FACTORS AFFECTING LOBLOLLY PINE GROWTH FOLLOWING SITE PREPARATION

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(ABSTRACT)

Site preparation is a required silvicultural practice for establishing loblolly pine plantations in the Piedmont physiographic region of the southeastern U.S.; however, relatively little is known about its effect on soil and site factors that influence growth and yield. In this study, the effect of seven different site preparation prescriptions on competing vegetation, tree nutrition, and the spatial distribution of planted seedlings was examined. Three treatments had a soil tillage component and differed with respect to the number of operations employed in removing residual trees and logging slash prior to discing. One treatment involved roller chopping and broadcast burning, one an application of the herbicide glyphosate followed by a broadcast-burn, one involved shearing and raking logging debris into windrows, and one was no site preparation prior to planting. All treatments were applied to 12 sites in the South Carolina and Georgia Piedmont. After four years in the field, 756 trees within the site preparation treatment areas were randomly selected for analysis of foliar nutrients, soil nutrients, and competing vegetation. Herbaceous, woody shrub, and hardwood competition levels were not significantly different among site preparation treatment areas after four years. However, hardwood competition levels had increased at a faster rate during the last two growing seasons on chopped and disced areas than on the other areas. Hardwood competition became the predominant factor limiting pine basal diameter when 83% of the total basal area was in hardwoods or hardwood basal area levels exceeded 3.5 m^2ha^{-1}. Potassium was identified as the most limiting nutrient 38% of the time, compared to 28% for phosphorous, 14% for nitrogen, 7% for calcium, and 13% for magnesium. A significant linear relationship between soil and foliar nutrients confirmed these results. No treatment effect on nutrient deficiencies was evident. Foliar nutrient critical levels were derived using the Diagnosis and Recommendation Integrated System

(DRIS) and were the same as those reported in the literature for nitrogen, phosphorous, and magnesium while potassium and calcium critical levels were determined to be twice as high as those reported (0.52% and 0.19%, respectively). The spatial distribution of seedlings at planting and after 2 years was determined. Spatial patterns varied from uniform to random as the degree of logging slash removal decreased. After two years, the spatial distribution shifted toward random and clustered. The degree of change was similar in all but the herbicide burn and untreated areas, which exhibited the greatest change and whose mortality tended to be clustered.

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Introduction

The southeastern portion of the United States has become the most important timber-producing region in the U.S. and is likely to remain so for the forseeable future. In 1976, 44% of the softwoods harvested in the U.S. came from the Southeast and removals increased 17% by 1984 (Boyce et al. 1986). Concurrent with this increase in timber removals has been a decline in the timber-producing land base. Since 1962, commercial timberland in the Southeast has declined 7.3% (Boyce et al. 1986). In response to this situation, forest management has intensified. The goal has been to accelerate growth and increase yields on fewer hectares. Pine plantations provide the greatest opportunity to realize these goals and their establishment has nearly doubled since 1975 as a consequence (Anonymous 1986).

Southern yellow pines are the predominant softwoods in the southeast, occurring mostly in the Piedmont and Coastal Plain physiographic regions. The pine inventory is nearly equally divided between the two regions (Anonymous 1986) with loblolly pine (*Pinus taeda L.*) plantations predominating in the Piedmont (Boyce et al. 1980).

Loblolly pine plantations are currently established on previously forested sites and typically require some form of site preparation to ensure that they will be successful (Boyce and Knight 1980, Clutter and Dell 1978). Residual vegetation, logging slash, and competing vegetation have been the predominant concerns in plantation establishment; however, soil-site factors are also becoming recognized as influential to loblolly pine growth and yield. The extent and distribution of logging slash affects the number, spatial distribution, and quality with which seedlings are planted. Interspecific competition affects seedling survival and growth. Early competition control is considered essential for reducing the length of time required for the crowns to close, in addition to minimizing the extent of hardwood competition thereafter. Once stands reach crown closure, the proportion of hardwood competition whose crown extends into the canopy remains relatively constant; however, its presence inflicts a disproportionate reduction in pine yield. Unfortunately, little is known about competition dynamics prior to crown closure.

Tree nutrition is a primary soil-site concern. Abusive agricultural practices in the past have left a depleted nutrient base and many havesting and site preparation practices remove small branches and twigs, the nutrient-rich biomass, along with tree stems. However, detection of nutrient deficiencies has been difficult and growth responses to fertization have been unpredictable.

Numerous site preparation methods are available and used for stand regeneration in the Piedmont; however, the plantations that follow exhibit highly variable survival and growth patterns depending on the site preparation prescription imposed, the characteristics of a site, and the degree to which growth-limiting factors are affected (Haines et al. 1975, Sarigumba 1985). If preparation is to be cost effective and predictable, identification of limiting conditions and information on the extent to which limiting conditions affect growth and yield is required. In addition, information on how the various site preparation treatments affect limiting conditions is needed.

The overall purpose of this research was to investigate relationships between loblolly pine survival and growth, site preparation, and the amelioration of growth-limiting conditions four years after regeneration. Results of this study should increase the predictability of site preparation and increase the chances of regeneration success.

Literature Review

Factors Limiting Loblolly Pine Growth and Yield in the Piedmont

Water, nutrients, light, oxygen (O_2), carbon dioxide (CO_2), and heat are the fundamental factors regulating the growth of loblolly pine. They do not exert their influence independently, rather they interact to generate an integrated effect. Successful loblolly pine management depends on the silviculturist's ability to optimize the supply and timing of these factors. Some of the factors such as nutrients, can be directly manipulated; however, all are primarily affected through the indirect manipulation of the plant and soil environments. Competing vegetation, soil physical properties, and nutrients are the primary environmental factors manipulated and managed.

COMPETING VEGETATION

Competing plants exert their effect on loblolly pine growth by influencing water, light, and nutrient regimes. Generally, light and water are the predominant factors affected (Korstian and Bilan 1957, Carter et al. 1983). Grass, herbaceous, and woody competition growing and developing with newly planted pines can affect their growth. Knowe et al. (1985) found that seedlings receiving weed control for two consecutive years were twice the height and diameter of non-weeded trees after four growing seasons. Bacon and Zedaker (1985) report that two-year-old trees free of herbaceous competition and either free or with 1/3 woody competition had twice the volume growth of non-weeded trees. Lantagne and Burger (1986) report that the level of grass competition was an important variable in accounting for height growth of two-year-old loblolly pine, while both hardwood and grass cover were important in volume growth.

Grass and herbaceous competition tend to exert their influence during the early stages of stand development where they can be vigorous competitors for available water. Hardwood competition is influential both initially as well as over the long term. Hardwoods tend to have leaves with a large planar surface area which effectively intercept light required by loblolly pine, which is shade intolerant and requires full sunlight for maximum photosynthesis (USDA 1965). Hardwoods also require abundant water to cool their leaves and as a consequence confiscate much of the soil water. In effect, hardwoods can consume a disproportionate share of resources while also placing the pines at a competitive disadvantage, particularly when they overtop the pines. Ferguson (1963), for example, found pine-seedling height to be linearly related to the hardwood basal area of a residual stand at least through the first two growing seasons.

Following crown closure, Burkhart and Sprinz (1984) report that the amount of hardwood competition in the canopy causes a disproportionate reduction in loblolly pine yield. Below 10 to 15% hardwood basal area, there is no relationship between hardwood competition and yield; however, as the percent of hardwoods increases, pine yield decreases exponentially. When 30% of the basal area in a stand is in hardwood competition, for example, only 50% of the pine volume is obtained compared to when no hardwood is in the stand. Fewer trees per acre and smaller diameter distributions account for the yield reduction. While some of the hardwood influence under these conditions relates to water availability, much of it is likely to be related to light.

SOIL PHYSICAL PROPERTIES

Soil physical properties can play an important role in loblolly pine growth in the piedmont. In addition to influencing the level of water, nutrients, and aeration (O_2 and CO_2 levels), soil physical properties affect the rate at which these become available.

Root penetration and soil volume exploitation are potential problems on many Piedmont soils. Greenhouse studies indicate that root growth is restricted in fine textured soils when the bulk density exceeds 1.4 g cm^{-3} and in coarse textured soils at 1.6 g cm^{-3} (Lull 1959). In a sandy loam, Mitchell et al. (1982) found root growth ceased at densities of 1.8 g cm^{-3}. While bulk densities in the Piedmont approach these limiting levels, particularly following harvest on clay textured soils (Gent et al. 1984), no field studies have shown a consistently strong relationship between bulk density and growth (Greacen and Sands 1980, Lantagne 1984). Interactions between bulk density, other soil factors, nutrition, and competing plants complicates the identification of cause and effect relationships. Augspurger et al. (1985) reported that seedling height was significantly greater when both soil resistance to penetrometer penetration (an alternative measure of bulk density) was least and depth to the argillic horizon greatest.

Soil exploitation has also been examined with regard to the thickness of the A horizon, which has been found highly correlated with loblolly pine growth on the Piedmont (Coile 1953, Maki et al. 1962). Coile (1953) reported that site index increased logarithmically with increasing thickness of the A horizon. A change from 5 to 10 cm resulted in a 7 m increase in site index, while a change from 10 to 20 cm was associated with only a 1 m increase. The A horizon is characterized by its high organic matter content, high nutrient status, and soil physical properties favorable for water infiltration, water retention, and aeration.

Soil aeration is critical to loblolly pine growth. Aeration porosity values below 10% are considered restrictive to growth because not enough O_2 is available for respiration and nutrient and water absorption (Volmicil and Flocker 1961, Grable 1971). Soil aeration not only depends on the arrangement and volume of pore space, but also on the status of that pore space. Coile (1953), for example, found the imbibitional water value of the B horizon inversely related to loblolly height growth in the Piedmont. High imbibitional water values indicate excessive moisture, poor drainage and insufficient O_2 as a consequence. Aeration also affects nutrient availablity in addition to root efficiency and growth. Nitrogen (N) mineralization declined 70% in an Australian soil when bulk density was increased from 1.3 to 1.6 g cm^{-3} (Pritchett 1980). The response was attributed to a corresponding reduction in aeration.

NUTRITION

Nitrogen and phosphorous (P) deficiencies are the most common in loblolly pine while deficiencies of other nutrients have rarely been demonstrated (Pritchett and Smith 1975). Phosphorous is frequently deficient on poorly drained Coastal Plain sites (Pritchett and Smith 1975, Wells et al. 1973), while N deficiencies have been reported on upland Coastal Plain and Piedmont sites (Pritchett and Smith 1975, Maki 1960, Ballard 1981).

Nitrogen availability is not only a function of the size of the N pools, but also on the rate at which N is released and becomes available for uptake. Nitrogen mineralization (the change of N from organic to inorganic form) is regulated by temperature and moisture conditions, the amount of organic matter present, and its resistance to change. The fate of mineralized N depends on immobilization, utilization, and processes associated with losses. Immobilization occurs by soil adsorption and microbial confiscation with the amount of N confiscated by microbes being directly proportional to the amount of organic-carbon remaining on site (Vitousek and Matson 1985, Ralston 1978). If microbes have a disproportionately large carbon source for energy, they will utilize much of the N with that remaining being available for plant uptake. The confiscated N will gradually become available as microbes die (Barber and Van Lear 1984, Covington 1981). If the organic carbon pool remaining on site is relatively small, microbial immobilization will be relatively low and the mineralized N will be available for uptake by crop trees, competing vegetation, or it can be lost from a site by leaching or denitrification. In short, while nutrition depends on absolute nutrient levels, availability is also affected by the manipulation of the nutrient pools.

In summary, numerous factors affect the growth of loblolly pine in the Piedmont, none, one, or many of which may simultaneously be limiting. Few generalities hold across this extremely diverse and heterogeneous region. In addition, interactions between the limiting factors makes their diagnosis difficult. While light, water, nutrients, O_2, CO_2, and heat are the basic factors regulating loblolly pine growth, it is difficult to directly change their availablity without manipulating the soil and plant environments, which both affect and are affected by these factors. As a consequence, loblolly pine management requires that competing vegetation, soil physical conditions, and nutrition be managed to impart changes in the level and timing of the basic growth factors.

Site Preparation Effects on Competition, Soil, and Nutrition

Site preparation is a silvicultural practice aimed at optimizing growth factors to increase stand productivity, and, as a consequence, is frequently required to regenerate loblolly pine in the Piedmont. Control of competing vegetation, amelioration of soil physical properties, elimination of logging slash, and enhancement of short- and long-term nutrition are often objectives of site preparation.

Site preparation studies indicate that loblolly pine survival, diameter distributions, and height growth are significantly affected by the type of site preparation treatment imposed (Burns and Hebb 1972, Worst 1964, May et al. 1973, Lantagne and Burger 1983, Sarigumba 1985). However, the results are often inconsistent across sites and uncertainty exists as to whether the differences observed at young ages are maintained to rotation age. Sarigumba (1985) found that while remaining significant, the effects of site preparation declined differentially across different Coastal Plain sites with age. Unfortuately, few replicated experiments have been in place long enough in the Piedmont to examine the interactions between site and site preparation method as they jointly affect growth.

ELIMINATION OF COMPETING VEGETATION

Competing vegetation is a major concern in stand regeneration and both heraceous and hardwood competitors have been recognized as important components exerting limiting constraints on growth. Hardwood competition is important because of its potential long term impact. Burkhart and Sprinz (1984) report that the hardwood basal area in the canopy of a stand relative to the total basal area remains relatively constant after crown closure, and that once the percent hardwood basal area was known, growth and yield estimates can be improved. Unfortunately, relatively little is known about the relationship between hardwood dynamics and site preparation prior to crown closure, particularly in the Piedmont.

In general, aside from the use of herbicides, treatments that include soil tillage or soil displacement have been found to be more effective at controlling hardwood competition than other treatments. However, few studies have been conducted on the Piedmont from which to document the relationship between hardwood dynamics and site preparation. In an unreplicated study, Miller (1980) compared the vegetation on an area that had been roller chopped and broadcast burned with an adjacent treatment area in which residual trees had been sheared followed by raking the debris into windrows (shear rake). Twenty-five percent fewer hardwood sprouts occurred on the shear rake area than on the chopped area. In a replicated study, Lantagne and Burger (1986) compared competition among seven site preparation treatments after 2 yr and found that those treatment areas that had been disced exhibited significantly lower levels of hardwood competition than non-disced areas. In examining competing vegetation in the Coastal Plain, DeWit and Terry (1983) report similar findings. Significantly more hardwood competition exsisted 8 yr after site preparation by tree crushing (comparable to chopping) than treatments involving shearing and raking, or shearing, raking, and discing (shear rake disc). During the shear rake treatment, the surface soil was removed (scalped) and is thought to have reduced the competing hardwood vegetation to a level comparable to that on the shear rake disc treatment. The hardwood basal area in these treatments ranged from 5.6 m^2ha^{-1} in the chopped areas to 1.9 m^2ha^{-1} in the shear rake disc areas.

SOIL AMELIORATION

Amelioration of the soil is sometimes a secondary objective of plantation establishment. Root penetrability, aeration, water infiltration, and water holding capacity are soil physical properties that influence survival and early growth and may be affected by site preparation. A less than optimum status in these properties is a common occurrence across much of the Piedmont. Those soils derived from gneiss and schist parent materials are often characterized by a clayey texture at or near the surface and are likely to benefit from tillage. Erosion has removed much of the original sandy-loam A horizon and exposed the B horizon. These soils typically exhibit shallow rooting depths, poor water infiltration and high soil strength during the growing season, which restricts root penetration and mycorrhizal strand exploitation. They are also vulnerable to compaction from machine travel during harvesting and site preparation. In evaluating a Cecil soil (a frequently occurring soil of this type in the Piedmont), Gent et al. (1984) found that bulk density increased from an average 1.14 to 1.43 g cm^{-3}, aeration porosity decreased from 23.0 to 10.5%, and hydraulic conductivity in the surface 8 cm (a measure of infiltration rates) decreased from 1.76 to 0.51 m h^{-1} as a result of harvesting. The significance of these changes has been difficult to assess because several are at threshold levels or affect growth only indirectly, as in the case of infiltration. Stransky (1981) examined bulk density three growing seasons after site preparation in eastern Texas and found significantly higher levels in chop burn and shear rake treatment areas than in untreated and broadcast-burn only areas but was unable to ascertain the importance of the differences.

Discing can reverse some of these detrimental soil physical conditions. Gent et al. (1984) found that shortly after discing cut-over sites on a Cecil soil bulk density and aeration porosity returned to preharvest levels; however, surface soil hydraulic conductivity remained depressed. The natural rate at which bulk density returns to pre-disturbed levels in forest soils varies depending on soil texture and mineralogical characteristics, temperature and moisture cycles, and root growth. However, estimates range from 8 to 30 yr (Dickerson 1976).

Juvenile loblolly pine growth has benefited from discing. Lantagne (1984) reported that areas in the Piedmont in which discing was part of the site preparation prescription had significantly greater tree growth the first and second seasons after site preparation than non-tilled areas. Seedling survival may or may not be affected by site preparation. In addition to the way seedlings are handled and planted (Slocum 1951, Dierauf 1982), a site preparation-weather interaction apparently affects early survival patterns. Several studies indicate no significant difference in early survival by site preparation method (Haines et al. 1975, Campbell 1973); however, in a very dry year, Lantagne (1984) reported that treatments in which discing was used had significantly higher survival rates than non-disced treatment areas. Although not well documented, discing is thought to result in improved survival by reducing soil strength and facilitating planting. It also improves moisture relations by providing a soil volume easily exploited by roots.

LOGGING SLASH ELIMINATION AND TREE NUTRITION

Tree nutrition, particularly long-term N nutrition in the Piedmont, is likely to be affected by the type of site preparation imposed. Removal of the forest floor and logging slash is the focal point of interest. Historically, logging slash has been a major concern in site preparation because it interferes with stand access and planting (Haines et al. 1975). Lantagne (1984), for example, reports that the degree of logging slash removal during site preparation is directly related to the number of seedlings planted as well as those surviving. However, logging slash removal can also have deleterious affects on growth. Logging slash contains relatively high concentrations of nutrients (Barber and Van Lear, 1984) and its removal during such operations as raking or burning may be detrimental. Glass (1976) found that logging slash raked into windrows had 36 to 340% higher nutrient levels and 21% more organic matter than the surrounding surface soil after 20 yr. In addition, logging slash is an effective mulching material for maintaining soil moisture and reducing the deleterious impact of rainfall on soil displacement and erosion.

Disturbance of the forest floor and surface soil during harvest results in an initial increase in available N because temperature and moisture conditions improve to simulate decomposition and N mineralization. Breaking organic material into smaller pieces by chopping or discing and incorporating it with mineral soil during site preparation further enhances the mineralization process.

Fox et al. (1983) examined nutrients in the soil solution on an intensively site prepared watershed 3 mo after a shear rake disc treatment and found higher N, potassium (K), calcium (Ca), and magnesium (Mg) levels than occurred prior to harvest. Soil solution nutrients in a chop burn watershed remained unchanged. Aside from leaching losses, Vitousek and Matson (1985) report that Piedmont sites receiving a shear rake disc treatment had 5 to 7 times more N losses via denitrification than sites receiving a chop burn treatment.

Covington (1981) examined nutrient relations with regard to the forest floor and residual logging slash and suggested that the forest floor was the primary supplier of N prior to crown closure whereas logging slash was the primary supplier thereafter. Logging slash is slower to decompose and accumulates nutrients initially via microbial immobilization.

Burger and Kluenderer (1982) hypothesize that intensive site preparation such as the shear rake disc treatment on sites marginally sufficient in N may improve early growth rates because planting proceeds efficiently, competition is held in check, N mineralization proceeds rapidly, and N is available because microbial immobilization is minimal due to the absence of organic carbon. However, long term growth may suffer because slash removal and losses associated with rapid initial mineralization could create a depleted N pool shortly after crown closure; a time when N demands become greatest, particularly on sites marginally sufficient in N and where N inputs are not compensating.

In their review of N in southern pine ecosystems, Neary et al. (1984) indicated that the potential for N deficiencies is large on the Piedmont compared to the Coastal Plain because 55% of the N pool is in the forest floor and overstory compared to 26% in the Coastal Plain. Harvesting or site preparation that removes or displaces these pools could lead to long term N deficiencies. Activities such as whole tree harvesting and delimbing at a central loading area are culprits because they remove foliage and small twigs, the components with the highest N concentrations. Similarly, raking displaces logging slash into windrows and frequently carries much of the forest floor with it (Morris 1983). Since Piedmont sites are prime candidates for N deficiencies, the type of site preparation treatment imposed could have a profound affect on the occurrence of N deficiencies.

Methods for Diagnosing Conditions Limiting Loblolly Pine Growth

CRITICAL LEVELS

The critical value or sufficiency range technique is an extensively used method for diagnosing the occurrence of limiting conditions. Critical or sufficiency values have been primarily used to assess the nutrient status of the soil or foliage (Wells et al. 1973); however, other aspects of the growing environment such as soil aeration, bulk density, temperature, moisture, and competing hardwoods can be evaluated in terms of critical levels (Sands and Rutter 1959, Lull 1959, Grable 1971, Burkhart and Sprinz 1984). Even though this presentation is restricted to nutrient assessments, parallels can be made to the other factors.

The basic concept of critical values is that some minimum amount (the critical value) of a nutrient is required to acheive near maximum growth. Below this level, the nutrient is considered limiting, and above it, luxury consumption is said to occur (Macey 1936). Difficulties arise in the use of critical levels because they are frequently established under assumptions that may not hold in all situations. Foliar critical values, for example, are assumed to be constant; however, the concentration of a mobile nutrient such as nitrogen varies with the type, location, and physiological age of the foliage, in addition to the age of the tree (Miller et al. 1981, Comerford and Fisher 1984). Foliar N levels decline in needles of all ages during active growth and recover during quiescence (Tamm 1955, Powers 1983). Optimum nutrient levels may also vary depending on the type of growth. The optimum foliar N concentration for height growth of *Pinus nigra* is 0.15 g kg^{-1} compared to 0.20 g kg^{-1} for basal area growth (Miller et al. 1981). In addition to these complexities, foliar critical values fail to consider balance or interaction among nutrients (Beaufils 1973). They are single factor oriented.

A critical value has intrinsic appeal for diagnosis, particularly as an initial assessment, and techniques have been proposed to overcome its drawbacks. One technique involves the use of nutrient ratios. Comerford and Fisher (1984) found the foliar N/P ratio the most accurate and consistent index of a N deficiency on clayey Lower Coastal Plain sites. In addition to incorporating balance, ratios are beneficial in that they minimize the effect of changing foliar nutrient concentrations over time. Nutrient ratios eliminate the disproportionate increase in foliar dry matter weight relative to nutrient content as plant tissue ages. Beaufils (1971) found that the concentration of corn declined 40% on a dry matter basis over the growing season, but increased 11% on a fresh matter basis. Standardization of sampling methods and nutrient analysis is also being used to improve the utility of critical values. Such standards are currently being identified in forestry (Miller et al. 1981).

DRIS

The Diagnosis and Recommendation Integrated System (DRIS) is a diagnostic technique that identifies factors limiting plant productivity and has an advantage over critical levels in that many nutrients and their interrelationships can be considered simultaneously. Diagnosis of foliage to correct nutrient deficiences with fertilizer recommendations has been the primary use to which DRIS has been applied and tested (Sumner 1977, Beaufils and Sumner 1977, Jones 1981 Beverly et al. 1986).

DRIS is based on the theory that a plant exhibits or tolerates increasingly less variation in growth-determinant levels as it attains its growth potential. A prerequiste to the use of DRIS for diagnosis is the development of norms or criteria which specify the form a variable should take and the optimum level to be used in an evaluation. Once DRIS norms are established, a site is inventoried and the results are subject to a DRIS evaluation which not only identifies those factors limiting growth, but also provides a relative measure of the degree to which they are limiting.

DRIS has been thoroughly tested for latex production of rubber trees, corn, and sugar cane production (Beaufils 1971, Beaufils and Sumner 1976). It has been found to produce correct diagnoses 73 to 94% of the time compared to 61 to 72% correct diagnoses with critical levels (Beaufils and Sumner 1976). The advantages of DRIS over the critical value approach for diagnosis of crops include (Tisdale et al. 1975):

1. Nutrient balance is taken into account.
2. Assessment criteria (norms) do not appear to be restricted by geographic local.
3. Diagnosis can be made over a wide range of stages in plant development.
4. Nutrients limiting yield either through excess or deficiency can be identified and ranked according to their order of importance.

DRIS is difficult to understand in its current form of presentation and is only beginning to be critically evaluated and researched. Its drawbacks for use in forestry appear to revolve around a lack of understanding, use, and testing. The two published investgations involving the use of DRIS with forest trees parallel those in agronomy. Truman and Lambert (1981) examined the nutrient balance between N,P, and sulfur (S) in the foliage of *Pinus radiata* and Leech and Kim (1981) examined the foliage of hybrid poplar. Both studies followed DRIS procedures put forth by Beaufils (1973), and found DRIS valuable for examining nutrient balance, particularly as it relates to fertilizer recommendations.

CLASSIFICATION

Classification provides a method for identifying limiting factors in a two step process. The first step requires that trees or sites be classified by some predetermined criteria. For example, the SCS soil classification scheme based on soil series has been used to classify sites (McKee 1976, Ballard 1979). Researchers have also classified sites by a measure of productivity, such as site index (Carmean 1975) or a combination of site index, basal area, and mean annual increment (Harding et al. 1985). Comerford and Fisher (1982) classified sites by growth response to fertilization relative to a control, and Leech and Kim (1981) utilized volume growth to classify trees.

Once classified, all soil-site factors which may influence the classification are measured and techniques such as regression, discriminant analysis, and mean and variance evaluations have been used to identify those factors important in separating or distinguishing classes. Regression has been predominantly used, but discriminant analysis is gaining popularity (Harding et al. 1985, Comerford and Fisher 1982). These multivariate techniques have appeal because the classification scheme they attempt to analyze is the result of multiple environmental conditions. In contrast, comparisons of factor means across classes examines factors likely to distiguish classes individually and relies on t-tests or ANOVA to identify significantly different factor means between classes (Jones 1981). Comparisons of factor variances between classes has been little used in forestry. The principle behind it is that a growth determinant exhibits a significantly smaller variance in classes composed of high-yielding members compared to low-yielding counterparts (Beaufils 1973, Comerford and Fisher 1982, Stone 1984). The variance ratio between high- and low-yielding classes is computed for each factor, and, if significant, the factor is identified as important in separating classes.

SOIL-SITE EVALUATIONS

Methods such as classification and DRIS are well suited to identifying limiting conditions if a measure of the degree of response to changes is not required; otherwise, prediction oriented models are preferred. Conceptually, regression-based soil-site evaluations are well suited for such use. They relate some measure of site quality, usually site index, to soil-site factors. The combination of factors that best explain the variation in site index are assumed to control growth. Many regression-based soil-site evaluations have been developed throughout the country; however, their accuracy and utility has generally been disappointing (Carmean 1975). The precision of the equations and the relative importance of the factors comprising the models have been highly variable depending on the study area, the soil-site conditions, and the researcher's ability to define and measure the important growth factors (Carmean 1975). The poor performance of many regression-based soil-site evaluations is often due to the failure of the investigator to realize that site classification may be a prerequisite. When using regression, it is assumed that the factors affecting site index are the same on all sites and that site index varies only according to the level of those factors. The regression coefficients are the same for all sites, implying that a unit change in some factor results in the same change in site index for all sites. However, it is widely believed that while sites may exhibit the same site index, growth may be directed by entirely different factors or in different ways (Carmean 1968).

Coile (1953), for example, reported loblolly pine site index prediction equations in which the imbibitional water value of the B horizon was inversely related to site index on the Piedmont but positively related on the Coastal Plain. Consequently, separate soil-site equations were required for each region.

The best regression-based models are developed when only sites affected by the same factors are included. McKee (1976) predicted site index from soil-site variables both before and after sites were classified by soil series. The coefficient of determination of the equations increased 38 to 52% following classification. Kushla and Fisher (1980) developed regression equations to predict the relative volume reponse of slash pine to phosphorous fertilization for each CRIFF soil group (a forest-soil classification scheme developed for the Coastal Plain). The predictive ability of most equations was high ($R^2 = .98$); however, many variables and coefficients were illogical and could not be interpreted independently.

Multicollinearity, the result of correlation between the independent variables, can cause illogical and uninterpretable coefficients. Unfortunately, many soil-site variables are intercorrelated. Techniques for identifying truly independent variables are available and have been utilized. Principle component analysis (PCA), for example, is a mathmatical technique for summarizing a set of related measurements in terms of a new set of derived components which are defined as independent linear functions of the original variables. Unfortunately, when used to identify the independent variables in soil-site evaluations, the new regression models have exhibited little to no improvement in prediction over original models (Graney 1974, Page 1974). However, a better understanding of the factors influencing site index and their intercorrelations has been obtained.

The use of site index as a measure of productivity is accepted but often debated with regard to soil-site evaluations. Site index is considered to be unaffected by stand density compared to other measures of productivity, and given the age, average height of dominants and codominants, and an appropriate site index equation, it is easily determined. However, finding an accurate equation and assuming that height reflects the growing capacity of a site are also its weaknesses (Carmean 1968). Volume, not height, is usually the growth determinant of interest and there is no reason why two sites with the same site index (height growth potential) should have the same volume growth potential.

Although not based directly on experimentation nor directly derived with statistical methods such as regression, Baker and Broadfoot (1977) have used a wealth of experience to develop a soil-site evaluation technique for diagnosing sites for southern hardwood production. The evaluation predicts site index for a given species from the soil-site conditions assessed on a given site. Height growth is assumed to depend on four primary factors; soil physical conditions, moisture availability during the growing season, nutrient availabilty, and soil aeration. These major factors are composed of specific soil-site factors that account for a portion of the major factors′ contribution to site index. The unique aspect of the approach is that some of the specific soil-site factors influence more than one major factor and as a result contribute to site index in varying ways. Comparing observed conditions with those of an ideal site identifies which conditions are limiting growth, to what extent, and indicates how changes will affect productivity.

GROWTH MODELS

The most complex method for identifying factors limiting growth and for predicting growth responses to treatment, is through the use of growth models. Growth models can be classified as mensurational, environmental or a combination of the two. Mensurational models are extensively used empirical models that rely primarily on site index, age, and a measure of density (number of trees or basal area per unit area) to predict growth and yield. Modifiers that create changes in these three variables account for the effects of fertilization and competition (Belcher 1982, Daniels 1975, Burkhart and Sprinz 1984). The effect of N dynamics on site index has been modeled in a hybrid model known as FORCYTE (Kimmins and Scoullar 1982). The model utilizes mensurational characteristics to grow trees but adjusts those characteristics by simulating biologic processes. Environmental models such as JABOWA (Botkin 1972) are almost entirely biologically process oriented. Growth is expressed as a function of leaf weight, current tree size, and the maximum attainable tree size of the given species. Expansion of JABOWA has led to the inclusion of light interception parameters, transpirational effects (Reed 1980), and soil temperature and moisture relationships as they affect microbial processes and N dynamics (Pastor and Post 1986).

An ultimate goal of many of these models is to depict the forest environment to the extent that growth and yield results of proposed changes to the environment can be accurately predicted. Growth models are valuable because they incorporate many growth and yield determinants simultaneuosly and consider interactions as well as absolute levels. They attempt to model environmental dynamics in the prediction of growth and yield.

SUMMARY

In summary, site preparation is essential for regenerating loblolly pine plantations in the Piedmont and site specific prescriptions are required if intensive forest management is to be successful. The diversity of the Piedmont, both in terms of vegetation and soil-site conditions, prevents solitary use of only one prescription. Competing vegetation, soil physical properties, and nutrition are potential problems exerting limitations on loblolly pine growth; however, identifying levels at which they become a problem has been difficult and has been limited to mature stands. Juvenile stands are only beginning to be researched. In addition, relatively little is known about the extent to which the various site preparation alternatives affect these potential problems. The purpose of this study was to examine competing vegetation and tree nutrition in four-year-old loblolly pine stands; identifying if and when they became problems limiting tree growth; and determining how site preparation affected them.

Methods

Historical Review

A site preparation research project was initiated in 1980 on twelve, 16 ha study sites located across four counties in the South Carolina and Georgia Piedmont. Prior to harvest, each study site was inventoried using 40 systematically-located sample points. Pine and hardwood stand-level data were obtained by point sampling and soil-site data were collected. Except for one site which was harvested by a shortwood operator who delimbed all felled trees on site, the sites were clearcut and only hardwoods were delimbed on site. Pines were skidded full length to a landing area where they were delimbed using a delimbing gate.

The seven site preparation treatments descibed in Table 1 were installed on each study site. The treatments include no preparation, in which seedlings were planted in untreated areas (no preparation or untreated); a chop followed by a broadcast burn treatment (chop burn); an aerial application of glyphosate followed by a broadcast burn (herbicide burn); shearing residual trees while simultaneously pulling a disc harrow to till the soil (shear disc); shearing residual trees followed by a second operation in which debris was aligned into "mini windrows" with a V-blade while the soil was simultaneously tilled with a disc harrow (shear V-blade disc); shearing residual trees followed by raking the debris into windrows in a second operation (shear rake); and, shearing resi-

Table 1. Description of seven site preparation treatments applied on each of 12 sites in the South Carolina and Georgia Piedmont in a randomized complete block experimental design.

TREATMENT	NUMBER MACHINE PASSESS	PLANTING METHOD	DESCRIPTION
No Preparation	0	Hand	No site preparation following harvest.
Herbicide Burn	0	Hand	Glyphosate in water aerially applied in mid September at 3.9kg/ha ai. Burned 6 weeks later.
Chop Burn	1	Machine	An empty 3m wide double drum offset chopper behind a D7 tractor. Burned 2-6 weeks later.
Shear disc	1	Machine	KG blade on D7 sheared and aligned debris while pulling tandem harrow (35" discs) to till the soil.
Shear V-blade disc	2	Machine	Residual vegetation sheared with a KG shearing blade on first pass. V-blade mounted to D7 created mini windrows while pulling tandem harrow (35" discs)
Shear Rake	2	Machine	Residual vegetation sheared with KG blade on first pass. Slash raked into windrows on second pass.
Shear Rake Disc	3	Machine	Residual vegetation sheared with KG blade. Slash raked into windrows. Soil disced with tandem harrow (35" discs).

dual trees, raking the debris into windrows, and tilling the soil with a disc harrow in three separate operations (shear rake disc). While the treatments are not all-inclusive of the many alternatives, they represent a range of operationally feasible site preparation prescriptions varying in cost, method (i.e. mechanical versus chemical), and degree of site disturbance.

The experiment is a randomized complete block design with five permanent sampling plots (subplots) approximately 0.04 ha in size located within each treatment area.

Approximately 6 mo after site preparation, seedlings were planted (March 1981), their location mapped, and post site preparation soil-site data were collected at each permanent plot. Competition, soil and foliar nutrients, and soil erosion were measured annually for the first 2 yr while tree growth and survival were measured for the first 3 yr. Since the permanent sampling plots were not located in the same place as preharvest inventory plots, pre- and post-harvest comparisons were based on average conditions of the treatment areas.

A more detailed presentation of the study layout, preharvest data, and results through two growing seasons can be found in Lantagne (1984).

Sampling Methods and Data Collection

Individual trees were the sampling unit for the assessments at age four with nine trees in each treatment area randomly selected from within the permanent sampling plots. Competing vegetation measurements, foliage samples, soil samples and tree size measurements were obtained. The information was used in 1) an individual tree assessment in which tree size was related to competing vegetation or nutritional factors and 2) in an assessment of treatment effects on competition and tree nutrition. The spatial distribution of seedlings was investigated using the seedling location maps of the 420 permanent sampling plots. Planting and surviving seedling spatial patterns were examined by treatment. Methodology specific to each aspect of the research is presented in subsequent chapters.

Results and Discussion

Four individual papers each with its own introduction, methods, results, and discussion sections follow. The first paper examines competing vegetation in four-year-old loblolly pine stands. Competing vegetation levels between the seven site preparation treatments are compared, changes in competition levels over time are examined, and the relationship between competition and tree size is investigated. Papers two and three examine tree nutrition. In the second paper, site preparation treatment effects and the relationship between tree size and nutrition is investigated with DRIS, which is critically reviwed and evaluated. In the third paper, critical level and DRIS theory are discussed, the relationship between the two examined, and an illustration of how and why DRIS can be used to determine nutrient critical levels is presented. The last paper examines site preparation treatment effects on the spatial distribution of seedlings at planting and after two years of mortality.

Competition Four Years After Site Preparation

INTRODUCTION

Hardwood and herbaceous competition can be important factors limiting loblolly pine growth in the Piedmont of the southeastern United States. Research begining in the 1950's and extending into the 70's investigated the need for controlling competing vegetation following the conversion of hardwood stands and mixed pine-hardwood stands to pine plantations. The results show a significant and consistent increase in growth when pine seedlings were released from over-topping residual competitors compared to no release (Muntz 1951, Shoulders 1955, Miller and Tissue 1956, Hatchell 1964). Competition from understory vegetation, or that vegetation that predominates after the elimination of the overstory, can also affect the growth of pine seedlings. Current research is directed toward assessing this affect; however, the results have been less conclusive than with overstory competition (Carter et al. 1975, Cain and Mann 1980, Stransky 1980, Bacon 1986).

Sampling competition has proved to be an arduous task and numerous competition components have been measured. Glover (1982) found hardwood basal area, number of rootstocks, and average hardwood height most appropriate in juvenile stands while Bacon (1986) found the proportion of total basal area in hardwoods and the presence or absence of herbaceous cover the best measures. Burkhart and Sprinz (1984) found the proportion of total basal area in hardwoods the best measure after crown closure.

Survival and early growth of loblolly pine in plantations is enhanced by site preparation (Pehl and Bailey 1983, Lantagne 1984, Stafford et al. 1984) and the improved performance is often attributed to control of overstory and understory competition although little is known about competition dynamics following site preparation.

The objectives of this study were to compare competition levels in four-year-old loblolly pine plantations that were established using seven different site preparation methods and to relate the competition levels to tree size after four growing seasons.

METHODS

Within the framework of the site preparation study, competition was measured in late summer of the fourth growing season around 756 randomly selected trees that were located in the permanent sampling plots in each site preparation treatment area. Each treatment and site was equally represented. A circular plot whose radius was equal to the height of each sample tree was established and the following competition measurements taken:

1. Total height and the crown dimensions of all hardwood stems by species,
2. the height and crown dimensions of woody shrubs,
3. an occular estimate of percent herbaceous cover, and
4. a 1 to 5 ranking to reflect the pine's free-to-grow status, where 1 indicated free to grow, 5 indicated suppression, and 2 through 4 represented a corresponding gradient.

Species-specific regression equations were used to convert crown dimensions to ground line basal area (Bacon, 1986). The free-to-grow ranking criteria used (Appendix A) were similar to those proposed by the Virginia Division of Forestry (Dierauf and Garner).

The basic measures of competition were used both individually and in the derivation of 1) hardwood basal area per ha, and 2) percent hardwood basal area. Percent hardwood basal area is the proportion of total basal area in each plot consisting of hardwood basal area. A potential bias in the estimate of percent hardwood basal area as a result of using a variable sized plot was investigated by examining the linear relationship between pine basal area and pine tree height-squared. There was no evidence to suggest that the measurements were biased.

Competition had been assessed the first and second growing seasons after site preparation using the line transect method. Estimates of the percent cover of various competition components were made (Lantagne and Burger 1986). These measures along with preharvest hardwood basal area were used to investigate changes in competition levels over time.

Analysis of variance was used to assess the effect of treatment on competition after averaging competition levels across treatment areas. Regression and scatter diagrams were used to investigate competition effects on indiviudual tree size.

RESULTS and DISCUSSION

Treatment Comparisons

The percent cover of herbaceous, woody shrub, and hardwood competition by treatment after 4 yr is presented in Table 2. Except for the areas receiving no site preparation (33% herbaceous cover), herbaceous coverage was similar among treatment areas, averaging 65%. There were no differences in the amount of hardwood cover among site prepared areas, which averaged 20% compared to 35% in the untreated areas. Woody shrub cover was low, 1% on the average, and there was no treatment effect. The total percent cover shows that the sites were not fully occupied and that competition for resources was only beginning to occur at age four.

Preharvest and fourth-year hardwood basal area results are compared in Fig. 1 and Table 3. Preharvest levels averaged 5.1 $m^2\ ha^{-1}$ or 20% of the total basal area with no significant differences among treatments (Fig. 1). By age four, hardwood basal area was significantly less than preharvest levels in all but the untreated areas which remained unchanged. Analysis of covariance indicated no significant preharvest hardwood basal area influence on hardwood basal area levels occurring at age four. There were no significant differences in hardwood basal area levels among treatments at age four with the exception of the untreated areas which averaged 5.2 $m^2\ ha^{-1}$ (Table 3) and the herbicide burn areas which supported an average hardwood basal area of 2.4 $m^2\ ha^{-1}$. The very intensive shear rake disc treatment areas supported significantly lower levels averaging 1.2 $m^2\ ha^{-1}$.

Table 2. Site preparation treatment comparison of competition crown cover at age four and the change since year two on sites in in the S. Carolina and Georgia Piedmont.

Site Preparation Treatment	Herbaceous		Woody Shrub		Hardwood		Total	
	Year 4	Change	Year 4	Change	Year 4	Change	Year 4	Change
	%							
No Preparation	33.3a[1]	-1.9[2]	0.8a	-6.3	35.0b	11.8	72.2a[3]	1.0
Herbicide-Burn	61.9b	22.8	1.1a	-10.6	23.2ab	12.7	91.7b	16.5
Chop-Burn	67.2b	30.6	1.9a	-7.0	24.2ab	18.4	102.3b	35.3
Shear-Disc	67.6b	39.3	2.0a	-4.7	16.7a	12.9	96.5b	27.3
V-Blade Disc	64.5b	36.2	1.2a	-4.8	22.1ab	16.9	96.0b	31.3
Shear-Rake	64.4b	30.4	1.5a	-3.4	18.9a	11.6	94.1b	26.9
Shear-Rake-Disc	64.2b	39.6	1.1a	-5.0	15.1a	12.0	93.5b	34.3
Average	64.9	28.1	1.4	-6.0	22.2	13.7	92.3	24.6

[1] Values are means of 12 observations. Each observation is a composite of 9 subsamples. Means within columns followed by the same letter are not significantly different at $p < 0.05$ according to Duncan's multiple range test following an acrsine data transformation.

[2] Change= year 4 - year 2.

[3] Total cover includes pines.

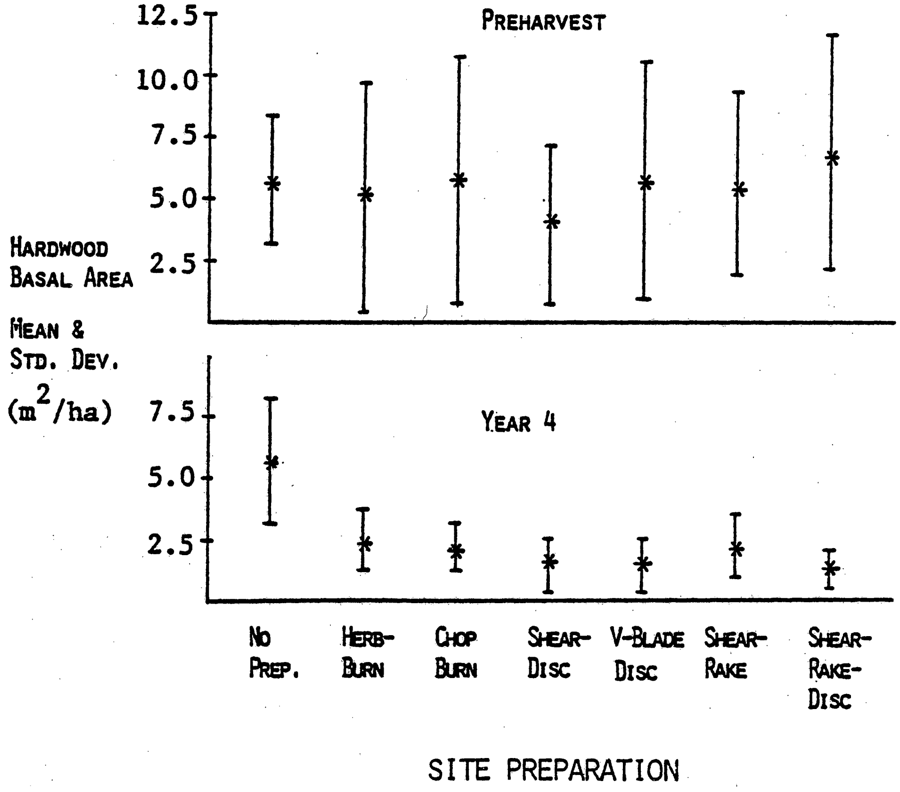


Figure 1. Site preparation treatment comparison of pre-harvest hardwood basal area and that occurring after four growing seasons in loblolly pine plantations in the S. Carolina and Georgia Piedmont.

Table 3. Site preparation treatment comparison of hardwood competition in the S.Carolina and Georgia Piedmont four growing seasons after regeneration.

Site Preparation Treatment	Hardwood Basal Area	Percent Hardwood Basal Area	Free-to-Grow Rank
	(m^2 ha^{-1})	(%)	
No Preparation	5.2c	85 d	3.6
Herbicide-Burn	2.4b	68 c	2.0
Chop-Burn	2.0ab	59 bc	1.6
Shear-Disc	1.4ab	43 a	1.4
V-Blade Disc	1.4ab	49 ab	1.4
Shear-Rake	2.0ab	59 bc	1.6
Shear-Rake-Disc	1.2a	43 a	1.3

[1] Values are means of 12 observations. Each observation is a composite of 9 subsamples. Means within columns followed by the same letter are not significantly different at $p < 0.05$ according to Duncan's multiple range test following an arcsine data transformation for variables expressed as a percent.

In general, all treatments were equally successful in reducing the level of competing hardwood basal area.

The free-to-grow status of the pines was similar in all areas except the herbicide burn and untreated areas which averaged 2.0 and 3.6, respectively, compared to an average rank of 1.5 for the other treatments (Table 3). Even though the herbicide burn rank is greater than the others, it is below the 2.5 rank used to indicate that a release treatment is justified (Todd 1983).

Percent hardwood basal area was significantly different between some treatments. The shear disc and shear rake disc treatment areas exhibited significantly lower levels than the non-disced treatment areas (Table 3). The differences in percent hardwood basal area were generally due to treatment differences in pine growth rates compared to hardwood growth rates. Pine growth rates were greater in the chop and disced treatment areas compared to areas receiving no site preparation or the herbicide burn treatment (Fig. 2), while changes in hardwood levels were the same or less in the no preparation and herbicide burn treatment areas compared to the disced treatment areas between year two and four. (Fig. 3). Consequently, percent hardwood basal area tended to be less in areas receiving a chop or discing treatment compared to areas receiving no soil tillage.

The change in herbaceous, woody shrub, and hardwood competition cover among treatments from year two to four is presented in Table 2. All site prepared areas exhibited a large increase in herbaceous cover, 33% on the average; however, those that were disced exhibited the largest increases, 10 to 15% larger than non-disced areas. Woody shrub coverage declined in all treatment areas and hardwood cover increased an average of 14%. Figure 3 illustrates the change in hardwood cover associated with each treatment since year one. Except for the chop burn and V-blade disc treatment areas which had greater hardwood cover increases from year two to four than the others, the increases were similar among treatments. Hardwood growth rates increased during the year two to four period relative to the year one to two period in those areas that were chopped or disced, and exhibited no change or a decrease in those treatment areas not receiving some form of soil disturbance.

Relative increases in hardwood crown cover from year two to four were also greater, nearly three times, in those treatment areas receiving some form of soil disturbance compared to the no

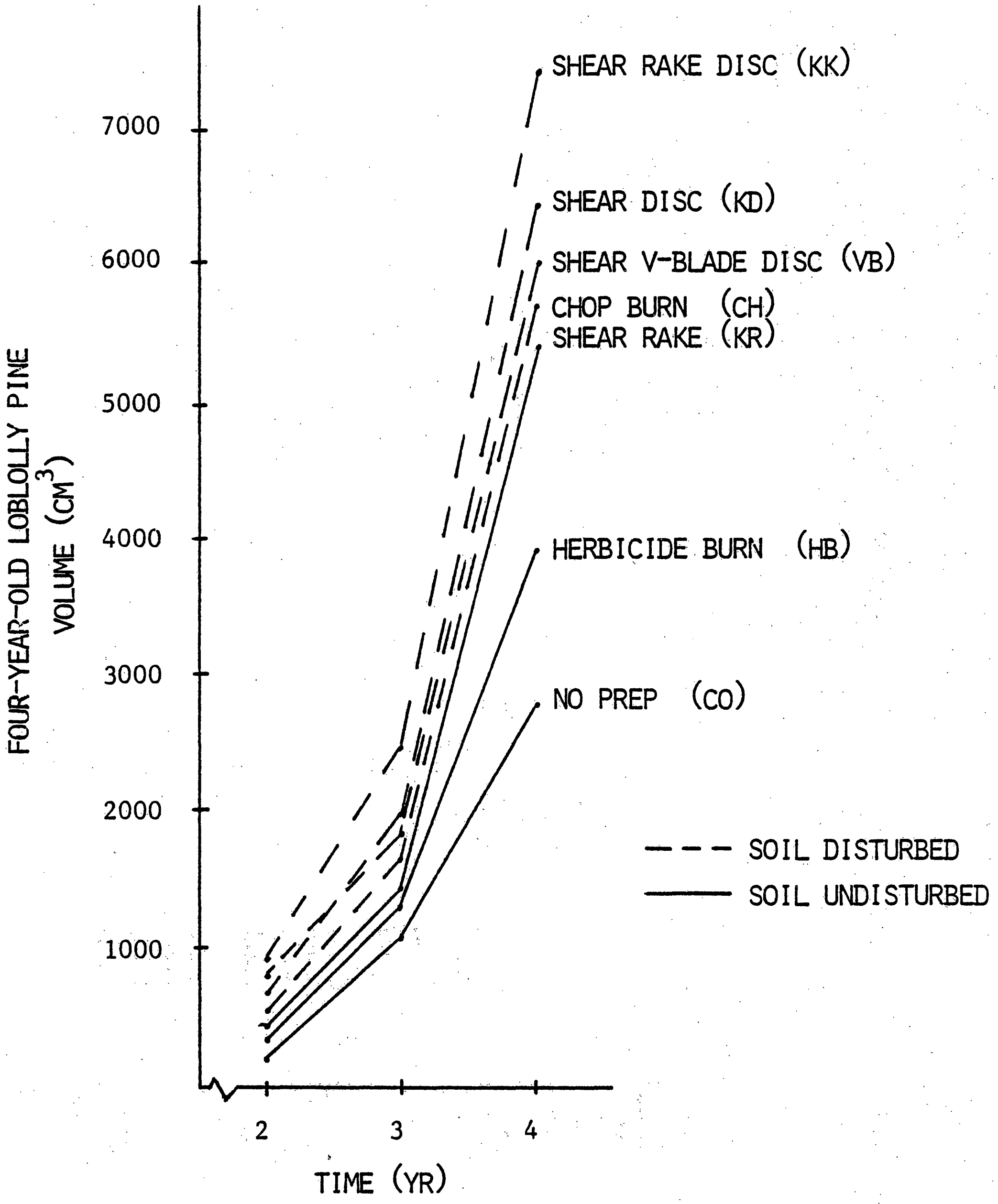


Figure 2. Loblolly pine volume growth in the S. Carolina and Georgia Piedmont during the first four years after regeneration using seven different site preparation treatments.

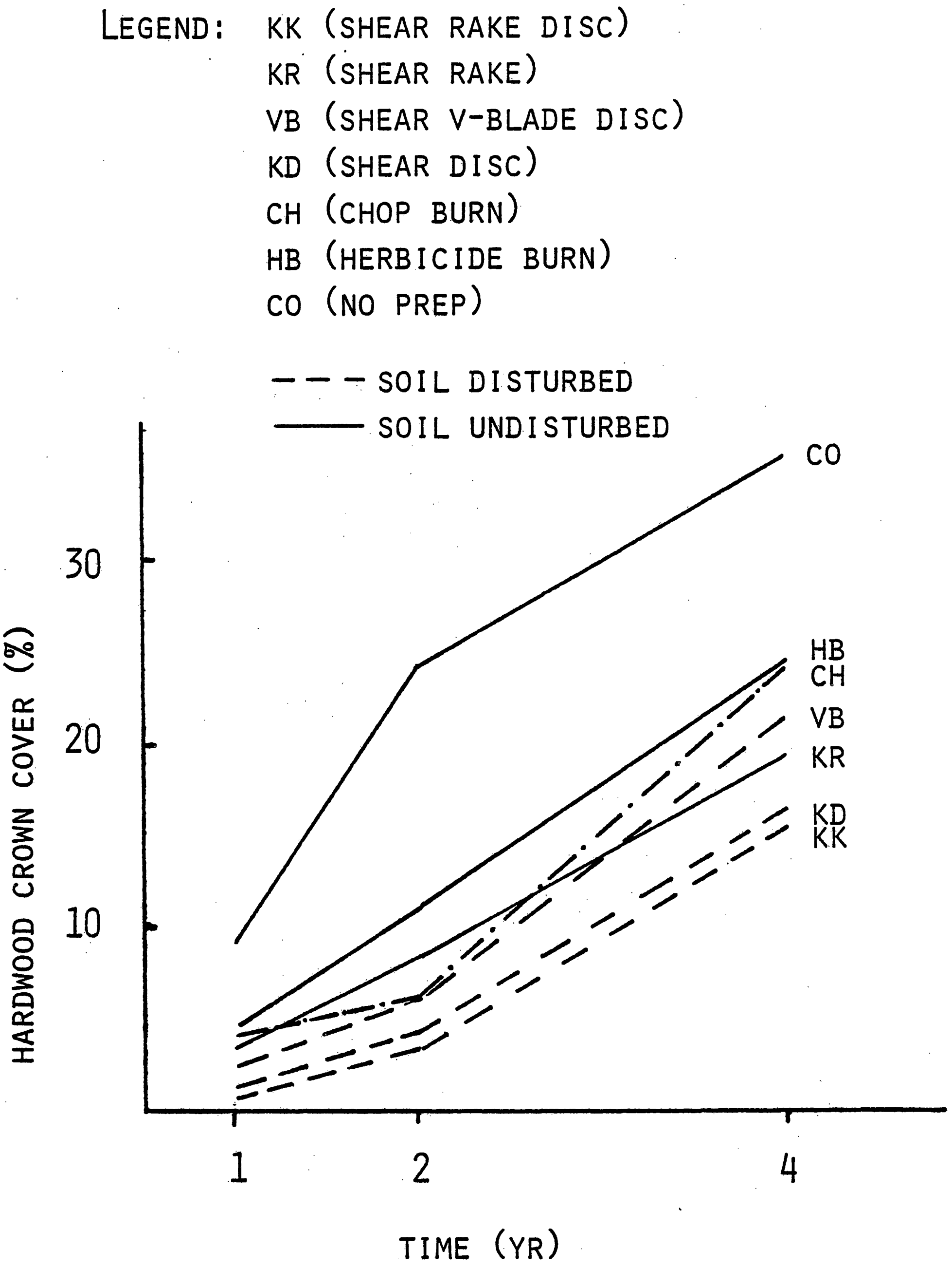


Figure 3. Percent hardwood crown cover during the first four years after loblolly pine stand regeneration using seven different site preparation treatments in the S. Carolina and Georgia Piedmont.

Table 4. Relative change in percent hardwood crown cover over time in seven different site preparation treatment areas in the S. Carolina and Georgia Piedmont.

Site Preparation Treatment	Hardwood Cover Year 1	Year 2 Increase Above Year 1	Year 4 Increase Above Year 2
	- - - - - - - -	%	- - - - - - -
No Preparation	9.2d[1]	152[2]	51[3]
Herbicide-Burn	4.4c	140	121
Chop-Burn	2.7b	115	317
Shear-Disc	1.8a	116	339
V-Blade Disc	2.1ab	147	325
Shear-Rake	2.8b	161	159
Shear-Rake-Disc	1.3a	138	387

[1] Values are means of 12 observations. Each observation is a composite of 5 subsamples. Means within columns followed by the same letter are not significantly different at $p < .05$ according to Duncan's multiple range test following an arcsine data transformation

[2] Percent Increase = ((Year 2 - Year 1)/ Year 1) x 100

[3] Percent Increase = ((Year 4 - Year 2)/ Year 2) x 100

preparation, herbicide burn, and shear rake treatment areas (Table 4). They were also higher in the year two to four period than the year one to two period in treatment areas receiving soil disturbance, but remained unchanged or declined in the other treatment areas over these two periods. In short, while chopping and particularly discing stifled hardwood competition and its growth initially, they appear to have provided an environment favorable for accelerated growth thereafter.

The question is whether hardwood levels were low enough to foster pine growth and permit the pines to establish dominance and control. Hardwood cover levels were similar among treatments at age four; however, at year two they were significantly different (Lantagne and Burger 1986), which may partially account for the differences in pine growth patterns among treatments at year four (Fig. 2). The lower hardwood cover levels at year two in the chopped and disced areas (Fig. 3) indicate better initial hardwood control by these treatments compared to treatments that did not disturb the soil. Accelerated hardwood growth thereafter suggests that the competition had recovered under the favorable growing conditions that were created. Bacon (1986) found hardwood control at the beginning of the second growing season resulted in the best relative pine growth whereas control during later periods was less effective at increasing pine growth relative to the untreated pines. In short, competition levels at year two may be important to subsequent pine growth.

In summary, the results of treatment comparisons indicate that control of preharvest competition was achieved in areas receiving a site preparation treatment. The type and intensity of site preparation created only small differences in the competition levels by age four. All measures of hardwood competition exhibited similar results. Most of the difference in competition levels occurred between treatment areas receiving some form of soil disturbance and those not chopped or disced. While a competition problem was only beginning to prevail at age four as the stands were just beginning to reach full occupancy, competition levels at age two may have influenced tree size at age four. There were significant differences in hardwood competition levels among treatments at age two with those receiving a chop or disc treatment being lower (Lantagne and Burger 1986). Hardwood competition accelerated in these treatment areas over the period from year two to four so that by age four, there were no differences in competition levels among treatments.

Individual Tree Assessment

The relationship between individual tree size and the competition variables was examined both with and without regard to treatment. Overall, no single competition variable explained a large portion of the variation in tree size. Hardwood basal area, percent hardwood basal area, and percent herbaceous cover were the competition variables most associated with tree growth. Other research has also shown them to be the best measures for describing the competition tree size relationship (Bacon 1986, Burkhart and Sprinz 1984, Glover 1982). Diameter of the pines was generally more sensitive to tree size than height or volume.

Across all treatments, no relationship between pine ground-line diameter and percent herbaceous cover was evident. Within individual treatments, percent herbaceous cover accounted for no more than 3% of the variation in pine diameter, and this occurred in the chop burn treatment areas. The percent herbaceous cover within each treatment accounted for more variation in pine tree height than diameter; however, it amounted to no more than 7% of the total and was typically about 2%.

Percent hardwood basal area exhibited the strongest relationship with pine ground-line diameter. Overall, the R^2 was 0.10. The strength of the relationship was entirely dependent on the small-diameter trees occurring at the highest percent hardwood basal area levels (Fig. 4). The segmented regression line depicted in Fig. 4 indictes that prior to the join point there is no relationship between diameter and percent hardwood basal area. Above 83% hardwood basal area, the relationship is fairly strong with an R^2 of 0.44. The pine trees affected by high levels of hardwoods were predominantly located in the untreated areas; however, all treatments had some pines affected by high levels of hardwood competition. All treated areas also had pines affected by the entire range of percent hardwood basal area. Except in the herbicide burn treatment, the relationship between pine diameter and percent hardwood basal area was similar, with no relationship occurring prior to 83% hardwood basal area. The herbicide burn treatment was only slightly different in that it exhibited a significant, albeit small negative slope from 0 to 83% hardwood basal area at which point the relationship became stronger and followed the trend of the general relationship.

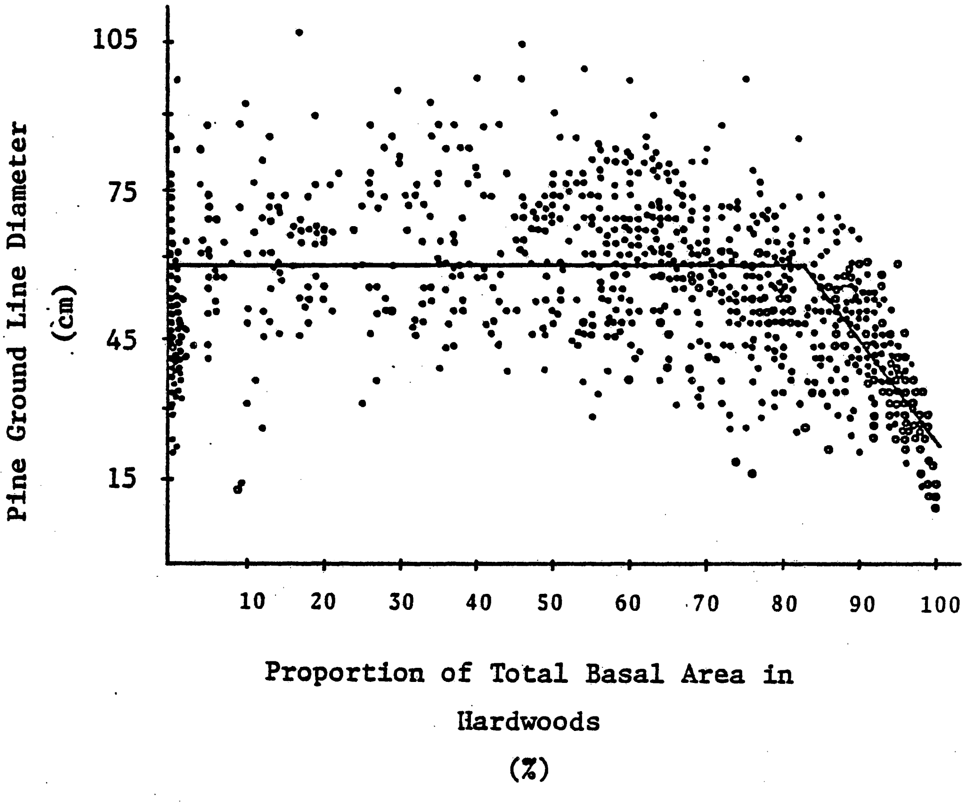


Figure 4. Scatter diagram of the proportion of total basal area in hardwoods (percent hardwood basal area) and loblolly pine ground-line diameter after four growing seasons with a segmented regression line to describe the relationship.

The join point might be considered a "critical" or response level. It is the level at which competition becomes a significant factor limiting tree size, and below which percent hardwood basal area is not related to tree diameter. Only 25% of the trees sampled had percent hardwood basal area levels greater than 83%, and 16 of these 25% were from the untreated areas.

Figure 5 is a scatter diagram depicting pine ground-line diameter as a function of hardwood basal area. Again, no strong relationship is evident, indicating that hardwood competition is not the predominant factor affecting pine diameter. The average hardwood basal area is only 1.7 m^2 ha^{-1} which is low compared to the 5.2 m^2 ha^{-1} average found on the untreated areas. A boundry line indicating the upper diameter attainable given any level of hardwood basal area is depicted on the scatter diagram. The curve indicates that the probability of obtaining the largest diameters occurs between 0.25 and 3.5 m^2 ha^{-1} hardwood basal area. Outside this range, diameters become significantly less and on the upper end of the range, diameter drops off precipitously. If hardwood competition, expressed in terms of hardwood basal area, were the only or the predominant factor limiting tree size (diameter), all data points would fall close to this boundary line (aside from measurement error, etc.). The actual data distribution is quite distant from the boundary line.

In short, hardwood competition on prepared sites did not appear to be the predominant growth limiting factor at age four. The variation in tree size must have also been due to other site factors as a result.

CONCLUSION

There were significant differences in tree size among the seven site preparation alternatives after four growing seasons. However, there is little evidence to suggest that the level of competing vegetation at age four was the predominant factor affecting those differences. There were few significant differences in competition levels among the various treatments and individual tree assessments showed very weak relationships between the levels of hardwood competition that exsisted and tree size.

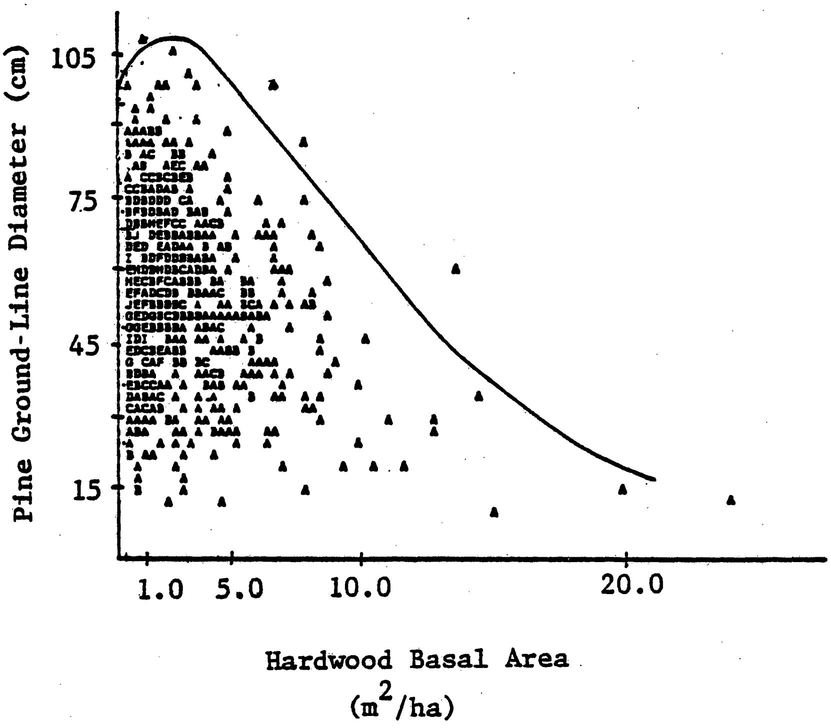


Figure 5. Scatter diagram of hardwood basal area per hectare and loblolly pine ground-line diameter after four growing seasons. The boundary line indicates the maximum pine diameter for a given hardwood basal area level.

All measures of hardwood competition, i.e. percent crown cover, hardwood basal area, and percent hardwood basal area, exhibited similar treatment differences which not only adds strength to the conclusions, but indicates that no one measure is likely to be superior. Selection of the most appropriate measure depends on the needs of the user.

Although competition levels were similar among treatments at age four, they were different at age two. Hardwood growth rates in chopped and disced areas accelerated faster after the second year than hardwood growth rates in treatment areas receiving no soil disturbance. Pine growth rates also accelerated faster in those areas receiving soil disturbance compared to areas where soil was not disturbed. Together these indicate that hardwood levels at year two may be important to susequent pine growth and development.

Although competition alone, at least as of year four, was not the predominant factor limiting the growth and development of the pines on the site prepared areas examined in this study, this is not to say that in some instances competition was not the most limiting factor. When percent hardwood basal area levels were greater than 83% or hardwood basal area was greater than 3.5 m^2 ha^{-1}, competition predominated. Below these levels, other factors were likely to have played an important role either in combination with, or in place of competition to limit loblolly pine growth.

A DRIS Nutrient Assessment of Four-Year-Old Loblolly Pine

INTRODUCTION

Systematic identification of the soil-site factors having a predominant influence on loblolly pine growth in the Piedmont of the southeastern U.S. formally began in the 1950's. The emphasis at that time was on soil physical properties (Coile 1952). More recently, tree nutrition has become an important consideration, particularly since whole tree harvesting and many stand establishment practices remove logging slash from a site prior to planting. Among other attributes, the logging slash contains a store of nutrients on what is otherwise considered a marginally nutrient sufficient landscape (Neary et al. 1984).

Assessing the nutritional status of loblolly pine growing in the Piedmont has been accomplished with varying degrees of success using foliar and soil critical levels. Foliar analysis is the favored method since the plant is the object of interest and an integrator of the many environmental factors acting upon it. The use of foliar critical levels has a long history and is fairly well established with most agronomic crops; however, this is not the case with loblolly pine. Relatively few studies have been explicitly designed to study foliar critical levels, and except for N and P, little work has been done to support or validate them.

Foliar critical levels are reported to vary according to the type, location, and physiological age of the foliage, age of the tree, the status of other elements in the tree, atmospheric and soil meteorologic conditions, and variety or cultivar (Miller 1966, Snowdon 1973, Bevege 1978, Miller et al. 1981). They also vary depending on the type of growth considered. Miller et al. (1981) reported that foliar critical levels were different for height growth than basal area growth. This variation makes the establishment and utilization of critical levels difficult and possibly unreliable for nutrient assessment.

One method for improving the stability of critical levels, at least with respect to sampling time, may be to use nutrient ratios in their development. Nutrient ratios eliminate a major factor affecting foliar critical levels, namely the accumulation of dry matter weight over time. The foliar concentration of a mobile nutrient such as N declines with foliage age partly because the dry matter weight of the tissue increases disproportionately with the increase in N content (Beaufils 1971, Sumner 1977). The use of nutrient ratios has an additional advantage in that it provides an assessment of nutrient balance. Nutrient balance has been found to be as important for high yields as are sufficient concentrations of individual nutrients (Heeney and Hill 1961, Bevege 1978, Comerford and Fisher 1984). Standardization of sampling methods and nutrient analysis is also used in agronomy to minimize nutrient variation and improve the utility and validity of foliar critical levels; however, such standards are only in the developmental stage in forestry (Miller et al. 1981).

Soil analysis has been used to assess the nutritional status of loblolly pine with varying degrees of success even though it does not directly assess the trees nutritional status. Soil nutrient critical levels have been established for some nutrients; however, since both soil type and nutrient-extraction method affect the results, the interpretation and utility of soil critical levels are limited (Wells et al. 1973, Lea et al. 1980). Soil critical levels for N, P, K, Ca, or Mg are not well established (Wells et al. 1986) because of the heterogeneous nature of the Piedmont. As such, an assessment of tree nutrition using soil analysis alone is inadequate.

An alternative to critical levels for assessing the nutritional status of plants via foliage or soil analysis is a technique known as the Diagnosis and Recommendation Integrated System or DRIS (Beaufils 1973). DRIS is in its infancy with regard to application and degree to which it is understood; however, it is gaining popularity in agronomy. It is only beginning to be explored for use with forest trees (Truman and Lambert 1981, Leech and Kim 1981).

DRIS theory states that as plants approach their growth potential, they exhibit and tolerate increasingly less variation in nutrient concentrations. The probability of maximum growth is greatest at optimum nutrient levels and declines as nutrients deviate from the optimum. The scatter diagrams in Fig. 6 illustrate this concept. A nutrient index of zero indicates an optimum level, and as the nutrient level deviates from the optimum, the liklihood of obtaining high yields declines, as indicated by the boundary lines.

DRIS relies on nutrient ratios for assessing nutrition not only because they add stability to the assessment, but because they provide a direct link between nutrients, allowing them to be assessed relative to, and under the influence of, one another. As a consequence, nutrient balance is incorporated into the assessment and nutrients can be ranked according to their deficiency or excess relative to one another. The relative status of nutrients is expressed in terms of indicies rather than absolute levels.

DRIS diagnoses are usually superior to those made using critical levels because secondary and tertiary limiting nutrients can be identified by DRIS whereas they may go undiagnosed with critical levels. In addition, since DRIS relies on nutrient ratios, daily and seasonal nutrient fluctuations unrelated to absolute nutrient levels but influential to nutrition are minimized.

The objectives of this study were to determine DRIS indicies for four-year-old loblolly pine and examine the utility of the findings for assessing pine nutrition following various site preparation alternatives.

Methods

Sampling and Laboratory Procedures

A random sample of 504, four-year-old loblolly pine trees growing in the South Carolina and Georgia piedmont were obtained for study. The trees were located in permanent plots across eight study sites. Each site and site preparation treatment area was equally represented.

Foliage was collected from the upper third of each tree crown during the summer of the fourth growing season between August and September and during the following winter between January and February. Sampling was confined to those needles that emerged during the first needle flush the

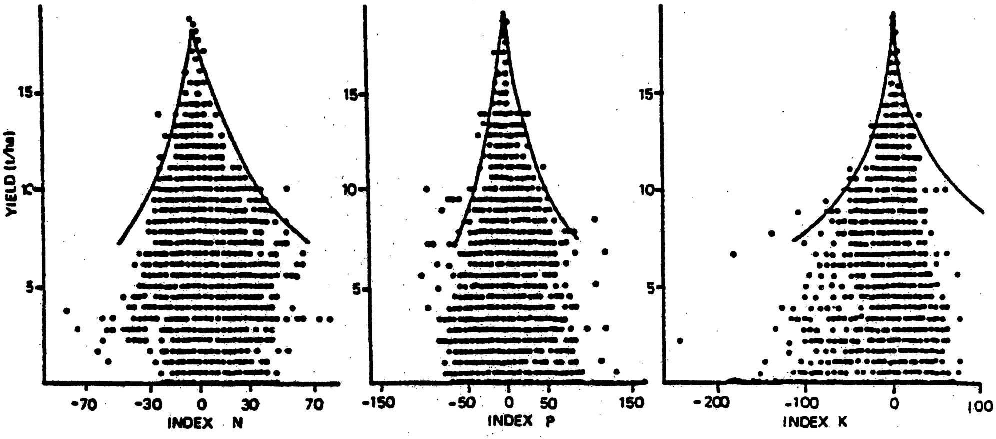


Figure 6. Scatter diagrams illustrating DRIS theory using corn yields: The range in DRIS nutrient indicies declines as yield increases as indicated by the boundary lines (from Walworth et al. 1986).

spring of the fourth year. The foliage was oven dried to a constant temperature of 65C and ground in a Wiley mill to pass through a 0.25 mm mesh screen. The N concentration was determined using a micro-Kjeldahl procedure with analysis performed on a Technicon Auto Analyzer. Phosphorous, K, Ca, and Mg were extracted with 6M HCl following dry ashing at 500C for 8 hr. Phosphorous was determined colorimetricly by the phosphomolybdate complex while cations were determined by atomic absorption (Ca and Mg) and flame emmission spectrometry (K). National Bureau of Standards Pine Needle Tissue (NBS 1979) was used as a calibrant for all elements.

A composite soil sample to a depth of 20 cm was also collected during the winter sampling period. Soil cores were extracted at the four cardinal positions around each tree, two within and two between planting rows. The sampling distance from each tree was the lesser of the height of the tree, half the distance to the adjacent tree or row, or beneath the mini-windrow of logging slash created during site preparation by the shear disc and shear V blade disc treatments. The soil was air dried and sieved to pass through a 2 mm screen. Nitrogen was assessed following extraction with KCl, and P, K, Ca, and Mg were assessed following extraction with double acid (0.5M HCl and 0.25M H_2SO_4). Nitrogen and P were analyzed on a Technicon Auto-analyzer, while the cations were analyzed by atomic absorption (Ca and Mg) and flame emmission spectrometry (K). Samples from two randomly selected soils were carried through each run of the extraction and analysis procedures and served as a calibrant.

Total tree height (H) and ground line diameter (D) were measured during the foliage-collection periods and used singly or in the formation of volume index ($V = D^2H$). The same measurements were also obtained on all sample trees during the winter after the third growing season and used to determine absolute and relative growth measurements. In all, the following size or growth parameters were examined to see which were most suitable to a DRIS assessment:

1. Total tree height at age four (H_4)
2. Ground line diameter at age four (D_4)
3. Volume (D^2H) at age four (V_4)
4. Height growth (H_4-H_3)
5. Diameter growth (D_4-D_3)
6. Volume growth (V_4-V_3)

7. Relative height growth $((H_4-H_3)/H_3)$
8. Relative diameter growth $((D_4-D_3)/D_3)$
9. Relative volume growth $((V_4-V_3)/V_3)$

DRIS Derivation and Analysis

DRIS assessments are based on the identification and separation of plant populations into two groups, those exhibiting desirable (good) growth and yield characteristics and those exhibiting undesirable (poor) characteristics. The nutritional status of plants in the desirable or reference population serve as the basis for all DRIS evaluations. Therefore, accurately identifying good and poor populations is important. Since no standards are established in forestry from which to determine good and poor populations of juvenile trees, individuals in the upper quartile of a given growth characteristic were identified as the good population while the remainder were considered undesirable. The objective of this criterion was to have a sufficiently large number of samples in the desirable population, but ones that also reflected the growth potential of the trees.

The various expressions of tree size and growth and the nutrient concentration data from two foliage sampling seasons were examined to identify which were compatible with DRIS theory. The criterion to evaluate these was the number of nutrient ratios that would make a significant contribution to the DRIS assessment. Significant ratios were those in which the variance of a nutrient ratio in the good population was significantly less than its counterpart in the poor population.

This criterion is slightly different from those initially proposed by Beaufils (1973) where he suggested that significant ratios should have the following characteristics:

1. A normal distribution in the good population.
2. A mean value that was not significantly different between good and poor populations.
3. A significantly smaller variance in the good population than in the poor population.

Reasons for the normality requirement are not apparent for rarely do the ratio of two numbers result in a new variable with a normal distribution. Empirical evidence from this study and others (Walworth et al. 1986) corroborates this statistical theory. Of the 225 ratios examined here, less than

1% exhibited a normal distribution when evaluated using the Kolmogorov-Smirinov test for normality. As a result, the normality criterion was considered unsubstantiated and dropped. The criterion of similarity among population means was examined by Jones (1981) who illustrated both theoretically and empirically that a significant difference in the means between good and poor populations was a valuable characteristic of a significant ratio that would not detract from a DRIS assessment. Therefore, the no difference between means criterion was also dropped. The variance criterion was maintained since it is the essence upon which DRIS theory is based.

Table 5 contains a list of the possible combinations of mean and variance nutrient ratio differences between good and poor populations and ranks them with regard to the strength they give a DRIS formulation. The first three give DRIS its power to discriminate because they fulfill the criteria of a significant ratio. The fourth can at best be considered neutral (Beaufils 1973). The others are undesirable since they describe a condition in which the variance of the nutrient ratios is greater in the good population than the poor, which is counter to the theory upon which DRIS is founded.

In this study, there were 20 possible nutrient ratio combinations considered for inclusion in the DRIS assessment. Since a ratio and its inverse cannot both be used, only the more significant of the two was included and at most 10 different ratios could be used.

If significant, the concentration of each nutrient (% of dry matter) was also used in the DRIS assessment (Walworth et al. 1986). Nutrient concentrations expressed on a percent basis are ratios of the nutrient content to dry matter weight and their use is compatible with DRIS theory. They should be benefical to the assessment since they provide a reference that is absolute in addition to the relative reference provided by the nutrient ratios.

A DRIS assessment produces a set of nutrient indicies which describe the status of each nutrient relative to the others. The nutrient indicies are generated by equations comprised of significant ratios that have been standardized. Standardization of the ratios serves two purposes. First, it indicates the degree to which an observed nutrient ratio deviates from its position in the reference population, and secondly, standardization puts all ratios on an equal basis allowing them to be directly compared with one another. The standardization equations (Table 6) proposed by Beaufils

Table 5. Possible outcomes when comparing the mean and variance of nutrient ratios between desirable and undesirable plant populations. The significance of these outcomes to a DRIS assessment is identified.

Outcome	Mean	Variance	Rank	Comments
1	ns[1]	*[2]	1	Desireable (Significant)
2	*	*	2	
3	*	ns	3	
4	ns	ns	4	Neutral
5	*	ns (inv)[3]	5	Undesireable (Not significant)
6	ns	ns (inv)	7	
7	*	* (inv)[4]	6	
8	ns	* (inv)	8	

[1] ns indicates no significant difference at the $p < 0.05$ level.

[2] * indicates a significant difference at the $p < 0.05$ level.

[3] ns (inv) indicates no significant difference at $p < 0.05$ but the variance relationship between good and poor populations was reversed with the variance of the good population tending to be greater than that of the poor population.

[4] * (inv) indicates a significant difference at $p < 0.05$ but the variance relationship between good and poor populations was reversed with the variance of the good population significantly greater than that of the poor population.

(1973) were used. Jones (1981) showed that one of the equations was equivalent to a standardization method typically used in statistical analyses where the population mean is subtracted from a sample value and the result divided by the standard deviation. The reason Beaufils (1973) proposed two equations is uncertain except that he may have wanted to place more weight on the detection of deficiencies, which is what his second equation does (Jones 1981).

Indicies were determined for each nutrient using the DRIS index equations presented in Table 6. The index equations describe the average degree to which standardized nutrient ratios simultaneously deviate from their position in the reference population. Only significant and neutral ratios were used even though other researchers have included at least one ratio expression for each nutrient pair whether significant or not (Beaufils 1977). Their assumption is that a ratio of every nutrient with every other nutrient should be included so that the relationship between all nutrients will be incorporated into the assessment. If a ratio is not significant though, it can only reduce the power of DRIS to detect nutrient deficiencies. A sufficient number were included in each equation here to maintain nutrient relationships.

RESULTS AND DISCUSSION

Significant Ratios and DRIS Norms

Table 7 contains a summary of the effects of summer versus winter foliage sampling on the number of significant nutrient ratios. Overall, winter sampling provided nearly twice the number of significant ratios as summer sampling (76 versus 45). Winter sampling provided more significant ratios for fourth-year size and growth variables, while summer sampling provided more for assessing relative growth. These results suggest that a DRIS assessment, like a critical level assessment, is sensitive to the season of sampling. Supportive of this contention is the fact that there was only 30% agreement between the winter and summer DRIS diagnoses for identifying the most limiting nutrient in each treatment area (Table 8). Although Beaufils (1973) and Sumner (1977) indicate that DRIS is invariant to sampling date with several agronomic crops, it does not hold for loblolly

Table 6. DRIS index and standardizing equations for a nutrient diagnosis of four-year-old loblolly pine growing in the S. Carolina and Georgia Piedmont using foliage collected in the winter.

$$\text{N index} = \frac{f(n) + f(n/p) + f(n/k) - f(Mg/n)}{4}$$

$$\text{P index} = \frac{f(p) - f(n/p) + f(p/k) - f(Ca/p) - f(Mg/p)}{5}$$

$$\text{K index} = \frac{-f(n/k) - f(p/k) - f(Ca/k) - f(Mg/k)}{4}$$

$$\text{Ca index} = \frac{f(Ca) + f(Ca/p) + f(Ca/k)}{3}$$

$$\text{Mg index} = \frac{f(Mg) + f(Mg/n) + f(Mg/p) + f(Mg/k)}{4}$$

where:

$$f(n/p)^{*} = \left[\frac{n/p}{N/P} - 1\right] \text{ X } \left[\frac{100}{CV_{N/P}}\right] \text{ if } n/p > N/P$$

$$f(n/p) = \left[1 - \frac{n/p}{N/P}\right] \text{ X } \left[\frac{100}{CV_{N/P}}\right] \text{ if } n/p < N/P$$

where: N/P refers to reference population
n/p refers to sample being evaluated

Note: $f(n/p)^{*} = \dfrac{n/p - N/P}{\text{Std. dev.}_{N/P}}$

Table 7. Number of significant nutrient ratios by season of foliage collection and growth parameter for DRIS nutrient diagnosis of four-year-old loblolly pine growing in the S.Carolina and Georgia Piedmont.

Growth Parameter	Season	
	Summer	Winter
Height[2]	6	12
Diameter[3]	5	10
Volume[4]	8	12
subtotal	19	34
Height growth[5]	5	11
Diameter growth	4	10
Volume growth	6	12
subtotal	15	33
Relative height growth[6]	3	2
Relative diameter growth	2	3
Relative volume growth	6	4
subtotal	11	9
Total	45	76

[1] Significant ratios have desirable or neutral mean variance relationships as described in table 1.

[2] Total tree height (H) at age 4

[3] Ground line diameter (D) at age 4

[4] Volume = D^2H

[5] Growth = size at year 4 minus size at year 3

[6] Relative growth = $\frac{\text{size year 4 - size year 3}}{\text{size year 3}} \times 100$

Table 8. A summer vs. winter foliage collection comparison of DRIS diagnosed nutrients most limiting four-year-old loblolly pine growing in the S. Carolina and Georgia Piedmont established using seven different site preparation treatments.

			Site Preparation Treatment						
Site	Block	Season	No Prep	Herbicide Burn	Chop Burn	Shear Disc	Shear V Blade Disc	Shear Rake	Shear Rake Disc
1	1	Summer	P	P	Mg	N	Ca	Ca	Ca
		Winter	K	Mg	P	K	N	N	N
2	2	Summer	K	K	K	N	N	N	N
		Winter	K	K	Mg	Mg	Mg	N	Mg
3	5	Summer	P	K	K	P	N	N	P
		Winter	P	K	K	P	P	K	P
4	8	Summer	N	N	N	Ca	P	Mg	P
		Winter	N	Mg	K	P	K	N	P
5	9	Summer	P	N	K	N	Ca	K	N
		Winter	P	P	P	P	P	P	P
6	10	Summer	Mg	N	Ca	N	Ca	Ca	P
		Winter	P	Ca	Ca	Ca	N	P	K
7	11	Summer	K	N	Mg	Mg	K	K	Mg
		Winter	K	K	K	K	K	N	Mg
8	12	Summer	P	N	K	P	P	P	K
		Winter	K	Ca	K	K	K	K	K

pine when comparing winter (dormant season) and summer (active metabolism) foliar nutrients. This is not to say that within the dormant season or within the growing season, DRIS may not be less sensitive to nutrient variation than critical levels. This study cannot answer that question. It only shows that between seasons a DRIS diagnosis is likely to result in different diagnoses and that winter sampling appears more powerful than summer sampling since it utilizes a larger number of significant ratios.

Table 7 also contains the number of significant ratios by growth or size category. Except for the relative growth variables, a DRIS assessment will be equally appropriate for growth or size since there are few differences in the number of significant ratios between them. Relative growth variables do not have a large number of significant ratios because the trees with the highest relative growth rates are often the smallest and poorest-performing trees. Their high relative growth rates have less to do with tree vigor than it does with the fact that these smaller trees have an intrinsically greater capacity for increasing their relative size than larger trees.

Fourth-year tree volume was singled out for study because 1) it integrates both height and diameter, 2) there were few differences in the number of significant ratios between it and the other growth parameters, and 3) because there were very few significant differences (as indicated by t-tests) between its norms and those of the other growth parameters. A similar DRIS ranking of nutrients would be expected for each growth parameter as a result. Since winter sampling is more powerful than summer sampling, DRIS analyses were based on characteristics of the winter foliage. Significant winter ratios and respective norms are presented in Table 9. They were obtained from the statistics of all nutrient ratios for both good and poor populations given in appendix B.

Indicies were calculated for each of the 504 observations and Fig. 7 shows the relationship between tree volume and each respective nutrient index. The horizontal lines on the scatter diagrams show the point of separation between good and poor populations and the vertical lines show the general tendancy of the index levels as tree volume increases. An index value of zero depicts the optimum nutrient level, a negative index depicts a deficiency, and a positive value an excess relative to the other nutrients in the sample. The greater the deviation from zero, the more deficient or excessive a given nutrient becomes relative to the others. For several nutrients there is a tendency

Table 9. DRIS norms for assessing the nutrition of four-year-old loblolly pine growing in the S. Carolina and Georgia Piedmont using foliage collected in the winter.

Nutrient Ratio	Mean	Std. Dev.	C.V.
% N	1.222	.130	10.8
% P	.118	.012	10.7
% Ca	.185	.050	27.1
% Mg	.081	.190	24.4
N/P	10.426	1.209	11.6
N/K	2.361	.427	18.1
Mg/N	.066	.016	24.5
P/K	.227	.037	16.6
Ca/P	1.589	.452	28.4
Mg/P	.696	.197	28.5
Ca/K	.362	.126	35.2
Mg/K	.158	.050	31.9

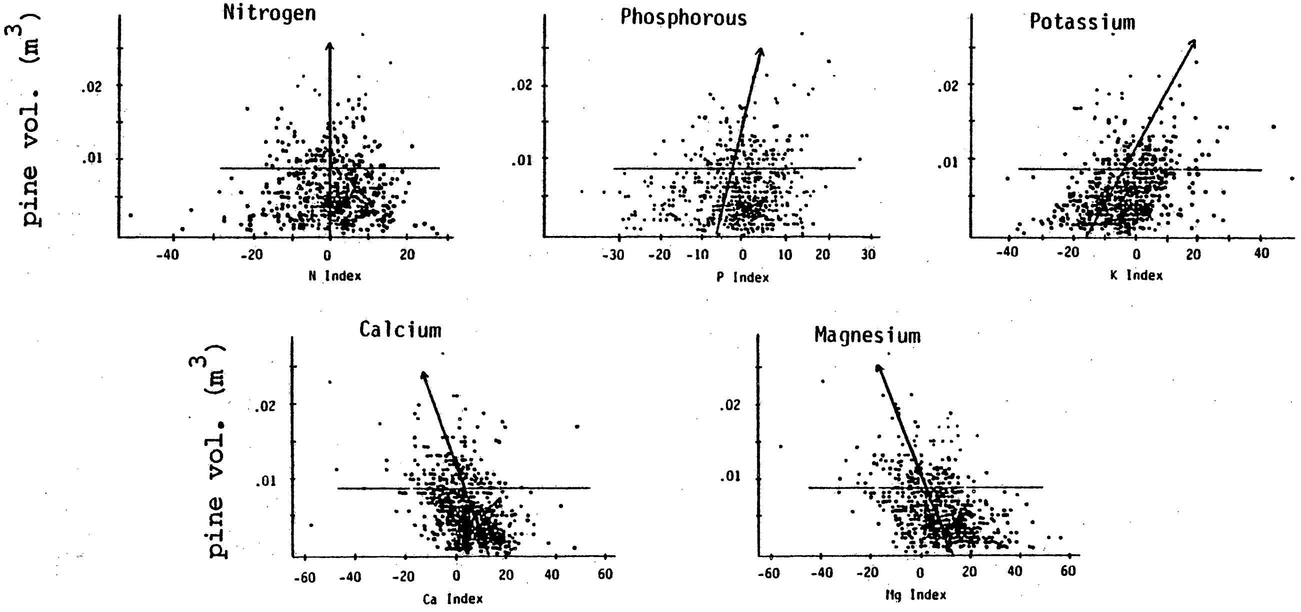


Figure 7. Scatter diagrams of four-year-old loblolly pine volumes and DRIS nutrient indicies. Relationship trends and the demarcation of desireable and undesireable populations are identified.

for the optimum to increase or decrease with increasing tree size (Fig. 7). These tendancies were determined using simple linear regression on average index levels when the data was grouped into seven volume classes. The N index showed no change with increasing tree volume, whereas the P and K indicies tended to increase and the Ca and Mg indicies tended to decrease with increasing volume. The fact that a negative relationship exsists for Ca and Mg indicies and tree size does not necessarily mean that "the less of these the higher the chances of large trees; rather it shows the results of N, P, K, Ca, and Mg interactions in which there is a relatively more intense uptake and utilization of P and K than Ca and Mg as trees increase in size" (Beaufils 1973, p.48).

Utility and Evaluation of the DRIS Results

DRIS has been exclusively used to assess the nutritional status of crops for fertilizer recommendations. In this study, an assessment of the nutritional status of loblolly pine following seven different site preparation treatments was the objective. The average nutritional status of each treatment area was assessed after the average nutrient concentrations were expressed in terms of significant ratios. These were then standardized using the norms in Table 9, and indicies were derived using the index equations in Table 6. The results (Table 10) were a set of nutrient indicies for each treatment area on each of eight study sites. Since nutrient indicies are derived from ratios, the sufficiency of each nutrient relative to the other nutrients can be identified; however, indicies are not comparable across treatments. The sign and magnitude of each index value indicates a nutrient's degree of excess or deficiency relative to the others within the treatment area.

Table 10. DRIS nutrient indicies for diagnosing the nutrition of four-year-old loblolly pine in eight site preparation treatment areas in the S. Carolina and Georgia Piedmont.

		Index Values				
Site	Treatment	N	P	K	Ca	Mg
1	No prep	2.4	-2.2	-6.3	5.6	4.2
	Herbicide, burn	4.6	0.2	-2.2	0.8	-3.3
	Chop, burn	2.5	-0.6	-0.0	4.3	1.9
	Shear-disc	-0.2	-0.7	-6.3	4.7	15.8
	Shear, V blade-disc	-3.7	3.1	1.2	0.5	3.4
	Shear, rake	-8.0	0.3	-0.2	6.5	11.1
	Shear, rake, disc	-7.3	2.8	6.3	-3.8	3.5
2	No prep	1.5	3.8	-14.7	11.4	11.1
	Herbicide, burn	-2.2	-0.1	-5.8	5.4	7.8
	Chop, burn	7.1	10.1	-0.7	-3.6	-9.3
	Shear-disc	-2.3	3.1	4.9	-2.9	-5.6
	Shear, V blade-disc	-2.3	3.0	1.6	-1.7	-2.7
	Shear, rake	-5.3	0.7	-4.8	5.1	10.9
	Shear, rake, disc	-3.0	5.2	5.1	-3.4	-4.9
3	No prep	1.7	-7.4	4.1	1.1	4.2
	Herbicide, burn	3.1	1.8	-8.9	6.8	2.8
	Chop, burn	-0.1	-2.6	-7.4	14.3	8.3
	Shear-disc	2.4	-9.5	-2.8	7.5	13.4
	Shear, V blade-disc	-3.4	-6.3	-1.9	7.2	10.0
	Shear, rake	3.0	-3.5	-4.8	8.2	10.8
	Shear, rake, disc	2.9	-4.3	-3.8	2.2	4.7
4	No prep	-7.3	2.5	-5.2	7.2	6.9
	Herbicide, burn	-1.5	7.2	-1.9	2.7	-3.0
	Chop, burn	3.3	3.2	-4.6	3.0	2.2
	Shear-disc	-0.7	-4.7	-3.1	1.3	15.7
	Shear, V blade-disc	-0.1	-3.2	-4.7	4.8	10.7
	Shear, rake	-1.7	2.7	0.1	0.1	0.8
	Shear, rake, disc	-0.4	-3.0	0.6	-2.4	6.2
5	No prep	2.1	-20.8	-2.3	9.4	18.6
	Herbicide, burn	3.9	-16.4	-7.2	18.9	18.9
	Chop, burn	3.1	-21.2	-16.4	15.6	30.5
	Shear-disc	3.1	-14.2	-1.7	7.4	11.1
	Shear, V blade-disc	0.7	-16.5	1.3	4.8	14.3
	Shear, rake	-1.0	-19.3	-9.5	14.3	26.4
	Shear, rake, disc	4.2	-10.3	-6.7	3.1	16.6

Table 10. Continued.

		Index Values				
Site	Treatment	N	P	K	Ca	Mg
6	No prep	-4.3	-5.8	-1.7	7.7	9.4
	Herbicide, burn	1.0	1.1	-3.7	-4.4	8.3
	Chop, burn	5.7	1.8	1.7	-7.8	-2.7
	Shear-disc	-3.1	-1.9	4.4	-4.8	4.1
	Shear, V blade-disc	-2.8	-1.3	-1.2	1.4	7.9
	Shear, rake	4.3	-5.2	-4.5	1.5	10.8
	Shear, rake, disc	1.7	-5.6	-6.1	3.4	12.6
7	No prep	-4.3	-0.3	-7.7	2.5	4.6
	Herbicide, burn	1.1	-0.6	-4.1	7.0	5.1
	Chop, burn	0.2	1.1	-10.3	13.7	1.2
	Shear-disc	0.5	3.9	-6.5	6.0	1.7
	Shear, V blade-disc	-1.6	-2.3	-8.4	6.6	7.6
	Shear, rake	-4.9	3.5	-1.5	6.5	-0.1
	Shear, rake, disc	1.1	7.2	-2.8	-2.2	-6.1
8	No prep	1.7	1.6	-5.9	4.3	0.9
	Herbicide, burn	-2.0	6.7	1.2	-6.1	-2.6
	Chop, burn	0.2	2.6	-4.5	8.3	7.5
	Shear-disc	1.7	-0.3	-4.4	3.9	8.4
	Shear, V blade-disc	2.9	3.1	-2.2	-0.2	3.2
	Shear, rake	2.2	-2.7	-5.6	8.6	12.6
	Shear, rake, disc	3.7	-2.4	-11.7	5.1	12.9

The degree to which an index level must deviate from zero before a nutrient deficiency occurs is uncertain. Jones (1981) indicated that any nutrient with an index less than zero should be considered deficient; however, sampling and measurement error would suggest that some variation would occur. To account for such variation, a 10% confidence interval about the optimum of the reference population may be a more appropriate descriptor of the sufficiency range. Beaufils (1973) established a precedent (Sumner 1977) that suggests that indicies within 4/3 standard deviations of the optimum of the reference population indicate nutrient sufficiency. Outside this range, they indicate a nutrient deficiency, and outside 8/3 standard deviations, an extreme deficiency is claimed. Aside from representing an 80% confidence interval, the 4/3 standard deviation level appears to have no theoretical or empirical foundation.

Table 11 summarizes the frequency with which nutrients were deficient in each treatment area under these criteria. In no case did the assessment indicate nutrient indicies outside the 8/3 standard deviation range, which suggests that no extreme nutrient deficiencies occurred at age four as a result. Using an 80% confidence interval, the assessment indicated that a deficiency occurred nine times. Seven were P deficiencies and two were K. The P deficiencies all occurred on the same site (#5), and were not associated with any particular treatment (Table 9). The K deficiencies occurred on different sites and in different treatment areas. One K deficiency occurred on an already P deficient site where P was the more deficient of the two nutrients. According to Jones' theory with adjustments for possible measurement error, K was deficient most often (had a negative index value) occurring 40 times for 38% of the nutrient deficiencies (Table 11). Phosphorous was deficient 25 times representing 24% of the deficiencies, N was deficient 19 times or 18% of the total, and Ca and Mg were identified as deficient a combined total of 20 times, or 6% of the total number of deficiencies. In addition to being deficient most often, K was the most deficient element in any sample 38% of the time (i.e. 21 of 56 times), followed by P (28%), N (14%), Ca (7%), and Mg (13% of the time).

The preponderance of K deficiencies in trees on these sites was unexpected. There is no evidence based on fertilizer trials to suggest a K deficiency in loblolly pine and no foliar K concentrations were below 0.43% (Appendix C), which is twice the 0.26% critical level typically used

Table 11. Frequency of DRIS diagnosed nutrient deficiencies of four-year-old loblolly pine established with seven different site preparation treatments in the S. Carolina and Georgia Piedmont using three deficiency criteria.

Criteria	Site Prep Treatment	# times deficient				
		N	P	K	Ca	Mg
Most Deficient	No prep	1	3	4	0	0
	Herbicide, burn	0	1	3	2	2
	Chop, burn	0	2	4	1	1
	Shear-disc	0	3	3	1	1
	Shear, V blade-disc	2	2	3	0	1
	Shear, rake	4	2	2	0	0
	Shear, rake, disc	1	3	2	0	2
	Total	8	16	21	4	7
Deficient in excess of .13 std.dev.	No prep	3	4	7	0	0
	Herbicide, burn	3	1	7	2	3
	Chop, burn	0	2	5	2	2
	Shear-disc	2	4	6	2	1
	Shear, V blade-disc	5	5	4	1	1
	Shear, rake	4	4	6	0	0
	Shear, rake, disc	2	5	5	4	2
	Total	19	25	40	11	9
Deficient in excess of 4/3 std.dev.	No prep	0	1	1	0	0
	Herbicide, burn	0	1	0	0	0
	Chop, burn	0	1	1	0	0
	Shear-disc	0	1	0	0	0
	Shear, V blade-disc	0	1	0	0	0
	Shear, rake	0	1	0	0	0
	Shear, rake, disc	0	1	0	0	0
	Total	0	7	2	0	0
Deficient in excess of 8/3 std. dev.	Total	0	0	0	0	0
Index value at 1 standard deviation		10.2	10.8	14.4	17.3	17.1

[1] A deficiency is indicated by a negative index value.

[2] A 0.13 standard deviation is equal to a 10% confidence interval.

[3] A 4/3 standard deviation is equal to a 80% confidence interval.

[4] A 8/3 standard deviation is equal to a 99% confidence interval.

(Pritchett 1979, Sucoff 1961). A similar discrepancy occurred between the observed nutrient concentration and critical level for Ca. Unfortunately, the K and Ca critical levels reported in the literature are not validated and suspect as a result. The results suggest that K and Ca are not in balance with respect to the other nutrients in the reference population. They may not be deficient but may only be the least sufficient.

Our confidence in the results comes from accuracy assessments made in other studies, knowledge of the relationship between DRIS and critical levels, the proper interpretation of DRIS results, and primarily from an examination of soil nutrients.

Accuracy assessments of DRIS diagnoses have been conducted in agronomic settings using fertilizer trials, and results indicate that diagnoses are more reliable than critical levels (Jones 1981). DRIS typically provides correct assessments 70 to 95% of the time compared to 60 to 75% accuracy with critical levels (Beaufils and Sumner 1976, Jones 1981). Discrepencies or errors with DRIS are thought to occur because non-nutrient factors affect the outcome of nutrient assessments even in the relatively controlled settings of agricultural fields.

No corrective treatments were applied in this study. Therefore, it is unknown whether the application of appropriate fertilizers would have resulted in a growth response or not. The diagnoses do not include an assessment of non-nutrient growth determinants such as competition, soil physical properties, or soil moisture, any of which may be more limiting than the nutrients, and none of which had been held constant across all sites. If these other factors are more limiting, a response to the addition of fertilizer may not be realized.

In addition to the empirical evidence provided through fertilizer trials in agronomic studies, Needham (next chapter) found supportive theoretical evidence that a DRIS assessment should be no worse than a critical level assessment because foliar nutrient critical levels can be derived from DRIS.

Correct interpretation of DRIS is essential when evaluating the reliability of the results. The fact that K, for example, is the most limiting or least sufficient nutrient (has the most negative index value) on 21 of 56 sites does not necessarily mean that K is limiting tree size on those sites. It means that K compared to N,P, Ca, and Mg is lower on those sites than K relative to N,P,Ca and

Mg in the reference population. If nutrients are limiting growth, K is likely to be the most limiting nutrient. If K is most deficient (the largest negative index value), but not limiting growth, the other nutrients are even less likely to be limiting. Only when the status and relative relationship between all growth determinants is known can an assessment conclusively identify the most limiting factor or factors.

Since DRIS indicies describe the relative nutritional status of a sample in terms of a continuum, the index level at which a given nutrient will become the most limiting factor is uncertain, particularly in the absence of information on the status of all other environmental factors that exert an influence on yield, especially when these other factors are suboptimal. However, as a nutrient index becomes more negative, the chances that the nutrient is or will limit growth increases. Beaufils' 4/3 rule provides a guideline for identifying when an index value is sufficiently large to indicate that it is limiting growth. This level is particularly relevant when the status of the other growth determinants is unknown.

Finally, the relationship between soil and foliar nutrient levels provides additional validity to the DRIS nutrient assessments. DRIS procedures similar to those used with foliar nutrients were followed with extractable soil nutrients. Significant ratios were identified (Appendix D), norms were calculated based on the reference populations (Appendix D), and indicies for each treatment area were determined after averaging soil nutrient concentrations across treatment area and subjecting the results to the DRIS standardization and index equations (Appendix E). Simple linear correlations between foliar nutrient DRIS indicies and respective soil nutrient indicies (Appendix F) are presented in Table 12. A significant linear relationship between the two occurred for all nutrients except nitrogen. Phosphorous and the cations had correlation coefficients ranging from $r = 0.34$ with Ca, to $r = 0.55$ with Mg. Potassium exhibited a linear correlation coefficient of $r = 0.43$. The results corroborate the DRIS foliar diagnoses.

An objective of this research was to investigate the effect various site preparation treatments have on tree nutrition. The first of two approaches for such an assessment was to average nutrient concentrations across treatments and evaluate the results using the DRIS norms and index equations (Table 13). No extreme nutrient deficiencies or imbalances are evident. The ordering of

Table 12. Relationship between DRIS diagnosed foliar nutrient status and soil nutrient status of four-year-old loblolly pine growing in the S. Carolina and Georgia Piedmont.

	Correlation Coefficient (r)				
	N	P	K	Ca	Mg
Soil vs. foliage concentrations	.02	.38**[1]	.39**	.26*	.64**
Soil vs. foliage DRIS indicies	-.13	.47**	.43**	.34*	.55**

[1] * significant at $p < 0.05$

** significant at $p < 0.01$

Table 13. DRIS indicies describing the average nutritional status of areas established with seven different site preparation treatments in the S. Carolina and Georgia Piedmont using winter collected foliage.

Site Preparation Treatment	Dris Foliar Nutrient Indicies					Absolute Sum
	N	P	K	Ca	Mg	
No Prep	-0.9	-3.2	-4.7	6.0	7.3	22.1
Herbicide, burn	0.8	0.1	-4.0	3.8	4.2	12.9
Chop, burn	2.4	0.0	-4.7	5.5	4.2	17.0
Shear-disc	0.0	-2.8	-2.0	2.8	8.1	15.8
Shear, V blade-disc	-1.5	-2.2	-1.7	2.8	6.7	14.9
Shear, rake	-1.4	-2.6	-3.7	6.2	10.1	24.2
Shear, rake, disc	-0.2	-1.2	-2.1	0.2	5.6	9.3

nutrient deficiencies was similar in nearly all treatments with K being most deficient followed by P. The magnitude of the indicies is small which suggests no serious deficiencies. The sum of the absolute value of the indicies indicates the degree of nutrient imbalance. A sum of zero indicates perfect balance while larger values indicate an increasingly larger imbalance. The level at which nutrient balance becomes growth-limiting is unknown; however, the intensive shear rake disc treatment exhibited the best balance followed by the herbicide burn, and discing treatments. One would conclude from these results that all treatments produced a similar nutrient protocol and no striking deficiencies were evident at age four as a result of the various site preparation treatments. Nutrient balance varied among treatments but followed the general pattern of increasing nutrient balance with increasing site preparation intensity.

The second approach used in this study was to make site specific nutrient assessments and tally the results by treatment (Table 11). No striking patterns were evident except that on four of eight sites receiving the the shear rake treatment, N was the most deficient element, a condition that was hypothesized due to the removal of logging slash from the site. The deficiency did not occur across all sites probably because N levels were not reduced by the treatment to the point that a deficiency at this age would result. This illustrates the fact that treatment-site interactions prevent any treatment from producing the same result on all sites. The results also identify those sites exhibiting a deficiency and isolates them for further examination and comparison with non-deficient sites, providing information essential to establishing cause and effect relationships.

SUMMARY AND CONCLUSIONS

The Diagnosis and Recommendation Integrated System (DRIS) is a method of diagnosis which indicates the status of nutrients in a sample relative to one another. Consequently, nutrient deficiencies and imbalances can be identified.

Prior to using DRIS, assessment criteria or the "DRIS model" must be available or established. The DRIS model is based on the nutritional characteristics of a reference population or a population that exhibits desirable growth, yield, or quality. Nutrient ratios (ratios of nutrient concentrations) form the basis of the models and are used because they are less sensitive to daily and seasonal fluctuations than nutrient concentrations, they incorporate nutrient balance into the assessment, and most importantly, they provide a link between nutrients, which implicitly allows them to be assessed in relation to one another.

The DRIS model is a series of equations, one for each nutrient, comprised of ratios and associated DRIS norms. Norms are the mean and coefficient of variation of each significant ratio and are used to standardize sample nutrient ratio values. Standardization puts all ratios on an equal basis so they can be directly compared. Standardization also indicates the degree to which a sample value deviates from its respective position in the reference population.

A DRIS model for assessing the nutritional status of four-year-old loblolly pine via foliar nutrient concentrations was developed and the nutrient status of trees following seven different site preparation treatments were examined. DRIS diagnoses were most powerful using nutritional characteristics of winter foliage. Overall, K was diagnosed as the most deficient element. This was surprising since there is no precedent to suggest that such a deficiency should occur on the Piedmont. Even though no fertilizer trials were incorporated to evaluate the accuracy of the diagnoses, soil nutrient evaluations and proper interpretation of the results suggest they are correct. Soil K nutrient indicies were highly correlated with the foliar K indicies, $r = 0.42$. Although DRIS diagnosed K as deficient more often than the other nutrients, it is deficient only in comparison to the other nutrients included in the model and relative to the status of K in the reference population. Potassium may not be limiting growth if some other undiagnosed condition such as competition or moisture is more limiting. Potassium may also not be deficient, but rather the least sufficient, and hence out of balance with the other nutrients.

DRIS was used to examine the average nutrient status created by various site preparation treatments across the Piedmont. The results suggest that N tended to be the most deficient element on the shear rake treatment on 4 of 8 sites; a condition that was hypothesized since raking removed much of the potentially available N pool. Otherwise, no treatment-induced nutrient deficiencies or imbalances were evident; however, nutrient balance tended to improve with increasing site preparation intensity. DRIS assessments did identify one study site exhibiting a P deficiency across all treatments. In all, results will lead to further examination of the study sites to ascertain cause and effect relationships between site characteristics, site preparation, and subsequent tree growth.

The Relationship Between Critical Levels and DRIS

INTRODUCTION

Successful agriculture and forestry requires that conditions limiting plant growth or quality be identified and alleviated. Plant nutrition has been a major concern and a great deal of research has been directed toward identifying methods for assessing the nutritional status of plants and recommending remedial treatments.

Plant tissue analysis, particularly foliage, is frequently used to evaluate plant nutrition since the plant is the object of interest and an integrator of the many factors affecting nutrition. Foliar critical levels have been established for most agronomic crops and many tree species to assess whether the nutritional demands of the plant are being met. While critical levels are extensively used, they have shortcomings which led to the development of alternative methods of diagnosis such as the Diagnosis and Recommendation Integrated System or DRIS (Beaufils 1973).

The objective of this paper is to review the history and current philosophies of critical levels and DRIS, illustrate the relationship between the two, and describe a mechanism wherein critical levels can be derived from DRIS methodologies.

Critical Levels

Critical levels have a long history of use and are frequently relied upon to assess nutrient sufficiency because they are simple to use and easy to understand. Both conceptually and in application critical levels have been extensively researched and discussed. However, a great deal of ambiguity still surrounds them.

Historically, critical levels have been defined as the nutrient concentrations in a plant sample required for optimum growth, yield, or quality, under the assumption that **no other factor is limiting or suboptimal** (Chapman 1967, Munson and Nelson 1973, Mead 1984). If all growth determinants are simultaneouly optimum, a single critical level theoretically exists for each nutrient. Frequently stressed in the definition of critical levels is the meaning of optimum. In some instances optimum refers to the concentration reqired for maximum yield while in other instances it refers to the concentration at 90% or 95% of the maximum yield. In either case, the definition of optimum should not overshadow the essential concept of critical levels, which is that **no other factor is limiting.**

Recently, researchers have begun to question the utility if not the theory behind the original concept of critical levels. Contrary to theory, "critical levels" have been found to vary in excess of that normally associated with measurement error or tissue type. They have been found to vary with physiological age of the foliage, age of the plant, atmospheric and soil meteorologic conditions, as well as with the status of other nutrients in the plant (Miller et al. 1981, Snowdon 1973, Ulrich and Hills 1973, Comerford and Fisher 1984, Bevege 1978). Consequently, many feel that a range of concentrations rather than a single value should be used to describe the critical level of a given nutrient (Pritchett 1978). The assumption that all other growth determinants be simultaneously non-limiting has been relaxed.

This conceptual shift in critical levels from a theoretical basis to an utilitarian one is illustrated in Fig. 8 (Bevege, 1978). The joint relationship between P and N foliar concentration levels and volume growth is illustrated and the critical level (CL) is defined at 90% of maximum yield. While knowledge of such relationships is essential for effective management, using them in the context of critical levels leads to much of the confusion associated with critical levels. The critical level varies because one or both elements is simultaneously suboptimal, which violates the underlying assumption of critical levels. To preserve the integrity of the critical level concept and remove much of the ambiguity surrounding it, another term such as "response level" should be used in those instances where all factors are not simultaneously optimum.

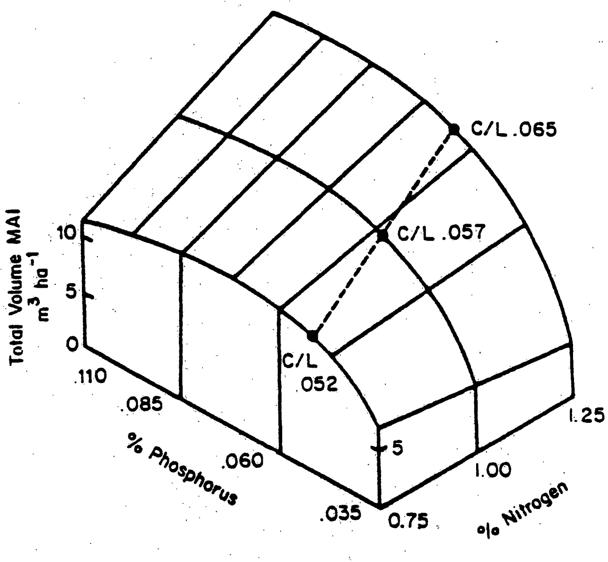


Figure 8. Simultaneous affect of foliar N and P concentrations on volume growth in Pinus caribaea at age 13.5 years. The critical levels (CL) are identified at 90% of the maximum increment (from Bevege 1978).

Aside from the question of variability, critical levels have been criticized because they are typically determined only for individual elements, and yet nutrient balance, typically defined by nutrient ratios, has been shown to be as important for high yields as are sufficient concentrations of individual nutrients (Heeney and Hill 1961, Bevege 1978, Comerford and Fisher 1984).

Generally, critical levels are difficult to determine. The classic method for determination is with solution culture in which increasing amounts of a deficient element are added while all others are maintained in adaquate amounts (Ulrich and Hills, 1973). A calibration curve or response surface is then developed relating growth or yield to the nutrient concentration in question. The advantage of such a method is that all factors are controlled. The disadvantage is that such conditions seldom occur in nature, and as a result, the critical levels thus established may be unrealistic (Zurbicki 1961, Leaf et al. 1970, Archibald 1964). An alternative is to use fertilizer trials (Bevege 1978, Wells et al. 1973). Regression or Cate-Nelson plots are then used to identify critical levels by relating the growth or yield response to the range of foliar nutrient concentrations created in the trial (Wells et al. 1973).

DRIS

In contrast to critical levels, DRIS (Beaufils 1971, Beaufils and Sumner 1976, Jones 1981) is a relatively new and more complex method for assessing the nutritional status of agronomic crops. Although it is gaining popularity for use with agronomic crops, it is only beginning to be explored for use with forest trees (Truman and Lambert 1981, Leech and Kim 1981).

DRIS theory states that as plants approach their growth potential, nutrient levels become less variable. Fig. 9 depicts this type of relationship with scatter diagrams between corn yield and foliar N, P, and K concentrations. Boundry lines on the scatter diagrams indicate the yield limit attainable given any nutrient level. The probability for maximum growth is greatest at some optimum nutrient level, and as the nutrient concentration deviates from this optimum, the probability of attaining high yields declines. High yields may not be obtained even when a nutrient is at its optimum level if one or more of the other nutrients or some other growth determinant is suboptimal.

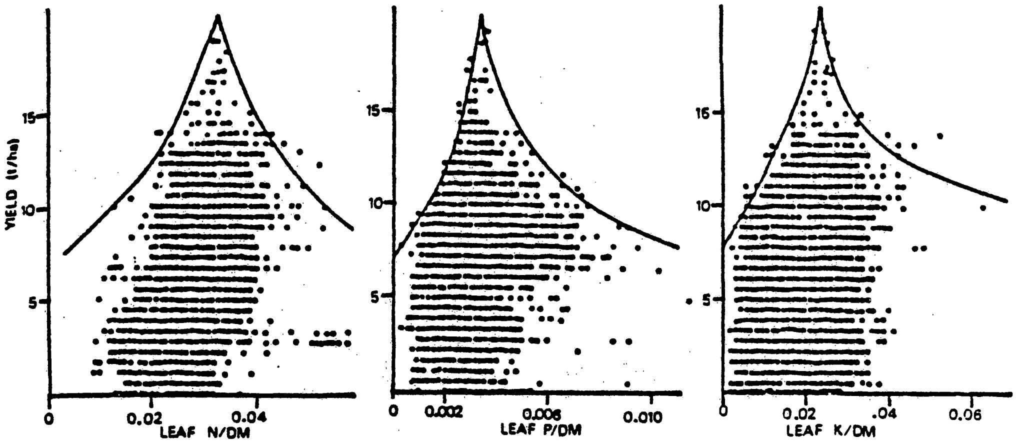


Figure 9. Scatter diagrams between corn yield and N,P, and K foliage concentrations (from Walworth et al. 1986).

DRIS identifies limiting factors within a framework which considers many nutrients and their interactions simultaneously. For any sample, a ranking of the status of each nutrient relative to the other nutrients in the sample is generated. This provides a comparative basis for evaluating the total nutritional status of the plant.

DRIS accomplishes its objectives by 1) standardizing all nutrient factors, and 2) linking these standardized values together. Beaufils (1973) originally proposed two different equations for standardization and Jones (1981) showed that they essentially involved subtracting the mean of a high performance population from a sample value then dividing by the standard deviation of the high performance population. The result is a measure of the degree to which a sample deviates from that in the reference population. Standardization also permits nutrients to be compared without the influence of their concentration magnitudes. That is, standardization allows N to be compared with P even though N levels tend to be 10 times greater. Linkage is accomplished through the use of nutrient ratios. Nutrient ratios not only permit nutrient balance to be incorporated into the assessment, they indicate the relationship between the different elements thereby allowing them to be compared to one another.

The final result of DRIS is an index value for each nutrient which has been derived from the average of all significant, standardized ratios. Nutrient indicies of a sample are comparable as a result of the standardization and linkage processes, and the effects of both balance and absolute level can be integrated into the assessment. The DRIS indicies of a sample indicate the status of each nutrient relative to the other nutrients. An index value of 0 indicates an optimum level while negative values indicate a nutrient deficiency and positive values a nutrient excess relative to the other nutrients in the sample.

The power and success of DRIS depends on 1) accurately specifying a reference population, 2) identifying nutrient ratios which make a significant contribution to the assessment, and 3) determining accurate norms for use in the standardization process. The accuracy of DRIS results has been assessed with fertilizer trials and the results are frequently compared to assessments made with critical levels. DRIS assessments have been correct as often, if not more often, than critical level assessments (Beaufils and Sumner 1976, 1977, Meldal-Johnsen and Sumner 1980, Beverly et al.

1986). The DRIS system is less sensitive to nutrient variation due to plant age, and it gives a relative ranking of the elements in terms of plant requirements (Sumner 1977). As a consequence, DRIS diagnosis can identify the second, third, etc. most limiting nutrients in addition to the most limiting one.

Many proponents of DRIS expound upon the superiority and advantages of DRIS over critical levels; however, few have recognized the relationship between the two. The purpose of this paper is to describe this relationship using loblolly pine foliar analysis. Foliar nutrient critical levels are derived using DRIS and compared with critical levels reported in the literature.

METHODS

Foliage was taken from 504 randomly selected, four-year-old loblolly pine trees growing in the South Carolina and Georgia Piedmont. The trees were located on a range of soils and sites. Foliage was collected from the upper third of each tree crown during the summer of the fourth growing season between August and September and during the following winter between January and February. Sampling was confined to those needles that emerged during the first needle flush the spring of the fourth year. The foliage was oven dried to a constant temperature of 65C and ground in a Wiley mill to pass through a 0.25 mm mesh screen. The N concentration was determined using a micro-Kjeldahl procedure with analysis performed on a Technicon Auto Analyzer. Phosphorous, K, Ca, and Mg were extracted with 6M HCl following dry ashing at 500C for 8 hr. Phosphorous was determined colorimetricly by the phosphomolybdate complex while cations were determined by atomic absorption (Ca and Mg) and flame emmission (K) spectrometry. National Bureau of Standards Pine Needle Tissue (NBS 1979) was used as a calibrant for all elements.

Total tree height (H) and ground line diameter (D) were measured during the foliage-collection period and used to create volume index ($V = D^2H$), the response variable.

DRIS norms were developed after dividing the 504 sample trees into two populations. The superior or good population was composed of those trees whose volume index was greater than

8700 cm^3, the upper quartile of the entire data set. DRIS indicies were calculated for each sample tree and used to derive critical levels which were then compared with loblolly pine critical levels established under more traditional methods and reported in the literature. The significant ratios, associated norms, and index equations presented in the previous paper (Tables 8 and 11) were used to determine DRIS indicies.

RESULTS and DISCUSSION

The scatter diagrams in Fig. 10 show the relationship between the DRIS nutrient indicies for each tree included in the high yielding population and their respective foliar nutrient concentrations. Simple linear regression was used to describe the relationships and 95% prediction intervals about the regression lines were determined.

A DRIS index level of zero represents the optimum nutrient level suggesting that the associated nutrient concentration should be equivalent to the "critical" level of the nutrient. However, the results indicate that a range in nutrient concentrations occurs at the optimum DRIS index value of each nutrient. The 95% prediction intervals describe this variation and Table 15 gives the range. In addition to measurement error, a range exsists because all nutrients are not simultaneously optimum. While the nutrient under consideration may be at an optimum level, the fact that others may be suboptimal affects the associated nutrient concentrations. This is analogous to the situation presented earlier in which the optimum P concentration varied with the concentration of N (Fig. 8).

A single critical level, one that fulfills the essence of the critical level concept, can be identified when the index values of all nutrients are simultaneously optimum and the plant response is high yielding. Results in Table 14 give critical levels under conditions of simultaneouly optimum nutrition. The critical levels identified for N, P, and Mg using DRIS are similar to those reported in the literature. Potassium and Ca critical levels are much different.

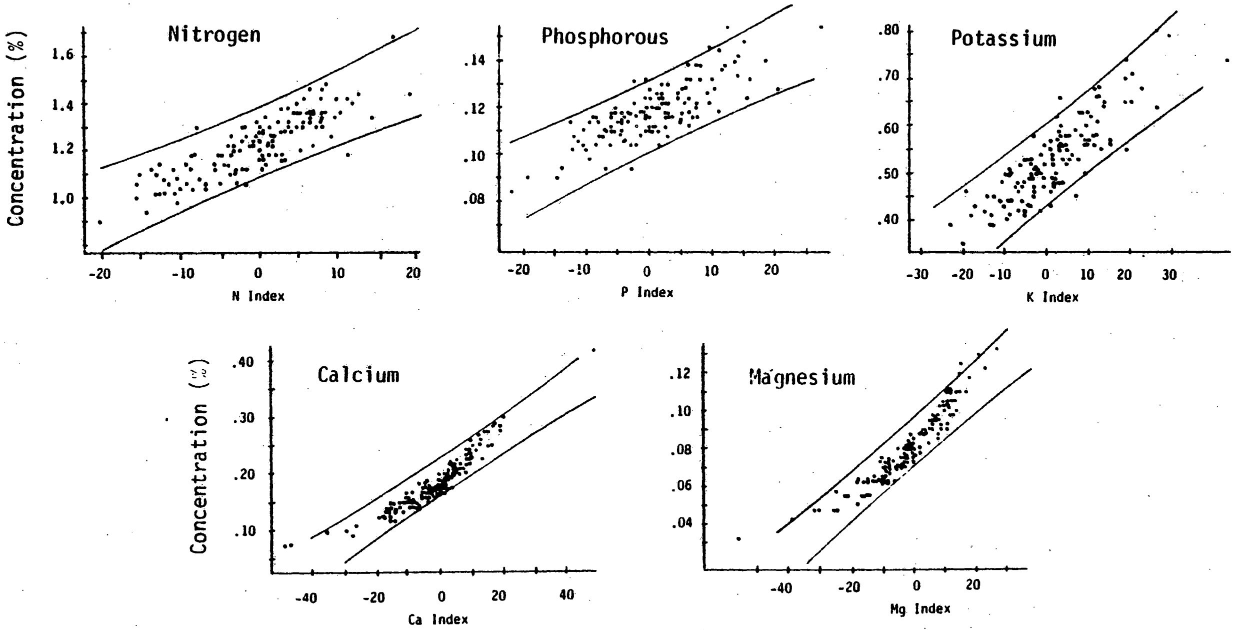


Figure 10. Scatter diagrams between DRIS foliar nutrient indicies and respective foliar nutrient concentrations of four-year-old loblolly pine in the S. Carolina and Georgia Piedmont. 95% prediction intervals indicate the concentration range at a given nutrient index.

Table 14. Comparison of DRIS-derived loblolly pine foliar nutrient critical levels with those derived by more traditional methods and reported in the literature.

	Foliar Nutrient Concentration				
	N	P	K	Ca	Mg
			%		
DRIS Critical Level Range	1.08-1.37	.10-.13	.42-.61	.16-.23	.07-.10
DRIS Critical Levels	1.23	.11	.52	.19	.08
Critical Levels Reported in Literature	1.2[1]	.11[4,1]	.26[2]	.10[3]	.08[2]

[1] Fowells and Krauss. 1959. Loblolly Pine.
[2] Sucoff. 1961. Loblolly Pine.
[3] Pritchett. 1979. Slash Pine.
[4] Wells and Crutchfield. 1973. Loblolly Pine.

It is possible that the DRIS determination is inaccurate since all factors affecting nutrition were not simultaneously optimized. That is, the critical levels were derived only for simultaneously optimum nutrition of five elements. Other nutrient elements, soil meterologic conditions, and other environmental conditions such as competition were not considered and yet they may have an effect on the critical level determination. Only one season and a relatively small data set was examined. Ideally, a much larger data set and one that spans many growing seasons would be best. Although occurring on 12 sites which span five counties in the South Carolina and Georgia Piedmont, the sample trees were confined to a small area relative to the geographic range in which loblolly pine grows. The importance of sampling under numerous conditions is illustrated by Snowdon's work (1973) where *Pinus radiata* remained in a healthy condition with foliar boron (B) levels as low as 4 ug g^{-1} during years of adequate rainfall but exhibited dieback and signs of boron deficiency when levels were 8 ug g^{-1} during dry years. Foliage was collected for this study in the winter following an unusually wet growing season. In short, the main weakness with the DRIS-derived critical levels is the limited scope of the data. Supportive of the DRIS results is the work by Wells and Metz (1973) who report foliar K and Ca nutrient concentrations similar to those presented here.

Equally likely in the comparison is that the critical levels presented in the literature and established under more traditional methods are in error. Many are the result of only one study, and except for N and P little-critical level work with the elements has been reported for loblolly pine. No critical level was found for Ca. The value reported here is for *Pinus elliottii* (slash pine), a similar species. Except for N and P, the critical levels used have not been verified or validated and are suspect as a consequence.

CONCLUSIONS

DRIS and critical levels are similar in that they both define an optimum nutrient status required for good growth. DRIS is appealing because it is more comprehensive, incorporating many facets of nutrition including nutrient balance into the assessment. However, DRIS is also more cumbersome. The index values it generates provide little intuitive meaning as to the nutrient status of a plant because they are relative. It is also difficult to predict the degree of response following remedial treatments based on a DRIS diagnosis. Critical levels on the other hand are absolute and in terms of nutrient concentrations, values with which users can identify. The use of nutrient concentrations rather than the relative measures resulting from DRIS, provides a method for estimating the growth response should adjustments be made. Critical levels also provide a quick assessment of nutrition and do not require analysis of numerous elements. However, they should be developed and used in the context that no other factor is limiting growth.

DRIS provides an excellent method for determining critical levels under the assumption that no factor is limiting and has the following advantages over other methods:

1. It does not require special experiments.
2. Critical levels are determined from plants growing in their natural environment.
3. DRIS considers both nutrient balance and absolute nutrient concentration.
4. DRIS incorporates many nutritional factors simultaneously.
5. DRIS relies on nutrient ratios which helps counteract changes in nutrient concentrations as the plant ages.

DRIS and critcal level diagnoses often generate similar results (Beaufils and Sumner 1977, Beverly et al. 1986), which is logical since the two are related. However, DRIS diagnoses are often superior and frequently lead to higher yields than those based on critical level diagnoses (Beaufils and Sumner 1977, Beverly et al. 1986) because DRIS is less sensative to nutrient variation during the growing season; it ranks nutrients according to their degree of deficiency indicating when more than one nutrient may be deficient; and it considers both nutrient concentration as well as nutrient balance. Critical levels consider nutrient concentration only and assume perfect balance. In short, both DRIS and critical levels have an important place in the diagnosis of factors limiting plant growth and development and the essence and limitations of each should be understood.

Site Preparation Effect on Seedling Spatial Distribution

INTRODUCTION

Regeneration success in southern pine plantations is often based on the number of seedlings surviving after the first year. However, the spatial distribution of trees should also be considered. A distribution that permits full utilization of a site is preferred. Therefore, among other things, site preparation should promote a pattern of well distributed trees.

A regular spatial pattern is usually sought to completely utilize a site. As either the spatial distribution shifts away from regular, or the number of trees changes, a change in yield and product is expected to occur. A guideline used by many foresters to assess the potential ability of a stand to produce an acceptable yield at rotation is 740 trees per ha (300 trees per acre) assuming they exhibit a "good" spatial distribution.

The purpose of this study was to determine how several site preparation alternatives used in the regeneration of loblolly pine affected seedling spatial distribution patterns at the time of planting and after two growing seasons.

METHODS

A site preparation study was installed on twelve, 16 ha sites across the South Carolina and Georgia piedmont in 1980 and the seven site preparation prescriptions described in Table 1 were replicated on each site in an approximately 2 ha area. The treatments represent a range of operationally feasible site preparation prescriptions varying in cost and intensity. Following planting in March 1981, five 0.04 ha plots were randomly located within each treatment area. The location of every planted seedling within these 420 permanent plots was identified by a row distance from the plot corner and a tree distance from the plot baseline. The plot corner began half the distance planting rows and all plots were 20 m long. The second year after planting, each plot was revisited and survival by tree location assessed.

Pielou's index of nonrandomness (Pielou 1959) was used to assess seedling distribution. Research by Payandeh (1970), indicates that it is the best alternative for assessing the spatial distribution of trees. The index is based on point-to-plant distances. After the location of every planted tree was mapped, computer techniques were used to randomly locate 50 points within each plot and determine mean squared point-to-tree distances. The spatial distribution index for each plot was then calculated as follows:

$$I = (N \cdot \pi \, / \, 43560) \cdot \bar{W}$$

WHERE:

I = PIELOU'S INDEX OF NONRANDOMNESS

N = DENSITY IN TREES PER ACRE

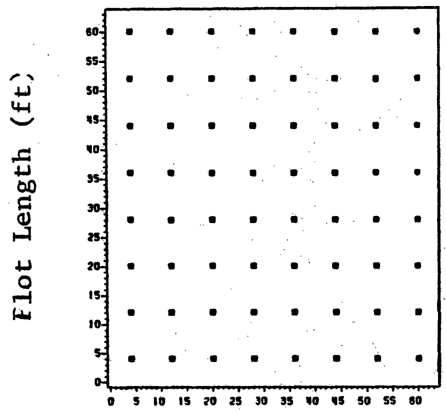
π = 3.14159

$\bar{W}$ = MEAN OF SQUARED POINT-TO-PLANT DISTANCES

Analysis of variance was used to compare Pielou's indicies of nonrandomness by site preparation treatment at the time of planting and after two years mortality.

Spatial patterns were classified as clustered, random, or uniform according to the 95% confidence interval criterion reported by Pielou (1959). Confidence interval adjustments to account for changes in the variance structure as described by Mountford (1961) were not required since plot density (n) was known.

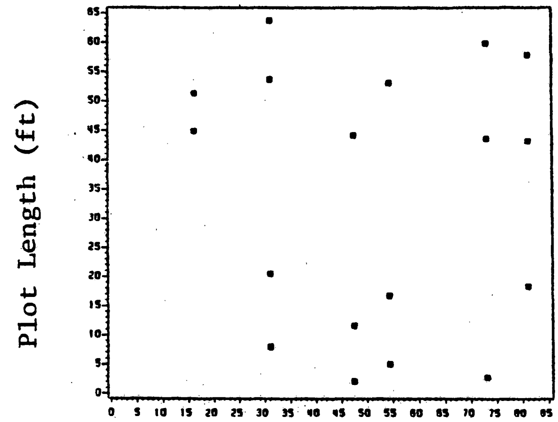
Following analysis of variance, spatial distribution index values were standardized so a value of 1.00 would indicate a perfectly regular spatial distribution while larger values would indicate increasingly less regular patterns. This was done by creating a perfectly regular spatial pattern at the intended planting spacing (2.5 m x 2.5 m), determining its index value (I= 0.56), and dividing all index values by this number. Essentially, these distribution indicies indicate the degree to which the observed spatial patterns deviated from the intended pattern. The plots in Fig. 11 illustrate a range of spatial distribution patterns and give corresponding index values.



UNIFORM

1680 Trees/ha

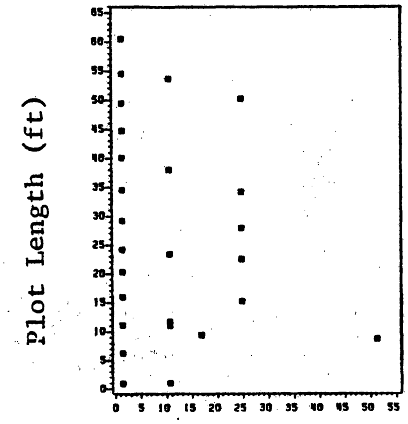
Distribution Index 1.00



RANDOM

340 Trees/ha

Distribution Index 2.32



CLUSTERED

755 Trees/ha

Distribution Index 8.41

Figure 11. Examples of seedling spatial distributions and corresponding spatial distribution index values as determined by Pielou's index of nonrandomness.

RESULTS AND DISCUSSION

The bar chart in Fig. 12 shows the average spatial distribution index values of planted seedlings by treatment as it occurred at planting and after two growing seasons. No treatment promoted a clustered distribution among the trees on the average; however, several treatments tended to promote more clustered distributions than others. The least intensive treatments, no preparation and herbicide burn, exhibited the highest degree of uniformity followed by the most intensive treatments, shear rake, and shear rake disk. The intermediate treatments exhibited random distributions.

Spatial patterns can partially be attributed to planting technique and to the amount and distribution of logging slash and residual vegetation left on the site after harvest. Machine planting could not be used on the no preparation or herbicide burn sites because residual vegetation and logging slash obstructed equipment. Hand planting was required and a relatively regular spatial distribution among seedlings resulted.

Sites that were raked provided a relatively smooth surface for the machine planter to traverse, which in turn permitted consistent and regular planting. As the amount and roughness of logging slash distributed across a site increased, planting patterns became more irregular. The V-blade treatment, which was designed to create small windrows of slash between each row of seedlings, caused a significantly more clustered distribution than the other treatments. The reason for the irregular spacing in the prescription can be attributed to irregular accumulations of slash which had be to skirted by the planter. The distribution of trees within a row was fairly regular, while the distance between rows was variable as a result. Figure 13 is an example of the type of spatial pattern exhibited by plots receiving this treatment.

Among the machine planted treatments, the distribution of trees surviving after 2 yr (Fig. 12) was highly dependent upon the tree distribution at planting. The relative spatial distribution of trees remained nearly the same even though there was a large shift toward a more clustered pattern. Consequently, the V-blade treatment remained significantly different from the others. Hand planted areas exhibited the most dramatic change from uniform toward clustered distributions. The no preparation and herbicide burn areas exhibited extremely varible planting and growing conditions

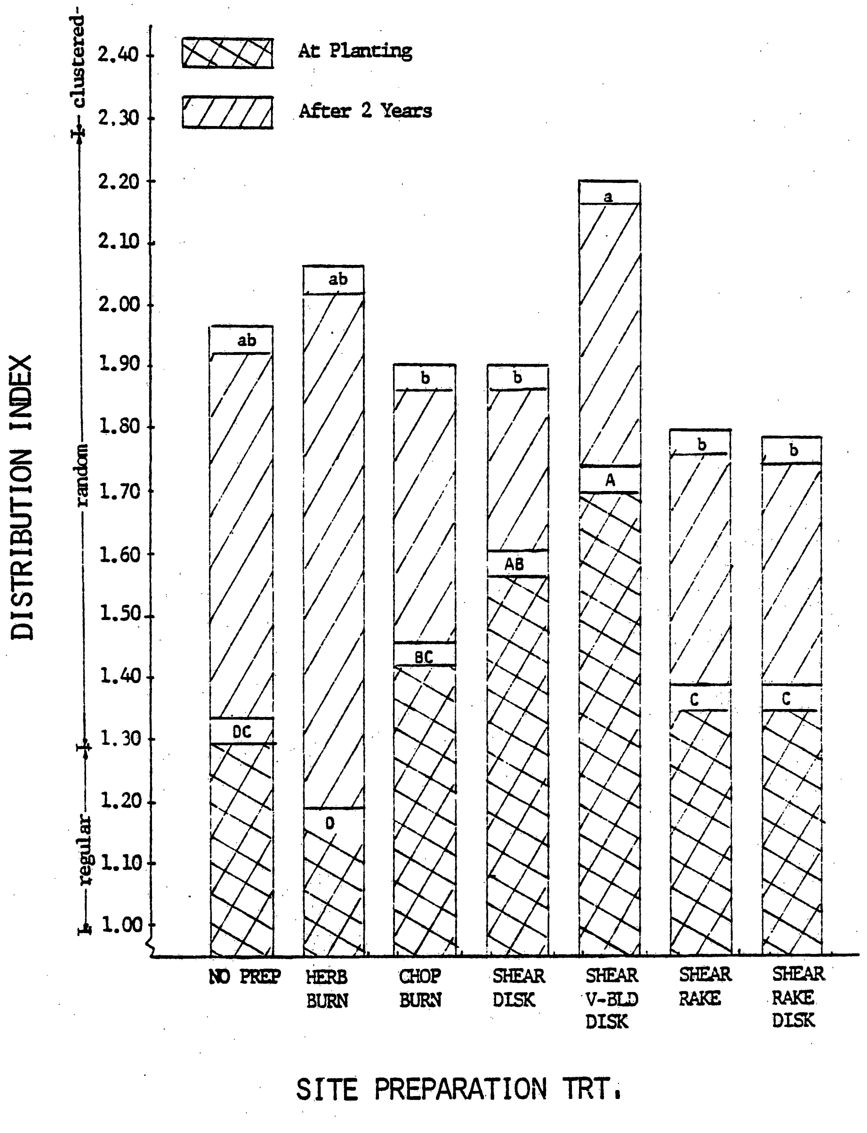


Figure 12. Site preparation treatment comparison of planted and surviving loblolly pine seedling spatial distribution patterns quantified by Pielou's index of nonrandomness. Letters within bars indicate significant differences ($p < 0.05$) in spatial distribution index values between treatments for each assessment period.

DISTRIBUTION INDEX 3.19

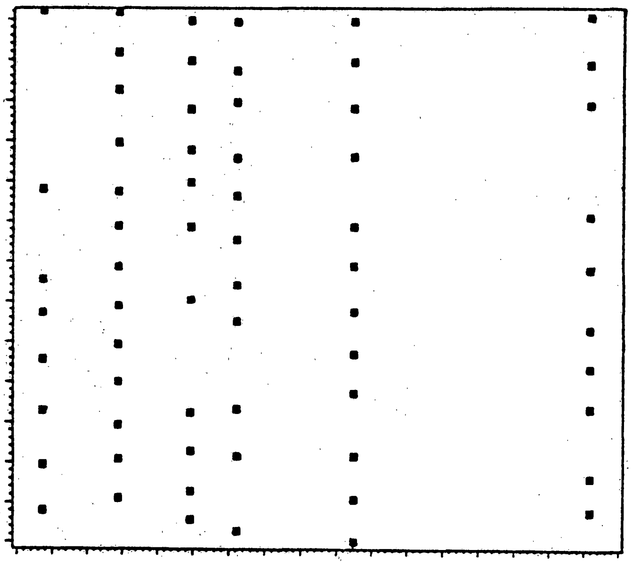


Figure 13. Example of the spatial pattern and respective spatial distribution index value of seedlings in the shear V-blade disc site preparation treatment areas.

largely the result of the distribution of residual hardwoods and logging slash which were not removed during site preparation. Pockets of favorable and unfavorable planting and growing conditions occurred which promoted a clustered spatial pattern among surviving seedlings.

Across all treatments, Lantagne (1984) found seedling mortality high the first growing season with little subsequent change the second year. The high mortality was attributed to a drought following planting; however, seedling care and planting quality have also been found to affect survival (Dierauf 1982). The surviving spatial patterns observed in the untreated and herbicide burn treatment areas is attributed to poor planting among and within logging slash and residual hardwoods, in combination with droughty conditions. The other treatment areas tended to create more homogeneous site conditions, and, as a result, the distribution of the mortality was random.

The spatial pattern of seedlings is of little consequence unless it affects yield, the product mix, or the harvestability of the future stand. While only time will tell, computer simulations by Smith et al. (1965) on the spatial patterns of Douglas-fir suggest that yield is unaffected by spatial patterns as long as 740 trees per ha (300 trees per ac) remain and the distribution of trees is not fully clumped. Full clumping reduces yield in direct proportion with the size of the area involved. No work has been reported on the effect of spatial patterns on harvestability; however, an influence is likely to result directly from the spacing and indirectly from the influence of spatial patterns on diameter distributions.

CONCLUSIONS

Significant differences in seedling spatial patterns at the time of planting were observed among the different site preparation treatments imposed. The differences relate to the degree to which a site was cleared of logging slash and whether the site was machine or hand planted. Hand planting resulted in the most uniform spatial patterns at planting even though no logging slash was removed from the site. The success of machine planting depended upon the degree of logging slash removal; cleared sites had more uniform spatial patterns than non-cleared sites.

Surviving spatial patterns were similar among all treatments; however, the hand planted treatment areas, no preparation and herbicide burn, exhibited the greatest change in seedling spatial patterns, which tended toward clumping. The distribution of logging slash is thought to have promoted the observed spatial patterns because of its effect on planting conditions and the growing environment.

Summary and Conclusions

Seven different site preparation prescriptions were applied to 12 mixed-pine hardwood sites in the South Carolina and Georgia Piedmont in a randomized complete block experimental design in 1980. Tree growth and survival were monitored the first 3 yr after installation and at age four an intensive individual tree assessment was conducted on 756 randomly selected trees (each site and treatment was equally represented) to investigate competition and tree nutrition effects on size and growth. In addition to these, the effect of site preparation treatment on the spatial distribution of seedlings at planting and after 2 yr was examined in 420, 0.04 ha permanent sampling plots.

Competition was not found to be the most limiting factor on tree size at age four until 83% of the total basal area was in hardwoods or 3.5 m^2 ha^{-1} (15 ft^2 ac^{-1}) of hardwood basal area existed. These levels occurred infrequently across the study sites (only 25% of the time) and were primarily associated with areas not receiving some form of site preparation.

Aside from untreated areas, there were few significant differences in competition levels among treatment areas. In effect, at age four, all treatments reduced the level of competition to relatively low levels. Competition levels were different among treatments at age two, being less in those treatment areas receiving soil disturbance. However, hardwood growth rates accelerated in these areas from year two to year four to overcome the initial differences. Pine growth rates also accelerated faster on areas receiving soil disturbance compared to the other areas, and, as a result, the competitive pressure from the accelerated hardwood growth may not have been realized at age four.

Tree nutrition was examined with the Diagnosis and Recommendation Integrated System (DRIS) which is a relatively new and poorly understood method for diagnosis. DRIS has been researched and used in agronomy but is only beginning to be considered for forestry applications. A DRIS diagnosis assesses the nutritional status of a sample relative to a reference, and DRIS defines a theory and set of procedures which define that reference. DRIS theory is based on the contention that for a plant to reach its growth potential, growth determinants are tolerable only within narrow limits. As the level of a growth determinant deviates from the optimum, the chances for attaining the growth potential declines. DRIS relies on ratios of the nutrients with one another for the assessment. Nutrient ratios are primarily used because they provide a direct link among the nutrients allowing them to be assessed relative to and under the influence of one another. As a consequence, a DRIS assessment generates a list of the nutrients ranking their deficiency or excess relative to one other and to the reference population.

DRIS foliar assessments identified K as the nutrient element causing the greatest imbalance. This was an unexpected result, particularly since no treatment area was below the critical level typically used to identify K deficiencies. Whether K critical levels or DRIS is in error is unknown; however, a DRIS assessment should be no worse than a critical level assessment since DRIS can be used to derive critical levels. Supportive of the DRIS foliar diagnosis is the fact that DRIS soil assessments where correlated with the foliar assessments for all elements except N. While K was identified as the element in lowest supply (relative to N, P, Ca, and Mg) it may not be limiting growth if some other conditions such as excessive competition (hardwood levels greater than 3.5 m^2 ha^{-1} or more than 83% hardwood basal area at age 4) is more limiting.

Pielous index of non-randomness was used to quantify seedling spatial patterns both at planting and after 2 yr when early mortality had changed initial spatial patterns. At planting, the seedling spatial patterns in machine planted sites where logging slash had been raked into windrows were fairly uniform. Where logging slash remained on the site but was oriented to lie in "mini windrows" between rows where trees were to be planted, the distributions were random and tended toward a clustered pattern. Hand planting was required on the no preparation and herbicide burn treatment areas because logging slash was not displaced after harvest The spatial pattern in these areas at planting was as uniform as that occurring in the cleared areas. The distribution after 2 yr in the hand planted areas exhibited the largest shift toward a clustered distribution. It is hypothesized that survival was clustered because the logging slash and residual hardwoods were located in clusters and hand planting among the debris did not proceed with sufficient care to promote seedling survival. Surviving spatial patterns in all machine planted treatment areas changed a similar extent, resulting in random patterns on the average. The effect of tree spatial patterns on stand growth, yield, and harvestibility is unknown; however, previous research with Douglas-fir indicates that as long as 740 trees per hectare (300 trees per acre) remain, and the trees are not fully clumped, there will be no effect on yield.

Numerous factors affect loblolly pine growth and yield in the Piedmont. Three were examined in this study and done so in isolation of each other. Additional factors, such as moisture and soil physical properties need to be considered, and all factors need to be considered jointly. Regression alone has not proved fruitful either here or in other studies; however, it may be more useful on sites that have been stratified by certain soil-site properties. DRIS also has potential as a method for providing a simultaneous evaluation of growth determinants as different as competition, nutrition, and soil textural properties.

In addition, stand growth and yield is dynamic because the environment is dynamic. The assessments in this study are for one point in time. Soil-site factors need to be monitored over time and their effect on tree growth evaluated accordingly.

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Appendix A. Criteria for ranking loblolly pine free-to-grow status from competing vegetation.

Rank	Status	Criteria
1	No Significant Competition	Competing vegetation is less than 1/2 the pine tree height when bent to touch the bole.
2	Some Competition	When bent, competing vegetation is greater than 1/2 the pine tree height, but does not overtop the tree.
3	Moderate Competition	When bent, competing vegetation is less than 1/2 the pine tree height on one side and overtops the tree on the opposite side.
4	Heavy Competition	When bent, competing vegetation is greater than 1/2 the pine tree height on one side and overtops the pine on the opposite side.
5	Extreme Competition	When bent, competition overtops the pine on both sides.

Appendix B. Statistical data for different expressions of four-year-old loblolly pine nutrient composition of needles collected in the winter for large (vol > 8700 cm^3) and small (vol < 8700 cm^3) trees.

	High Yielding Population				Low Yielding Population						
Nutrient Form	# Observ.	Mean	Variance (S_a)	C.V.	# Observ.	Mean	Varaince (S_b)	C.V.	Variance Ratio (S_a/S_b)	Comparison of Means (p-value)	Ratio significance (rank)
% N	127	1.22	.02	10.8	370	1.27	.03	14.4	1.90 **[1]	.001	1
% P	127	.12	.0002	10.7	370	.12	.0003	15.1	2.04 **	.371	2
% K	127	.53	.008	16.7	370	.51	.0076	17.2	.97	.008	5
% Ca	127	.19	.003	27.1	370	.22	.0028	24.4	1.10	.0001	3
% Mg	127	.08	.0004	24.4	370	.10	.007	26.3	1.85 **	.0001	1
N/P	127	10.43	1.46	11.6	370	10.75	1.97	13.1	1.34 *	.01	1
P/N	127	.10	.001	11.6	370	.095	.0015	13.1	1.21	.03	3
N/K	127	2.36	.182	18.1	370	2.56	.244	19.3	1.34 *	.0001	1
K/N	127	.44	.007	19.4	370	.41	.007	21.5	1.05	.0003	3
N/Ca	127	7.08	4.87	31.2	370	6.16	2.286	24.5	.47	.0001	6
Ca/N	127	.15	.002	30.9	370	.17	.0016	23.8	.74	.0002	5
N/Mg	127	16.03	18.68	27.0	370	13.22	13.61	27.9	.73	.0001	6
Mg/N	127	.07	.0003	24.5	370	.08	.0005	27.7	1.93 **	.0001	1
P/K	127	.23	.0014	16.6	370	.24	.0021	19.2	1.51 **	.001	1
K/P	127	4.52	.58	16.8	370	4.32	.787	20.5	1.36 *	.01	1
P/Ca	127	.68	.046	31.6	370	.58	.024	26.8	.52	.0001	6
Ca/P	127	1.59	.20	28.4	370	1.84	.225	25.8	1.10	.0001	3
P/Mg	127	1.56	.235	30.9	370	1.25	.147	30.7	.63	.0001	6
Mg/P	127	.69	.04	28.5	370	.86	.071	30.4	1.80 **	.0001	1
K/Ca	127	3.10	1.23	35.8	370	2.50	.653	32.4	.53	.0001	6
Ca/K	127	.36	.016	35.2	370	.44	.018	30.4	1.10	.0001	3
K/Mg	127	7.70	6.925	37.2	370	5.35	3.456	34.7	.50	.0001	6
Mg/K	127	.16	.0025	31.9	370	.21	.0046	32.5	1.81 **	.0001	1
Ca/Mg	127	2.35	.35	25.2	370	2.18	.279	24.1	.78	.005	5
Mg/Ca	127	.45	.013	25.3	370	.48	.012	23.2	.96	.007	5

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[1] * Significant at $p < 0.05$
** Significant at $p < 0.01$

Appendix C. Winter foliar nutrient concentrations of four-year-old loblolly pine stands established with seven site preparation treatments and replicated on eight sites in the S. Carolina and Georgia Piedmont.

		Concentration (%)				
Site	Treatment	N	P	K	Ca	Mg
1	No prep	1.24	.11	.46	.21	.09
	Herbicide, burn	1.27	.12	.49	.19	.07
	Chop, burn	1.34	.12	.57	.22	.09
	Shear-disc	1.36	.13	.54	.22	.12
	Shear, V blade-disc	1.25	.13	.57	.20	.09
	Shear, rake	1.21	.13	.58	.24	.11
	Shear, rake, disc	1.21	.13	.62	.18	.09
2	No prep	1.32	.13	.45	.25	.11
	Herbicide, burn	1.21	.12	.48	.21	.10
	Chop, burn	1.42	.14	.55	.18	.07
	Shear-disc	1.19	.12	.56	.18	.07
	Shear, V blade-disc	1.19	.12	.53	.18	.07
	Shear, rake	1.20	.12	.51	.22	.10
	Shear, rake, disc	1.22	.13	.58	.18	.07
3	No prep	1.28	.11	.58	.19	.09
	Herbicide, burn	1.27	.12	.46	.22	.09
	Chop, burn	1.27	.12	.50	.27	.10
	Shear-disc	1.32	.11	.54	.22	.11
	Shear, V blade-disc	1.18	.11	.51	.22	.10
	Shear, rake	1.40	.12	.54	.24	.11
	Shear, rake, disc	1.17	.11	.46	.18	.08
4	No prep	1.13	.12	.49	.23	.09
	Herbicide, burn	1.24	.13	.52	.21	.08
	Chop, burn	1.34	.13	.52	.21	.09
	Shear-disc	1.30	.12	.54	.19	.12
	Shear, V blade-disc	1.27	.12	.51	.21	.10
	Shear, rake	1.24	.12	.54	.19	.08
	Shear, rake, disc	1.24	.11	.53	.17	.09
5	No prep	1.22	.09	.49	.21	.11
	Herbicide, burn	1.33	.10	.51	.28	.12
	Chop, burn	1.22	.09	.40	.23	.13
	Shear-disc	1.25	.10	.50	.21	.10
	Shear, V blade-disc	1.22	.10	.53	.20	.11
	Shear, rake	1.19	.09	.45	.24	.13
	Shear, rake, disc	1.30	.11	.48	.19	.11

Appendix C. Continued.

		Index Values				
Site	Treatment	N	P	K	Ca	Mg
6	No prep	-3.4	-3.5	4.4	-1.6	2.9
	Herbicide, burn	-0.7	-2.1	8.6	-6.9	6.9
	Chop, burn	-0.9	6.9	3.9	-1.0	-7.1
	Shear-disc	6.5	-4.5	6.2	-18.6	5.6
	Shear, V blade-disc	-0.5	-6.6	-8.2	-6.7	6.4
	Shear, rake	1.1	-7.5	3.8	-6.5	2.9
	Shear, rake, disc	-2.4	-12.9	0.0	1.7	16.4
7	No prep	14.3	74.9	-21.6	-37.8	-40.6
	Herbicide, burn	3.5	28.8	-8.5	-13.1	-16.6
	Chop, burn	16.6	41.5	-21.3	-13.7	-46.4
	Shear-disc	-3.5	51.3	-17.4	-11.2	-36.1
	Shear, V blade-disc	6.8	3.9	-10.9	-6.8	-7.3
	Shear, rake	11.3	24.5	-12.7	-13.7	-27.6
	Shear, rake, disc	5.0	52.3	-13.8	-17.9	-40.7
8	No prep	11.4	19.8	-2.0	-23.1	-27.5
	Herbicide, burn	-0.8	15.6	-3.4	-2.9	-6.4
	Chop, burn	-4.1	-4.0	0.1	-6.7	11.9
	Shear-disc	-0.0	-10.4	0.9	-3.3	8.6
	Shear, V blade-disc	-0.7	-4.6	4.7	-5.4	4.6
	Shear, rake	-5.4	-6.1	5.3	-6.4	11.5
	Shear, rake, disc	1.5	-6.8	-2.6	-3.7	5.4

Appendix D. Statistical data for different expressions of soil nutrients in the upper 20 cm of S. Carolina and Georgia Piedmont soils in respect to large (vol > 8700 cm^3) and small (vol < 8700 cm^3) four-year-old loblolly pine trees.

	High Yielding Population				Low Yielding Population						
Nutrient Form	# Observ.	Mean	Variance (S_a)	C.V.	# Observ.	Mean	Varaince (S_b)	C.V.	Variance Ratio (S_a/S_b)	Comparison of Means (p-value)	Ratio significance (rank)
N[1]	125	14.15	30.61	39.1	369	14.56	30.54	37.9	1.00[2]	.46	6
P	123	1.12	.84	82.1	372	.95	.89	99.6	1.05	.06	4
K	125	49.0	520.3	46.5	375	51.95	455.9	41.1	.88	.21	6
Ca	125	269.6	32308.	66.6	375	306.38	35846.	61.7	1.11	.05	3
Mg	125	61.8	2285.8	77.4	375	75.81	2169.5	61.4	.95	.005	5
N/P	121	21.70	471.8	100.1	365	25.83	416.8	79.0	.88	.06	6
P/N	121	.092	.008	98.8	365	.075	.0075	116.8	.91	.05	5
N/K	123	.352	.045	60.7	368	.321	.025	49.6	.55	.14	8
K/N	123	3.73	4.017	53.7	368	3.89	3.42	47.5	.85	.42	6
N/Ca	123	.075	.002	65.6	368	.066	.002	69.7	.88	.09	6
Ca/N	123	19.5	163.6	65.6	368	22.62	247.0	69.5	1.51**	.03	2
N/Mg	123	.433	.191	101.0	368	.317	.085	91.93	.45	.007	7
Mg/N	123	4.89	21.2	94.1	368	5.89	18.9	73.77	.89	.04	5
P/K	123	.036	.003	148.5	372	.025	.002	158.9	.56	.04	7
K/P	123	80.7	6741.	101.6	372	99.60	7387.	86.29	1.10	.03	3
P/Ca	123	.008	.0003	187.0	372	.006	.0001	193.7	.49	.07	8
Ca/P	123	453.3	324741.	125.7	372	602.4	393681.	104.1	1.21	.01	3
P/Mg	123	.058	.021	246.8	372	.032	.0056	233.1	.27	.05	7
Mg/P	123	117.5	25071.	134.7	372	161.7	27216.	102.0	1.09	.01	3
K/Ca	125	.221	.011	46.5	375	.214	.012	50.31	1.10	.52	4
Ca/K	125	5.40	4.907	41.03	375	6.054	13.01	59.56	2.65**	.01	2
K/Mg	125	1.10	.322	51.37	375	.926	.270	56.13	.84	.002	5
Mg/K	125	1.19	.492	59.15	375	1.51	1.00	66.49	2.05**	.001	2
Ca/Mg	125	5.475	6.38	46.15	375	4.73	4.88	46.73	.76	.003	5
Mg/Ca	125	.245	.029	69.13	375	.278	.032	64.65	1.13	.06	4

[1] KCl extractable N in ppm.
Double acid extractable P, K, Ca, and Mg in ppm.

[2] * significant at the .05 level
** significant at the .01 level

Appendix E. DRIS index and standardiziation equations used in analyzing winter soil nutrients in four-year-old loblolly pine plantations in the S. Carolina and Georgia Piedmont.

$$\text{N index} = \frac{f(n) - f(p/n) - f(k/n) - f(Ca/n) - f(Mg/n)}{5}$$

$$\text{P index} = \frac{f(p/n) + f(p) - f(k/p) - f(Ca/p) - f(Mg/p)}{5}$$

$$\text{K index} = \frac{f(k/n) + f(k/p) + F(k) - f(Ca/k) - f(Mg/k)}{5}$$

$$\text{Ca index} = \frac{f(Ca/n) + f(Ca/p) + f(Ca/k) + f(Ca) - f(Mg/Ca)}{5}$$

$$\text{Mg index} = \frac{f(Mg/n) + f(Mg/p) + f(Mg/k) + f(Mg/Ca) + f(Mg)}{5}$$

where:

$$f(n/p) = \left[\frac{n/p}{N/P} - 1\right] X \left[\frac{100}{CV_{N/P}}\right] \quad \text{if } n/p > N/P$$

$$f(n/p) = \left[1 - \frac{n/p}{N/P}\right] X \left[\frac{100}{CV_{N/P}}\right] \quad \text{if } n/p < N/P$$

where: N/P refers to reference population
n/p refers to sample being evaluated

Appendix F. DRIS soil nutrient indicies for four-year- old loblolly pine stands established with seven site preparation treatments and replicated on eight sites in the S. Carolina and Georgia Piedmont.

		Index Values				
Site	Treatment	N	P	K	Ca	Mg
1	No prep	-5.3	-16.3	3.9	9.6	4.1
	Herbicide, burn	-11.0	-9.6	4.5	16.3	2.7
	Chop, burn	1.5	-3.7	-0.1	6.4	-1.5
	Shear-disc	-4.1	-1.1	-0.9	2.8	4.3
	Shear, V blade-disc	-1.9	12.6	-6.2	1.8	-4.2
	Shear, rake	-2.5	4.3	-3.8	-2.0	-0.5
	Shear, rake, disc	-1.9	4.4	-2.1	2.3	-1.5
2	No prep	2.3	-14.2	-9.5	7.5	12.0
	Herbicide, burn	12.5	1.5	-2.4	-6.2	-5.8
	Chop, burn	1.1	14.5	-3.8	1.7	-10.4
	Shear-disc	4.7	10.6	-5.5	-5.1	-5.0
	Shear, V blade-disc	6.7	8.0	-9.7	-0.9	-3.7
	Shear, rake	3.3	-6.4	-7.6	-1.9	13.8
	Shear, rake, disc	-6.5	8.6	0.8	-1.4	0.8
3	No prep	9.4	-14.3	1.3	7.6	2.2
	Herbicide, burn	12.4	2.4	-10.6	6.3	-10.3
	Chop, burn	9.2	-3.1	-0.4	11.6	-9.7
	Shear-disc	12.5	-23.4	3.4	14.7	-0.3
	Shear, V blade-disc	7.1	-5.2	3.5	4.5	-5.4
	Shear, rake	8.9	-10.4	0.6	5.2	-3.5
	Shear, rake, disc	14.4	-27.9	2.3	8.4	0.9
4	No prep	5.1	13.4	5.9	-12.6	-16.2
	Herbicide, burn	4.2	35.5	-5.0	-15.5	-21.3
	Chop, burn	5.3	22.5	-0.2	-13.6	-16.2
	Shear-disc	1.4	-8.5	3.5	-8.6	11.6
	Shear, V blade-disc	3.6	-0.9	1.7	-0.1	-5.6
	Shear, rake	6.4	14.5	0.6	-10.4	-16.1
	Shear, rake, disc	6.0	-8.1	3.8	-7.8	-3.5
5	No prep	-0.2	-3.1	-11.5	8.6	6.5
	Herbicide, burn	-10.1	-11.1	-4.5	18.2	10.7
	Chop, burn	0.5	-6.2	-24.9	18.4	15.2
	Shear-disc	0.7	-10.2	1.6	8.3	5.2
	Shear, V blade-disc	-9.5	-5.5	-1.6	2.7	10.6
	Shear, rake	-1.8	-6.3	-6.7	6.9	7.1
	Shear, rake, disc	5.0	-3.1	-5.3	5.3	2.0

Appendix F. Continued.

Site	Treatment	Index Values N	P	K	Ca	Mg
6	No prep	1.17	.11	.52	.22	.10
	Herbicide, burn	1.29	.12	.50	.16	.10
	Chop, burn	1.34	.12	.54	.15	.08
	Shear-disc	1.20	.11	.56	.16	.09
	Shear, V blade-disc	1.23	.12	.53	.19	.10
	Shear, rake	1.34	.11	.51	.19	.11
	Shear, rake, disc	1.27	.11	.48	.20	.11
7	No prep	1.06	.11	.40	.18	.08
	Herbicide, burn	1.30	.12	.52	.23	.09
	Chop, burn	1.19	.12	.44	.25	.08
	Shear-disc	1.26	.13	.48	.22	.08
	Shear, V blade-disc	1.15	.11	.43	.21	.09
	Shear, rake	1.17	.13	.52	.23	.08
	Shear, rake, disc	1.22	.13	.48	17	.07
8	No prep	1.24	.12	.47	.21	.08
	Herbicide, burn	1.22	.13	.53	.16	.08
	Chop, burn	1.36	.14	.56	.25	.10
	Shear-disc	1.34	.12	.53	.21	.10
	Shear, V blade-disc	1.37	.13	.55	.19	.09
	Shear, rake	1.38	.13	.55	.24	.11
	Shear, rake, disc	1.30	.12	.45	.20	.11