8118	

5.3.3. Sub-stand scale effects

The final model for the RCSI response indicated that soil-site quality was a function of bedding, prior site index (m), relative elevation in a 30-ha neighborhood (m), soil order (Mollisol), and distance to landing (m) (Table 5.4). The adjusted r-square was 62 percent. The final model for the RCTB response was a function of bedding, prior tree biomass (kg $tree^{-1}$), prior site index (m), relative elevation (m), and soil order (Mollisol) (Table 5.5). The adjusted r-square was 51 percent. The final model for the RCSB response was a function of bedding, prior plot biomass (kg ha^{-1}), stand density (trees ha^{-1}), and relative elevation (m) (Table 5.6). The adjusted r-square was 67 percent.

Table 5.4. Components representing silvicultural practices, inherent site factors, and disturbance factors to predict change in site index relative productivity rank (RCSI) between rotations on wet pine flats.

Component	Coefficient	Significance p-value	Type II Sums of Squares %
Intercept	994.3	< 0.0001	
Bedding	106.9	< 0.0001	22.8
Prior Site Index (m)	-45.34	< 0.0001	69.7
Relative Elevation (m)	46.69	0.0010	3.5
Soil Order (Mollisol)	-51.05	0.0037	2.7
Distance to Landing (m)	0.1621	0.0447	1.3

Table 5.5. Components representing silvicultural practices, inherent site factors, and disturbance factors to predict change in biomass relative productivity rank (RCTB) between rotations on wet pine flats.

Component	Coefficient	Significance p-value	Type II Sums of Squares %
Intercept	296.0	0.0011	
Bedding	109.1	< 0.0001	30.1
Prior Tree Biomass (kg tree^{-1})	-3.005	< 0.0001	46.6
Prior Site Index (m)	-10.30	0.0084	4.2
Relative Elevation (m)	95.24	< 0.0001	14.6
Soil Order (Mollisol)	-57.93	0.0063	4.5

Table 5.6. Components representing silvicultural practices, inherent site factors, and disturbance factors to predict change in biomass relative productivity rank (RCSB) between rotations on wet pine flats.

Component	Coefficient	Significance p-value	Type II Sums of Squares %
Intercept	32.69		
Bedding	106.8	< 0.0001	18.0
Stand density (trees ha^{-1})	0.1174	< 0.0001	13.4
Relative Elevation (m)	27.25	0.0357	1.0
Prior plot biomass (Mg ha^{-1})	-10.06	< 0.0001	67.6

Although each models' r-squares are not especially high and their ability to predict the true change in rank is poor, they were able to at least predict the direction of the change reliably (Figures 5.2, 5.3 and 5.4). The models were between 73 and 78 percent accurate in predicting the direction of the change at the sub-stand scale. They falsely predicted an increase in rank in only five percent of the cases of the RCSI model, 17 percent of the cases in the RCTB model, and 12 percent of the cases in the RCSB model. Each model was below 30 percent accurate at predicting the true value of the rank change within 40 places. The standard that the absolute value of the residual be no greater than 40 is arbitrary. It was chosen because it represents a shift of about one tenth within the neighborhood's population.

At the operational scale the RCSI regression model was 73 percent accurate in predicting the true direction of the change in rank; both the RCTB and RCSB models were 93 percent accurate and falsely indicated an increase in just one case. The RCSI model was 46 percent accurate predicting the true change in rank within 40 places; the RCTB model was 93 percent accurate, and the RCSB model was 60 percent accurate.

In each regression, three outliers and leverage points were identified, and were deemed true outliers based on their location at stand edges, near the deck, or within gum ponds. However, we did not eliminate them because our purpose for the model is to identify which factors are important, rather than build a model specifically for prediction purposes. Eliminating the outliers does increase the adjusted r-square for the RCSI model to 66 percent, slightly increases the significance of the minor components, and slightly increases their type II sums of squares. The effect of eliminating the outliers on the RCTB and RCSB models was also to slightly increase the adjusted r-square, slightly increase the significance of the model components, and slightly alter their type II sums of squares. However, the outliers were ultimately retained in the final model because the coefficients did not change much, the same model components were significant, and it did not substantially alter either model's accuracy or precision.

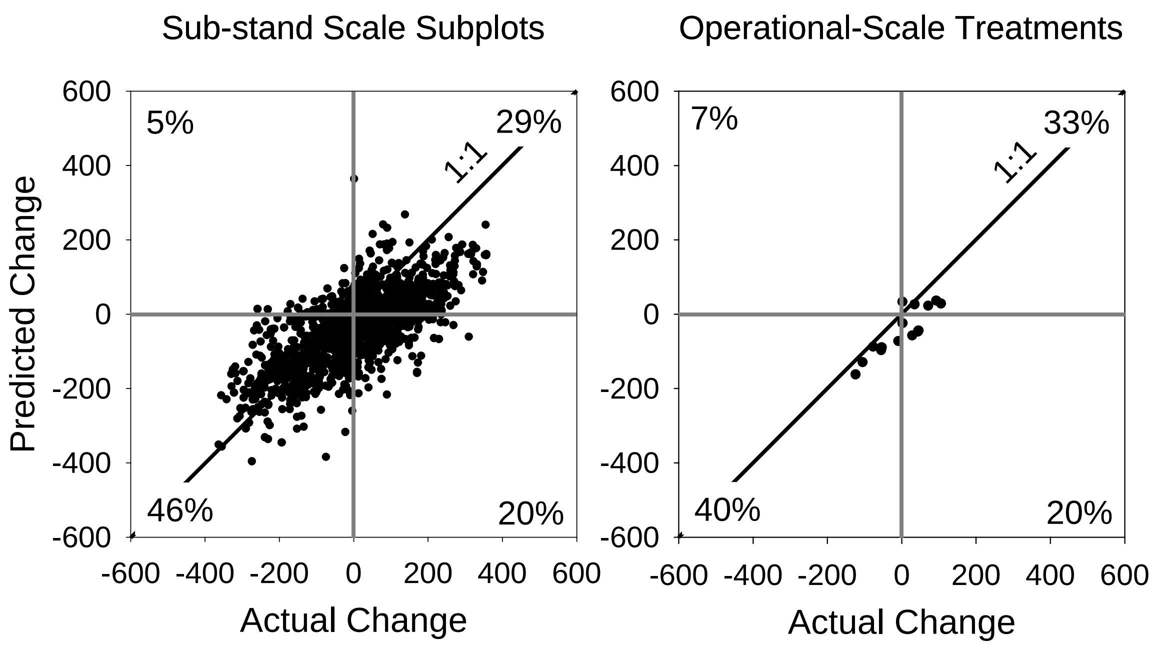

Figure 5.2. Model accuracy at the 0.008-ha sub-stand scale plots and 3.3-ha operational scale treatments for the RCSI model. Percentages represent the proportion of points falling within each quadrant. Quadrant one and three represent those points for which the direction of change in rank was successfully predicted.

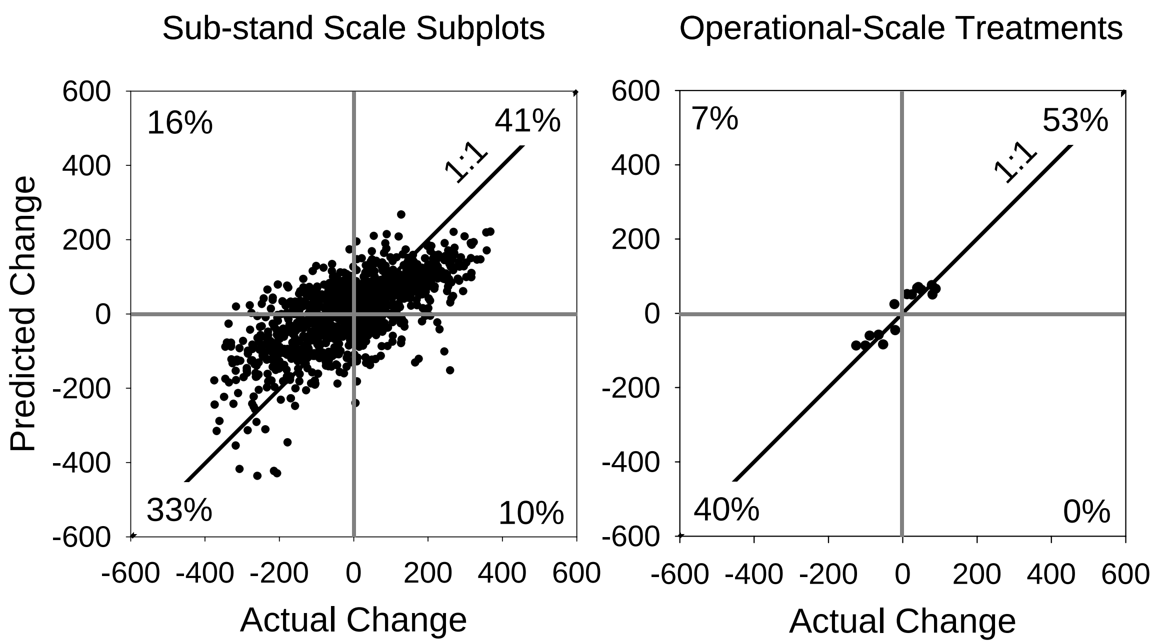

Figure 5.3. Model accuracy at the 0.008-ha sub-stand scale plots and 3.3-ha operational scale treatments for the RCTB model. Percentages represent the proportion of points falling within each quadrant. Quadrant one and three represent those points for which the direction of change in rank was successfully predicted.

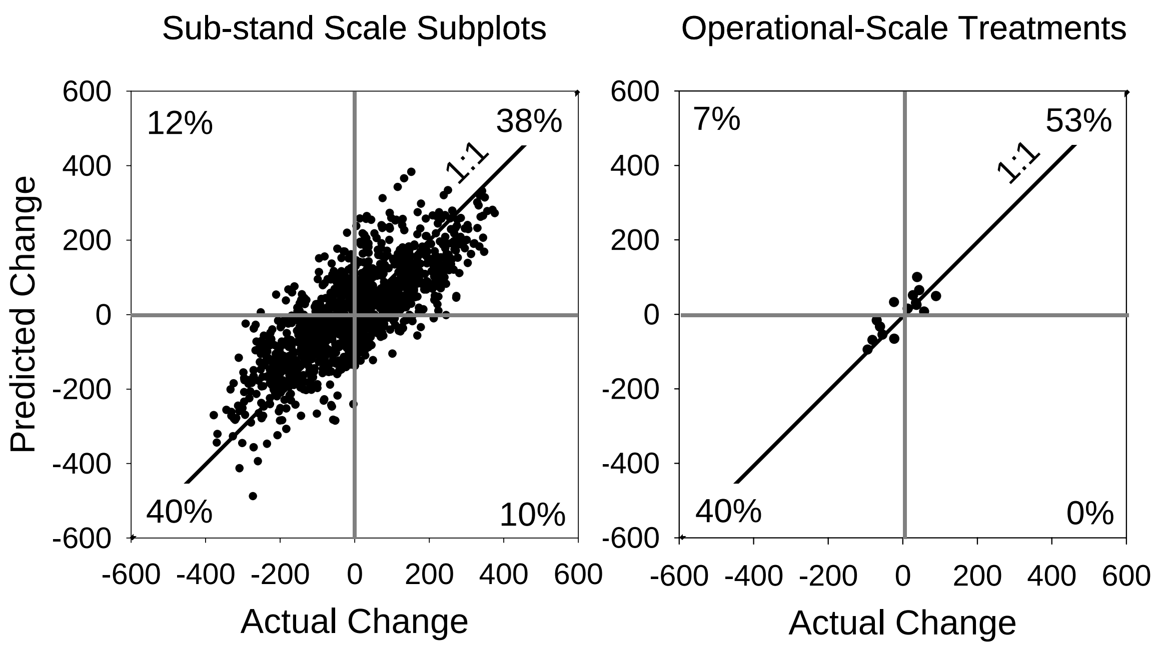

Figure 5.4. Model accuracy at the 0.008-ha sub-stand scale plots and 3.3-ha operational scale treatments for the RCSB model. Percentages represent the proportion of points falling within each quadrant. Quadrant one and three represent those points for which the direction of change in rank was successfully predicted.

5.3.4. Mapping harvesting risk

The significance and proportion of the regression sums of squares explained by the model components is part of their interpretation, but we are also interested in assessing the harvesting risk on the surrounding landscape. In order to make statistical inferences about the landscape from our model we must satisfy randomization rules: random selection of units and random allocation of treatments (Ramsey and Schafer, 1997). Soil-site results apply only to the area studied, and only to the particular results apply only to the area studied, and only to the particular soil and topographic conditions sampled within the study area (Carmean, 1975). Therefore risk maps for the surrounding are can be created in GIS that reflect each model, but are constrained by the bounds of our observations. A map based on RCSB reflects productivity risks based only on relative elevation, which only explains about one percent of the total variability (Figure 5.5). A map based on RCSI indicates productivity risk based on a combination of topography, soils, and road systems (Figure 5.6). Each map could be greatly enhanced by a landowner if used in conjunction with a stand map containing site index information. We cannot say how large of an area these risk assessments would have statistical inference, but they should be at least valid for the landholdings and soil types in the immediate vicinity and within the bounds of our observations.

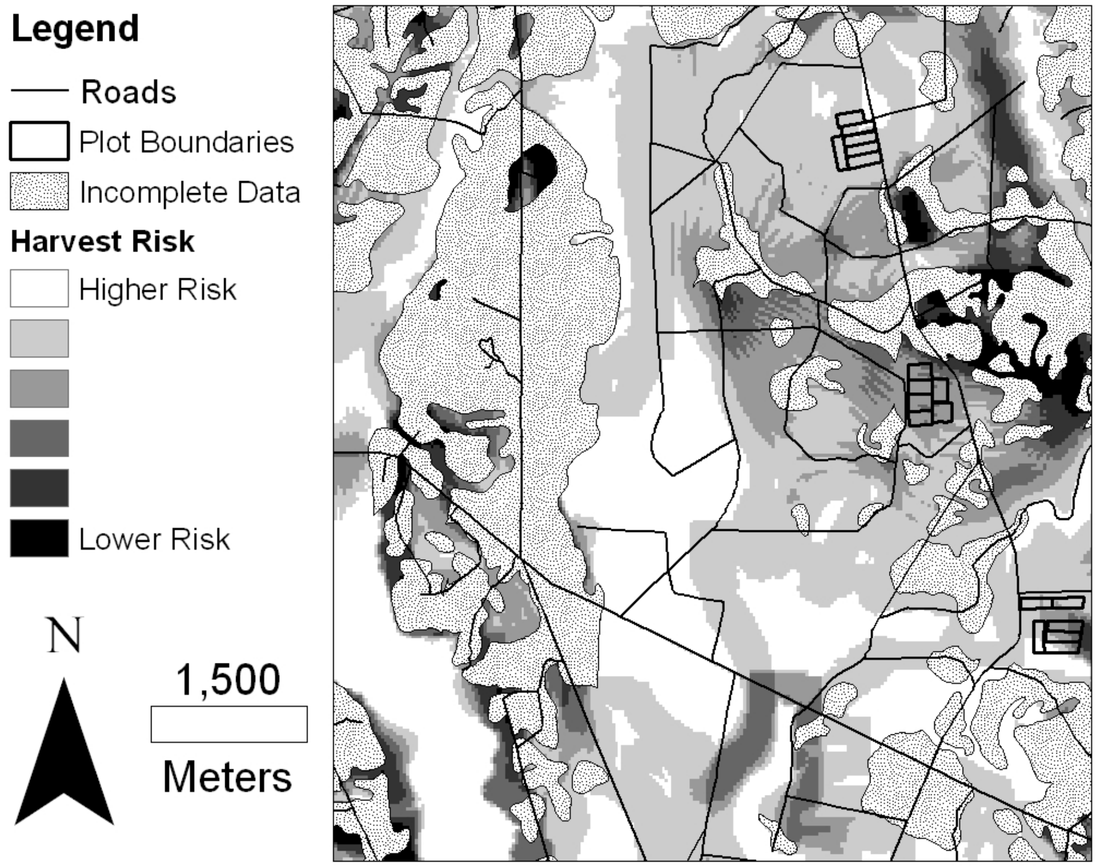

Figure 5.5. RCSB derived map indicating productivity risk based on relative elevation within a 30-ha neighborhood. Each color gradation represents a one-meter increase in relative elevation. Stippling indicates areas where complete information is not available.

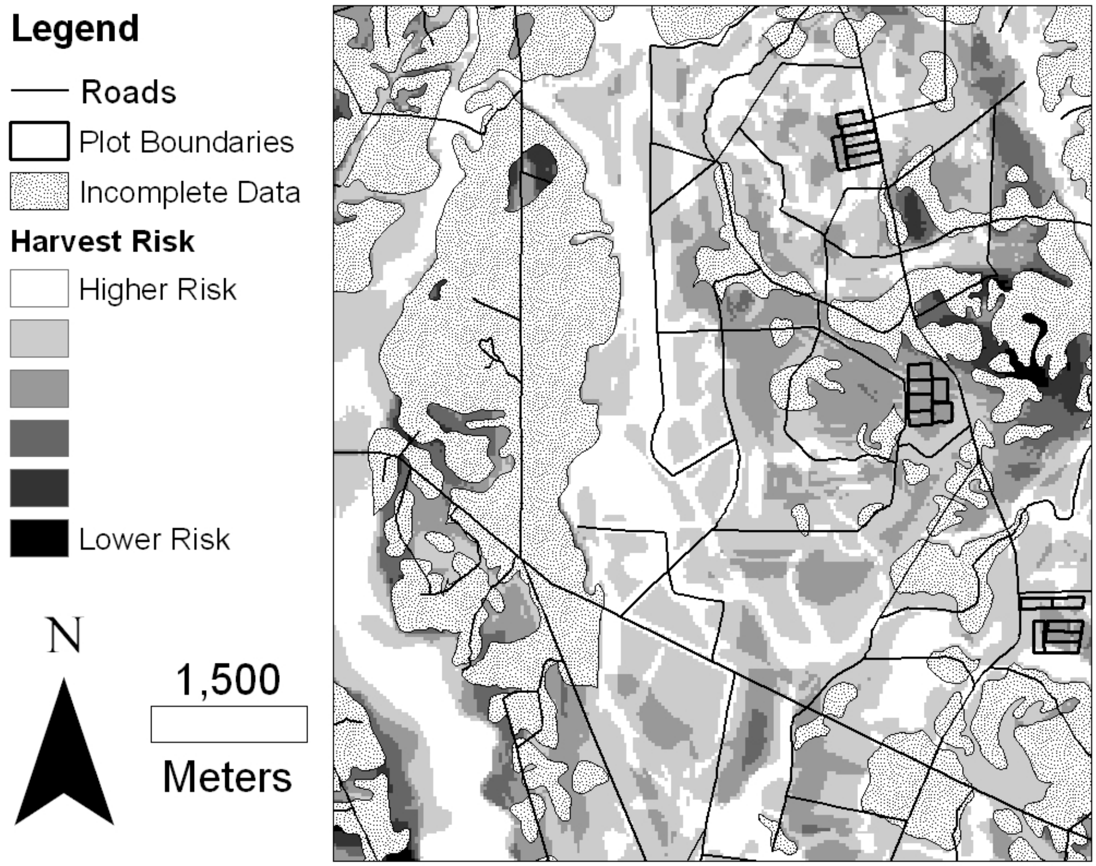

Figure 5.6. RCSI derived map indicating productivity risk based on a combination of topography, soils, and road system. Stippling indicates areas where complete information is not available.

5.4. Discussion

5.4.1. Operational scale treatment effects

The benefits of bedding these types of sites are well established (Schultz and Wilhite, 1974; Terry and Hughes, 1975; Gent et al., 1983; McKee et al., 1985; Pritchett and Fisher, 1987; Morris and Lowery, 1988; Aust et al., 1995). This study goes a step beyond just revalidating bedding as a desirable practice. It also shows that bedding successfully mitigates the loss in productivity associated with wet-weather harvesting, and flat planting previously bedded wet pine flats; at least relative to the DB treatment which would be considered our operational norm and the most desirable practice on these types of sites. It may be inferred from the operational scale results (Figure 5.1) that if all of the sites had been bedded the change in rank would have been essentially zero. This relationship suggests that our assumption in section 2.3.1. is fair; that is, rank will remain essentially the same under uniformly applied or equivalent treatments, unless there is a treatment by site interaction associated with a improperly bounded neighborhood.

It is interesting that the analysis of RCSI and biomass ranks are in slight disagreement whether the D and W treatments are indeed different. One explanation is that competition is sometimes initially suppressed on wet harvested sites (Aust et al., 1997; Lister, 1999; Murphy and Firth, 2004). Pines growing on the D sites among competing herbaceous species will have more height growth, but pines growing on W sites have sufficient diameter growth to close the gap in relative biomass due to less competition.

Another interesting result is the low variance associated with the WMB treatment in both the RCSI, RCTB, and RCSB analyses (Table 5.2). As the regressions show, site drainage is one of the primary factors controlling productivity on these sites. The WMB treatment was specifically designed to restore/optimize water table equilibration on the sites. If this is the case, the effect might not be to increase the carrying capacity, but to reduce the variability in the productivity response.

5.4.2. Sub-stand scale treatment effects

The accuracy values reported are meant to illustrate the utility of these models beyond predicting an exact response, and not to contrast the applicability of a given response variable for assessing changes in productivity. Each of the three response variables gives a slightly different perspective. The models are surprisingly powerful considering the only information required directly from the field was subplot height, or height and diameter, in two measurement years. Obviously there are other site-specific factors that could have been included such as the least limiting water range, oxidation depth, and nitrogen mineralization rates (Kelting, 1999). However, the components used were available for all 1170 subplots, which allow the approach's effectiveness as a diagnostic to be verified.

We are not sure why the regression models failed to detect the wet-weather harvesting effect and bedding interaction shown by the operational scale RCSI results. There was probably too much variability associated with those components, or the distance to landing term captured enough of the wet-harvesting effect that the wet-harvesting term was not included among the candidate models as rated by the Cp statistic. In addition, the RCTB and RCSB models did not detect either the soil or organic matter disturbance components as being significant, and the RCSI model only selected distance to landing. During the selection process, models that included the disturbance factors had favorable Mallows Cp statistics, but were ultimately not significant in the final analysis. This could be because these factors are not important. For instance, Scheerer (1994) found the physical properties on highly disturbed, poorly drained loblolly pine stands had almost fully recovered only a few years after site preparation on similar sites. It is also possible that collinearity was involved between these factors and our other model components, that there was too much variability, or that we simply failed to measure those factors in a meaningful way; specifically, visual estimates of soil disturbance may not be sufficient for quantifying harvesting impacts on soil physical quality.

A component that was purposefully excluded from the models was the mean flow accumulation within a 30-ha neighborhood as calculated by GIS. Although there was no multicolinearity detected, the type II sum of squares was very small. Ultimately, we felt this component was redundant when paired with relative elevation. It added very little to the models total r-square, and since both are indicators of landscape-scale drainage we determined that only one was necessary.

The effect of bedding

As demonstrated at the operational scale, bedding is an important factor affecting the change in relative rank at the sub-stand scale. Bedding serves the function to enhance microsite drainage and restore physical properties (Schultz and Wilhite, 1974; Terry and Hughes, 1975; Gent et al., 1983; McKee et al., 1985; Pritchett and Fisher, 1987; Morris and Lowery, 1988; Tippett, 1992; Aust et al., 1995), which enhances survival and growth of young loblolly pine (Baker and Langdon, 1990; Shultz, 1997).

The effect of prior site index and prior biomass

The model predicts that sites with higher initial site index are more likely to lose rank relative to other plots. This result is contrary to a large part of the literature that has shown that higher quality sites are in fact more resilient to disturbance (Burger and Scott, 2001). However, that conclusion frequently has to do with fertility rather than physical properties. On these sites soil-site quality, as reflected by site index, is primarily a function of drainage rather than fertility. Intuitively, soil physical quality has a minimum limit, such that poor sites can only be made so bad. Sites that have high physical quality would have more to lose as a result of trafficking (Scheerer 1994, Aust et al., 1995).

There is a possibility that the negative coefficient associated with prior site index in the RCSI model, and prior biomass in the RCTB model, is a statistical effect rather than a biological one. In regression, values naturally converge toward the population mean. Specifically, the chance that the rank of sites with high initial site indexes, or biomass, to remain the same or decrease is much larger than the chance that rank would increase. A t-test of the four quartiles indicated that the magnitude of the change for the first and fourth quartiles was significantly higher than the second and third.

To address this question, we performed a regression that included only data points from the interquartile range so that the observation had a chance to both increase as well as decrease. The adjusted r-square in this regression dropped to 53 percent for the RCSI model, and dropped to 51 percent for the RCTB model. However, the identical model components were selected, and their coefficients were all similar. The type II sums of squares for prior site index decreased to 25 percent in the RCSI model, and prior biomass increased to 55 percent in the RCTB model. Thus we conclude that although the statistical effect is present, there is also a biological effect.

A further question would be whether bedding completely remediates the sites with high initial site indexes or biomass. We tested this by performing regressions on the bedded-only sites using only the interquartile range. Prior site index was still significant in the RCSI model and still had a negative coefficient, as was prior biomass in the RCTB model. Therefore, bedding does not fully remediate sites with high initial site quality after five years at the sub-stand scale. High soil physical quality is a product pedogenic processes that require many years of natural development (Stone, 1975). Good structure, porosity, hydraulic conductivity, and ideal texture are not properties that would necessarily be corrected by a bedding plow that only affects a portion of the soil profile. However, another consideration is that higher quality sites, where drainage may already be adequate, would be less sensitive to the effects of bedding.

The effect of stand density

Stand density was only included in the RCSB model, but has an overwhelming influence on the response compared to other site factors. Stand density is an important determinant of biomass production and like site index can also be another reflection of site quality (Zedaker et al., 1987). Needless to say, the number of trees present will have a major influence on plot biomass. The three years of drought prior to stand remeasurement (Eisenbies et al., 2004) may have affected survival.

The effect of relative elevation

Drainage class is very influential on the productivity of wet pine flats (Shoulders, 1976; Fisher and Garbett, 1980; Haywood et al., 1990; Hauser et al., 1993). Water tables rose in response to harvesting (Xu et al., 1999; Xu et al., 2002). Although relative elevation was calculated for several neighborhood sizes, the most significant was the 30-ha neighborhood. Relative elevations varied by 2 meters within our blocks. The flow accumulation regressor also indicated that 30-hectares was an important size for expressing landscape-level drainage. The connotation of this size appears to relate to stream and drainage density, while not being so large as to only mimic regular elevation.

The effect of soil order

The pedogenesis causing Mollisol formation among these sites is primarily due to poor drainage leading to the retention of carbon (Stuck, 1982). The Santee soil series (fine, mixed, thermic Typic Argiaquoll) is generally found in broad depressional areas, and differs from the other three soil series represented by this study mainly by its mollic epipedon and slightly coarser textures.

The effect of soil disturbance

Distance to landing was the only disturbance factor that was significant in our candidate models. The fact that distance to landing was selected rather than our indicators of rutting and organic matter disturbance implies that there is something more to disturbance than just presence or absence. The number of passes, disturbance depth, rut orientations (Greene and Stuart, 1985, Burger et al., 1988; Carter et al., 1999), harvest residues (Hall, 1999), as well as logging operational delays intensifies the disturbance near the landing. Disturbance across the rest of the sites may have simply recovered within five years, as other sites were shown to do (Scheerer, 1994, Lacey and Ryan, 2000).

Distance to landing had a relatively high P-value in our regression ($P = 0.045$), which led us to consider how localized the effect was to the landing. When we model with the observations within 40 meters of the landing removed, distance to landing becomes non-significant ($P = 0.765$). Obviously within 40 meters of the landing, soils receive repeated trafficking in random directions such that surface drainage has no clear path away from those locations. Maintaining surface drainage is a central issue for these sites, as subsurface drainage can be very slow and most water leaves sites similar to these primarily via evapotranspiration during the growing season (Konyha et al., 1988, Aust et al., 1993).

5.4.3. Considerations using change in rank to evaluate long-term productivity

The key advantage of using change in rank as a diagnostic is that unlike standard bioassays that just reflect current production, it provides a means to evaluate changes in productivity between rotations. Change in rank successfully controls a great deal of the confounding biotic and abiotic factors discussed in section 5.2.2. Using this approach to compare treatment effects is a useful tool because, if you accept that in this case the treatments are more likely to converge than diverge, it can identify relatively benign treatments early into the rotation. The relationship indicated by our results WMB = WB = DB > D > W using RCSI and WMB = WB = DB > D = W using RCTB are both in contrast to the relationship determined by a standard bioassay, which was WMB = WB > DB > D = W when actual tree biomass is used (Eisenbies et al., 2004). Specifically, the bioassay approach used might lead to the false conclusion that there is some benefit associated with the combination of wet harvesting and bedding. Through regression, we can extend this approach to identify important factors that are influencing changes in soil-site productivity.

Another advantage of the ranking approach is the ability to control within-neighborhood heterogeneity. A MeadWestvaco researcher had expressed a concern that some treatment plots had been placed on higher quality sites by random chance. Indeed, due to their size there was sufficient variability in initial productivity within the blocks to cause some concern. However, this approach apparently limits the effect of within-block variability of site quality when prior rank is used as a covariate. Unlike change in rank, prior biomass or site index are not significant covariates when evaluating untransformed biomass or site index.

Although the change in rank method has useful advantages for evaluating treatment effects on changes in productivity, but there are also certain limitations that should be noted. First and foremost, because this approach purposefully negates the gains associated with technology (e.g. genetic improvement, silviculture) it does not allow statements about decreases in long-term productivity such as those attributed to second and third rotation decline (Powers, 1990; Kimmins, 1996b; Worrell and Hampson, 1997). Obviously this method provides a partial solution to the problem of evaluating long-term productivity; however, by sacrificing some information we gain the ability to evaluate the specific question of change. Second, the rank transformation is irreversible and cannot be returned to a more meaningful productivity measure (Ramsey and Schafer, 1997), thus, it is difficult to put results in concrete biological terms, which is why we choose to refer to it as a diagnostic. Change in rank is probably most valuable when complemented by some biologically meaningful information; however, change in rank can be viewed as shifts through the quartiles of normally distributed site index or biomass data, but large rank differences may have small practical differences. Third, in this study the sheer number of observations allows the changes in rank to assume a normal distribution. If fewer observations were used, this approach may not have worked because the changes would become increasingly discrete, although how many fewer was not investigated. Lastly, while benign effects can be identified because we do not expect these treatments to diverge as the stands age, it will still be necessary to wait the entire rotation before any definitive statements about potentially negative treatments associated with flat planting is possible. It has been shown that the production response to treatments can converge as sites approach their carrying capacity (Burger and Kluender, 1982; Powers et al., 1994, Cerchiaro, 2003). While rank could remain significant far into the rotation, the practical differences in actual site index or biomass may also become less important.

Certain considerations should be made before using this approach. Since the results are not in concrete biological terms, care should be taken not to introduce confounding factors that prevent meaningful interpretation. (1) The bounds of the neighborhoods are critical; defining the area is very important (Carmean, 1975). Each neighborhood must contain all treatments, and sites should be similar enough that a separation in rank is a possibility. (2) Site history should also be similar. If our plots had been half flat planted and half bedded in the prior rotation without our knowledge, the results could have been very confusing or without interpretation. (3) Within a given neighborhood the subplots should be the same age at individual time steps in order to avoid introducing the error associated with decreasing variance with stand age. (4) It is very important to include a reference treatment that is similar to the pre-harvest treatments. In the case of this study, the dry-harvested bedded sites would be considered our reference, although the dry-harvested flat planted could also have been used as a reference. (5) A limitation of the regression approach is that results apply only to the area studied, and only to the particular soil and topographic conditions sampled within the study area (Carmean, 1975). (6) Including too many factors may reduce the resolution with which treatment differences can be detected at the operational scale. (7) If a new species or genotype is used in the following rotation, each should probably be suited for the same site conditions. (8) Finally, it is still necessary to wait a full rotation before definitive statements are made about changes in soil-site quality associated with specific treatments because sites may recover at different rates.

5.4.4. Importance of scale

From the operational scale we can conclude that as long as bedding is utilized, there should be no negative effects of wet-weather harvesting compared to our operational norm. The sub-stand scale RCSI model indicates that proximity to the landing is also an issue, but this effect is not unique to the dry or wet-weather harvested sites. At the disturbance scale (0.001 ha), Kelting (1999) showed that compression and rutting were not completely remediated by bedding; however, these disturbances only represent about one third of the total area. In chapter 6 we show that at the sub-stand scale (0.008 ha) sites that are heavily disturbed, with a greater than 25 percent bare soil after harvesting, do not respond to bedding; however these sites represent less than 5 percent of the wet harvested area. Obviously these important stand and disturbance scale effects are not manifested at the operational scale. This illustrates the importance of using multiple observational scales to enhance our understanding.

5.5. Conclusions

Using change in rank as a diagnostic to evaluate site productivity is a new approach that has some limitations, but also offers definite advantages. Change in rank is probably most valuable when used in conjunction with other methods. While the method may not be able to establish widespread productivity decline, it does reflect how the sites have changed from the prior rotation. It is therefore able to determine which treatments are relatively benign compared to an operational norm. This determination can be made independently of the confounding factors (genetics, climate, technology) normally associated with comparing productivity between rotations. While benign treatments can be identified, it will still take a full rotation to know the true long-term effects of potentially negative treatments and disturbance on carrying capacity. Given time, both flat-planted treatments may recover as well. Rank will also be an effective means to compare productivity change at the end of the rotation as well; however, large rank differences in the future might be small from the standpoint of absolute amounts of wood volume, biomass, or height growth.

Wet pine flats are among the most important intensively managed forest types in the Southeast (Hallbick, 1976; Messina and Conner, 1998). They represent about 16 percent of the intensively managed plantations in the South (Shepard et al., 1998). This study shows that bedded sites have fully recovered at the operational scale within five years relative to the operational norm. Based only on the RCSI results, a tentative conclusion can be drawn that there is a potential risk to site productivity between rotations associated with wet weather harvesting when bedding is not used. This may be of particular concern for non-industrial private landownership where bedding is not always employed. Non-industrial private landownership makes up about two-thirds of the land ownership in the Southern US and South Carolina (USDA Forest Service, 2001a; AFPA, 2001). The combination of wet harvesting and flat planting should probably be avoided on wet pine flats.

Past recommendations suggest that logging during wet seasons should be limited to better-drained sites (Moehring and Rawls, 1970). In the case of more fertile wet pine flats such as these it appears that in some cases wet weather logging could be conducted on poorer quality sites where drainage is already limited and cannot be worsened, and where bedding will definitely be applied as a site preparation. Due to the within-site variability, it may be very difficult to target specific operational sites that are at risk. In addition, site preparation should be a consideration when sites are being evaluated using BMPs. The ability to preserve or restore site drainage should be an important consideration in site selection.

Mole-plowing is used in other agricultural systems in various places in the world with heavy clay soils (Spoor et al., 1982; Spoor and Fry, 1983; Weil et al., 1991) and appears to have some benefit. Although we did not detect significant differences in magnitude due to non-constant variance, some increase in soil productivity is possible in the WMB over other bedded treatments. This difference may be masked by a type-II error. The low variances observed among the WMB treatment suggests that it is doing what it was designed for; specifically, to equilibrate water tables and create a more uniform biomass response. Therefore, it bears further investigation, and may have an application for remediating certain types of sites.

Change in site productivity on fertile, wet pine flats is a function of silvicultural treatments, inherent site factors, and harvesting disturbance. Regression analysis indicates that sites in low relative elevations, and residing within about 40 meters of the landing appear to be the most at risk. Sites with high initial site indexes may either be more at risk, or may receive less benefit from bedding. All components in the model indicated that site drainage is a principal factor influencing the change in site productivity, although more site-specific factors will have to be examined in future studies. In terms of trafficking effects, proximity to landing appears to be associated with detrimental disturbance factors associated with harvesting. It may be necessary to take extra measures to restore productivity in these areas. Improving bed quality, surface drainage, and subsurface drainage may be necessary in these areas. Double bedding, or the mole-plow treatment, may be options for the remediation of logging decks.

The ability to make the connection between landscape and changes in soil-productivity change is important. The harvesting risk map emphasizes the heterogeneity of these sites, and the difficulty in making a universal prescription for these types of sites. Relative elevation is certainly useful as a guide, but its influence was small relative to other components according to our sub-stand scale models. At the operational scale the influence of relative elevation is less because it becomes relatively constant among the treatment units within a neighborhood. If disturbance does prove to be a long-term detriment to productivity, it will have to be addressed somewhere between the sub-stand (0.008-ha) and operational scale (3.3-ha).

CHAPTER 6

Soil Physical Disturbance and Logging Residue Effects on Changes in Soil Productivity

6.1. Introduction

This research is the third of four sub-studies that evaluates the effect of wet- and dry-weather harvesting on forest productivity and site quality. The literature indicates that long-term productivity is a function of erosion, soil physical disturbance, and organic matter quality and quantity (Greacen and Sands, 1980; Childs et al, 1986, Powers et al., 1990; Morris and Miller, 1994). Based on the topography of wet pine flats erosion should be minimal on these sites (Terry and Hughes, 1975). Therefore, we hypothesize that changes in soil/site productivity will be a function of silviculture, soil physical disturbance and harvesting residue disturbance. The objectives of this paper are to: 1) evaluate the effect of soil disturbance and harvesting residues on changes in site/soil productivity and the ability of bedding to remediate productivity, and 2) describe the prevalence and determine the specific cause of disturbance combinations that do not respond to bedding.

6.2. Materials and methods

6.2.1. Data collection

Prior to harvest each treatment plot was overlain with a 20 x 20-meter grid (Figure 3.3). At each cell, a 0.008-ha measurement subplot was permanently established. A total of 1170 subplots were installed and all subsequent stand measurements were collected at these "sub-stand scale" subplots. Height and diameter of all trees within the 0.008-ha subplots were measured prior to treatment installation. The sampling intensity was 20 percent of the entire study area. A second inventory of height and diameter was conducted at age five in the second rotation at the same 0.008-ha subplots across the study.

After harvest, site disturbances associated with logging were characterized for the 20-m grid by visually determining (Terry and Chilingar, 1955) the percent coverage of five physical disturbance classes (undisturbed, compressed, shallow rutting (< 30 cm deep), deep rutting (> 30 cm deep), and churning) (Figure 6.1), and five harvesting residue classes (bare soil exposed by logging, litter, light slash (< 2.5 cm diameter), heavy slash (> 2.5 cm diameter), and slash piles greater than 30 cm deep) (Figure 6.2). At the 20-m scale logging these disturbances occur as a mosaic; therefore, a physical disturbance index (PDI) was used to classify disturbance for the individual sub-stand scale (0.008 ha) subplots. PDI was determined by calculating a weighted average based on percent coverage and the ordinal score for each level of increased disturbance: undisturbed (1), compacted (2), shallow rutted (3), deep rutted (4), and churned (5). The index of organic matter was determined by calculating a weighted average based on the percent coverage and ordinal scores for decreasing amounts of harvesting residue: piles (1), heavy slash (2), light slash (3), litter only (4), and bare soil (5).

6.2.2. Data analysis

A 3x3x2 factorial design with three replications was used to test the hypothesis that changes in soil-site productivity increase with decreasing levels of soil disturbance (heavy, moderate, and minimal), and increasing levels of harvesting residue (Class III, II, and I), with two levels of site preparation (flat-planted and bedded) (Figure 6.3). The soil physical disturbance of each 20-m grid cell was separated into three categories: “minimal” disturbance if the PDI was exactly 1, “moderate" disturbance if the PDI was between 1 and 2.5, and “heavy" disturbance if the PDI was between 2.5 and 5. The combination of the rutting and churning type disturbances was based on the suggestion by Aust et al. (1998) that these classes may be over differentiated in terms of certain soil properties (e.g. bulk density, soil moisture, and saturated hydraulic conductivity).

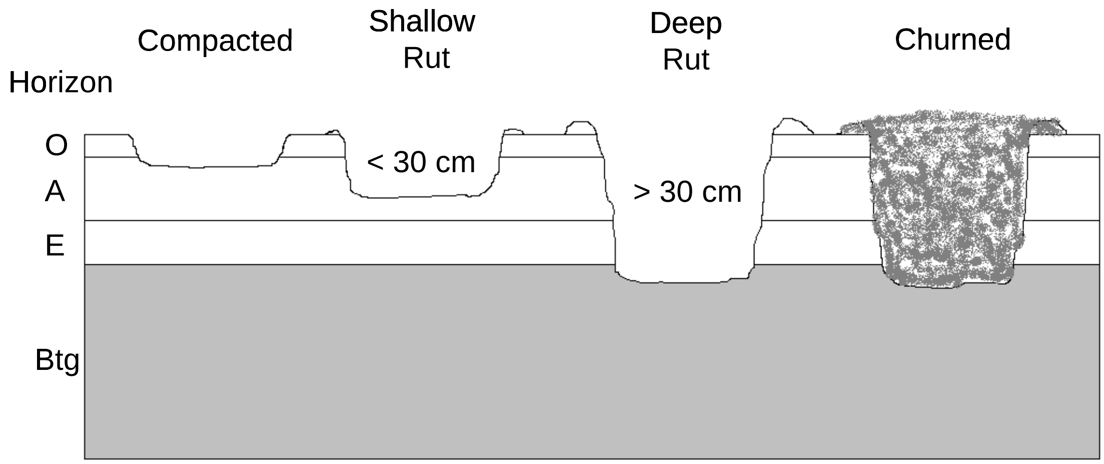

Figure 6.1. Diagram illustrating the typical levels of soil physical disturbance after harvesting classes of a poorly drained soil on a wet pine flat.

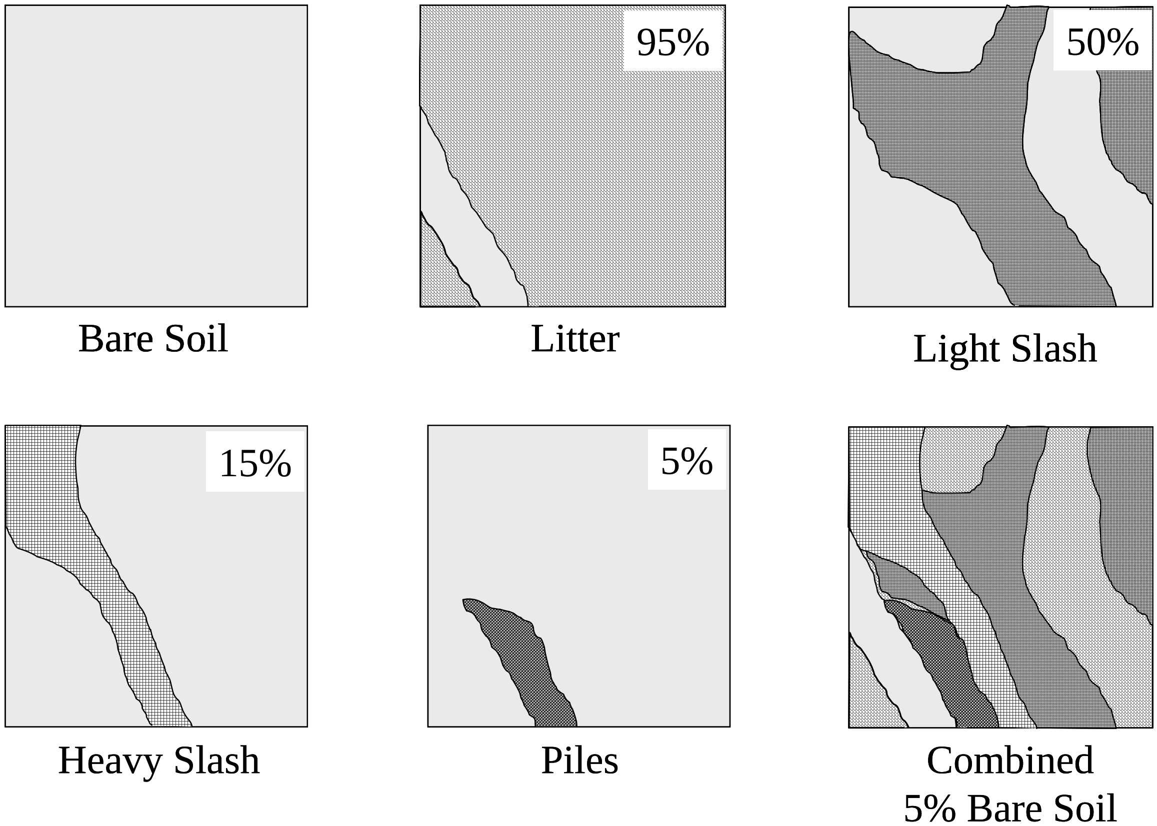

Figure 6.2. Representation of a 20 x 20 m subplot fitting a Class II harvesting residue category, and illustrating how residues were quantified on the site.

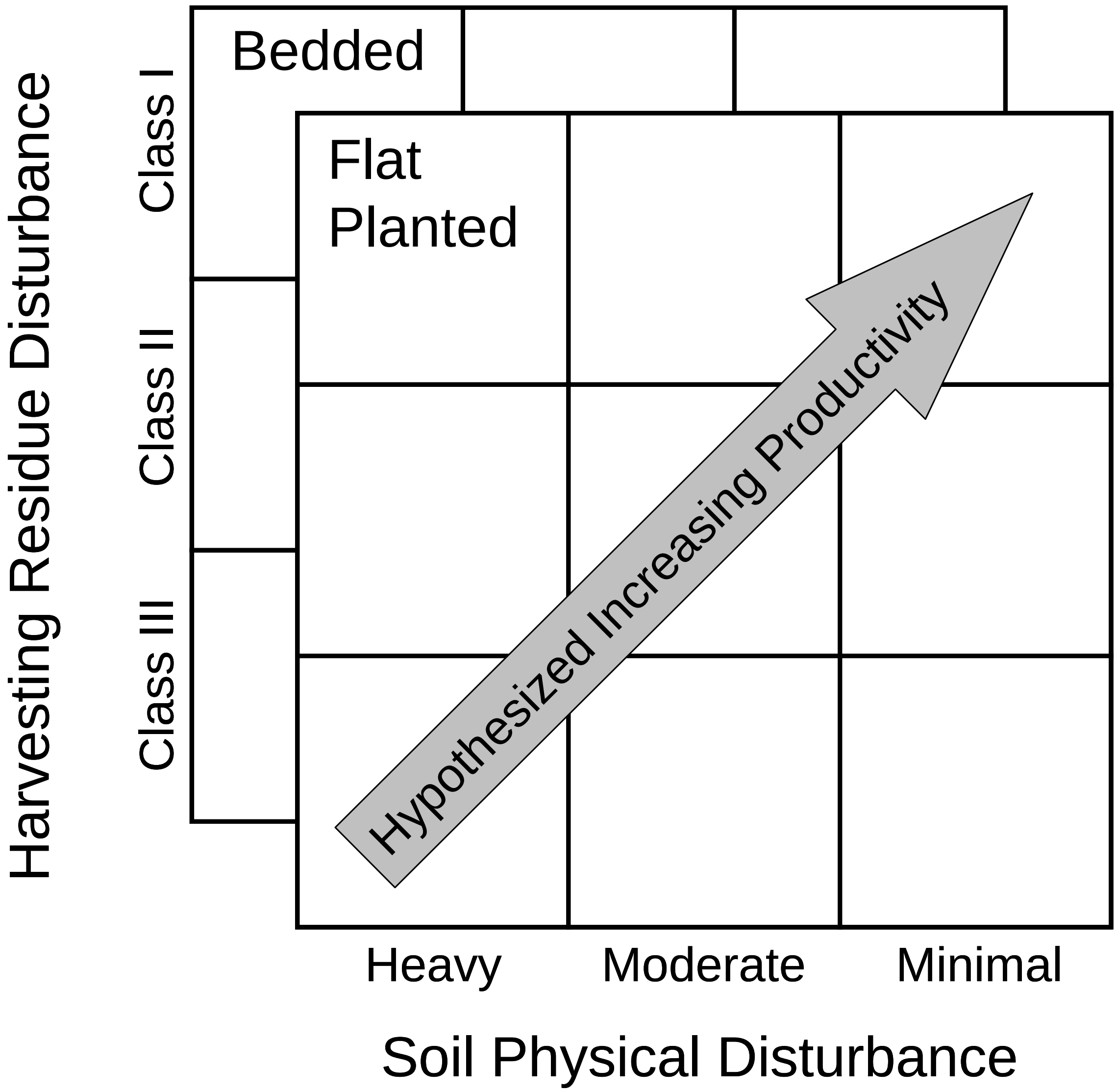

Figure 6.3. Hypothetical response of productivity to lower levels of physical disturbance and greater amounts of harvesting residues for two levels of site preparation.

The harvesting residues of each 20-m grid cell were categorized as: “Class I” if the residue index was 3.3 or less and there was less than 25 percent bare soil after harvesting, “Class II” if the residue index was greater than 3.3 and there was less than 25 percent bare soil, and “Class III” if there was more than 25 percent bare soil regardless of the residue index. The total dry weight biomass of the residues in the 20-m cell was calculated using regressions that estimated biomass from the percent coverage of each of the five residue categories (Eisenbies et al., 2002). The mole plow treatment and the wet-bedded treatments were not differentiated between due to the similarity of their response in other analyses (Eisenbies et al., 2004).

Site index (base age 25) was calculated to the nearest 0.1 meter for each sub-stand scale subplot (0.008-ha) at the end of the prior rotation and for the age-5 third quartile heights (Carmean et al., 1989). The equations used were developed for loblolly pine in all but very poorly drained soils on the North Carolina and South Carolina coastal plain (Pienaar and Shiver, 1980). Tree green weight biomass was calculated as a function of height and diameter for the end of the prior rotation (Bullock and Burkhart, 2003), and at age 5 for the new rotation (Phillips and McNabb, 1982) to three significant digits.

The ascending rank of all 1170 subplots was determined based on site index and stand biomass within three neighborhoods (blocks) for years 1993 and 2001 (SAS Institute Inc, 2001). Rank values ranged between 1 (best sites) and 390 (worst sites). Ties were assigned the average rank for that set of observations. Change in rank was calculated as the rank in 1993 minus the rank in 2001. Change in rank is normally distributed, and can be modeled using standard parametric procedures.

Change in rank was analyzed as a 3 x 3 x 2 factorial for both site index (RCSI) and green weight biomass (RCSB) using the general linear model at the alpha = 0.1 level with prior rank as a covariate (SAS Institute Inc., 2001) to assess changes in soil and site productivity as it relates to soil physical disturbance and organic residues. Means separations were determined by Fisher's protected least significant difference. Slicing (Schabenberger and Pierce, 2002) was used to address three specific contrasts at the sub-stand scale. (1) Were the bedded sites of each specific combination of soil physical disturbance and harvesting residue significantly greater than its flat-planted counterpart? (2) Was the site quality diagnostic for any combination of soil physical disturbance and harvesting residues significantly different than a reference category among the bedded sites? (3) Was the site quality diagnostic for any combination of soil physical disturbance and harvesting residue significantly different than a reference category among the flat-planted sites?

The purpose of the reference category is similar to that of an experimental control. Since the rank method evaluates relative productivity rather than a concrete biological term, some sort of benchmark should be selected in order to give context to the rank diagnostic. Although any treatment can be used as the benchmark, for the purposes of this study sites that received minimal disturbance, with moderate amounts of harvesting residues (Class II). This combination should represent a site that received little or no soil physical disturbance, and retains a litter layer in tact with scattered slash.

6.3. Results

6.3.1. Summary of the disturbance categories

Each of the three soil physical disturbance classes represented about one third of the 20-m grid cells (Table 6.1). Large machinery or vehicle traffic was not observed to visually affect soil surfaces within the minimal category. The moderate disturbance category was 66 percent undisturbed, and compression was the main disturbance observed. Rutting and churning affected 72 percent of the heavy disturbance category. Compression and rutting led to slight increases in bulk density, and 25 percent losses in macroporosity, although churning itself was not significantly different from undisturbed in most physical properties (Lister et al., 2004).

Table 6.1. Comparison of the five levels of post-harvest soil physical disturbance for each of the soil disturbance categories and the percentage of 20-m grid cells placed in each category. Letters indicate Fisher's least significant differences at the alpha = 0.05 level within column only.

Disturbance Category	Undisturbed	Compressed	Shallow Rutted	Deep Rutted	Churned	All Subplots
			< 30 cm deep	> 30 cm deep		
	----------	----------	---------- %	----------	----------	----------
Minimal	100.0 a	0.0 c	0.0 c	0.0 b	0.0 b	29.3
Moderate	66.9 b	22.3 a	5.5 b	1.1 b	4.2 b	35.4
Heavy	16.5 c	11.5 b	19.3 a	23.6 a	29.1 a	32.4
Unclassified						2.9

The distribution of the harvesting residue classes among the 20-m grid cells was 39 percent as Class I, 48 percent as Class II, and 11 percent as Class III (Table 6.2). The Class I category had almost no bare soil after harvesting and was 70 percent covered by light slash or heavier material. The mean total dry biomass of harvesting residues was 9.1 kg m^{-2}. The Class II category had 9.6 percent bare soil and was 50 percent covered by light slash with little heavy slash. The mean total dry biomass of harvesting residues was 6.9 kg m^{-2}. The Class III category averaged near 50 percent bare soil after harvesting. Despite the amount of bare soil, the mean total dry biomass of harvesting residues was 5.6 kg m^{-2}.

Table 6.2. Comparison of the five levels of harvesting residues for the post-harvest (pre-site preparation) organic matter disturbance categories, the total dry-weight residue biomass, and the percentage of 20-m grid cells placed in each category. Letters indicate Fisher's least significant differences at the alpha = 0.05 level within column only.

Disturbance Category	Slash Piles	Heavy Slash	Light Slash	Litter	Bare Soil	20-m Cells Classified	Harvest Residue
	----------	----------	---------- %	----------	----------	----------	kg m^{-2}
Class I	2.1 a	32.3 a	70.8 a	96.1 a	3.9 b	38.8	9.1 a
Class II	1.5 a	13.9 b	51.7 b	90.5 a	9.6 b	47.6	6.9 b
Class III	2.2 a	11.9 b	34.2 c	51.2 b	48.8 a	10.7	5.6 c
Unclassified						2.9	

The minimal disturbance category was uncommon on wet-weather harvested sites. In contrast, over 60 percent of dry-harvested sites were undisturbed based on the visual estimation with little or no bare soil exposed by harvesting. The majority of heavy and moderate disturbance classes for the 20-m gird cells occurred on wet harvested sites (Table 6.3). When moderate disturbance did occur on dry-harvested sites it corresponded with bare soil exposure. Despite the low prevalence (6.2%) of the minimal disturbance category on wet-weather harvested sites at the sub-stand scale, these sites were still 40 percent undisturbed at the operational scale (Eisenbies et al., 2004). These results justify selection of the minimal-Class II category as the reference for the three contrasts. The minimal disturbance category represents a site where the effects of harvest traffic on soil-site quality should be very small. The Class II category is consistent with the results reported by Pritchett and Fisher (1987) where little additional improvement in slash pine (*Pinus elliottii* Engelm.) growth is observed with harvesting residues greater than 7 kg m^{-2}.

Table 6.3. Percentage of the 20-m grid cells for each combination of the soil disturbance and harvesting residue categories occurring within wet- and dry-harvested sites.

Disturbance Category	Wet Harvested	Dry Harvested	Entire Study
	-------------------------------	%	---------------------------
Minimal			
Class I	5.2	15.4	9.3
Class II	1.0	45.8	18.8
Class III	0.0	3.2	1.2
Moderate			
Class I	26.6	1.9	16.8
Class II	13.0	9.2	11.5
Class III	0.4	17.4	7.1
Heavy			
Class I	20.8	0.2	12.7
Class II	28.7	0.0	17.3
Class III	3.9	0.0	2.4
Unclassified	0.4	6.9	2.9

6.3.2. Summary of site index and the RCSI factorial

The mean site index ranged between 19.6 m and 26.3 m (base age 20) for the range of disturbances categories (Table 6.4). Mean site index (base age 25) was 24.8 m on the bedded plots and 21.0 m on the flat-planted plots. The global analysis of covariance (ANCOVA) was significant (P = 0.0072) and prior site index was significant as a covariate (P = 0.0098). On the flat-planted sites, the heavily disturbed areas tended to have lower post-harvest heights and site indexes. On the bedded sites, the heavily disturbed - Class III sites had the lowest post-harvest site index.

Table 6.4. Post-harvest site indices (base age 25) associated with each of the disturbance classes and site preparation. Capital letters indicate significant differences within rows (alpha = 0.1), and lower case letters indicate significant differences within columns.

Disturbance Category	Flat-planted	Bedded
	-------- Site Index (m) † --------	
<u>All Categories</u>		
Mean	21.0 B	24.8 A
<u>Minimal</u>		
Class I	21.2 A ab	23.7 A ab
Class II	22.0 A ab	24.2 A ab
Class III	23.8 A a	26.6 A a
<u>Moderate</u>		
Class I	20.5 B ab	25.5 A a
Class II	20.9 B ab	26.5 A a
Class III	22.1 A ab	24.8 A a
<u>Heavy</u>		
Class I	19.8 B b	24.3 A ab
Class II	19.8 B b	24.1 A ab
Class III	21.5 A ab	21.3 A b

†Values for distinct disturbance categories are least squares means.

The global ANCOVA of the RCSI factorial was significant ($P < 0.0001$) and prior rank was significant as a covariate ($P < 0.0001$). There were no significant differences between the three physical disturbance classes on the flat-planted sites, but moderate disturbance resulted in a significantly higher change in rank than the heavily disturbed sites (Figure 6.4). There were no significant differences between the three residue classes for either site preparation (Figure 6.5). The mean rank change of the bedded sites (36.3) was significantly higher than the flat-planted sites (-45.4), and the total differential of 82 represents almost a full quartile difference (Table 6.5). According to our first contrast, the change in rank on the bedded sites were significantly higher than the flat planted sites on all but the heavily disturbed-Class III sites. Based on the second contrast, the only disturbance combination that outperformed the reference category among the bedded sites was the moderate-Class II category ($P = 0.0952$). There were no significant differences in the third contrast comparing the other combinations of soil-disturbance and harvest residue to the reference among the flat-planted sites.

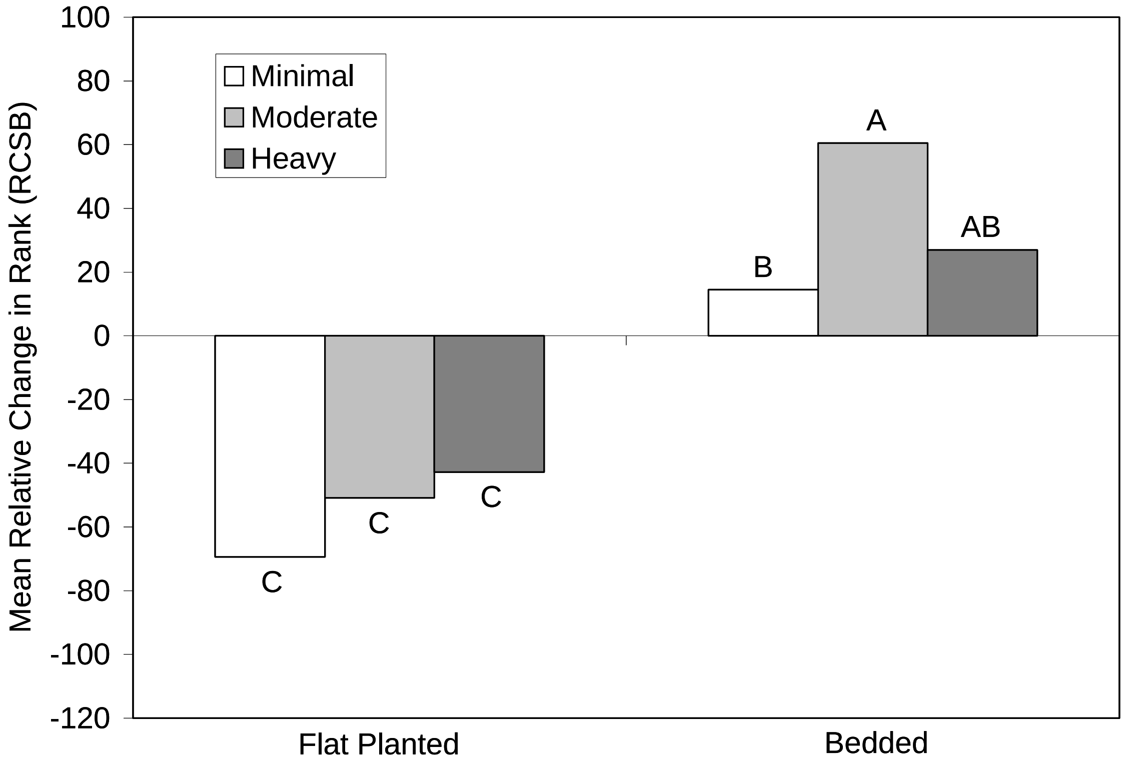

Figure 6.4. Relative change in soil/site productivity between rotations for combinations of soil physical disturbance categories and site preparation as reflected by the change in rank based on site index (RCSI). Different letters indicate Fisher's least significant differences for each series at the alpha = 0.05 level using prior rank as a covariate.

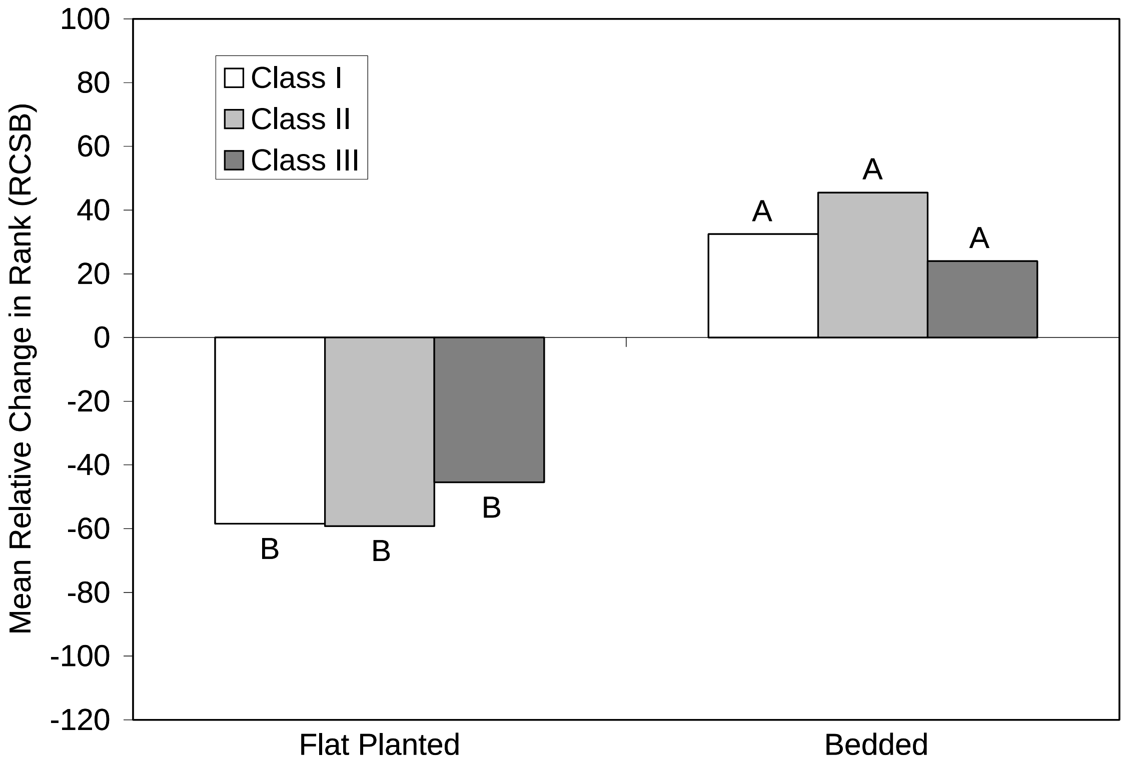

Figure 6.5. Relative change in soil/site productivity between rotations for combinations of harvesting residue categories and site preparation as reflected by the change in rank based on site index (RCSI). Different letters indicate Fisher's least significant differences for each series at the alpha = 0.05 level using prior rank as a covariate.

Table 6.5. Relative change in soil/site productivity between rotations for combinations of soil physical disturbance, harvesting residue, and site preparation as reflected by the change in rank based on site index (RCSI).

Disturbance Category	Flat-planted	Bedded	Contrast 1†	Contrast 2‡	Contrast 3§
	---------- RCSI --------				
All Categories					
Mean	-45.4	36.3	*	N/A	N/A
Minimal					
Class I	-48.9	25.4	**	NS	NS
Class II	-48.8	25.6	**	Reference	Reference
Class III	-21.6	81.6	*	NS	NS
Moderate					
Class I	-65.1	85.6	*	NS	NS
Class II	-63.1	97.9	*	**	NS
Class III	-44.2	41.0	**	NS	NS
Heavy					
Class I	-92.8	50.4	*	NS	NS
Class II	-77.3	46.3	*	NS	NS
Class III	-46.3	-27.9	NS	NS	NS

†Contrast 1: Significant Response to Bedding
‡Contrast 2: Significantly Different from Bedded Reference
§Contrast 3: Significantly Different from Flat-Planted Reference

6.3.3. Summary of biomass and the RCSB factorial

The mean green weight biomass ranged between 12.1 and 24.9 kg tree^{-1}, and 23.4 and 46.4 Mg ha^{-1} for the range of disturbance categories (Table 6.6). Mean tree biomass was 7 kg tree^{-1} and 13 Mg ha^{-1} higher on bedded plots versus flat-planted plots. However, although these and other trends are noted in the table, the global ANCOVA was not significant for both individual tree biomass (P = 0.2383) and stand biomass (P = 0.2537) using the prior biomass or prior stand biomass as covariates.

Table 6.6. Post-harvest mean green weight biomass associated with each of the disturbance classes and site preparation. No significant differences are presented because the global ANCOVAs were non-significant.

Disturbance Category	Flat-planted	Bedded	Flat-planted	Bedded
	--------- kg tree^{-1} † --------		----------- Mg ha^{-1} †-------	
All Categories				
Mean	14.1	21.5	25.3	38.8
Minimal				
Class I	14.1	19.4	23.9	34.5
Class II	14.0	18.5	24.1	34.6
Class III	17.5	19.0	26.3	35.8
Moderate				
Class I	12.1	24.1	24.2	43.5
Class II	13.3	24.9	24.7	46.4
Class III	13.4	21.3	24.6	37.1
Heavy				
Class I	14.0	22.3	26.3	39.1
Class II	12.3	22.6	23.4	39.3
Class III	17.1	21.4	32.5	37.4

†Values for distinct disturbance categories are least squares means

The global ANCOVA of the RCSB factorial was significant (P < 0.0001) and prior rank was significant as a covariate (P < 0.0001). There were no significant differences between the three physical disturbance classes on the flat-planted sites, but moderate disturbance resulted in a significantly higher change in rank than the minimal sites (Figure 6.6). There were no significant differences between the three residue classes for either site preparation (Figure 6.7). The mean rank change of the bedded sites (28.6) was significantly higher than the flat-planted sites (-50.2), and the total differential of 79 represents nearly a full quartile difference (Table 6.7). According to our first contrast, the change in rank on the bedded sites was significantly higher than the flat planted sites on all but the heavily disturbed-Class III sites and the minimal-Class III sites. Based on the second contrast, the only disturbance combination that outperformed our reference category of the bedded sites was the moderate-Class II category (P = 0.0514). There were no significant differences in the third contrast comparing the other combinations of soil-disturbance and harvest residue to the reference among the flat-planted sites.

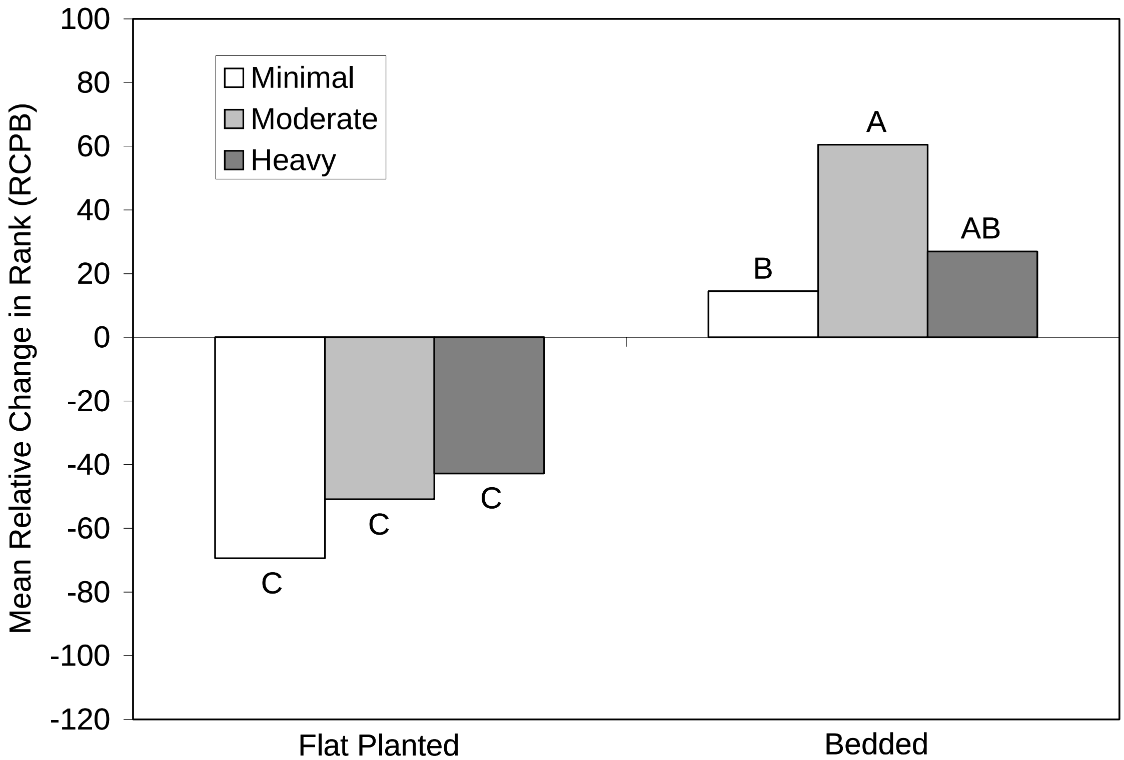

Figure 6.6. Relative change in soil/site productivity between rotations for combinations of soil physical disturbance categories and site preparation as reflected by the change in rank based on mean green weight stand biomass (RCSB). Different letters indicate Fisher's least significant differences for each series at the alpha = 0.05 level using prior rank as a covariate.

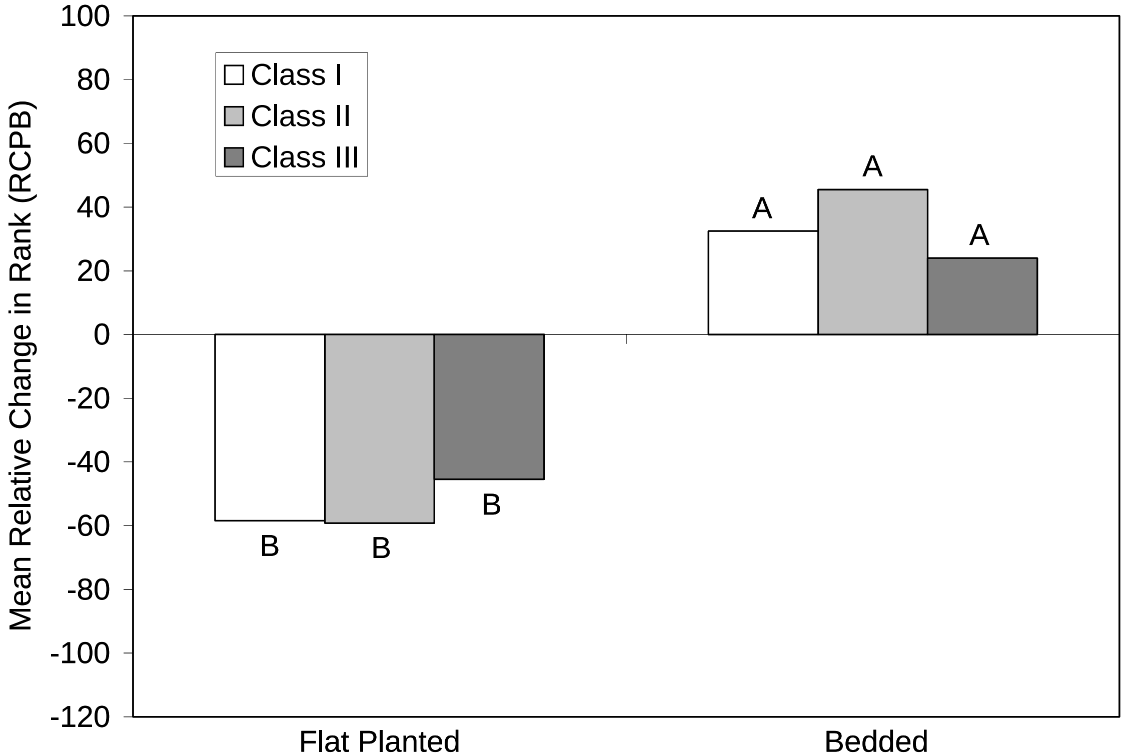

Figure 6.7. Relative change in soil/site productivity between rotations for combinations of harvesting residue categories and site preparation as reflected by the change in rank based on mean green weight stand biomass (RCSB). Different letters indicate Fisher's least significant differences for each series at the alpha = 0.05 level using prior rank as a covariate.

Table 6.7. Relative change in soil/site productivity between rotations for combinations of soil physical disturbance, harvesting residue, and site preparation as reflected by the change in rank based on biomass (RCSB).

Disturbance Category	Flat-planted	Bedded	Contrast 1†	Contrast 2‡	Contrast 3§
	---------- RCSB --------				
All Categories					
Mean	-50.2	28.6	*	N/A	N/A
Minimal					
Class I	-71.2	0.4	**	NS	NS
Class II	-61.1	11.0	*	Reference	Reference
Class III	-75.9	32.0	*	NS	NS
Moderate					
Class I	-70.4	59.7	*	NS	NS
Class II	-40.3	83.7	*	**	NS
Class III	-42.0	37.9	*	NS	NS
Heavy					
Class I	-33.6	39.2	**	NS	NS
Class II	-76.2	41.5	*	NS	NS
Class III	-18.5	1.9	NS	NS	NS

†Contrast 1: Significant Response to Bedding
‡Contrast 2: Significantly Different from Bedded Reference
§Contrast 3: Significantly Different from Flat-Planted Reference

6.3.4. Disturbance-independent site attributes

There are four disturbance-independent site attributes that may provide insights into our study results: the pre-harvest rank of site index and stand biomass, the distance to landing, and the relative elevation. Analysis of pre-harvest rank indicates that there may be a propensity of higher quality sites to become heavily disturbed (Table 6.8). Class III harvest residue sites were significantly closer to the landing, but this was the only significant difference among the disturbance-independent site attributes. The heavily disturbed sites tended to have higher initial ranks in terms of site index and biomass, were significantly closer to the landing, and tended to have higher relative elevations. The heavy disturbance-Class III sites had the best pre-harvest ranks, were closest to the landings, and had the highest relative elevation among the specific soil disturbance harvesting residue combinations.

Table 6.8. Comparison of disturbance-independent site attributes. Capital letters indicate Fishers least significant differences within column only for the main soil physical disturbance effect. Lower-case letters indicate Fishers least significant differences within column only for the main harvesting residue effect

Disturbance Category	Pre-Harvest Site Index	Pre-Harvest Biomass	Distance to Landing	Relative Elevation‡
	-------------- Rank†	--------------	----------------- m	-----------------
Soil Disturbance Category				
Minimal	231 A	219 A	170 A	2.2 A
Moderate	195 AB	194 AB	154 A	2.6 AB
Heavy	166 B	173 B	121 B	3.0 B
Harvesting Residue Category				
Class I	181 a	190 a	162 a	2.7 a
Class II	195 a	189 a	155 a	2.7 a
Class III	216 a	207 a	126 b	2.5 a
Heavy-Class III Combination				
Mean	146	159	91	3.3
All Sites				
Mean	197	195	148	2.6

† Lower numbers are assigned to sites with higher initial site index or average tree biomass.
‡ Elevation above lowest point within a 30-ha neighborhood as determined from a 30-m digital elevation model.

6.4. Discussion

6.4.1. Effects of disturbance

According to the RCSI and RCSB diagnostic variables, moderate physical disturbance coupled with bedding appears to benefit soil-site productivity (Figures 6.4 and 6.6). Aust et al., (1998) noted that soil water field capacities were higher on the moderately disturbed sites, which may indicate increased localized water retention. These sites suffered drought conditions for three of the first five years of growth (Eisenbies et al., 2004) and water retention may have been a particularly important factor. The second contrast indicates that none of the disturbance categories significantly under-performed relative to the reference category (physical disturbance = minimal, harvest residue disturbance = Class II) (Tables 6.5 and 6.7). However, the moderate-Class II sites outperformed the reference, which indicates that moderate disturbance may improve relative productivity absent of excessive bare soil or excessive slash, although this result was obtained in conjunction with droughty conditions. Moderate physical disturbance can be beneficial to plant growth, although the threshold where it becomes detrimental can be narrow (Greacen and Sands, 1980; Kozlowski, 1999). Lister et al., (2004) found that average pine volume after two years was 30 to 50 percent greater in compressed soils than minimal or heavily disturbed soils. Within the flat-planted sites there was a trend for the more heavily disturbed sites to have lower relative soil-site productivity, and with increased replication this trend could become significant. However, in terms of the main disturbance effects, this study revealed few statistically significant or meaningful relationships in spite of the fact that the classes do represent distinct levels of physical disturbance.

We did not observe any significant effect or meaningful patterns on changes in soil-site productivity among the residue categories. The potential benefits of increased organic matter on overall productivity are great although they are not entirely predictable. Childs et al. (1986) show that increasing residues can have an irregular effect on moisture availability. In addition, excessive residues can interfere with proper bed formation (Terry and Hughes, 1975), and these sites had large amounts of harvesting debris incorporated in the upper 30 cm of soil (Lister et al., 2004). After operational harvesting, the quantity of residues on each of the disturbance classes was greater on average than 5.3 kg m^{-2} for all combinations of physical disturbance and harvest residue categories. This may not be sufficiently below the 7 kg m^{-2} threshold reported by Pritchett and Fisher for slash pine (*Pinus elliotii* Engelm.) flatwoods (1987) to provide a suitably strong response at the sub-stand scale. Wet-weather harvesting actually resulted in larger amounts of harvesting residue (mostly in the form of light and heavy slash) on the site, and less bare soil (Eisenbies et al., 2004). The loggers that harvested this study, acting as they would if this were a commercial harvest, topped the trees by hand on the wet-harvested sites to reduce drag and improve traction during skidding. On the dry-harvested sites trees were skidded whole to a delimbing gate near the landing.

The benefits of bedding poorly drained pine flats are well established (Schultz and Wilhite, 1974; Terry and Hughes, 1975; Gent et al., 1983; McKee et al., 1985; Pritchett and Fisher, 1987; Morris and Lowery, 1988; Aust et al., 1995; Lister et al., 2004). Change in rank was significantly higher on bedded plots versus the flat-planted equivalents with the exception of the heavily disturbed-Class I sites (Tables 6.5 and 6.7). However, this discrepancy was not necessarily because these sites failed to respond to bedding, but instead due to the fact that the heavily disturbed, Class I, flat planted plots appeared to have higher production relative to the other disturbance categories. An Interesting feature of the heavily disturbed sites was the ridges between the ruts that formed 'pseudo-beds', which were utilized by the hand planters. Heavy disturbance can also suppress competition (Aust et al., 1997; Lister, 1999; Murphy and Firth, 2004). This may explain why these sites did well on the flat-planted plots, but after the additional traffic associated with the shearing and bedding treatments, the benefit of the pseudo-beds was negated. These sites tended to reside close to the landing in higher elevations and were of higher initial quality (Table 6.8). Harvest equipment operators probably avoid depressions in wet weather in order to prevent bogging. The heavily disturbed-Class III combination was rare on the whole, and comprised less than 4 percent of the wet harvested 20-m grid cells, and less than 3 percent of the entire 60-ha study. At the operational scale there were no significant differences between wet- and dry-weather harvesting when bedding was used (chapter 5).

The moderately disturbed sites did consistently better relative to the minimal and heavily disturbed sites after bedding (Figures 6.4 and 6.6). One explanation may also be that competition can be initially suppressed on wet harvested sites (Aust et al., 1997; Lister, 1999; Murphy and Firth, 2004) where heavy disturbance is much more prevalent. If this is the case, pines growing on the less disturbed sites will tend to need more height growth in order to effectively compete, while pines growing on more disturbed sites can allocate resources toward diameter growth. A second explanation could be that bed formation is best on moderately disturbed sites. Bed quality can be profoundly important on poorly drained sites (Terry and Hughes, 1975). Minimally disturbed sites, which tend to reside at lower relative elevations, may be too wet to form proper beds. In addition, the bedding plows may not work as efficiently on heavily disturbed sites with irregular surfaces due to rutting, or wet-weather harvested sites where excessive debris (Eisenbies et al., 2004; Lister et al., 2004) may interfere with bedding quality (Terry and Hughes, 1975).

6.5. Conclusions

The main focus of harvesting BMPs has been on protecting water quality and maintaining site productivity (Aust and Blinn, 2004). Across a broad range of studies and forest types on the Southern Coastal Plain, one of the main concerns has to do with soil physical and organic matter disturbance associated with large machinery and vehicle traffic (Greacen and Sands, 1980; Childs et al, 1986, Powers et al., 1990; Morris and Miller, 1994; Kimmins, 1996a; Kelting et al., 1999). However, for wet pine flats drainage appears to be a much more important factor controlling soil-site productivity and pine growth (Terry and Hughes, 1975; Allen and Campbell, 1988; Conner, 1994). Disruption of drainage can reduce site indexes by 3 meters or more (Terry and Campbell, 1981), which is consistent with the 3.5 m decrease we observed. Xu et al. (2002) reported that harvesting disturbance did not have any significant affect on the hydrology of these same sites. This study indicates that not all BMP requirements are universally necessary, and some may be too stringent for sites that prove to be resilient. Richardson et al. (1999) and Fox (2000) both make the case that forest management must be carefully tailored to specific forests and specific management regimes. Certainly, there are sites that do not respond favorably to disturbance (Bates et al., 1993), but wet pine flats, with similar characteristics to our sites (e.g. high fertility, shrink-swell clays), may in fact be suited for harvesting during wet weather as long as they can be accessed economically, and receive appropriate site preparation (Terry and Hughes, 1975; Morris and Lowery, 1988).

There were no significant changes detected in soil-site productivity in response to increasing soil disturbance or increasing levels of harvesting residue after a typical harvesting operation. Bedding restored productivity in all cases except for the most heavily disturbed sites, and lack of response on those sites was due to the enhanced growth on the flat planted sites due to pseudo-bedding, but poor response after additional traffic. These heavily disturbed sites, with large amounts of bare soil after harvesting, represented a very small proportion of the entire harvesting units. Moderate disturbance appears to have some benefit to soil-site productivity, however a full rotation will be necessary to ascertain if our observations represent the true long-term response. The distribution of harvesting residues appears to be adequate to maintain site fertility, but in some cases may interfere with bed formation. Overall, these wet pine flats have proven to be resilient when site prepared. At age five, no disturbance category under performed relative to the minimal-Class II reference among bedded sites, which would be considered the operational desirable outcome of harvesting.

CHAPTER 7

Factors Affecting Changes in Soil-Site Quality on Intensively-Managed Pine Plantations

7.1. Introduction

This research is the third of four sub-studies that evaluates the effect of wet- and dry-weather harvesting on forest productivity and site quality. The objectives of this paper are (1) to evaluate the impacts of harvesting disturbance on changes in soil-site quality on intensively managed loblolly pine plantations located on a wet pine flats in South Carolina, (2) to establish which site, soil, and management factors are most significantly related to changes in soil-site quality as stands approach closure, (3) to track the change of key physical properties from pre-harvest conditions through stand establishment, and approaching stand closure, and (4) to relate soil-site indicators of site quality to harvesting disturbance and operational treatments. This chapter is an expansion of the regression approach used in chapter four, but utilizing a dataset that includes a much larger array of specific soils and site information.

7.2. Materials and methods

7.2.1. Data collection and processing

Prior to harvest each treatment plot was overlain with a 20 x 20-meter grid (Figure 3.3). In each cell, a 0.008-ha measurement subplot was permanently established. A total of 1170 subplots were installed and all subsequent stand measurements were collected at these "sub-stand scale" subplots. Height and diameter of all trees within the 0.008-ha subplots were measured prior to treatment installation. The sampling intensity was 20 percent of the entire study area.

After harvest and preceding site preparation, site disturbances associated with each treatment were characterized by the percent coverage of five harvesting residue classes, and five physical disturbance classes (Eisenbies, 2004). An index of soil physical disturbance was determined by assigning an integer value to successively increased levels of soil disturbance (undisturbed (1), compacted (2), shallow rutted (3; < 20 cm), deep rutted (4; > 20 cm), churned (5)) and calculating a weighted average based on percent coverage (Figure 7.1). An index of harvesting residues was similarly determined based on the percent coverage of bare soil (5), litter (4), light slash (3; < 2.5 cm diameter), heavy slash (2; > 2.5 cm diameter), and piles (1) (Figure 7.2). Harvesting residue biomass for each of these classes was calculated from percent coverage by regression (Eisenbies et al., 2002). A second inventory of height and diameter was conducted at age five at the 0.008-ha subplots across the study.

Intensive measurements of indicators of soil-site quality were obtained from a subset of 71 sub-stand scale subplots. In order to incorporate disturbance features into a regression model, the 1170 plots were partitioned into groups that represented three basic levels of soil physical disturbance (minimal, moderate, and heavy), and three basic levels of harvesting residues (Class I, Class II, and Class III) based on the indexes of physical disturbance (Figure 7.3). The minimal class had no apparent soil physical disturbance. The moderate class was 67% undisturbed and 33% compacted on average. The heavy disturbance class was 17% undisturbed, 11% compacted, 19% shallow rutted, 24% heavy rutted, and 29% churned on average. The class I residue category was typified by more abundant heavy slash and had approximately 9 kg m^{-2} of dry organic residue biomass on the surface. The class II residue category was typified by little slash residues and had approximately 7 kg m^{-2} of dry organic biomass. The class III residue category was typified by greater than 25% bare soil and had approximately 5.5 kg m^{-2} of dry organic residue biomass.

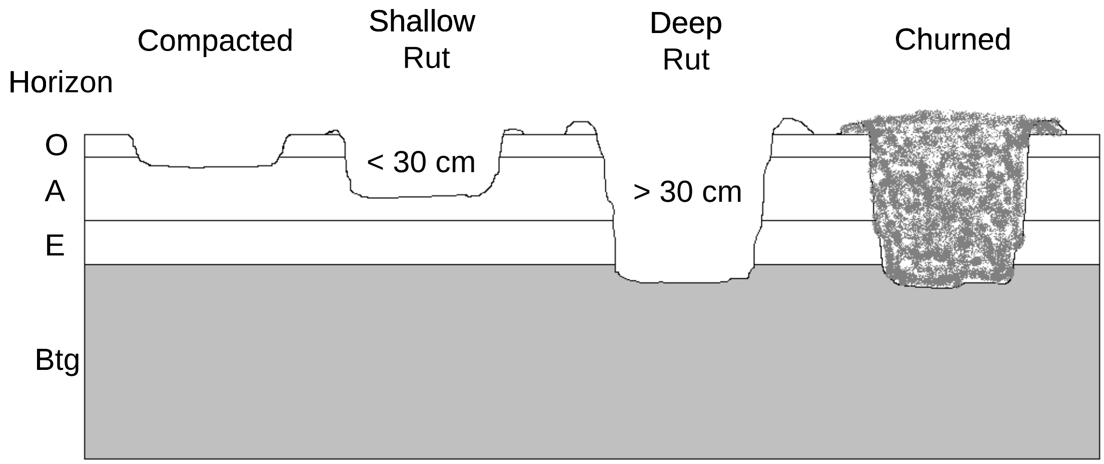

Figure 7.1. Diagram illustrating the typical levels of soil physical disturbance after harvesting classes of a poorly drained soil on a wet pine flat.

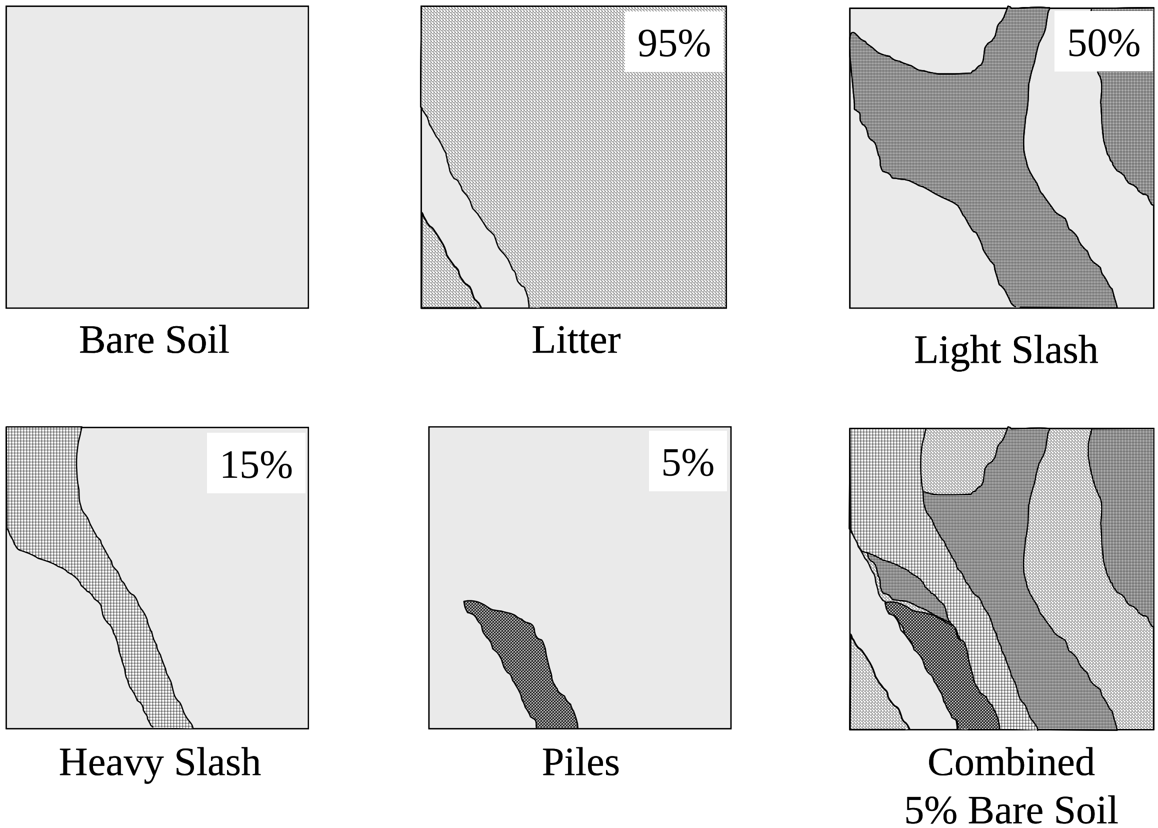

Figure 7.2. Representation of a 20 x 20 m subplot fitting a class II harvesting residue category, and illustrating how residues were quantified on the site.

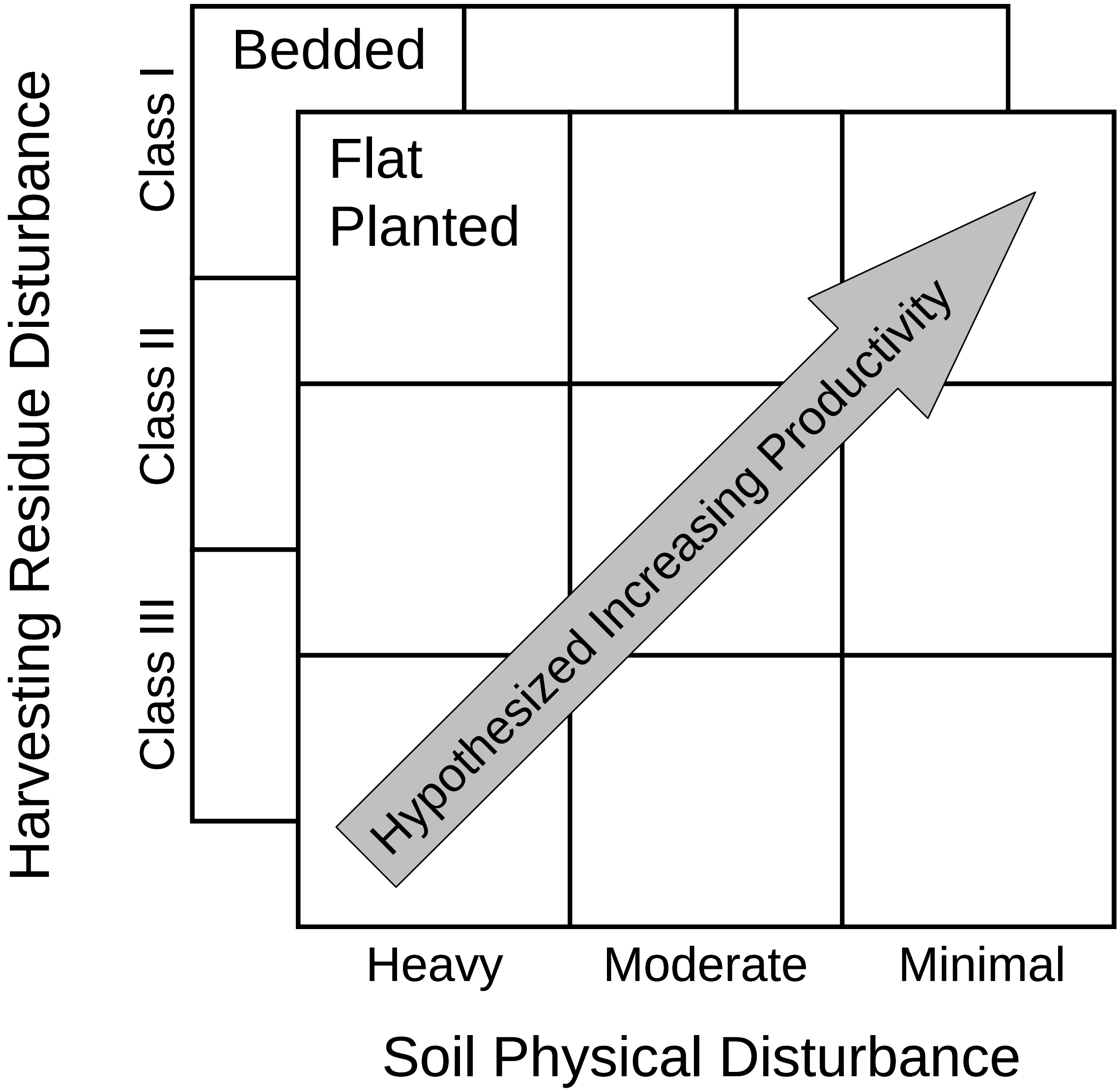

Figure 7.3. Hypothetical response of productivity to lower levels of physical disturbance and greater amounts of harvesting residues for two levels of site preparation.

The benefits of bedding wet pine flats are well established (Schultz and Wilhite, 1974; Terry and Hughes, 1975; Gent et al., 1983; McKee et al., 1985; Pritchett and Fisher, 1987; Morris and Lowery, 1988; Aust et al., 1995). Proper bed formation is an important factor in garnering the benefits of bedding (Terry and Hughes, 1975). Bed quality was quantified three ways: (1) by the total soil volume above the argillic horizon, (2) by the volume of soil occupied by prominent or abundant fine roots synonymous with the common or many description for soil mottles (Buol et al., 1989), and (3) by the ratio of slope length and linear distance along a transect perpendicular to three planting rows, which we designate as the S:T ratio. As beds become better defined, the S:T ratio becomes larger. We also hypothesized that the S:T ratio would be related to gas exchange between the soil and atmosphere, as well as a way to quantify "pseudo-bedding". Pseudo-bedding occurred on deeply rutted and churned non-bedded sites where the tree planters preferentially utilized the high spots between the deep furrows as beds. Trees generally did better on these sites. The depth of prominent rooting was thought to be a biologic indicator of fluctuating water tables and soil strength. Depth of prominent rooting was measured in shallow pits excavated along the same transects used to determine the S:T ratio. The total soil volume was determined by using a push probe to measure the depth to the argillic horizon at several points along the S:T transect.

Various soil samples and physical properties were measured after the fifth growing season. Soil bulk density (Grossman and Reinsch, 2002), total porosity, macroporosity, and microporosity (Flint and Flint, 2002) were calculated from 100 cm^3 intact soil cores (AMS Inc., American Falls, ID) at depths of 15 cm and 45 cm using a hammer-driven core sampler. Saturated hydraulic conductivity (K_{sat}) was also determined from these cores using a constant head flow-through apparatus (Klute and Dirksen, 1986). Oxidation depth on steel rods was measured to a maximum depth of 70 cm as an indicator of soil aeration (McKee, 1978; Carnell and Anderson, 1986). Bulk density and oxidation depth were also scored in terms of sufficiency for root growth (Kelting et al., 1999). The least limiting water range (LLWR) (DaSilva and Kay, 1997) was derived from soil texture, bulk density, and carbon content. Percent of time within the range (PIN)(Kelting et al., 1999) was determined by monthly observations of water content at 20 and 50 cm using time domain reflectometry (Topp and Ferre, 2002). Because of a drought there was no reliable continuously recorded water table or moisture data to correlate with the water content measurements. A mixed model (SAS Institute Inc., 2001) was used to predict the LLWR using elevation data and stage readings from the nearest US Geological Survey gauging station (located approximately 15 miles from the site on the Edisto River near Givhans, SC). PIN was calculated for a two-year period (October 1999 to September 2001) by dividing the number of days modeled within the range over the total number of days.

The net nitrogen mineralization rate was determined using the buried bag method (Eno, 1960). Eight paired cores were obtained from the upper 20 cm of the planting rows using a 2-cm diameter push probe at monthly intervals at each subplot. One set of cores was kept and dried immediately. The second set was buried in the bed in a polyethylene bag for one month and allowed to incubate. Monthly net nitrogen mineralization was calculated as the difference in inorganic N concentrations between the initial and incubated samples. Inorganic N was extracted from ground and sieved (2 mm) soil samples using a 2M KCl solution and analyzed for N-NO3 and N-NH4 using an auto-analyzer (Bran-Luebbe TRAACS 2000, Buffalo Grove, IL). The concentrations were converted to a bulk soil value by correcting for moisture content and bulk density. Mineralization rates were converted to an area basis using both an assumed 30 cm constant depth, and the rooted volume determined from the transect excavation. Net nitrogen mineralization was also scored in terms of sufficiency for root growth (Kelting, 1999). Percent total carbon and nitrogen content were determined for depths of 20 cm and 50 cm in the planting rows by dry combustion (Elementar Americas, Mt. Laurel, NJ). Total carbon and nitrogen were converted to a bulk soil value by correcting for bulk density and moisture content, and converted to an area basis using the soil volumes determined from the transects.

Macro soil organic matter (MSOM) and root biomass were determined from 500 cm^3 cores obtained at depths of 15 cm and 30 cm. A 6.5 diameter AMS (AMS Inc., American Falls, ID) bucket auger was modified by welding a carbide toothed band saw blade in the place of the standard scoops so that buried woody debris and roots would be cut, rather than torn from the sample hole. MSOM and roots were separated from the bulk soil through a 2 mm sieve using an elutriation root washing machine (Gillison's Variety Fabrication, Benzonia, MI). MSOM were separated from the live roots by hand, dried in a 60 C oven, weighed, and expressed on a mass basis by correcting for the bulk density of the soil. Pine roots were separated from non-pines and placed into a greater than 5 mm size class and a less than 5 mm size class.

ARCGIS (ESRI Corporation, Redlands, CA) was used to assign spatial and soils information to each of the 1170 sub-stand scale subplots. The fixed 20 x 20 m treatment plot grids were georeferenced using aerial photography and global positioning to locate the block corners (Magellan Inc., Santa Clara, CA). Elevation data were obtained from a United States Geological Survey 30-m grid digital elevation model (DEM). Relative elevations for a 30-ha neighborhood surrounding each 0.008-ha subplot were determined from the DEM and corrected with surveyed elevations. Relative elevation was calculated by subtracting the minimum DEM elevation within a 30 ha (18 x 18 cells) square neighborhood from the DEM elevation of the subplot. An on-site differential survey was also conducted in order to account for the course elevations provided by 30-m DEM. A local correction was applied to relative elevation to account for microtopography, and the height of the beds, by using the following equation:

$$\text{Relative Elevation}_{BED} = \text{Relative Elevation}_{DEM} - (\text{Elevation}_{DEM} - \text{Surveyed Elevation}_{BED})$$

Soil order and series were obtained from the NRCS Soil Survey Geographic (SSURGO) database. Data were assigned to the subplots using the spatial join function in ARCGIS.

7.2.2. Statistical analysis

Comparing soil/site productivity between rotations has traditionally been a challenge (Morris and Miller, 1994) due to a large number of confounding factors that prevent the direct comparisons of growth distributions between rotations in order to evaluate changes in soil/site productivity (Dyck and Cole, 1994; Burger, 1996). Climate

(Boardman, 1978; Shoulders and Tiarks, 1980; Valentine et al., 1999; Kirschbaum, 2000), intensive silviculture (Terry and Hughes, 1975; Hasenauer et al., 1994), the use of genetically improved trees (Schultz, 1997; Stanturf et al., 2003), physiography and drainage class (Terry and Hughes, 1975; Carmean et al., 1989), and even the specific productivity model selected (Carmean, 1975) alter the range and mean of growth distributions such as site index or biomass. Therefore using production of the current rotation, or the difference in production between the current rotation and the last, are not effective means to evaluate changes in soil-site productivity due to harvesting impacts.

In chapter 6 we show that rank distributions of site index or biomass could be used as a diagnostic to evaluate changes in soil-site quality. Rank distributions substantially reduce the effect of the confounding factors because their range and mean are constant. Therefore, changes in rank better reflect relative changes in soil-site productivity due to site factors or treatment effects. The main assumption of this approach is that regardless of a uniformly applied treatment, the rank of soil/site quality (as measured by site index or tree biomass) for a specific location will remain relatively constant within a designated neighborhood at any point across time (i.e. the best sites will always be the best, etc.).

While net primary productivity is considered the gold standard for quantifying site productivity, it is difficult to measure; therefore site index, the height of some portion of the canopy at a base age, and biomass are more commonly used in forestry (Morris and Miller, 1994). Site index (base age 25) was calculated to the nearest 0.1 meter for each sub-stand scale subplot (0.008-ha) at the end of the prior rotation and for the age-5 third quartile heights (Carmean et al., 1989). The equations used were developed for loblolly pine in all but very poorly drained soils on the North and South Carolina Coastal Plain (Pienaar and Shiver, 1980). Tree green weight biomass was calculated as a function of height and diameter for the end of the prior rotation (Bullock and Burkhart, 2003), and at age 5 for the new rotation (Phillips and McNabb, 1982) to three significant digits.

The ascending rank of all 1170 subplots was determined based on site index and green weight stand biomass within three neighborhoods (blocks) for years 1993 and 2001 (SAS Institute Inc, 2001). Rank values ranged between 1 (best sites) and 390 (worst sites). Ties values of site index or biomass were assigned the average rank for that set of observations. Change in rank was calculated as the rank in 1993 minus the rank in 2001. Change in rank is normally distributed, and can be modeled using standard parametric procedures.

Change in rank was evaluated at the sub-stand scale (0.008-ha subplots) using multiple linear regression (SAS Institute Inc., 2001). The candidate regressors reflect site preparation, site factors, and disturbance (Table 7.1). Site factors can be further divided into inherent site factors, such as elevation, which are not influenced by management practices, and site-specific factors, such as bulk density or nitrogen mineralization, which can be modified by management practices. Two models were constructed: change in rank based on site index (RCSI), and change in rank based on stand biomass (RCSB). A correlation matrix (SAS Institute Inc., 2001) was used to diagnose potentially collinear terms before model selection steps. The choice between two potentially collinear variables was based first on the precision of the measurement, second, on how well the variable reflects reality, and last on the ease of measurement. Final model selection was based on the model selection procedures outlined by Montgomery et al. (2001). Mallows Cp statistic and backwards variable selection were the primary means for generating candidate models. Collinearity was assessed in the candidate models by the variance inflation factor. Outliers were evaluated using the studentized residuals, diagonal elements, and DFITTS deletion influence (Belsley et al. 1980).

A 2 x 2 factorial was used to evaluate specific soil-site properties in terms of the interaction of site preparation (flat-planted and bedded) versus harvesting conditions (dry and wet weather). 2 x 3 factorials were used to evaluate soil-site properties in terms of the interactions between site preparation and soil physical disturbance (minimal, moderate, and heavy), and the interaction between site preparation and harvesting residues categories (class I, class II, and class III). Each factorial was analyzed in the general linear model at the alpha = 0.10 level, and means separations were conducting using Fisher's protected least significant difference (SAS Institute Inc., 2001).

Table 7.1. Candidate regressors representing the hypothesis that the change in site-soil quality will be a function of silvicultural treatments, inherent site factors, and harvesting disturbance.

Category	Candidate Regressors
Silviculture	
Treatments	Bedding
	Wet-harvesting
	Interaction of Bedding and Wet-harvesting
Inherent Site Factors	
Productivity	Pre-Harvest Site Index
	Pre-Harvest Mean Individual Tree Biomass
	Pre-Harvest Stand biomass
	Prior Ranks
Topography-Drainage	Mean Flow Accumulation
	Relative Elevation
Soils (NRCS Soil Survey Geodatabase[§])	Soil Order
Specific Site Factors	
Soil Chemical Properties	Net Nitrogen Mineralization
	Total Nitrogen
	Total Carbon
	C:N Ratio
Soil Physical Properties	Bulk Density
	Total Porosity
	Macroporosity
	Saturated Hydraulic Conductivity
	Least Limiting Water Range
	Oxidation Depth
Survival	Stem Density
Soil Profile	S:T ratio
	Total Rooted Volume
	Organic Residues (> 2mm)
Harvesting Disturbance	
Soil Physical Disturbance	Percent Undisturbed
	Soil Disturbance Composite Score
	Distance to Landing
Organic Matter Disturbance	Percent Bare Soil
	Total Harvesting Residues

[†] Prior individual tree biomass was only included in the regression where the change in rank was based on individual tree biomass.
[‡] 30-m grid digital elevation model (USGS)
[§] NRCS Soil Survey Geodatabase (SSURGO)

7.3. Results and discussion

7.3.1. Regression models

The best performing regression models for RCSI and RCSB both indicate that changes in soil-site quality are functions of silvicultural treatments, disturbance, and inherent site factors. The RCSI model indicates that soil/site quality was a function of prior site index (m), bedding, relative elevation in a 30-ha neighborhood, soil order (Mollisol), macroporosity of the upper 20 cm of the bed, and distance to landing (m) (Table 7.2). The model explained 77 percent (adjusted r-square) of the variability observed in the data.

Table 7.2. Components representing silvicultural practices, inherent site factors, and disturbance factors to predict change in relative productivity based on site index (RCSI) between rotations on wet pine flats.

Component	Coefficient	Significance	Type II Sums of Squares	
		P value	value	%
Intercept	933.6			
Site Preparation				
Bedding	91.03	< 0.0001	119308	11.2
Disturbance Factors				
Distance to Landing (m)	0.2937	0.0112	35419	3.3
Inherent Site Factors				
Bed Relative Elevation (m)	95.24	0.0003	74841	7.0
Soil Order (Mollisol)	-97.59	0.0009	62662	5.9
Site Specific Factors				
Pre-Harvest Site Index (m)	-46.26	< 0.0001	738047	69.1
Macro-porosity at 20cm	4.534	0.0095	37171	3.5

The best performing model for RCSB was a function of bedding, percent of pre-harvest rank, stand density, oxidation depth, undisturbed soil, soil order, macroporosity at a 50 cm depth, total soil carbon (Mg ha^{-1}), and the K_{sat} at a 50 cm depth (Table 7.3). The model explained 81 percent (adjusted r-square) of the variability observed in the data. The type II sums of squares were used to evaluate the relative importance of each of the model components. Site index and prior rank, both indicators of initial site quality, were the most influential factors in each model, and explained two thirds of the total variability explained by each model.

Table 7.3. Components representing silvicultural practices, inherent site factors, and disturbance factors to predict change in relative productivity based on stand biomass (RCSB) between rotations on wet pine flats.

Component	Coefficient	Significance	Type II Sums of Squares	
		P value	value	%
Intercept	-343.9			
Site Preparation				
Bedding	80.26	< 0.0001	93652	8.4
Disturbance Factor				
Undisturbed Soil (%)	-0.4829	0.0415	19187	1.7
Inherent Site Factors				
Soil Order (Mollisol)	-68.71	0.0151	27721	2.5
Site Specific Factors				
Pre-harvest Rank	1.026	< 0.0001	772258	69.0
Oxidation Depth	-2.766	< 0.0001	92937	8.3
Stand density (trees ha^{-1})	0.08042	0.0060	36023	3.2
Macro-porosity at 50cm	6.744	0.0096	31721	2.8
Soil Carbon (Mg ha^{-1})	0.7675	0.0156	27420	2.4
$\ln(K_{sat})$ at 50 cm	4.770	0.0453	18477	1.7

In each regression, five observations were eliminated due to missing values. Several outliers and leverage points were identified, and were deemed true outliers based on their location at stand edges, near the deck, or within gum ponds. However, they were retained because our purpose for the model is to identify which factors are important, rather than build a model specifically for prediction purposes.

This final model is very similar to the one reported in chapter 5; however the model selection procedures included a far more detailed array of site factors. Given that the soil-site properties are highly interrelated, there were a vast number of alternative variable combinations that explained as much variability as the models we selected. The qualitative and indirect site attributes (relative elevation, flow accumulation, soil order, distance to landing) and directly observed soil-site variables (site index, biomass, nitrogen, carbon, bulk density, porosity, hydraulic conductivity, least limiting water range, oxidation depth, rooted volume. MSOM, and disturbance levels) are interrelated such that the inclusion of certain qualitative variables can exclude a site-specific variable during model selection because they overlap. This is not to say that any specific variable excluded is not relevant, but that some qualitative or indirect measure may sufficiently explain the response such that others are redundant (Carmean, 1975). There are many alternate models that could be used, and could perform as well as the ones we have chosen. In any case, the full RCSI and RCSB candidate models fit our general hypothesis that changes in productivity are explained by silviculture, disturbance, and inherent site factors. The most useful and robust models are those that include many types and scales of data (Ryan et al., 1999). The qualitative and indirect measures are useful because they are easier to obtain and mappable beyond the study boundaries (Chapter 5). Specific soil-site attributes, on the other hand, are more biologically relevant and useful where little prior information is available (Kelting et al., 1999); however, they can be labor intensive, costly, or impractical to collect for quick site assessments, and can greatly restrict the allowable inferences space (Jones, 1994).

To evaluate which specific soil-site measurements are related to changes in productivity we created two additional models based only on our direct, field-measured site variables. The restricted model for RCSI indicated that soil/site quality was a function of prior site index (m), macroporosity at a 50 cm depth, oxidation depth (cm), and total soil carbon (Mg ha^{-1}) in the prominently rooted portion of the profile (Table 7.4). The model explained 62 percent (adjusted r-square) of the variability observed in the data. The restricted model for RCSB was a function of pre-harvest rank, stand density, macroporosity at a 20 cm and 50 cm depth, oxidation depth, and total soil carbon (Table 7.5). The model explained 74 percent (adjusted r-square) of the variability observed in the data. As with the best performing models, the initial condition was the most influential factor in each model by an order of magnitude, and explained over three fourths of the total variability explained by each model.

Table 7.4. Non-qualitative model components representing silvicultural practices, inherent site factors, and disturbance factors to predict change in relative productivity based on site index (RCSI) between rotations on wet pine flats.

Component	Coefficient	Significance	Type II Sums of Squares	
		P value	value	%
Intercept	975.9	< 0.0001		
Site Specific Factors				
Pre-Harvest Site Index (m)	-45.96	< 0.0001	740463	78.3
Soil Carbon (Mg ha^{-1})	2.600	0.0017	92422	9.8
Macro-porosity at 20cm (%)	8.795	0.0060	69393	7.3
Oxidation Depth	0.7672	0.0271	43903	4.6

Table 7.5. Non-qualitative model components representing silvicultural practices, inherent site factors, and disturbance factors to predict change in relative productivity based on stand biomass (RCSB) between rotations on wet pine flats.

Component	Coefficient	Significance	Type II Sums of Squares	
		P value	value	%
Intercept	-564.9			
Site Specific Factors				
Pre-Harvest Rank	1.020	< 0.0001	768235	77.6
Stand density (Trees ha^{-1})	0.1056	0.0014	69418	7.0
Macro-porosity at 50cm (%)	8.060	0.0060	50077	5.1
Oxidation Depth (cm)	-2.019	0.0105	43085	4.3
Macro-porosity at 20cm (%)	4.780	0.0250	32670	3.3
Soil Carbon (Mg ha^{-1})	0.7798	0.0402	27172	2.7

7.3.2. Effect of bedding

The benefits of bedding wet pine flats are well established (Schultz and Wilhite, 1974; Terry and Hughes, 1975; Gent et al., 1983; McKee et al., 1985; Pritchett and Fisher, 1987; Morris and Lowery, 1988; Aust et al., 1995). Bedding enhances microsite drainage, consolidates organic matter, and helps restore desirable levels of certain physical properties such as those affecting the air-water balance in soils. There are cases where some properties such as gas exchange may become limiting to growth rates or survival (Cain, 1978; Wilhite and Jones, 1981; Dulohery et al., 1996; Haywood, 1983; Tiarks, 1983), but in this study the benefits of bedding appear to dominate.

7.3.3. Disturbance factors

One disturbance factor was significant in both the RCSI and RCSB models. Percent of undisturbed soil was significant in the RCSB model. This factor is over 70 percent correlated with factors such as bulk density (negative), harvesting residues and incorporated organic matter (negative), and wet-weather harvesting (negative). Distance to landing was significant in the RCSI model, and could be related to both repeated trafficking, or to the distance to the main drainage ditch. We cannot conclusively say which is true; except that distance to landing is 30 percent correlated to the percent of undisturbed soil (positive), the total amount of harvesting residues (negative), and the log of K_{sat} at the 50 cm depth (negative). Therefore, distance to landing may better capture the essence of disturbance than our visual categories. The number of passes, rut orientations (Greene and Stuart, 1985, Burger et al., 1988; Carter et al., 1999), harvest residues (Hall, 1999), as well as logging operational delays, intensify the disturbance near the landing and are not captured by our rating system.

7.3.4. Inherent site factors

The models selected two inherent site factors: relative elevation within a 30-ha neighborhood and soil order (Mollisol). The pedology causing Mollisol formation among these sites is primarily due to poor drainage leading to the retention of carbon (Stuck, 1982). The Santee soil series (fine, mixed, thermic Typic Argiaquoll) is generally found in broad depressional areas, and differs from the other three soil series represented by this study mainly by its mollic epipedon and slightly coarser textures. Relative elevation is tied to drainage class, which is very influential on the productivity of wet pine flats (Shoulders, 1976; Fisher and Garbett, 1980; Haywood et al., 1990; Hauser et al., 1993). Water tables rose in response to harvesting (Xu et al., 1999; Xu et al., 2002). Relative elevation was not included in the RCSB model because it is 70 percent correlated with properties such as bulk density, porosity, total carbon, and oxidation depth, which were included. Relative elevation was an important factor in a simplified regression model presented in chapter 5.

7.3.5. Site-specific factors

All four models indicate that previous site conditions have the greatest influence on changes in site-soil productivity. Sites with higher initial site index or rank are more likely to have reduced soil-site quality. This is probably due both in part to a statistical effect as well as a biological one. Statistically, sites with the highest initial ranks have a higher probability to decrease in relative productivity, and sites with the lowest ranks have a higher probability to increase. Intuitively, soil physical quality must have a minimum limit, such that poor sites can only be made so bad using conventional operational harvesting methods, even in severely wet conditions. Sites that have high physical quality would have more to lose as a result of trafficking (Scheerer 1994, Aust et al., 1995), and simply bedding these sites will probably not recover certain properties such as structure or clay content (Stone, 1975; Fisher and Binkley, 2000). In chapter 5 we tested this question by eliminating points from the first and fourth quartile and concluded that there was also a biological effect. If true, this result is contrary to a large part of the literature that has shown that higher quality sites are in fact more resilient to disturbance (Burger and Scott, 2001). However, most of the literature has based that conclusion on studies regarding fertility rather than physical properties. On wet pine flats soil-site quality, as reflected by site index, is going to be a function of drainage rather than fertility.

Soil physical factors related to the air-water balance of the soil explained between 3.5 and 13 percent of the variability in the RCSI and RCSB models. As we might expect for sites where the air water balance is important, increases in relative soil-site productivity was positively correlated with macroporosity, and the natural log of saturated hydraulic conductivity. Oxidation depth was negatively correlated with the positive changes in rank, which is counter-intuitive (McKee, 1978; Hook et al, 1987; Kelting, 1999). At age 5 these sites were still experiencing a severe 3-year drought (Eisenbies et al., 2004), which may mean that wetter sites have done relatively better. Wet harvested sites had greater disturbance, which resulted in increased field capacity (Aust et al., 1998), and perhaps resulted in sites with more available water during the drought from ages three to five years because they were more poorly drained. Sites with moderate disturbance were observed to respond significantly better than the other disturbance classes after five years (Chapter 6).

Total soil carbon, or nitrogen, explained between 2.5 and 10 percent of the variability for the models in which it was included. Organic carbon content affects nutrition, water retention, and soil structure (Childs et al., 1986, Fisher and Binkley, 2000). Total carbon was 75 percent correlated with the total rooted volume (positive), relative elevation (positive), harvesting residues (positive), percent bare soil (negative), MSOM (positive), and net nitrogen mineralization (positive).

Stand density is another factor that was significant in the RCSB models, and explained 3-7 percent of the variability depending on the model. Stand density is affected by site quality, and affects tree form (Zedaker et al., 1987). At this point in our stands' development we are beginning to see differentiation between individual sites in terms of stand density. Within the context of our regressions it is difficult to differentiate between its inherent connection with stand biomass, and the effect disturbance has on survival. Stand density is 25 percent correlated with harvesting residues (negative), macroporosity (positive), and distance to landing (negative).

7.3.6. Other important site factors

Kelting et al. (1999) showed that oxidation depth, the least limiting water range, and net nitrification explained more than 60 percent of seedling growth on bioassay plots after 2-years. Net nitrogen mineralization, which was featured in several candidate models, was not included in our "best" models, but it was 55 percent correlated with the effect of bedding, relative elevation, site index, and root utilization. The percent of time within the least limiting water range is an integrative parameter that combines bulk density, water availability, texture, organic matter, and time in the context of conditions favorable for root growth (DaSilva and Kay, 1997; Kelting, 1999). We feel this parameter could have been more useful, but due to the drought we had to rely on a modeling approach for determining its values, which may have reduced its descriptive ability at the sub-stand scale. Root utilization, another factor that was included in several candidate models, was 65% correlated with relative elevation, percent bare soil, harvesting residues, net nitrogen mineralization, total carbon, and prior site index. Xu et al., (2002), who did an earlier assessment of the effects of physical properties on tree growth on these sites, concluded that soil physical properties might be overshadowed by competing vegetation. Hardwood competition was virtually non-existent after 5 years, but we did not evaluate herbaceous competition at this phase of this study.

It is important to restate that change in rank reflects the relative change in productivity between two rotations, and although rank is related, is not specifically addressing growth for this rotation. Modeling the current rotation's growth yields models that include the same site factors, but they assign different significance and relative importance to the regressors. In simple bioassay models, factors such as the relative elevation and bedding effects are the most significant terms. Therefore, although modeling the production of the current rotation can provide information as to which basic soil-site factors are important, it may not give the correct weight of their importance to preserving site productivity compared to the ranking diagnostic, which is insulated from confounded factors such as genetics, silvicultural technology, or climate.

7.3.7. Site preparation and harvesting condition effects on soil-site properties

Bulk density, saturated hydraulic conductivity, total porosity, and macro-porosity have been assessed on bedded and flat-planted sites during several phases of stand management and growth (Burger, 1994; Aust et al., 1998; Xu et al., 2002; Lister et al., 2004). The initial effect of wet harvesting was an approximate increase of 0.20 g cm^{-3} in bulk density, up to a 50% decrease in macro-porosity, and up to a 75% decrease in hydraulic conductivity (Xu et al., 2002). By age 7, bulk density averaged 1.21 g cm^{-1}, saturated hydraulic conductivity averaged 12.6 cm hr^{-1}, total porosity averaged 54 percent, and macro-porosity averaged 16 percent (Table 7.6). Although bulk density was shown to increase significantly on wet-harvested sites immediately after harvesting, bedding restored bulk density nearly to pre-harvest levels (Lister et al., 2004). Flat-planted sites had bulk densities greater than 1.40 g cm^{-3} two years after harvesting on both wet and dry harvested sites due to the drum chopping treatment. By age seven the bulk densities were all within the sufficiency range defined by Pierce et al. (1983). There were no significant differences detected in saturated hydraulic conductivity or macroporosity at age 7, and little apparent difference in these values across time.

Table 7.6. Key soil physical properties associated with wet- and dry weather harvesting on bedded and flat planted sites at four time steps.

Disturbance Category		Pre-Harvest†	Post-Harvest†	Age 2‡	Age 7
			Bulk Density§		
Flat Planted			$g\ cm^{-3}$		
	Dry	1.16 a	1.18 b	1.42	1.23 a
	Wet	1.16 a	1.39 a	1.44	1.23 a
Bedded					
	Dry	1.13 a	1.15 b	1.19	1.10 a
	Wet	1.14 a	1.38 a	1.17	1.28 a
			Saturated Hydraulic Conductivity§		
Flat Planted			$cm\ hr^{-1}$		
	Dry Harvested	15 a	14 a	12	4.5 a
	Wet Harvested	19 a	4.3 b	9.5	9.1 a
Bedded					
	Dry Harvested	6.5 a	6.2 b	19	24 a
	Wet Harvested	9.2 a	3.1 b	24	13 a
			Total Pore Space§		
Flat Planted			%		
	Dry Harvested	54 a	54 a	48	53 a
	Wet Harvested	55 a	49 b	48	54 a
Bedded					
	Dry Harvested	55 a	55 a	58	59 a
	Wet Harvested	54 a	50 b	58	52 a
			Macropores§		
Flat Planted			%		
	Dry Harvested	14 a	14 a	11	14 a
	Wet Harvested	17 a	8.9 b	9.5	14 a
Bedded					
	Dry Harvested	12 a	12 ab	11	13 a
	Wet Harvested	16 a	10 ab	12	15 a

† Pre and post-harvest reported in Xu et al., (2002).
‡ Age 2 interpolated from Lister et al., (2004) as reported in text
§ Least squares means

The analysis in chapter 5 showed that the combination of wet weather harvesting and flat planting resulted in a decrease in relative soil-site productivity in the case of site index but not biomass. Wet harvested-flat planted sites had at least 127 fewer stems per hectare than the other combinations at age 5 (P = 0.0005) (Table 7.7). Total carbon was 10 to 20 Mg ha^{-1} less on these sites (P = 0.0200), and the natural log of saturated hydraulic conductivity was also significantly lower. The only other significant interaction (P=0.0357) was with the S:T ratio in which the dry-harvested-flat planted sites had a ratio of 1.01 m m^{-1} versus 1.05 m m^{-1} on the other sites illustrating the "pseudo-bed" feature.

Table 7.7. Significant interactions† between site preparation and harvesting conditions seven years after planting.

		Stand density	Soil Carbon	ln(Ksat‡)	S:T§
		stems ha^{-1}	Mg ha^{-1}	ln (cm hr^{-1})	m m^{-1}
Flat Planted					
	Dry Harvested	1678 c	55 ab	-2.89 a	1.05 a
	Wet Harvested	1991 a	47 b	-5.37 b	1.01 b
Bedded					
	Dry Harvested	1854 b	56 ab	-2.42 a	1.05 a
	Wet Harvested	1805 b	67 a	-2.77 a	1.05 a

† Least squares means
‡ Saturated hydraulic conductivity
§ Ratio of slope length to transect length across bedding rows

There were no significant differences (alpha = 0.10) between the remaining soil-site properties for the wet or dry harvesting main effect (Table 7.8). There were few significant differences in the remaining soil-site properties for the site preparation main effect (Table 7.9). Bulk density in the lower 50 cm of the planting beds was 0.10 g cm^{-3} higher and total porosity was 4 percent lower (P = 0.0930). Nitrogen mineralization was 27.5 kg ha^{-1} yr^{-1} greater on bedded sites (P = 0.0797). Total soil carbon in the rooted zone layer was 8.8 Mg ha^{-1} higher (P = 0.0987), but was not significantly different for the total profile. Total nitrogen in the rooted zone was 0.52 Mg ha^{-1} greater on the bedded plots (P = 0.0614), and in the total soil volume it was 0.81 Mg ha^{-1} higher (P = 0.0031).

Table 7.8. Comparison of soil properties on wet and dry harvested sites seven years after planting.

Property	Units	Dry Harvested	Wet Harvested
---------------------------------- Soil Physical Properties ----------------------------------			
Bulk Density 50 cm Depth	g cm^{-3}	1.55	1.58
Total Porosity 50 cm Depth	%	42	41
Macro Porosity 50 cm Depth	%	14	14
Saturated Hydraulic Conductivity	cm hr^{-1}	14	11
Least Limiting Water Range (P_{in})	%	71	60
-- Bed Quality --			
Prominent Rooted Volume	m^3 ha^{-1}	882	863
Root Biomass (< 5mm)	Mg ha^{-1}	5.52	3.90
Oxidation Depth	cm	38	35
-------------------------- Carbon, Nitrogen, and Organic Matter --------------------------			
Post-Harvest Residues	Mg ha^{-1}	7.78	7.76
Macro-soil organic matter	Mg ha^{-1}	11.7	10.4
Total Soil C, Profile Volume	Mg ha^{-1}	55.6	57.3
Total Soil N, Profile Volume	Mg ha^{-1}	2.89	3.2
C:N Total Volume		18.7	18.3
Total Soil C, Rooted Zone	Mg ha^{-1}	27.8	27.6
Total Soil N, Rooted Zone	Mg ha^{-1}	1.54	1.58
C:N Rooted		17.8	17.7
Net N Mineralization	kg ha^{-1} yr^{-1}	31.3	30.5

Table 7.9. Comparison of soil properties on bedded and flat planted sites seven years after planting.

Soil-Site Property	Units	Flat Planted	Bedded
---------------------------------- Soil Physical Properties ----------------------------------			
Bulk Density 50 cm Depth	g cm^{-3}	1.61 a	1.51 b
Total Porosity 50 cm Depth	%	39 b	43 a
Macro Porosity 50 cm Depth	%	14	14
Saturated Hydraulic Conductivity	cm hr^{-1}	6.8	18
Least Limiting Water Range (P_{in})	%	62	69
-- Bed Quality --			
Prominent Rooted Volume	m^3 ha^{-1}	805	940
Root Biomass (< 5 mm)	Mg ha^{-1}	4.38	5.04
Oxidation Depth	cm	38	34
------------------------- Carbon, Nitrogen, and Organic Matter -------------------------			
Post-Harvest Residues	Mg ha^{-1}	77.2	78.1
MSOM	Mg ha^{-1}	8.33	13.8
Total Soil C, Profile Volume	Mg ha^{-1}	51.3	61.7
Total Soil Nitrogen, Profile Volume	Mg ha^{-1}	2.64 b	3.45 a
C:N Total Volume		19	18
Total Soil C, Rooted Zone	Mg ha^{-1}	23.3 b	32.1 a
Total Soil N Rooted Zone	Mg ha^{-1}	1.30 b	1.82 a
C:N Rooted		17.8	17.7
Net N Mineralization	kg ha^{-1} yr^{-1}	17.1 b	44.6 a

7.3.8. Soil physical disturbance and harvesting residue effects on soil-site properties

Bulk density, K_{sat}, total porosity, and macro-porosity were also assessed for the levels of soil physical disturbance during several phases of stand management and growth (Burger, 1994; Aust et al., 1998; Lister et al., 2004). We estimated the post-harvest and year 2 values for the physical disturbance categories by calculating a weighted average of the values reported by Aust et al., (1998) and Lister et al., (2004) based on the proportions of the specific disturbances found in each category as reported in chapter 6. Each category represents about one-third of the total study area. Bulk density increased from 1.17 g cm^{-2} by 0.08 to 0.20 g cm^{-3} immediately after harvest, and dropped to a net increase of 0.01 to 0.03 g cm^{-3} two years after planting on the bedded sites (Table 7.10). By age 7, the bulk densities on minimally disturbed sites were less than the pre-harvest level, and only the flat planted-moderate disturbance, and bedded-heavy disturbance combinations were still near the sufficiency limits (Pierce, et al., 1983). Over time, saturated hydraulic conductivities ranged between 2.5 and 48 cm hr^{-1} and macroporosity ranged between 8 and 20 percent, but there were no significant differences detected at age 7.

Table 7.10. Key soil physical properties associated with soil physical disturbances on bedded and flat planted sites at four time steps.

Disturbance Category		Pre-Harvest†	Post-Harvest‡	Age 2§	Age 7
		Bulk Density¶			
Flat Planted		------------------------------ g cm^{-3} ----------------------------			
	Minimal	1.17	1.25	1.42	1.14 b
	Moderate		1.31	1.43	1.31 a
	Heavy		1.42	1.44	1.20 ab
Bedded					
	Minimal	1.17	1.25	1.20	1.07 b
	Moderate		1.31	1.18	1.14 b
	Heavy		1.42	1.17	1.33 a
		Saturated Hydraulic Conductivity¶			
Flat Planted		----------------------------- cm hr^{-1} ------------------------------			
	Minimal	13	9.5	13	5.5 a
	Moderate		7.1	11	41 a
	Heavy		2.5	8.0	11 a
Bedded					
	Minimal	13	9.5	17	26 a
	Moderate		7.1	22	48 a
	Heavy		2.5	26	7.2 a
		Total Pore Space¶			
Flat Planted		------------------------------ % ------------------------------			
	Minimal	53	51	48	57 a
	Moderate		50	48	51 b
	Heavy		49	48	55 ab
Bedded					
	Minimal	53	51	58	60 a
	Moderate		50	58	57 a
	Heavy		49	58	50 b
		Macropores¶			
Flat Planted		------------------------------ % ------------------------------			
	Minimal	14	14	11	12 a
	Moderate		12	10	13 a
	Heavy		8	9.0	15 a
Bedded					
	Minimal	14	14	11	16 a
	Moderate		12	12	20 a
	Heavy		8	12	18 a

† Preharvest values from Burger (1994b)
‡ Post harvest interpolated from Aust et al., (1998) as indicated in text
§ Age 2 interpolated from Lister et al., (2004) as indicated in text
¶ Least squares means

Net nitrogen mineralization dropped 68 percent between ages 2 and 7 on flat-planted sites, and 50 percent on bedded sites (Table 7.11). Net nitrogen mineralization was significantly higher on the bedded plots versus the flat-planted plots at age 7 ($P = 0.0719$), which is commonly known as the assart effect (Messier and Kimmins, 1990). The removal of trees by harvesting results in increased surface organic matter, increased water availability, and higher soil temperatures, which in turn increase mineralization rates for nutrients such as nitrogen (Prichett and Fisher, 1979). There were no significant differences in nitrogen mineralization differences between the physical disturbance classes within each site preparation. The S:T ratio of the heavily disturbed-flat planted sites was equivalent to the bedded sites, but there was no equivalent increase in nitrogen mineralization rates (Table 7.12). Thus, the pseudo-beds provide some benefits of bedding, but do not provide a nutritional benefit. However, stand density on the moderate to heavily disturbed flat-planted sites was 50 to 75 stems ha^{-1} higher than the original planting density indicating the presence of volunteers. Being a pioneer species, loblolly pine is adapted to colonize scarified soil (Schultz, 1997).

There were few significant differences between the remaining soil-site properties for the soil physical disturbance (Table 7.12). Bulk density in the upper 20 cm was 0.14 g cm^{-1} lower on the minimally disturbed sites. There were also few significant differences between the soil-site properties for the harvesting residue classes (Table 7.13). Harvesting residues were significantly higher on the Class I category by definition ($P = 0.0425$). Despite the greater quantity of organic matter, total nitrogen and the nitrogen mineralization rates were not affected by it. Organic matter should be related to nutrition (Shultz, 1997), which may speak to the quality of this organic matter for providing nitrogen. The C:N ratio for the profile volume was 20:1 on the Class I sites versus 18:1 on the Class II and III sites ($P = 0.0014$). Pine root biomass (< 5 mm) was greatest on the Class III sites ($P = 0.0141$).

Table 7.11. Significant interactions between site preparation and soil physical disturbances.

	Net Nitrogen Mineralization†		Stand density†	S:T†
	Age 2‡	Age 7	Age 5	Age 7
	------------- $kg\ ha^{-1}\ yr^{-1}$ -----------		$stems\ ha^{-1}$	$m\ m^{-1}$
Flat Planted				
Minimal	47	16 c	1892 a	1.05 a
Moderate	52	16 c	1830 ab	1.05 a
Heavy	68	19 c	1718 b	1.05 a
Bedded				
Minimal	109	49 a	1718 b	1.01 b
Moderate	88	43 a	1919 a	1.02 b
Heavy	62	39 a	1931 a	1.06 a

† Least squares means

‡ Age 2 interpolated from Lister et al., (2004) as indicated in text.

Table 7.12. Comparison of soil properties for sites with three levels of soil physical disturbance seven years after planting.

Property	Units	Minimal	Moderate	Heavy
Bulk Density 20 cm Depth	g cm^{-3}	1.11 b	1.23 a	1.27 a
Total Porosity 20 cm Depth	%	58 a	54 b	52 b
Macro Porosity 20 cm Depth	%	14	16	16
Saturated Hydraulic Conductivity b20	cm hr^{-1}	44	16	8.9
lnKsat b20	ln(cm hr^{-1})	2.22	1.93	1.56
Bulk Density 50 cm Depth	g cm^{-3}	1.55	1.54	1.58
Total Porosity 50 cm Depth	%	42	42	40
Macro Porosity 50 cm Depth	%	14	12	14
Saturated Hydraulic Conductivity b20	cm hr^{-1}	0.26	5.8	3.3
Ln ksat B50	ln(cm hr^{-1})	-3.99	-4.96	-3.86
Least Limiting Water Range (P_{in})	%	80	64	61
Prominent Rooted Volume	m^3 ha^{-1}	846	801	855
Root Biomass (< 5mm)	Mg ha^{-1}	4.72	4.06	4.44
Oxidation Depth	cm	40	37	32
Post-Harvest Residues	Mg ha^{-1}	88.4	87.0	71.2
MSOM	Mg ha^{-1}	10.9	10.7	12.2
Total Soil C, Profile Volume	Mg ha^{-1}	55.1	55.1	54.0
Total Soil N, Profile Volume	Mg ha^{-1}	2.76	3.09	2.99
C:N Total Volume		19	18	18
Total Soil C, Rooted Zone	Mg ha^{-1}	28.6	27.1	27.4
Total Soil N, Rooted Zone	Mg ha^{-1}	1.55	1.56	1.56
C:N Rooted		18	18	18
Net N Mineralization	kg ha^{-1} yr^{-1}	32.1	29.3	29.4

Table 7.13. Comparison of soil properties for sites with three levels of harvesting residues seven years after planting. Letters indicate significant differences within row only.

Property	Units	Class I	Class II	Class III
Bulk Density 20 cm Depth	g cm^{-3}	1.19	1.22	1.29
Total Porosity 20 cm Depth	%	55	54	51
Macro Porosity 20 cm Depth	%	15	15	18
Saturated Hydraulic Conductivity b20	cm hr^{-1}	23	21	8.3
lnKsat b20	ln(cm $hr^{-1)}$	2.22	1.19	1.50
Bulk Density 50 cm Depth	g cm^{-3}	1.62	1.53	1.55
Total Porosity 50 cm Depth	%	39	42	42
Macro Porosity 50 cm Depth	%	14	14	14
Saturated Hydraulic Conductivity b20	cm hr^{-1}	0.38	0.15	4.6
Ln ksat B50	ln(cm $hr^{-1)}$	-4.00	-5.07	-1.74
Least Limiting Water Range (P_{in})	%	64	62	65
Stand density	trees ha^{-1}	1770	1786	1718
S:T	m m^{-1}	1.04	1.04	1.05
Prominent Rooted Volume	m^3 ha^{-1}	862	822	890
Root Biomass (< 5 mm)	Mg ha^{-1}	3.97 b	3.66 b	5.63 a
Oxidation Depth	cm	39	35	33
Post-Harvest Residues	Mg ha^{-1}	107 a	69.0 b	57.3 b
MSOM	Mg ha^{-1}	12.4	9.89	12.0
Total Soil C, Profile Volume	Mg ha^{-1}	58.1	58.7	49.2
Total Soil N, Profile Volume	Mg ha^{-1}	2.95	3.32	2.78
C:N Total Volume		20 a	18 b	18 b
Total Soil C, Rooted Zone	Mg ha^{-1}	28.5	27.5	27.0
Total Soil N, Rooted Zone	Mg ha^{-1}	1.52	1.61	1.55
C:N Rooted		18	17	18
Net N Mineralization	kg ha^{-1} yr^{-1}	29.7	30.9	34.9

7.3.9. Summary of soil-site properties

Differences in soil properties, when present, are generally subtle as the stands approach closure. Bedding appears to have the greatest effect on soil-site properties; in particular total soil carbon and nitrogen, nitrogen mineralization rates, bulk density and porosity. There were very few differences between the harvesting conditions, soil physical disturbance categories, and harvesting residue categories. Although properties such as bulk density have not yet reached initial conditions, they were lower than the post-harvest conditions and well below the 1.35 g cm^{-3} sufficiency threshold defined by Pierce et al. (1983) and Kelting et al. (1999). All other properties appear to be within ranges acceptable for loblolly production. Wet pine flats appear to be very resilient to harvesting disturbance in terms of soil properties.

7.4. Conclusions

After 7 years, soil physical properties were within acceptable ranges for loblolly pine growth. Bulk density in the surface horizons increased by as much as 21 percent after harvesting, but by age 7 years had returned to within 11 percent of pre-harvest conditions. Nitrogen mineralization rates on bedded plots were 2 1/2 times that of flat-planted plots. Oxidation depth indicated that soil site productivity was positively correlated to wetter sites. At the sub-stand scale (0.008 ha scale) drainage effects favor sites that have more water available in light of the drought. There were few other significant differences among soil-site properties.

Changes in soil-site productivity on wet pine flats are a function of silvicultural practices, inherent site properties, and disturbance. The most important factors affecting changes in soil-site quality are primarily a reflection of drainage. Prior site quality and bedding were the most influential variables. Individual site-specific soil properties and disturbance explain little about observed changes in productivity. Soil physical properties and organic matter quality and quantity are twice removed from tree growth; they influence properties that influence tree growth, but alone they do not explain enough through the noise of environmental heterogeneity. This fact may be why the direct link between site disturbance and productivity has been so hard to make in site sustainability studies. Site-specific quantitative properties are also highly correlated and interchangeable with qualitative landscape features. Quantitative data has its utility in establishing biological significance. Qualitative data has its utility in extending results to areas outside of a study area. It is important to include both types of data in models, and where possible establish which properties are interrelated so that we can understand both the critical soil factors controlling forest productivity as well as relate these factors to other sites using more readily available information.

CHAPTER 8

Project Summary

8.1. Introduction

8.1.1. Purpose

The purpose of this chapter is to review the body of work conducted on this site prior to this dissertation in order to provide context and reinforce key conclusions.

8.1.2. Prospectus

Scientists from Virginia Tech, Mead-Westvaco, and the USDA Forest Service established a cooperative project near Charleston, SC, in 1991 to evaluate the long-term sustainability of intensive forestry management practices. Funding from the National Council of Air and Stream Improvement Inc. (NCASI), Mead-Westvaco Corporation, USDA Forest Service, and the U.S. Department of Energy has supported this project. The purpose of this project was to conduct a rotation-length scientific study on wetland pine plantations to evaluate the long-term sustainability concerns associated with intensive forest management and its effect on soil-site quality. Three 20-ha loblolly pine plantations on wet pine flats in South Carolina were subjected to a wide gradient of soil physical disturbance, organic matter manipulation, and five site preparation treatments under operationally realistic conditions. The disturbances associated with harvesting, as well as the efficacy of standard site preparation in the remediation of soil and hydrologic function, was studied. Cause and effect relationships among forest management practices, soil productivity, wetland functions, and carbon sequestration were determined at the process level new field-based methods for evaluating the long-term effects of harvesting disturbance were developed. The results fill critical knowledge gaps in management guidelines and best management practices for protecting the long-term productivity of wet pine flat forests in the southeastern Unites States.

The study was divided into five phases of stand development (Figure 8.1). In the first funding cycle, covering the preharvest and stand establishment phases, the project supported two Ph.D. dissertations, and four M.S. thesis projects. The second funding cycle began in 2000 by NCASI and Mead-Westvaco Corporation to continue the research during the stand closure phase of forest development; this phase supported one Ph.D. project through May 2004.

8.2. Summary of prior research

Integrated conclusions from the first two project phases were summarized in a project report submitted to the National Council of Air and Stream Improvement Inc. (NCASI) in March, 2001 (Burger and Xu, 2001). The stated combined objectives of these phases of research were divided into basic research objectives and operational objectives (Table 8.1). There were three main objectives of the stand closure phase were to: (1) investigate if logging disturbances affect soil quality, hydrologic function, and forest productivity, (2) investigate whether and how forestry practices mitigate disturbance effects, and (3) investigate the effect of scale on interpretations of objectives 1 and 2.

Table 8.1. Stated research objectives of the first two project phases.

Basic research objectives
(1) Identify the determinants of soil, site, and forest productivity for Atlantic Coastal Plain wetland soils (i.e., decomposition, nutrient supply, and site hydrology) and determine the conditions under which intensive forest management enhances, maintains, or damages long-term soil productivity.
(2) Determine if wetland functions such as soil productivity and site drainage can be restored, if damaged, and at what rate of recovery.
(3) Determine the role of subordinate vegetation on soil quality, nutrient cycling, and recovery of disturbed soils.
(4) Determine how intensive forest management affects stand carbon cycling of a forest rotation.
Operational objectives
(1) Develop soil disturbance hazard ratings for trafficking soils based on their strength, moisture content, and depth to water table.
(2) Develop a decision support system that predicts the influence of management, both spatially and temporally, on pine yields based on soil, hydrology, and tree growth processes.
(3) Determine the effectiveness and assess the appropriateness of current BMP's in the context of sustainable forestry.

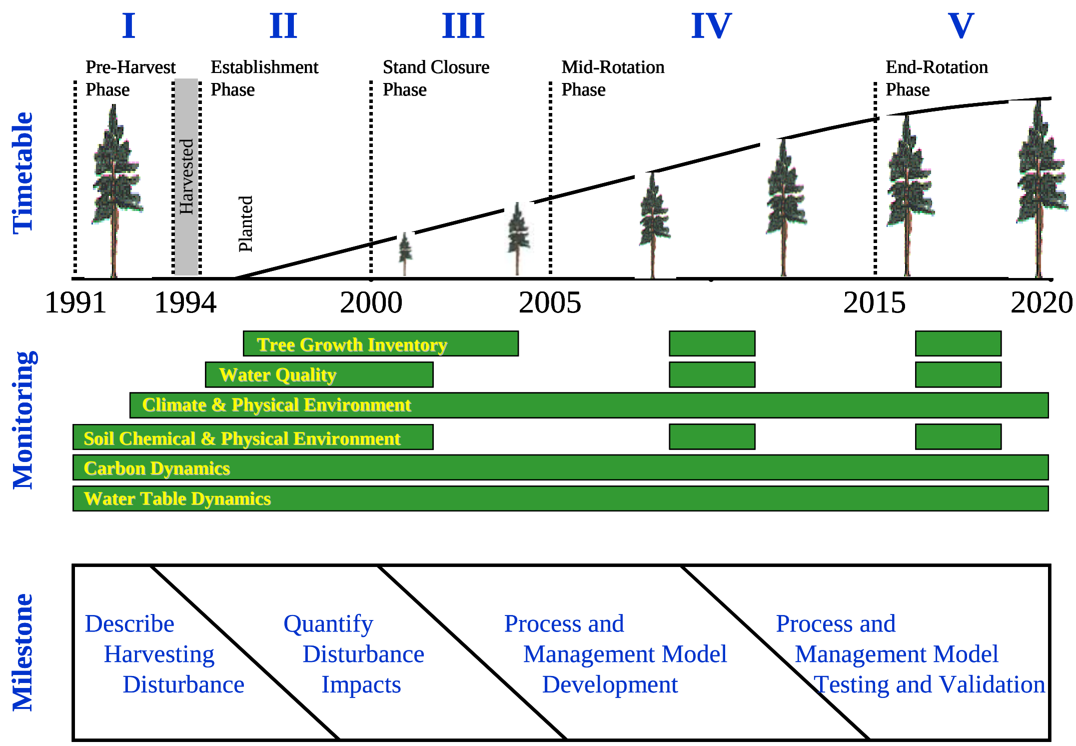

Figure 8.1. Five phases of stand development and research activities for the Horseshoe long-term productivity study.

8.2.1. Initial site conditions

Each of the three blocks had similar initial stand, soil, and hydrologic conditions (Burger and Xu, 2001). The predominant soil series was the Argent loam. Soils had variable depths: ranging between 0 and 51 cm for the A horizons (13-cm average), and 0 to 81 cm (15-cm average) for the E horizons. The median bulk density for the surface horizons was 1.10 g cm^{-3} (0.68-1.67 g cm^{-3}) and the median hydraulic conductivity was 0.175 cm hr^{-1} (0.00-23.67 cm hr^{-1}). The median bulk density for the argillic horizon was 1.15 g cm^{-3} (1.20-1.87 g cm^{-3}) and the median hydraulic conductivity was 0.00 cm hr^{-1} (0.00 - 7.09 cm hr^{-1}). Average water table depths during winter months ranged between 6 and 10 cm of the surface, and during the summer months ranged between 48 and 57 cm.

8.2.2. Trafficability and soil disturbance

Vehicle traffic during timber harvesting can cause different degrees of soil physical and residue disturbances. Wet-weather harvesting caused a greater degree of physical disturbance (Preston, 1996; Eisenbies, 2004), but had less displacement of harvesting residues toward the logging decks (Eisenbies et al., 2002). Soil physical disturbance was limited to 9 percent of the total area on dry-weather harvested sites, while wet-weather harvested sites were 60 percent disturbed (Table 8.2). Soil physical disturbance as quantified by Preston (1996) were based on the composite scores outlined in chapter 3 and tended to over-estimate total soil disturbance. In addition, because the composite score was rounded, it also lumped disturbance of an entire subplot into a single category. Eisenbies et al. (2004) based their soil disturbance figures on the representation of each disturbance category at the subplot level, and thus represented the actual levels of each disturbance class on the sites.

Table 8.2. Inventory of soil physical disturbance associated with wet- and dry-weather harvesting.

Class	Dry Harvest	Wet Harvest
	-------------- Percent --------------	
Undisturbed	91	41
Compressed	9	14
Shallow Rutted	0	14
Deep Rutted	0	13
Churned	0	18

Table 8.3. Harvesting residue biomass and percent bare soil associated with wet- and dry-weather harvesting. Numbers followed by an * indicate a significant difference between wet- and dry-harvesting conditions. Multiply by 10 to get Mg ha^{-1}.

Class	Dry Harvest	Wet Harvest
	--------------------kg m^{-2}---------------	
Piles (Heavy Slash > 30-cm deep)	0.16	0.16
Heavy Slash (> 2.54-cm diameter)	1.89*	2.49
Light Slash (< 2.54-cm diameter)	1.99*	2.47
Litter	2.36	2.50
Total Harvest Residue Biomass	6.40	7.62
	---------------------- % -----------------	
Percent Bare Soil	16	9

Soil physical disturbance was mainly evident in the mixing the A, E, and B horizons (Miwa, 1999). Clay content near the surface was 3 to 5 percent higher where rutting or churning occurred (Kelting, 1999) due to mixing with the clayier subsoil. Wet sites had some degree of physical disturbance on 60 percent of the area. Dry sites were 91 percent undisturbed. On the wet-harvested sites, saturated hydraulic conductivity, macroporosity, and total porosity decreased 72, 44, and 8 percent respectively, and bulk density increased 19 percent (Xu et al., 2000). The same variables on the dry-harvested sites were decreased 6, 3, 1, and increased 2 percent, respectively.

Soil strength increased exponentially with decreasing moisture content, and was the main soil property affecting the susceptibility of soils to physical disturbance (Burger, 1994). Harvesting risk was minimized when moisture contents were below 25 percent

(Figure 8.2). At this point soils were strong enough to support vehicle ground pressures of 1200 kPa or more. Water contents in the upper 15 cm were rarely below the 1200 kPA threshold in the months prior to harvesting, except for a single observation at a depth of 15-50 cm (Burger, 1994b). During stand establishment water contents were below this threshold less than 20 percent of the year on some sites (Kelting, 1999), causing concern regarding trafficking that occurs during site preparation under these same conditions.

Machine types and operator experience played a role in the degree of physical disturbance as well; loggers varied their behavior depending on harvesting conditions. In wet weather conditions, trees were topped as they were felled, causing more residues, (particularly slash) to be left out on the site. In dry conditions, loggers skidded the trees to limb-removing gates located near the landing. The sweeping action of the crowns caused about twice as much bare soil to be exposed prior to site preparation compared to wet-weather harvesting (Eisenbies et al., 2002).

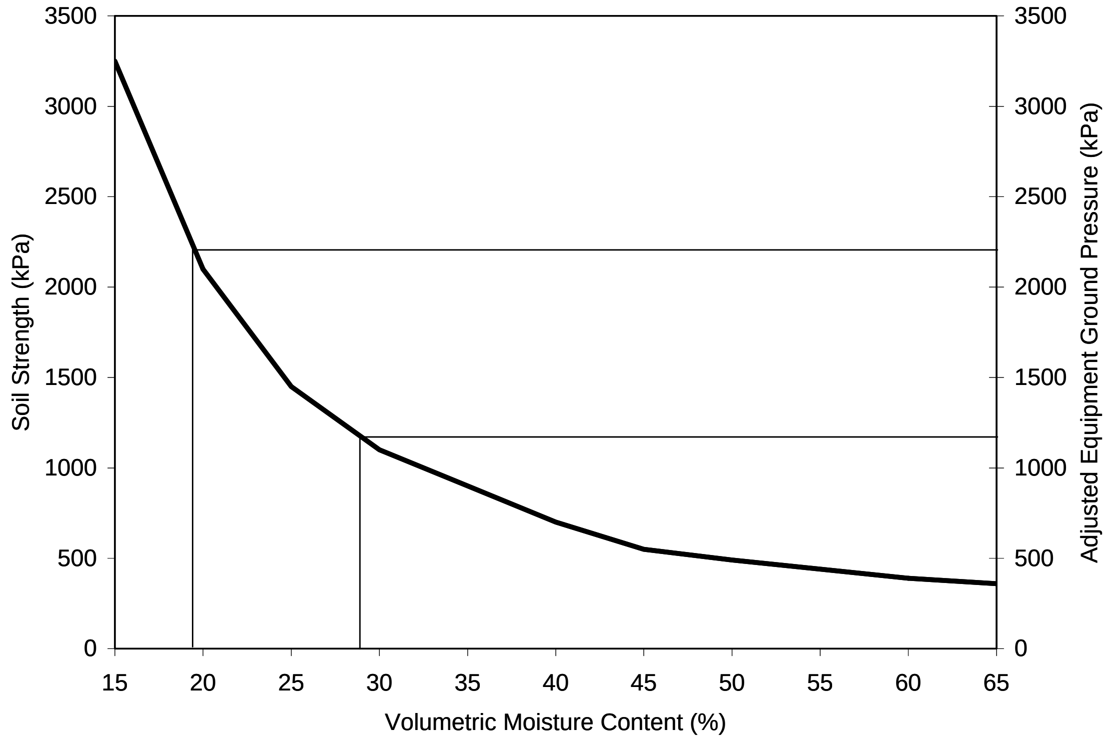

Figure 8.2. Trafficability as a function of soil water content.

8.2.3. Hydrologic responses

Harvesting

Throughout the year the water table fluctuated from above the surface to below the top of the argillic horizon. During the first several years of the project, water tables were generally highest between December and March (< 35 cm) and lowest from April to May (> 65 cm) (Burger and Xu, 2001). From age 3 to 6 (1999-2002) a severe drought affected the area and water tables were frequently immeasurable. Precipitation during this period was 50 to 60 percent of the 20-year average, and less than 50 percent during the first 4 months of the growing season (Eisenbies et al., 2004).

Evapotranspiration was a driving hydrologic force when there was no surface drainage, and accounted for 70 percent of the water leaving the site (Burger and Xu, 2001). The removal of pine trees after harvesting increased the surface water table to about 40 cm above the argillic horizon during the growing season (Table 8.4). Initially, wet-harvested sites had higher water tables than the dry-harvested sites, but after site preparation there was almost no difference. Differences at the operational scale were more likely due to a suppression of non-crop vegetation rather than an alteration of soil physical and hydrologic properties. The effect of wet-weather harvesting was more prevalent at the stand-scale (0.04 ha). Wet-harvested sites were subject to a greater degree of spatial heterogeneity with regards to hydrologic conditions, which may result in long-term effects on productivity according to previous studies (Burger and Xu, 2001). However, based on this dissertation, drainage indicators seem to be the driving force affecting changes in soil-site productivity as defined by the rank change diagnostic. As of age 7 no effects on water tables were detected at the stand and operational scale.

Table 8.4. Elevation in surface water table depths compared to uncut control references as affected by harvesting and site preparation treatments. Letters indicate significant differences within columns at the alpha = 0.05 level.

Treatment	Elevation in Water Table Depths			
	Post Harvest	Post Site Preparation	Year 1	Year 2
	---------------------------------- cm ----------------------------------			
Dry Harvested	14 b			
Flat planted		43 a	28 b	14 ab
Bedded		28 b	25 b	13 a
Wet-Harvested	21 a			
Flat Planted		45 a	36 a	21 a
Bedded		27 b	28 b	16 ab
Mole-Plow/Bedded		27 b	30 b	18 ab

Site Preparation

Both conventional bedding and bedding combined with mole-plowing, resulted in an approximate 15-18 cm decrease in water table elevation (Burger and Xu, 2001). During the dormant season there were almost no difference between treatments in the first two years of growth. By age 2 there were virtually no remaining differences in average water table depths between any of the five treatments. The principle difference between bedding and flat planting was that water was retained between in the inter-beds on the bedded plots after rainfall. There was a greater amount of aerated soil for pine seedling establishment in the mounds. However, standing water was present in the furrows on the bedded sites for a longer period during the year than in the flat-planted sites.

8.2.4. Early pine growth

Several early studies associated with this project have examined pine growth in response to soil disturbance and site preparation. Siegel-Issem (2002) performed a greenhouse study evaluating the growth of loblolly pine seedlings in Argent soils for a range of soil compaction and water content in constructed soil cores. Tree growth was compared to the root growth window as predicted by the least limiting water range (LLWR)(DaSilva and Kay, 1994). Loblolly root growth in the constructed cores did not follow the pattern predicted by the LLWR after one year. Root growth was greatest in the more compacted cores, as was available water.

Significant differences in second year tree growth among the undisturbed, compressed and shallow rutted areas were not found within 5 treatments at the operational scale (Burger and Xu, 2001). Pine growth was 30 percent greater on the rutted and churned areas compared to the other disturbance levels on the flat planted sites, but was lower on the bedded sites (Table 8.5). Above ground pine biomass on bedded sites was 2 to 4 times that of the flat-planted sites. At the disturbance scale (0.001 ha), there were also no significant differences in pine growth on dense (30 x 30 cm) bioassay plots among the various levels of soil disturbance (Kelting, 1999).

Table 8.5. Early pine growth responses to harvest-induced soil disturbances on flat planted, bedded, and mole-plow bedded (MPB) sites at a 2 x 3 m spacing.

Disturbance Class†	Height			DBH			Aboveground Biomass		
	Flat	Bed	MPB	Flat	Bed	MPB	Flat	Bed	MPB
	cm						g Tree^{-1}		
SD1	138 a	192 a	216 a	1.1 ab	1.7 a	1.9 a	238 b	634 a	857 a
SD2	130 a	200 a	209 a	1.0 b	1.8 a	1.9 a	228 b	693 a	839 a
SD3	127 a	187 ab	210 a	1.1 ab	1.6 a	1.9 a	246 b	602 a	852 a
SD4	141 a	168 b	185 b	1.2 a	11.5 a	1.7 b	320 a	526 a	678 b

† Disturbance classes based on visual survey: SD1 = undisturbed, SD2 = Compressed; SD3 = shallow rutted (< 20 cm), SD4 = deep rutting (> 20 cm)

‡ Means separations for within column only.

By age 5, there were virtually no significant differences between the disturbance categories using the rank diagnostic (Table 8.6 and Figure 8.3). In fact, there was some evidence that moderate disturbance was beneficial to tree growth on bedded sites. Excessive disturbance appeared to diminish bedding quality, and lower production relative to the other bedded sites. Wet-weather harvesting may have negatively impacted sites that were to be flat planted at the operational scale; however, bedding fully mitigated potential wet-weather harvesting disturbances relative to the operational norm. The results of the fifth-year pine response to harvesting and site preparation strongly imply that soil disturbance will not have a long-term effect on pine growth as long as sites are bedded, provided that the response of the three bedded treatments do not diverge at this point.

Table 8.6. Comparison of total green weight biomass per hectare associated with each treatment combination. Letters indicate significant differences within age class only.

Treatment	Total Green Weight Biomass Year 2	Year 5
	--------------------Mg ha^{-1}-----------------	
Wet Harvested - Mole Plow	1.21 a	45.1 a
Wet Harvested - Bedded	0.951 a	40.6 a
Dry Harvested - Bedded	0.797 a	33.8 b
Dry Harvested - Flat Planted	0.300 b	24.5 c
Wet Harvested - Flat Planted	0.221 b	22.3 c

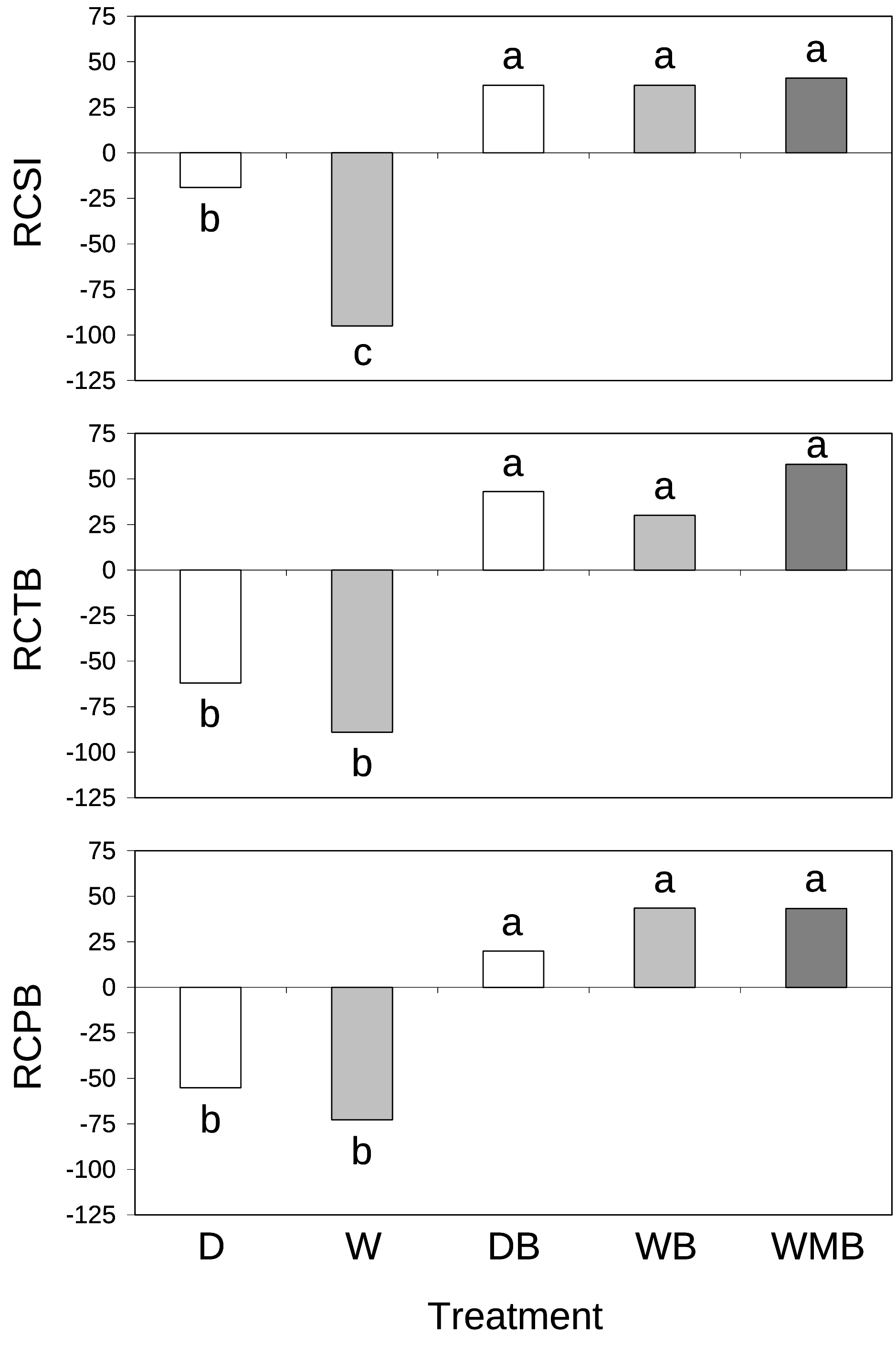

Figure 8.3. Relative change in soil-site productivity between rotations for five combinations of harvesting and site preparation treatments as reflected by the change in rank based on site index (RCSI) and biomass (RCTB and RCSB). Letters indicate Fisher's least significant differences for each series at the alpha = 0.05 level, and using prior rank as a covariate.

8.2.5. Non-Crop Vegetation

Several hardwood species were present in the understory prior to harvest: sweetgum (*Liquidambar styrasciflua*), winged elm (*Ulmus alata* Michx.), ash species (*Fraxinus spp.*), and oak species (*Quercus spp.*). In terms of biomass, soft rush (*Juncus effusus*) was the most prevalent non-crop vegetation type after harvesting. Bedding and disturbance controlled the reestablishment of hardwood species. In undisturbed areas, 50 percent of the non-crop biomass on flat-planted sites was a hardwood species component (Figure 8.4).

Non-crop vegetation that established on the sites after harvesting included obligate wetland, facultative wetland, facultative, and obligate upland species (Burger and Xu, 2001). The wetland prevalence index (Corps of Engineers, 1987) decreased from 3.03 to 2.39 as a result of harvesting, but no significant differences were found among the physical disturbance categories, site preparations, or within a vegetation control study after harvesting (Figure 8.5) (Lister et al., 2004). Facultative wetland species were the primary non-crop vegetation in all disturbance types on average (Figure 8.6). Rutted and churned sites favored the establishment of obligate wetland species, but tended to have no especially dominant species type. Non-crop vegetation served several ecosystem functions during stand establishment (Lister, 1999). Non-crop vegetation sequestered 74 percent of the nitrogen mineralized, compared to 59 percent on the operational, and 13 percent on the plots with total vegetation control.

8.2.6. Carbon Sequestration and Change

Total carbon amounted to over 200 Mg C ha^{-1}, and 60 percent was stored as pine biomass (Figure 8.7) (Burger and Xu, 2001). Logging practices and site preparation manipulated carbon pools after harvesting. About 70 Mg ha^{-1} of residues could persist as a potential carbon sink if harvesting was managed properly.

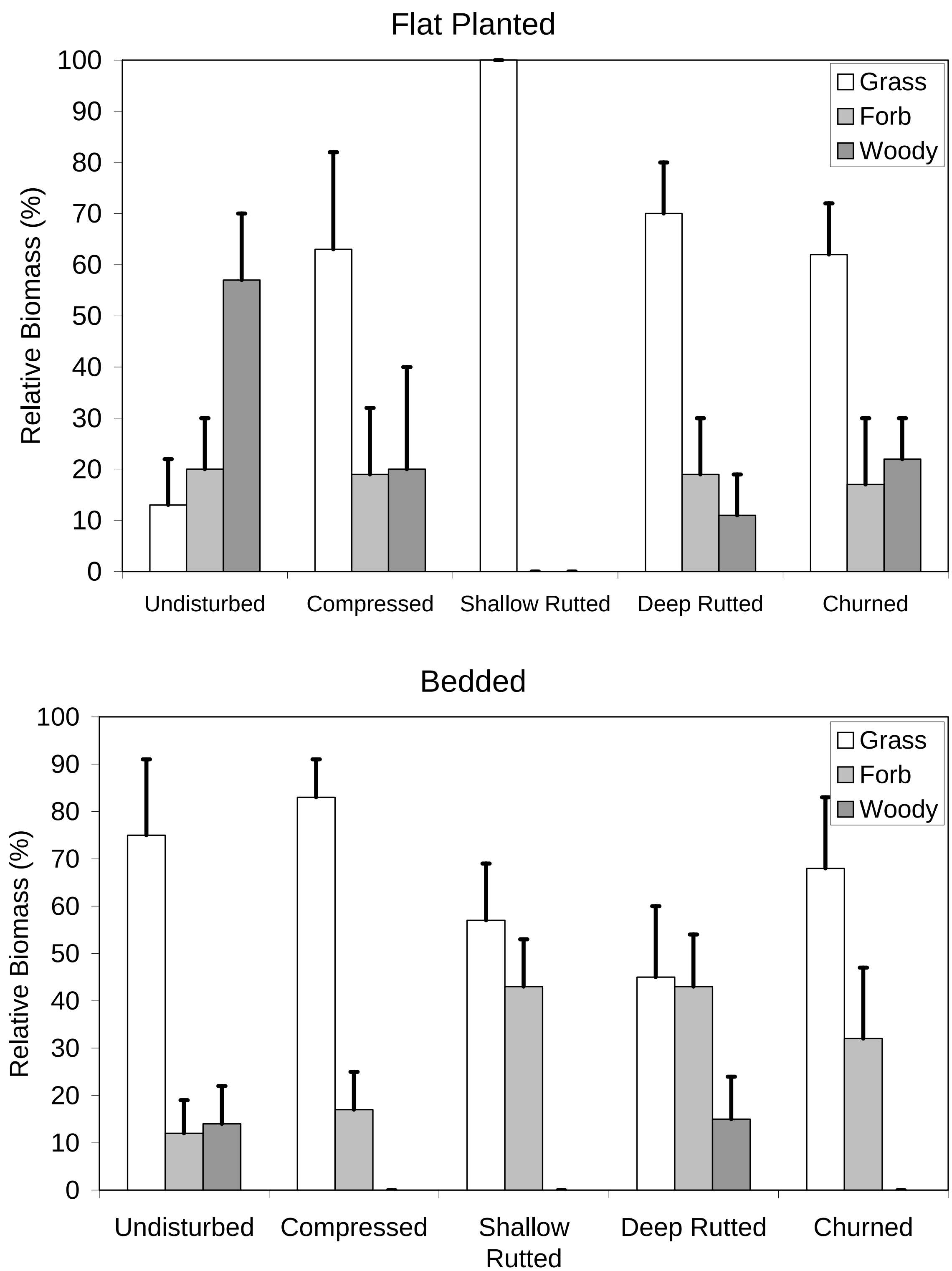

Figure 8.4. Effects of soil disturbance and site preparation on non-crop vegetation.

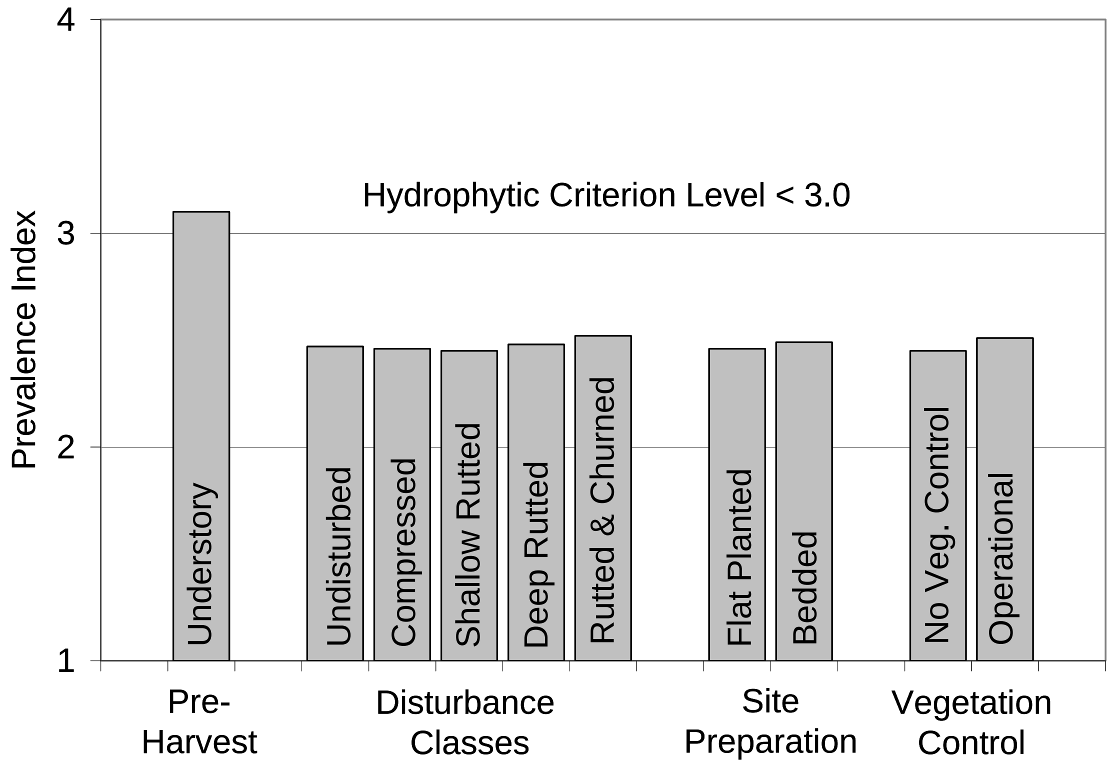

Figure 8.5. Changes in prevalence index of hydrophytic vegetation.

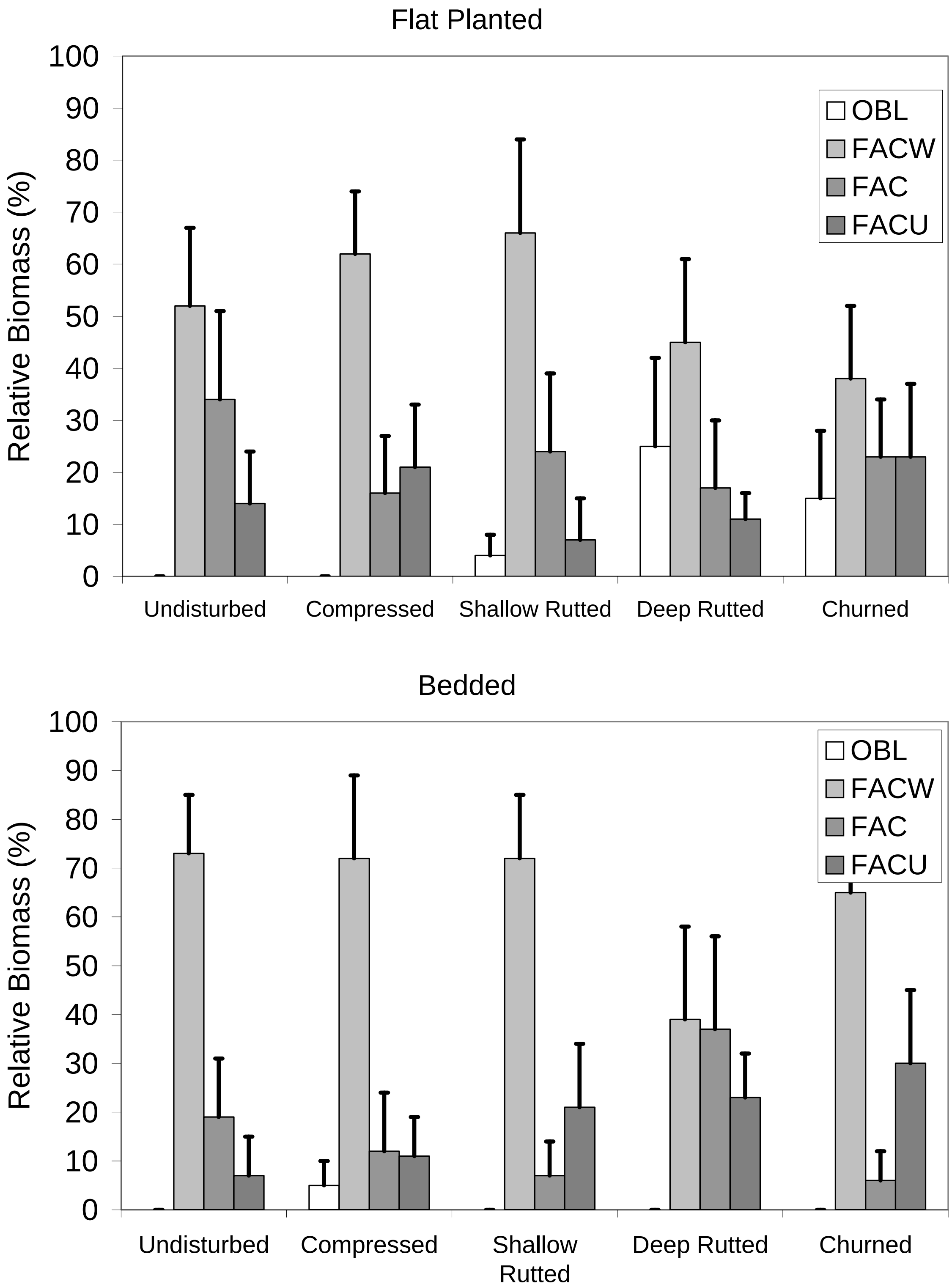

Figure 8.6. Effects of soil disturbance and site preparation on wetland classification groups for dominant species.

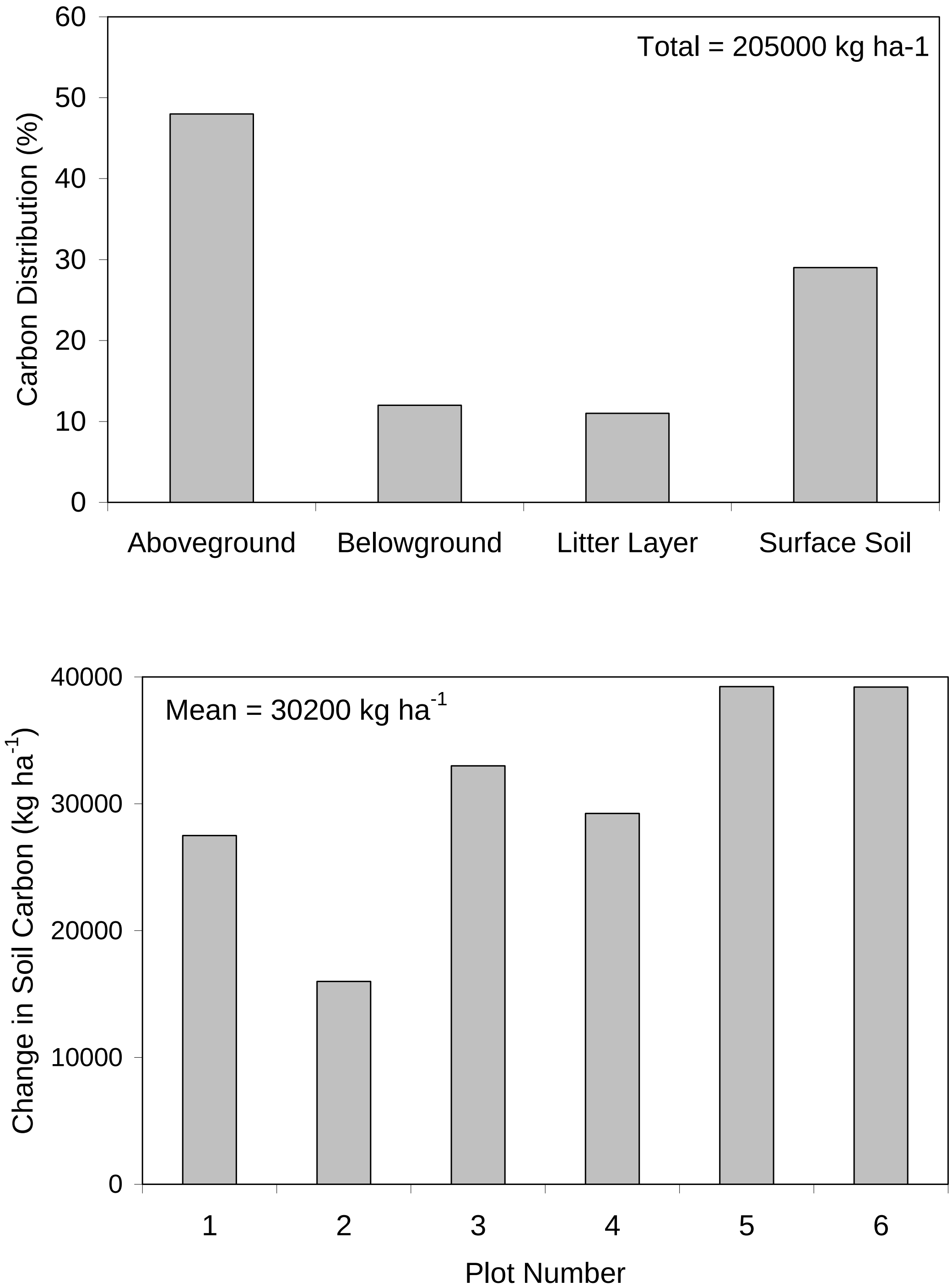

Figure 8.7. System carbon distribution (top) and changes in soil carbon following harvesting and site preparation (bottom).

8.2.7. Evaluating Soil Quality

Evaluating site quality is an on-going art and science. The development of new ways for modeling changes in soil-site quality associated with management has two fundamental purposes: (1) to understand the underlying soil functions and plant-soil interactions affecting biomass production, and (2) to provide a practical means to apply research results to operational systems.

Kelting (1999) developed a Soil Quality Index (SQI) model using densely planted (30 cm x 30 cm) bioassay plots that scored disturbed sites based on indicators of (1) the root growth environment, (2) the ideal air-water balance, and (3) soil fertility. Sufficiency levels of oxidation depth, the LLWR, and net nitrification were determined for 54 bioassay plots representing a gradient of soil physical disturbances on bedded and flat planted sites. After two years results indicated that SQI was reduced on soils that received compaction and deep rutting, and that the retention of organic matter tended to increase SQI. Pine growth was 73 percent correlated with the SQI scores.

When applied to stand-scale (0.008 ha) data the SQI model did not show the disturbance effect on aboveground productivity. Disturbance occurs as a mosaic on these sites (Chapter 6), so it is difficult to scale up the results developed for specific levels of disturbance. The SQI model could be further developed using data from later ages, but would assume that the factors that are limiting at age 2 are also limiting at later stages of growth. The advantage of an SQI approach is that sites can be evaluated on disturbed sites, or where prior information is not available, using information that is biologically relevant. The SQI approaches appear to do an acceptable job of estimating soil quality as a function of disturbance.

The disadvantage of SQI approaches are that determining some of the sufficiency scores are not necessarily quick, inexpensive, or easy to obtain. All three of the specific soil-site factors identified by Kelting (1999) require a minimum of one year to measure. Chapter 5 and 7 of this volume described 80 percent of the change in site quality using both site-specific factors and more general site attributes obtained at different scales.

Fifty to sixty percent of the changes in soil-site quality were explained using only the most general information.

Site-specific information provides biological context. Models based on more general information allow some generalizations to be drawn about sites where specific soil-site measurements have not been obtained. However, the factors used are often interrelated and highly correlated such that the relationship between the parameters is not always clear. Including a model component, or suite of components, may result in the exclusion of other components during model selection. The selection of components used in a model was dictated by the use of the model, but the best performing model included all types of information. Huh?

8.2.8. Changes in Soil-Site Quality

This volume describes a new field method for evaluating changes in soil-site quality due to treatment effects. Based on the rank diagnostic for site index, wet harvesting may have a negative impact on soil-site quality on flat-planted sites at the operational scale; however, it will still take a full rotation to determine if this effect is permanent as treatments may converge due to the autoremediative qualities of these sites. Regardless of the interpretations with regards to flat planting, the study results also showed that bedding fully mitigated any potential negative effects relative to the operational norm.

At the stand scale, change in soil-site quality based on the rank diagnostic could be 70 to 80 percent explained by management, disturbance, and inherent site factors. Of the total variability explained by the model, 75 to 90 percent of the change in soil-site quality is related to initial site quality and factors that represent site drainage. Disturbance and specific soil-site quality indicators explain the remaining 10 to 25 percent.

8.2.9. Harvesting Risks

Even when site-specific soil quality indicators are not available, management, disturbance, and inherent site-factors gleaned from remotely sensed data could still explain 50 to 60 percent of the change in soil site quality based on the rank diagnostic. Using this information, risk assessments can be determined for a neighborhood of sites residing outside the research boundaries. Risk can be mapped based on the amount and quality of information available to the land manager.

8.3. Management implications

8.3.1. Contrasting with phase I and II conclusions

Based on the initial phases of research, Burger and Xu (2001) drew several conclusions about the implications of these results toward the management of intensively managed forests on wet pine flats and coastal plain wetlands. This study confirmed the majority of them, and refined others.

Wood production, carbon sequestration and conservation

Burger and Xu (2001) concluded that these wet pine flats were very productive as intensive forest systems. The productivity of these systems through age five was primarily the result of high soil quality and site hydrology. The results of this dissertation showed that indicators of site drainage were the most important factors influencing changes in soil-site quality between rotations.

Burger and Xu (2001) also stated that up to 35 percent of the standing biomass could be incorporated into the soils as residues, and therefore could serve to both maintain productivity, and serve as a predictable sink for carbon. Maintaining harvesting debris is important because sites with a large amount of bare soil did not appear to respond to site preparation. However, the highest productivity was observed on sites with medium levels of harvesting residues. This may indicate that excessive slash can negatively affect production by reducing bed quality, or adversely alter the carbon and nitrogen ratio.

Harvesting disturbance and trafficability

Resistance to harvesting disturbance requires soil strengths above 1200 kPa (Burger, 1994b). Soil strength was primarily controlled by soil water content. The surface soils on these sites were infrequently below the liquid limit during normal precipitation regimes, and some rutting down to the argillic horizons probably occurred during harvesting (Burger and Xu, 2001). In order for rutting to be prevented in the surface horizons, the critical limits of moisture content must be determined and monitored. Water tables remain perched above the argillic horizon, and it? remains strong throughout most of the year. According to the five-year results, some degree of disturbance may have been beneficial for soil-site productivity during droughty conditions; disturbance may have increased available water, and the improved productivity on moderately disturbed sites may be evidence that the sites are better environments when water becomes scarce.

Hydrologic responses to harvesting and site preparation

Initial phases of this project showed that wet-weather harvesting had little long-term effect on the site hydroperiod at the operational scale (Burger and Xu, 2001). At the stand scale, microsites that were significantly disturbed showed signs of altered hydroperionds even after two years, which could have a negative affect on production for small areas. Between ages 2 and 6 the sites were subjected to several years of drought, so there was little opportunity to compare the hydroperiod of these sites. This study demonstrated that site productivity was restored by site preparation in all cases except when sites were both heavily disturbed, and had a large degree of bare soil after harvesting. Water availability may be improved on sites that were moderately disturbed, and this may have improved productivity during drought relative to other sites.

Soil quality and productivity responses to harvesting and site preparation

The Soil Quality Index model developed by Kelting (1999) explained about 70 percent of the variation in second year loblolly pine growth on bioassay plots. The SQI is a good method for assessing management effects on productivity (Burger and Xu, 2001). SQI was a good method for assessing old-field or disturbed sites where little prior information is available and specific site factors are known to be limiting; however, it required information that was difficult or expensive to obtain and it assumed that the factors limiting growth at the time of measurement were will also limit growth at later phases of stand development. In cases where abundant prior information was available, and where some properties were not limiting, the rank method outlined in chapters 5 through 7 described almost 80 percent of the change in soil-site quality.

Burger and Xu (2001) indicated that soil disturbance had no influence on loblolly pine growth at age 2 at a commercial spacing on flat-planted sites; however, they concluded that no long-term conclusion could be drawn until the entire soil volume was exploited. There was no change in relative productivity among the disturbance categories on flat-planted sites at the stand scale (0.008 ha); however, at the operational scale there was an overall wet harvesting effect using the RCSI diagnostic (but not the RCTB and RCSB diagnostic). Burger and Xu (2001) stated that bedding mitigated the productivity of compressed and shallow rutted sites, but did not mitigate deep-rutted sites. This study showed that bedding mitigated heavily disturbed sites as long as bare soil was kept to a minimum.

A full rotation is required to ascertain if the observed decrease in relative productivity associated with wet-weather harvesting on flat planted sites is a long-term effect. If this proves to be the case, wet-weather harvesting may need to be avoided by non-industrial private landowners and on public lands where bedding is not the norm.

A further implication is that state harvesting BMP assessments should take into account the ameliorative effects of site preparation on wet pine flats. In addition, the resilience of these sites when bedded may make them a possible alternative to more sensitive sites while maintaining the fiber supply to the mills when wet weather harvesting is unavoidable.

Vegetation responses and the role of vegetation in soil recovery

Soil disturbance and bedding reduced the growth of woody plant species (Burger and Xu, 2001). Heavier soil disturbance creates anaerobic microsites that favored the growth of hydrophytic vegetation. Non-crop vegetation appears to play a small role in the recovery of physical properties, but may play a role in the regulation of the nitrogen supply. On sites subject to nitrogen leaching, weed control could have a negative effect on water quality; however, very little water drains from theses sites via subsurface drainage due to the very low hydraulic conductivities.

Regional silvicultural implications

Harvesting disturbances varied across soil, water, and vegetation gradients, emphasizing the importance of scale in productivity studies. Some wetlands were more resistant and resilient than uplands with regards to harvesting disturbance due to high fertility and good water relations. Visual soil disturbance did not necessarily equate to site damage. Site preparation appeared to fully mitigate the potential disturbance effects of wet-weather harvesting relative to an operational norm.

Drainage and initial site quality were the key attributes affecting changes in soil site quality. Some regional factors are highly correlated to site-specific soil-site quality indicators. Sites with high initial site quality appeared to be more at risk, as well as sites residing in lower relative elevations for neighborhoods approximately 30-ha in size. Site quality on wet pine flats was controlled by drainage and high soil physical quality rather than high nutritional fertility. Sites that had low productivity due to poor drainage and poor physical properties were unlikely to be made worse by trafficking. However, sites that were highly productive due to drainage and good soil physical properties are more susceptible to damage. Site preparation was unlikely to completely restore soil structure or intrinsic properties that were formed through many years of pedogenesis.

Scale Issues

Spatial and temporal scales were critical considerations when evaluating harvesting disturbance effects on site productivity. Disturbance occurred as a mosaic and phenomena that were important at one scale may be transparent or irrelevant at other scales. This project has sponsored individual studies that have spanned multiple scales, and taken as a whole have different implications than taken individually. For example, the operational scale results implies that once bedded, wet-harvested sites suffered no adverse effect on changes in site productivity; however, the stand scale results revealed that the combination of heavy disturbance and large amounts of bare soil after harvesting near the landings were not as responsive to bedding. This result was not detectable at the operational scale because that combination of disturbance accounted for such a small proportion of the total area. A second example was the disturbance scale (0.001 ha) results that implied that certain levels of disturbance were more disruptive than others, but because these disturbances existed as a mosaic, the effects were suppressed at the stand scale (0.008 ha).

8.4. Key dissertation findings

(1) Nearly 60 percent of wet-weather harvested areas were affected by soil physical disturbance due to trafficking. Only 9 percent of dry-harvested sites sustained any disturbance (soil compaction). Dry-weather harvesting resulted in nearly twice the amount of bare soil exposed after harvesting: 16 versus 9 percent respectively. Soil profiles in heavily trafficked areas were visibly disrupted and resulted in several layers being mixed.

(2) After conventional harvesting, under operationally realistic conditions, harvest disturbances occurred as a mosaic pattern that were difficult to quantify at scales of 0.008 ha and larger. The heterogeneity associated with disturbance at these scales was very difficult to quantify. Visual estimates of harvesting disturbance were usually not significant predictors of changes in soil-site productivity.

(3) At the operational scale, fertile wet pine flats recovered from harvesting disturbance when they were bedded. These sites are very fertile due to the phosphatic parent material. They have a mixed mineralogy including shrink swell clays that seem to help important physical properties recover. Overall these sites were resilient to the disturbances associated with wet-weather harvesting. These sites might be good candidates for wet harvesting, when necessary, to reduce pressures on more sensitive sites. Soil physical properties such as bulk density and porosity had nearly returned to pre-harvest conditions after five years.

(4) Mole-plowing is used in other agricultural systems in various places in the world with heavy clay soils (Spoor et al., 1982; Spoor and Fry, 1983; Weil et al., 1991) and appears to have some benefit. Although we did not detect significant differences in magnitude due to non-constant variance, some increase in soil productivity is possible in the WMB over other bedded treatments. This difference may be masked by a type-II error. The low variances observed among the WMB treatment suggests that it is doing what it was designed for; specifically, to equilibrate water tables and create a more uniform biomass response. Therefore, it bears further investigation, and may have an application for remediating certain types of sites.

(5) According to the models of changes in soil-site productivity as a function of silviculture, inherent site factors, and disturbance, prior productivity and drainage are the most influential site factors controlling these changes. Prior productivity alone accounted for over two-thirds of the changes in soil-site quality based on the rank diagnostic. This may explain the difficulty expressed by the literature to link production to disturbances that affect important soil quality parameters. Site-specific soil factors explained no more than 5 percent of the changes in rank.

(6) Tree growth is the result of the cumulative influence of site factors through time. While drainage factors have been the most influential factors in the first five years of growth, our results suggest that nutritional factors, specifically nitrogen availability, may become the most influential in upcoming years.

(7) Sites with higher initial quality (sub-stand scale) are more likely to have a lower rank after harvesting disturbance. High-quality sites are those with the best air-water balance resulting from good soil physical qualities and drainage. These sites would probably gain less benefit from bedding. Conversely, already low-quality sites are minimally affected using conventional harvesting systems, and these sites have the most to gain by bedding.

(8) All combinations of soil physical disturbance and harvesting residues responded to site preparation except where heavy disturbance occurred and greater than 25% bare soil was exposed after harvesting. On flat-planted sites, this disturbance level had among the highest levels of production, and the enhanced soil-site productivity relative to the other flat-planted sites may have been the result of the creation of "pseudo-beds." These same sites had among the lowest levels of production among the bedded sites, and the diminished level of soil-site productivity may have been the result of excessive machine traffic (e.g., these sites were further disturbed by drum-chopping and bedding).

(9) Climate was an important factor influencing this study. Droughty conditions were prevalent between ages 3 and 5 years. Had the climate been "normal" or unusually wet, the relative effects of the treatments, particularly the wet- versus dry-weather harvesting comparisons, might have been different because of drainage issues.

(10) The change in rank method is a new approach for comparing forest productivity across time and space. It is an effective diagnostic tool for evaluating treatment effects on changes in soil and site quality relative to an operational norm. While it has some limitations, it offers the advantage that it evaluates changes in soil and site quality independent of the confounding factors (genetics, climate, technology) that limit standard bioassays. Change in rank is most valuable when used in conjunction with other methods.

(11) Even though this study only covers a short time frame, it does have specific long-term connotations. The rank method cannot evaluate widespread or negative

treatment effects until the end of the rotation; however, it can discern benign treatment effects if you accept that treatment biomass responses are more likely to converge rather than diverge. Prior studies of intensive management of pine plantations have found that treatment differences that are detectable early in the rotation can disappear by the end of the rotation (Burger and Kluender, 1984; Cerchiaro, 2003)

(12) Scale is a very important issue in evaluating productivity change. Properties and phenomenon that are important at some scales are not obvious or hidden at others. This project has encompassed experiments ranging across five scales (tree-soil interface, disturbance-scale, sub-stand scale, operational scale, landscape scale), and each provided critical insights into the other scales (Table 8.7).

Table 8.7. Key insights of the five major scales in this study.

Scale	Key Insight
Tree-Soil Interface (100-cm^{-2})	Individual seedlings can grow well despite heavy disturbances after 1 year of growth.
Disturbance scale (2-m^2)	Disturbances such as compaction and deep rutting can limit seedling growth after 2 years by negatively affecting the air-water balance. Site preparation does not necessarily improve the conditions of these disturbed microsites.
Sub-stand scale (0.008-ha)	Disturbances occur as a mosaic and can lower soil-site quality. Bedding will restore soil-site quality on all but the most heavily disturbed sites, which only represent a small percentage (< 5%) of the total area. Drainage is a key factor affecting changes in soil-site productivity at this scale.
Operational scale (3.3-ha)	Bedding fully remediates sites disturbed by heavy equipment after wet-weather harvesting relative to operational norms.
Landscape scale	Models can be developed to identify areas that are more at risk to decreased soil-site quality.

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Appendix 1. Copies of correspondence with Kluwer Academic Publishers concerning the permission to reprint an article titled "Loblolly pine response to wet-weather harvesting on wet flats after 5 years" as chapter 4 in this dissertation.

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Mr Mark Eisenbies
228 Cheatham Hall
College of Natural Resources
Virginia Tech
Blacksburg, VA 24061
USA

15/01/2004

Re: Water, Air, and Soil Pollution 4(1): 217-233, 2004 (Eisenbies)

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Leslie van Mil (Mrs)
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Fa.xnr.: +31-78-6576744

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(Focus) 1567-7230

Leslie van Mil

emailed Desk Ed

AP PC:014

From: Georgia Prince
Sent: Wednesday, January 07, 2004 4:40 PM
To: Leslie van Mil
Subject: FW: Request

WFR JAN 21

-----Original Message-----
From: meisenbi [mailto:meisenbi@vt.edu]
Sent: woensdag 7 januari 2004 14:50
To: Paul.Roos@wkap.nl
Cc: Permissions@wkap.com
Subject:

B - thesis
- author

Paul:

I am just following up on my email a month agi. I have not yet heard from your rights and permissions department about getting permission to use my article in Water Air and Soil Pollution as a chapter in my dissertation.

Thanks.
Mark Eisenbies

Graduate Student
228 Cheatham Halll
College of Natural Resources
Virginia Tech
Blacksburg, VA 24061 USA

Date: Mon, 08 Dec 2003 11:58:55 +0100
From: Paul Roos <Paul.Roos@wkap.nl>
Subject: RE: Question about Permissions
To: 'meisenbi' <meisenbi@vt.edu>
Cc: Permissions <Permissions@wkap.com>
X-Mailer: Internet Mail Service (5.5.2653.19)

Morning Mark,

Thanks for the email. This should be no problem but I like to bring you in touch with my collaegues at the rights and permissions department who will officially handle this futher. (I have cc'ed them on this email).

Thanks

Paul Roos

-----Original Message-----
From: meisenbi [mailto:meisenbi@vt.edu]
Sent: vrijdag 5 december 2003 17:54
To: Paul.Roos@wkap.nl
Subject: Question about Permissions

Hello:

4(1): 217-233 (2004)

My name is Mark Eisenbies. I am first author on a publication I submitted to the Journal of Water Air and Soil Pollution. It is to be published in a Focus (Proceedings of the NCASI BMP symposium) this coming January. The title of the article is "Loblolly pine response to wet-weather harvesting on wet flats after 5 years".

I would like to obtain permission to use this article as a chapter in my doctoral dissertation as it is a central element to my research. The chapter
would directly indicate the source. Please let me know the proper contacts and steps I will need to take.

Thank you
Mark Eisenbies.

Appendix 2. Letter from the South Carolina Forestry Commission confirming that the wet-harvested areas do in fact represent excessive disturbances.

SOUTH CAROLINA FORESTRY COMMISSION
P.O. Box 21707•Columbia, South Carolina 29221
(803) 896 8800, FAX (803) 798 8097
J. Hugh Ryan, State Forester

August sep

July 12, 1994

Mr. Steve Patterson
Westvaco Corporation
P. O. Box 1950
Summerville, S.C. 29484

Dear Steve:

I appreciate the opportunity to visit the logging impact research study that Westvaco is conducting in Colleton County. This study has the potential to answer quite a few questions that need to be addressed. I commend you and your staff in doing quality work under difficult conditions. With this letter, I will attempt to compare the level of disturbance on these research sites with the range of disturbance that I have seen in monitoring harvesting BMP compliance across the state.

The most recent BMP compliance survey was completed during the summer of 1993. The report for this survey is being formatted and will be published and released within 1-2 months. I visited 200 harvested sites across the state in conjunction with this survey. We evaluated 40+ individual BMPs on each site. Two specific BMPs were evaluated which relate to your study goals. On each of the 200 sites, we estimated the percent of the site that was affected by skidding equipment, resulting in churned soils. We considered it excessive if over 20% of the site was churned. We also estimated the percent of each site that was deeply rutted. Deep ruts were considered to be at least 10" deep. Deep rutting was considered excessive when over 20-25% of the site was affected. Using these criteria, deep rutting was considered to be excessive on 12 of the 200 sites. However, only 3 of the 12 sites with excessive deep rutting received an inadequate overall BMP rating due to likely water quality impacts.

In evaluating site impact, we make allowances for isolated wet areas or for high traffic areas where rutting may occur. Higher levels of disturbance is frequently associated with the deck and primary skid trails. On certain soils under waterlogged conditions, the skidding equipment cannot make more than a few passes before it must travel over new ground. This results in a very high percentage of these sites being rutted or puddled. It is these type of conditions that we considered excessively rutted in making a BMP compliance check. However, the sites only received an inadequate rating if the rutting resulted in a likely water quality violation.

As I understand your study goals, you wanted to log designated plots during waterlogged conditions so as to evaluate the impacts of rutting and churning on site productivity. In walking over the plots, I believe that you have accomplished this goal. Rutting depth and coverage on the North Horseshoe and Sycamore replications met our criteria for excessive. On these two replications, I would estimate 40-45% of the targeted plots were deeply rutted. The South Horseshoe replication appeared not to be impacted as uniformly over the treatment plots, but nevertheless met study goals. I estimated block 5 & 6 to be deeply rutted over 25% of the sites. Treatment block 3, though, appeared to be deeply rutted over 15% of the site. All areas except block 3 of the South Horseshoe replication would meet our criteria for excessively deep rutting.

Again, I appreciate the invitation to visit your research project. Feel free to call if I can be of further assistance.

Sincerely,

Tim Adams
Environmental Management Section Chief

Appendix 3. List of permanent measurement points. Permanent subplots consist of all annually measured subplots including legacy plots (used in the regressions in Chapter 5). Annual subplots (as indicated by a 1 in their column) consist of points that represent the mean response of the operational treatment plots. Monthly subplots (as indicated by a 1 in their column) consist of those used for all site specific data (Chapter 7). MosubID is a unique identifier for each monthy subplot

Block	Plot	Line	Row	Treatment	Monthly	Yearly	mosubID
1	1	A	4	WMB	0	1	
1	1	A	15	WMB	1	0	1
1	1	B	8	WMB	0	1	
1	1	B	11	WMB	0	1	
1	1	B	12	WMB	1	0	2
1	1	C	3	WMB	0	1	
1	1	C	7	WMB	0	1	
1	1	D	3	WMB	0	1	
1	1	D	5	WMB	1	0	3
1	1	D	11	WMB	1	1	4
1	1	D	13	WMB	1	1	5
1	1	E	5	WMB	0	1	
1	1	E	7	WMB	0	1	
1	2	A	4	W	0	1	
1	2	A	8	W	0	0	
1	2	A	11	W	1	1	6
1	2	B	8	W	1	0	7
1	2	B	10	W	1	0	8
1	2	C	1	W	1	0	9
1	2	C	6	W	1	1	10
1	2	C	10	W	0	1	
1	2	C	14	W	0	1	
1	2	C	15	W	0	1	
1	2	D	1	W	0	1	
1	2	D	5	W	0	1	
1	2	D	6	W	0	1	
1	2	D	9	W	1	1	11
1	2	D	10	W	1	0	12
1	2	D	11	W	0	1	
1	2	D	12	W	1	0	13
1	2	D	14	W	0	1	
1	2	E	1	W	0	1	
1	2	E	3	W	1	0	14
1	2	E	9	W	0	1	
1	2	E	10	W	0	1	
1	3	A	3	WB	0	1	
1	3	A	4	WB	0	1	
1	3	A	6	WB	1	1	15

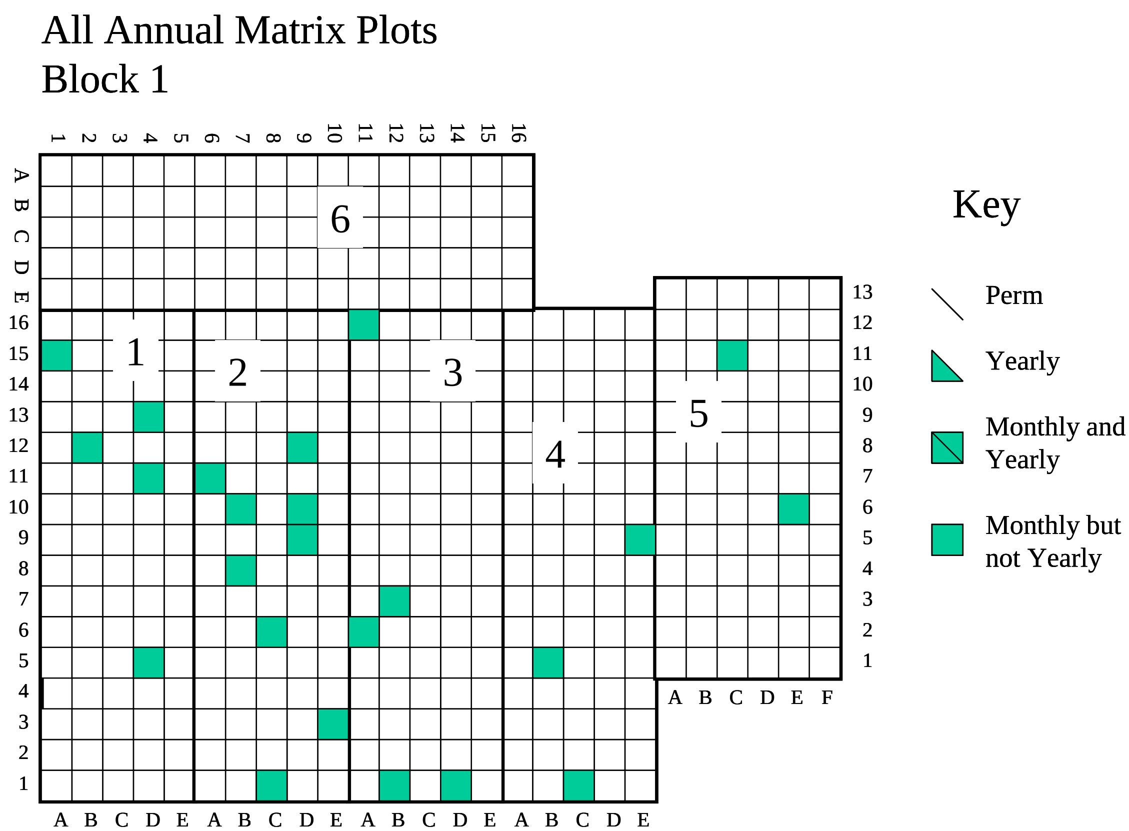
Block	Plot	Line	Row	Treatment	Monthly	Yearly	mosubID
1	3	A	16	WB	1	0	16
1	3	B	1	WB	1	1	17
1	3	B	7	WB	1	0	18
1	3	B	15	WB	0	1	
1	3	C	1	WB	0	0	
1	3	C	6	WB	0	1	
1	3	C	9	WB	0	1	
1	3	C	11	WB	0	1	
1	3	D	1	WB	1	1	19
1	3	E	1	WB	0	0	
1	3	E	12	WB	0	1	
1	4	A	2	D	0	0	
1	4	A	10	D	0	0	
1	4	A	15	D	0	1	
1	4	B	5	D	1	1	20
1	4	C	1	D	1	1	21
1	4	C	6	D	0	1	
1	4	C	8	D	0	1	
1	4	C	14	D	0	1	
1	4	D	2	D	0	1	
1	4	D	11	D	0	1	
1	4	E	9	D	1	1	22
1	4	E	11	D	0	1	
1	5	A	4	DB	0	1	
1	5	B	8	DB	0	1	
1	5	C	4	DB	0	1	
1	5	C	5	DB	0	1	
1	5	C	11	DB	1	1	23
1	5	D	5	DB	0	0	
1	5	E	2	DB	0	1	
1	5	E	6	DB	1	1	24
1	5	E	12	DB	0	1	
1	5	F	4	DB	0	1	
1	5	F	8	DB	0	1	
2	1	B	6	DB	0	1	
2	1	C	2	DB	0	1	
2	1	D	2	DB	0	1	
2	1	D	3	DB	1	1	25
2	1	D	4	DB	1	1	26
2	1	D	7	DB	1	1	27
2	1	D	10	DB	0	1	
2	1	E	4	DB	0	1	
2	1	E	5	DB	0	1	
2	1	F	8	DB	1	0	28
2	1	G	3	DB	0	1	

Block	Plot	Line	Row	Treatment	Monthly	Yearly	mosubID
2	2	B	2	D	0	1	
2	2	B	7	D	1	1	29
2	2	C	1	D	0	1	
2	2	C	2	D	1	1	30
2	2	C	11	D	1	0	31
2	2	D	1	D	0	1	
2	2	D	5	D	0	1	
2	2	E	2	D	1	1	32
2	2	E	10	D	0	1	
2	2	F	6	D	1	1	33
2	2	F	9	D	1	1	34
2	3	A	1	WMB	1	1	35
2	3	A	4	WMB	0	1	
2	3	A	9	WMB	0	1	
2	3	B	1	WMB	1	1	36
2	3	C	6	WMB	0	1	
2	3	D	3	WMB	1	1	37
2	3	D	9	WMB	1	0	38
2	3	D	10	WMB	0	1	
2	3	E	1	WMB	0	1	
2	3	F	8	WMB	0	1	
2	3	G	4	WMB	0	1	
2	5	A	1	W	1	0	39
2	5	B	6	W	0	1	
2	5	C	1	W	0	1	
2	5	D	1	W	0	1	
2	5	D	2	W	1	1	40
2	5	D	4	W	0	1	
2	5	D	8	W	1	1	41
2	5	E	1	W	1	1	42
2	5	E	5	W	0	1	
2	5	F	1	W	0	0	
2	5	F	2	W	1	0	43
2	5	G	3	W	1	0	44
2	5	G	5	W	0	1	
2	5	H	8	W	0	1	
2	5	I	2	W	0	1	
2	5	I	3	W	0	0	
2	5	I	6	W	1	1	45
2	5	I	7	W	0	1	
2	5	I	8	W	0	1	
2	6	A	1	WB	0	1	
2	6	A	9	WB	0	1	
2	6	B	7	WB	0	1	
2	6	B	11	WB	0	1	

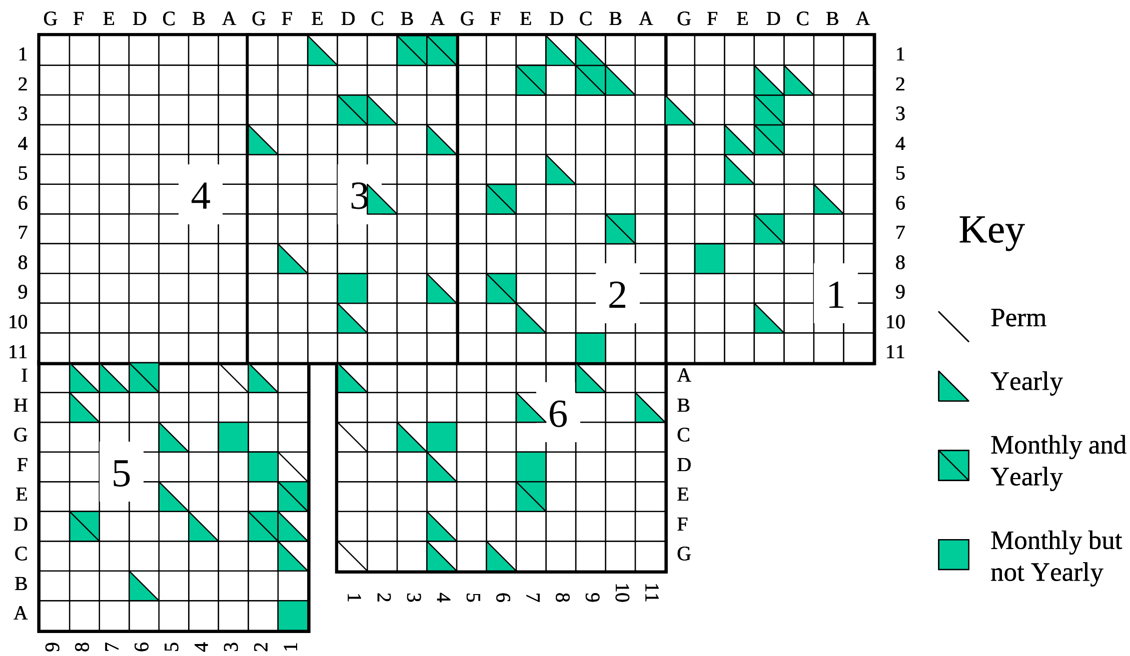
Block	Plot	Line	Row	Treatment	Monthly	Yearly	mosubID
2	6	C	1	WB	0	0	
2	6	C	3	WB	0	1	
2	6	C	4	WB	1	0	46
2	6	D	4	WB	0	1	
2	6	D	7	WB	1	0	47
2	6	E	7	WB	1	1	48
2	6	F	4	WB	0	1	
2	6	G	1	WB	0	0	
2	6	G	4	WB	0	1	
2	6	G	6	WB	0	1	
3	1	A	10	DB	0	1	
3	1	A	12	DB	1	1	49
3	1	B	6	DB	0	1	
3	1	B	9	DB	0	0	
3	1	C	1	DB	0	0	
3	1	C	2	DB	0	1	
3	1	C	9	DB	1	0	50
3	1	C	11	DB	0	1	
3	1	D	1	DB	1	1	51
3	1	D	2	DB	0	1	
3	1	D	13	DB	1	1	52
3	1	E	1	DB	0	1	
3	1	E	2	DB	1	1	53
3	2	A	2	W	1	0	54
3	2	A	9	W	1	0	55
3	2	A	12	W	1	1	56
3	2	A	13	W	0	1	
3	2	B	2	W	0	1	
3	2	B	8	W	1	0	57
3	2	B	14	W	1	0	58
3	2	C	1	W	0	0	
3	2	C	5	W	1	1	59
3	2	C	6	W	1	0	60
3	2	C	7	W	0	1	
3	2	C	8	W	0	1	
3	2	C	9	W	0	1	
3	2	D	1	W	1	1	61
3	2	D	4	W	1	1	62
3	2	D	5	W	0	1	
3	2	D	8	W	1	1	63
3	3	A	2	D	0	1	
3	3	B	2	D	0	1	
3	3	B	3	D	0	1	
3	3	B	8	D	0	1	
3	3	B	12	D	0	1	

Block	Plot	Line	Row	Treatment	Monthly	Yearly	mosubID
3	3	C	1	D	0	0	
3	3	C	2	D	0	0	
3	3	C	7	D	0	1	
3	3	C	15	D	1	1	64
3	3	D	5	D	0	1	
3	3	D	9	D	0	1	
3	3	E	4	D	1	0	65
3	3	E	14	D	0	1	
3	4	A	4	WB	0	0	
3	4	A	9	WB	0	1	
3	4	A	15	WB	0	1	
3	4	B	5	WB	1	1	66
3	4	C	1	WB	1	1	67
3	4	C	2	WB	0	1	
3	4	C	4	WB	0	1	
3	4	C	10	WB	1	1	68
3	4	C	12	WB	0	1	
3	4	D	15	WB	0	1	
3	4	E	6	WB	0	1	
3	5	A	12	WMB	0	1	
3	5	B	7	WMB	0	1	
3	5	B	16	WMB	0	1	
3	5	C	1	WMB	1	1	69
3	5	C	3	WMB	0	1	
3	5	C	5	WMB	0	1	
3	5	C	7	WMB	0	1	
3	5	C	15	WMB	1	1	70
3	5	D	2	WMB	0	0	
3	5	D	15	WMB	1	1	71
3	5	E	2	WMB	0	1	

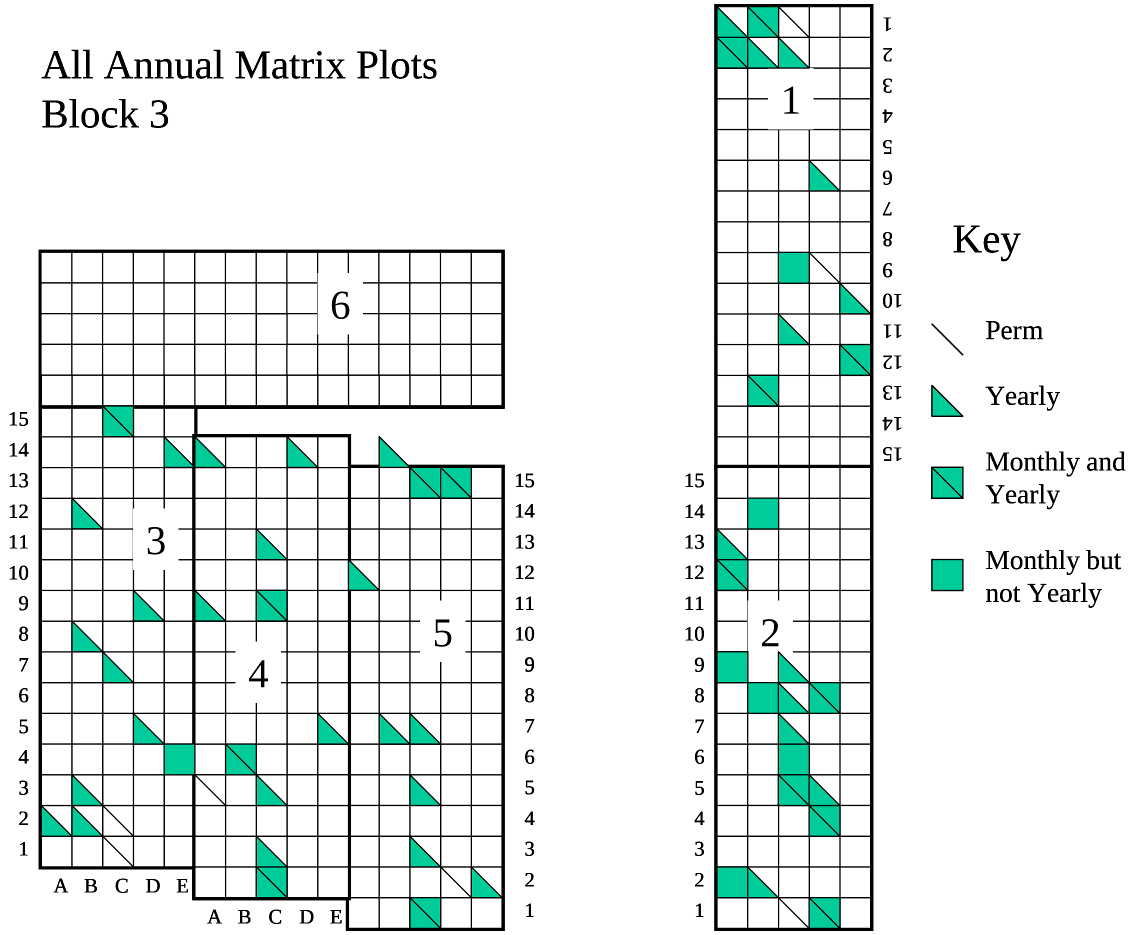
Appendix 4. Plot schematics of permanent subplot locations including legacy points.



All Annual Matrix Plots
Block 2

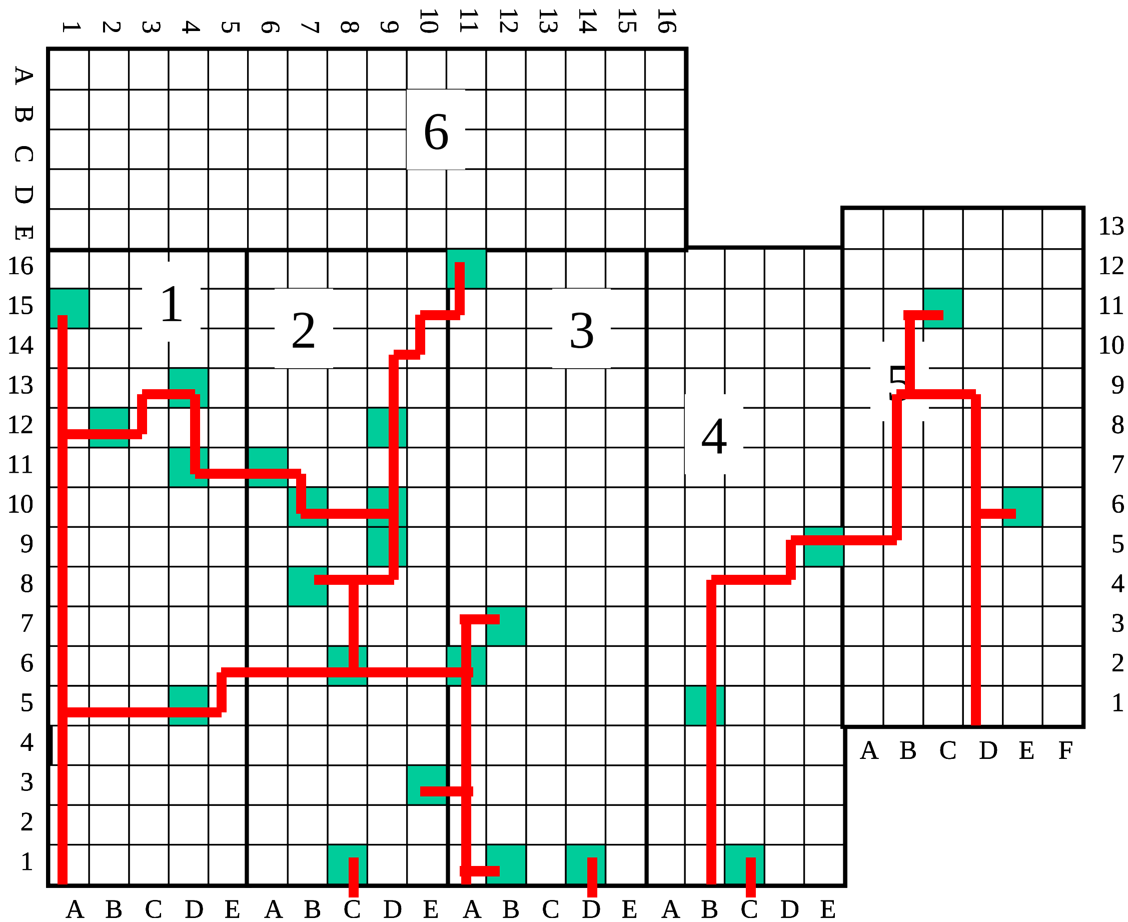


All Annual Matrix Plots
Block 3

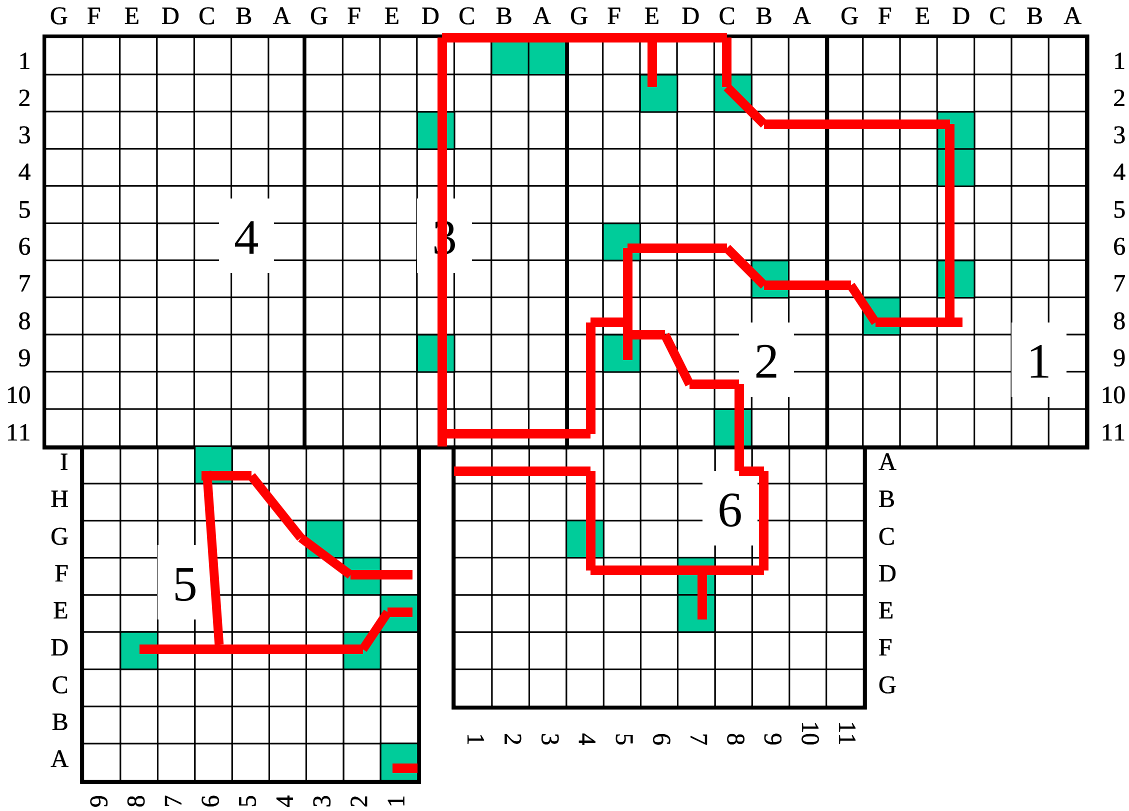


Appendix 5. Plot schematics of monthly subplot locations and trail maps installed by Mark Eisenbies.

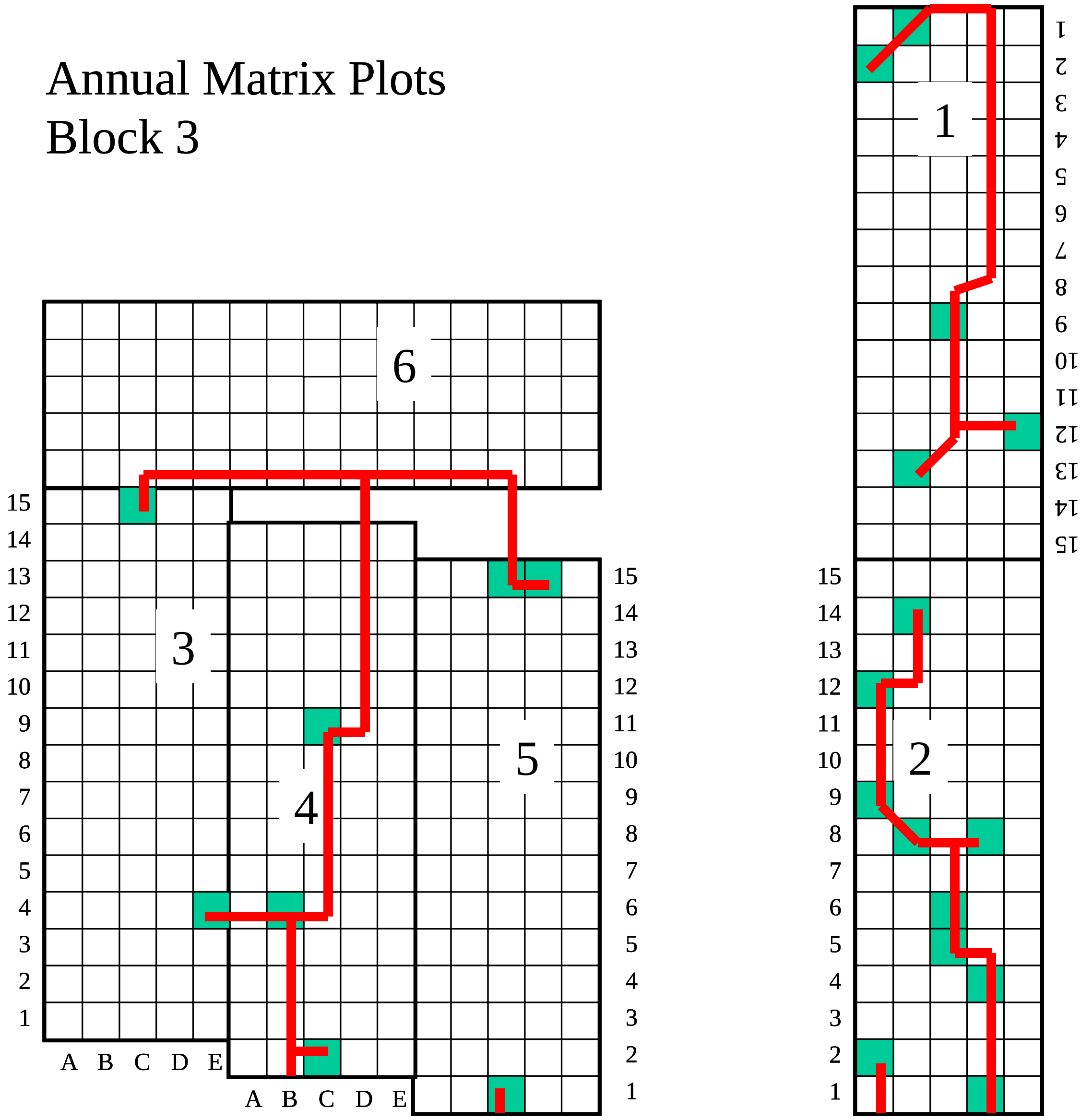
Annual Matrix Plots
Block 1



Annual Matrix Plots
Block 2



Annual Matrix Plots
Block 3



Appendix 6: Example of the implementation of the rank method within a hypothetical neighborhood of experimental units for site index. Change in rank of three hypothetical treatments is calculated relative to an operational norm. In actual practice, the number of observational units required per neighborhood may need to be large.

Observational Plot	Initial Site Index	Initial Rank	New Site Index	New Rank	Rank Change	Mean Rank Change
			Operational Reference (Norm)			
1	21	29.5	21	28.5	1	0.56
2	21	29.5	21	28.5	1	
3	22	24.5	22	23	1.5	
4	23	19	23	17.5	1.5	
5	24	12.5	24	12.5	0	
6	25	7.5	25	7.5	0	
7	25	7.5	25	7.5	0	
8	27	2	27	2.5	-0.5	
			Relative Productivity Diminished			
9	21	29.5	19.5	32	-2.5	-6.44
10	22	24.5	20.5	31	-6.5	
11	23	19	21.5	25.5	-6.5	
12	23	19	21.5	25.5	-6.5	
13	24	12.5	22.5	20.5	-8	
14	24	12.5	22.5	20.5	-8	
15	25	7.5	23.5	15	-7.5	
16	26	4	24.5	10	-6	
			Relative Productivity Maintained			
17	21	29.5	21	28.5	1	0.75
18	21	29.5	21	28.5	1	
19	22	24.5	22	23	1.5	
20	23	19	23	17.5	1.5	
21	23	19	23	17.5	1.5	
22	24	12.5	24	12.5	0	
23	26	4	26	4.5	-0.5	
24	28	1	28	1	0	
			Relative Productivity Improved			
25	21	29.5	22	23	6.5	5.13
26	22	24.5	23	17.5	7	
27	23	19	24	12.5	6.5	
28	23	19	24	12.5	6.5	
29	24	12.5	25	7.5	5	
30	24	12.5	25	7.5	5	
31	25	7.5	26	4.5	3	
32	26	4	27	2.5	1.5	

Appendix 7. Indicators of the normality assumption of the change in rank of site index.

```
                   Histogram                        #
375+*                                               4
   .****                                           13
   .*******                                        26
225+**************                                 55
   .************************                       93
   .**************************                    102
 75+*********************************             129
   .******************************************    165
   .**************************************        149
-75+*********************************             131
   .**************************                    102
   .*******************                            76
225+***************                                59
   .*********                                      35
   .****                                           13
375+*                                               3
    ----+----+----+----+----+----+----+----+--
    * may represent up to 4 counts
```

```
                  Normal Probability Plot
375+                                                  *
   |                                              +****
   |                                           *****
225+                                       *****
   |                                   *****
   |                                ****
 75+                            *****
   |                         ****
   |                      ****
-75+                  ****
   |               ****
   |            ****
225+        *****
   |   ******
   |****+
375+*
    +----+----+----+----+----+----+----+----+----+----+
        -2        -1         0        +1        +2
```

Appendix 8. Indicators of the normality assumption of the change in rank of individual tree biomass.

```
                    Histogram                        #
375+*                                                3
   .***                                             10
   .*********                                       33
225+**************                                  53
   .********************                            77
   .**************************                     101
 75+**********************************             134
   .********************************************   176
   .**************************************         152
-75+******************************                 118
   .*************************                       99
   .*********************                           82
225+***************                                 57
   .*********                                       34
   .******                                          22
375+*                                                4
    ----+----+----+----+----+----+----+----+----
    * may represent up to 4 counts
```

```
                  Normal Probability Plot
375+                                                  *
   |                                              ++***
   |                                           ******
225+                                       ****
   |                                   *****
   |                                ****
 75+                             ****
   |                         *****
   |                     *****
-75+                   ***
   |               +***
   |            *****
225+         ****
   |     *****
   |******
375+*+
    +----+----+----+----+----+----+----+----+----+----+
        -2        -1         0        +1        +2
```

Appendix 9. Indicators of the normality assumption of the change in rank of stand biomass.

```
                   Histogram                       #
375+*                                              3
   .*****                                         18
   .*********                                     35
225+**************                                56
   .******************                            71
   .************************                      96
 75+******************************               117
   .******************************************   165
   .*****************************************    163
-75+********************************             125
   .***************************                  107
   .********************                          79
225+*****************                             68
   .*********                                     34
   .****                                          15
375+*                                              3
    ----+----+----+----+----+----+----+----+--
    * may represent up to 4 counts
```

```
                  Normal Probability Plot
375+                                                  *
   |                                              *****
   |                                          *****
225+                                      *****
   |                                   ****
   |                                ****
 75+                             ****
   |                         *****
   |                      ****
-75+                   ****
   |                ****
   |            *****
225+        *****
   |    *****
   |****+
375+*+
    +----+----+----+----+----+----+----+----+----+----+
        -2        -1         0        +1        +2
```

VITA

Mark Hale Eisenbies was born on April 30, 1969 in Raleigh, North Carolina to Serita Keeling Weaver Eisenbies and John Lawrence Eisenbies. He received a B.S. in Forestry and Wildlife Management from Virginia Tech, Blacksburg, VA, in 1993. He received a M.S. in Soil Science from the University of Tennessee, Knoxville, TN, in 1996. He worked for the USDA Forest Service, Southern Research Station, Center for Forested Wetlands Research in Charleston, South Carolina, until beginning his Ph.D. program in April, 2000.