INTERSPECIFIC COMPETITION IN YOUNG LOBLOLLY PINE PLANTATIONS ON THE VIRGINIA PIEDMONT

by

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INTRODUCTION

The southern United States is a focal point in the production of forest products and will be increasingly important in the future, producing half of the nation's wood by the year 2000 (Barber 1979). This production is due, among other factors, to environmental conditions which are excellent for the growth of fast-growing trees, and the presence of valuable and versatile species such as loblolly pine (_Pinus taeda_ L.). In order to meet projected demands for wood products southern forest lands should be efficiently managed to maximize potential yield. Loss of productive land to other types of development has also had a negative impact on the industry and increases the importance of developing efficient management techniques.

In spite of the excellent growing conditions, intensive management of southern forest lands is necessary to maximize production due to several characteristics of these lands. Throughout the South numerous unwanted plants, or weeds, invade any uncontrolled cropland. Forest lands are no exception, with hardwood vegetation dominating after harvest on 40 percent of the pine acreage cut between 1957 and 1977

(Knight 1977). These hardwood plants along with herbaceous vegetation compete with the crop seedlings for light, water, and nutrients essential for growth (Newbold 1979). This competition limits the growth of loblolly pine and stand production can often be improved with the control of these weeds (Nelson et al. 1981, Cain and Mann 1980, Loyd et al. 1978).

Little work, however, has been done to quantify the competitive relationships between loblolly pine and weed species, or to determine the best timing and intensity of release operations. Quantification of the competitive relationships and the growth response to release will be necessary in order to make management decisions which will maximize the use of site resources.

Another limiting characteristic of southern forest lands is that 73 percent of the land is under private non-industrial ownership (USFS 1980). This implies that some weed control measures should be simple and inexpensive. Otherwise, the small-tract woodland owner, with little capital, will not invest in sophisticated weed control methods which require costly equipment. In addition, the weed control methods must be an effective incentive for the owner to invest in weed control. Therefore, it is desirable to develop a means of predicting exactly how much release is needed, and at what age, for the maximum increase in growth of the pine seedlings.

The purpose of this study was to quantify the competitive relationships in young loblolly pine plantations at both a stand and an individual tree level. The growth response of young loblolly pines to different levels of release from competing vegetation was evaluated in an attempt to determine the best timing and intensity of release. Predictive models for the growth response to release of young loblolly pine plantations were developed.

LITERATURE REVIEW

Competition Studies in Loblolly Pine Plantations

Numerous studies have, at least indirectly, explored the growth relationships between loblolly pine and competing vegetation. Most of the early studies only included the pine growth response to release and did not involve evaluation of the levels of competing vegetation or quantification of the competitive status of the pine or its competitors. However, these studies did establish the groundwork upon which further work can be based. Most importantly, they established that control of competing vegetation results in increased growth of the pines which leads to the hypothesis that the pines were in fact under competitive stress.

The studies conveniently fall into two groups. The first group includes stands with a closed canopy, or those over about ten years of age. The other, much larger group, includes stands before canopy closure, usually less than ten years old.

Stands With a Closed Canopy

In a couple of early studies, Bull (1939,1945) evaluated the effect of girdling understory hardwoods on the growth of 25 to 30 year old loblolly pines. Bull took no measurements of the competing hardwoods but found a definite increase in pine growth and a decrease in mortality with the removal of the hardwood overstory.

Four separate studies evaluated the growth response of loblolly pines to release from understory competitors but the results were contradictory. In two of these studies (McClay 1955 and Russell 1961) no increase was found in the growth of 26 and 40 year old loblolly pines, respectively, by the removal of understory hardwoods and shrubs. However, moisture was not a limiting factor at either site during the experiments which may partially explain the results. The other studies (Dierauf 1984a, 1984b and Grano 1970) in pine stands of about 10 and 50 years of age, respectively, found that the removal of understory hardwoods significantly increased the growth of the pines. An 111 percent increase in volume growth was attributed to release by Dierauf on seventeen sites.

Only one study in older loblolly pine stands measured the competing vegetation (Loyd et al. 1978). This study evaluated the effectiveness of three different treatments (mist blowing, prescribed burning, and injection) in removing understory and overstory hardwood competition and increasing the growth of the pines. The measurement of the hardwood competition was simply a count of the stems per hectare by diameter class and these data were used only to measure the effectiveness of each treatment in removing hardwood stems. All three treatments, however, significantly increased the radial growth of the pine as compared to the growth before treatment.

Stands Before Canopy Closure

The majority of the work on release response in loblolly pine plantations has been done in plantations prior to canopy closure. These studies dealt mostly with the conversion of low-quality hardwood stands to pine plantations through the release of underplanted pines or the control of sprouting hardwoods and brush competing with the young pines.

Several studies evaluated the growth response of underplanted loblolly pine to release from overstory hardwoods. These studies usually concentrated on the effectiveness of different herbicide treatments and included studies: 1) which only gave pine growth response results (Shoulders 1955 and Hatchell 1964) ; 2) which characterized the pretreatment stand by reporting the stems per acre of hardwood species (Miller and Tissue 1956 and Muntz 1951); and 3) which included before and after treatment hardwood measurements of stems per hectare (Miller 1961) or basal area (Huckenpahler 1954) to evaluate the effectiveness of each herbicide. All of these studies found a significant increase in growth of the released pine seedlings over control plots. The pine growth response was often measured in height growth. When diameter growth was measured, increases in growth were up to eight times greater than those reported for height growth. This indicates that diameter growth is more sensitive than height growth to competitive interactions.

Russell (1971) evaluated the response of underplanted pine to three levels of hardwood removal. Each level of release was also tested without the use of a herbicide. The hardwoods were evaluated after harvest to determine the comparative levels of sprouting among treatments. Russell found that over 95 percent of the stems that were cut but not treated with an herbicide resprouted as compared to only 15 percent resprouting of treated stumps. He also measured hardwood heights after the treatment but only used them to compare the effectiveness of the treatments and not to measure the competition. There have also been several experiments designed to measure the pine growth response to release from understory hardwood brush competition. These include Cain and Mann (1980), Carter et al. (1975), Ferguson (1958), Korstian and Bilan (1957), Stransky (1980), and Yocum (1962). A growth response to release was universal but was generally lower than the results from the overstory studies. However, growth was still substantial with a 45 to 66 percent increase in total pine volume reported by Cain and Mann (1980).

Two of these studies actually attempted to address the question of the competitive status of the pine seedlings. Ferguson (1958) utilized soil moisture measurements to ascertain the level of competition in the stand. Results showed that the removal of competition definitely affected the moisture regime of a stand. Plots in which the competition was completely removed retained sufficient moisture throughout the growing season while untreated plots were subjected to severe soil moisture stress. Ferguson concluded that most of the variations in survival and height growth were probably related to differences in the available moisture, but no attempts were made to quantify this relationship. Korstian and Bilan (1957) attempted to separate the effects of crown competition and root competition. Both crown and root competition were reduced by a treatment that killed all woody plants within a 3.8 m radius circle around each of 20 pines. Crown competition was reduced by tying back all the woody plants capable of shading 20 other pines while leaving the root competition undisturbed. A control treatment was also included. Results showed that the effects of crown and root competition were greater than root competition only and the authors concluded that both light and moisture are important factors in the growth of loblolly pine with competing vegetation.

Some attempts have been made to experimentally control the level of hardwood competition in plantations. In a two-year-old loblolly pine stand Ferguson (1963) evaluated the growth and survival of the pine under four degrees of hardwood control. These four levels were: 1) removal of small hardwoods (< 8.9 cm diameter at breast height (dbh)); 2) girdling and poisoning of large hardwoods (> 8.9 cm dbh); 3) removal of both large and small hardwoods; and 4) the control with no treatment. Before and after treatment basal areas of the hardwood vegetation were measured, and pine height and survival were determined after two years. Significant linear relationships were found between both height and survival, and residual basal area of hardwoods. In a similar study, Williston and McClurkin (1961) also used basal area as the measure of the level of competition created. With three treatments they created stands with 0, 0.078 and 0.215 m^2/ha of residual hardwood basal area. These treatments resulted in pine survival rates of 94, 88, and 83 percent, and average pine heights of 2.7, 1.6, and 1.2 m respectively. However, no attempt was made to predict survival or height given residual basal area.

More recently, Carter et al. (1983) studied the effect of competition on the moisture and nutrient status of five-year-old loblolly pine by creating five levels of competition. The five treatments removed the woody and/or herbaceous vegetation in two concentric circles centered on the pines. Treatments removed: 1) all vegetation within 1.5 m of the pine; 2) all vegetation within 0.5 m and woody vegetation within 1.5 m; 3) woody vegetation only within 1.5 m; 4) woody vegetation from 0.5 to 1.5 m; or 5) none of the vegetation. Elimination of all competing vegetation significantly lowered moisture stress over the no elimination treatment, and removal of woody vegetation only reduced pine moisture stress half as much as removal of all vegetation. The higher levels of competition significantly reduced available potassium concentrations in the soil, but none of the treatments affected foliar nutrients. No attempt was made to directly relate any of the variables tested to pine growth, nor was pine growth measured.

A study in western conifers evaluated the effects of removing different amounts of competing vegetation at two different stand ages. Peterson and Newton (1985) controlled three different levels of the competing vegetation (total weed control, control of woody stems only, and a check) in five- and ten-year-old Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) stands. The relative increase in growth was dependent upon age and intensity of release. Five years after treatment, the total weed control treatment resulted in the greatest stem diameter and volume at both ages, but was the only significantly better treatment in the older stands. In the younger stands, the woody control only treatment was significantly better than the check, but lower than the total weed control treatment. The growth response to release was greater in the younger stands, with the stem volume of trees from the total control treatment almost four times greater than the check, but only twice as great in the older stands. The authors concluded that total weed control was necessary, but they did not include intermediate levels of woody control in the comparison.

Intensive measurement of the hardwood competition was one of the strong points of a study by Roberts (1960). In an attempt to measure the competition Roberts hypothesized that five factors were likely to be important in the competitive situation. These factors were: 1) size of the pine; 2) size of the hardwoods; 3) hardwood species; 4) distance to the hardwoods from the pine; and 5) direction to the hardwoods. A knowledge of pine survival and growth responses to various combinations of these elements could lead to proper management decisions. One hundred-fifty separate competitive situations were studied which included the complete range of competition. For each situation several variables were measured including: 1) height of pine; 2) direction and 3) distance to its competitors; 4) species; 5) stump diameter of the hardwoods cut; 6) number of sprouts per clump; and 7) height of competitors, or the tallest member of a sprout clump. Trees shorter than the pine or those farther than six feet away were considered to be offering little or no competition to the pine. Unfortunately, Roberts was only able to come up with general recommendations for cleaning operations in loblolly pine plantations.

More recently, Glover (1982) located 167 different competitive situations in young loblolly pine plantations on the Alabama Piedmont. While using basically similar measurements to Roberts', Glover expanded them to include the effect of the herbaceous vegetation, by life form groups, and additional measures of competition involving an evaluation of the crowns of the pine seedlings. A crown volume index was computed by multipling crown height by crown area, both from measures of crown diameters in the field and by a photographic evaluation of the crowns. An analysis of the data revealed a high degree of variability in the growth of individual pines but also showed the effect of hardwood competition, based on linear correlation coefficients and partial F-tests of multiple regression. Hardwood basal area explained up to 67 percent of the variation in pine diameter growth. Correlation coefficients comparing the number of hardwood rootstocks and pine growth responses were nearly as high and sometimes higher. This may indicate that a fairly accurate estimation of the level of competition may be reasonably ascertained by simple field techniques. Therefore, this study showed that the competitive effects are quantifiable and that there are definite relationships between loblolly pine size and growth, and measures of competing vegetation.

Economic Evaluations

Evaluations of financial returns from competition control in young loblolly stands have shown the economic feasibility of such actions. Huckenpahler (1954) and Shipman (1954) compared the costs of different treatments and made general statements about the relative effectiveness of each treatment, indicating which ones seemed to be the most cost effective. Mann (1951) tested three intensities of hardwood treatment (removing hardwoods 15 cm dbh and larger, 5 cm dbh and larger, and all hardwoods greater than 1.5 m tall) in releasing understory pines in a stand dominated by low-grade hardwoods. Treatment costs were compared with stumpage returns from a thinning ten years after treatment. The medium intensity treatment gave the best financial return while removal of only the largest hardwoods resulted in a loss.

More recently, Balmer et al. (1978) undertook the financial analysis of a long-term study in North Carolina and Virginia. Growth responses and financial returns were based on the twenty year results of two studies of growth and yield effects of treating hardwoods and controlling density in young loblolly pine stands (Langdon and Trousdell 1974). Controlling large hardwoods was shown to increase the financial returns by over 200 percent compared to no treatment. More intensive cultural treatments, including precommercial thinning, resulted in even better returns on the investment.

These papers present convincing arguments for investment in cultural treatments. However, each of these studies was conducted in stands where the loblolly pine regeneration was natural. Similar studies in planted stands are not available but analogous results may be possible.

Herbaceous Competition

Herbaceous weeds also have an adverse impact on the growth of loblolly pine seedlings. Removal of herbaceous competition alone resulted in growth increases of 21 percent in height and 44 percent in groundline diameter during the first two seasons in a loblolly pine plantation in Louisiana (Haywood and Tiarks 1981). Nelson et al. (1981) discovered a strong relationship between pine height growth response and percent cover of herbaceous weeds in one-year-old plantations. Height growth responses of 8 to 12 cm followed treatments which chemically controlled the herbaceous vegetation. Equations developed to predict pine height growth as a function of percent ground cover of herbaceous weeds seven weeks after planting indicated a strong linear relationship, with R^2's of 0.72 to 0.91.

Volume growth of individual loblolly pines was significantly different between five different treatments in a plantation on the Alabama Coastal Plain (Knowe et al. 1982). Third year volume was maximized (3093 cm^3) by two years of broadcast herbaceous weed control, a significantly higher value than that of a two year, 1.2 m wide, band treatment (1770 cm^3). However, both of these means were significantly higher than the same treatments performed only in the first year (1104 and 1024 cm^3, respectively). All treatments were significantly higher than the control (342 cm^3). Fourth year results showed the same pattern of treatment differences (Knowe et al. 1985). Correlation coefficients (r^2) for mean height, groundline diameter, and volume index with dry weight and percent cover of the herbaceous competition on each plot were significant and ranged from 0.59 to 0.76. These studies indicate the importance of competition from herbaceous species in determining the early growth of loblolly pine.

Chemical Weed Control

The use of herbicides is the most common method of weed control in southern pine plantations. Because of their versatility, herbicides can be used for the conversion of low quality hardwood stands, site preparation after harvest, weed control in a newly established stand, and to release pines from woody competition in older stands (Haywood 1981). The versatility of herbicides is also evident in the numerous methods of application. The most common methods of application include: foliage sprays; dormant sprays; basal and stem spraying; stem injection; stump treatments; and other methods which usually involve pellets or granular formulations applied to the soil in some regular spacing pattern (Newton and Knight 1981).

The earliest method of chemical control, utilized in the 1940's and 1950's, involved notching or girdling the unwanted trees and applying ammate (ammonium sulfamate) to the wound to accelerate the kill and reduce sprouting. The introduction of the phenoxy herbicides in the 1940's and the further development of their uses, eventually led to their widespread use in forestry. The major phenoxy herbicides, (2,4,5-trichlorophenoxy)acetic acid (2,4,5-T) and (2,4-dichlorophenoxy)acetic acid (2,4-D), were the principal chemicals used in weed control in pine plantations for almost thirty years (Carter et al. 1975). Application methods varied from placement in notches to aerial spraying, but tree injection was the most commonly used method (Burns and Box 1961). However, the 1979 ban of 2,4,5-T for forest and other uses by the Environmental Protection Agency has forced the development and use of new compounds (Fitzgerald 1981). Actually, many of these compounds were already being tested before the ban, but were not widely used because they were less cost effective. As a result, many studies compare the effectiveness of these new herbicides with 2,4,5-T.

Herbicides in use today are those registered for forestry use in a particular state. Herbicides registered for use in the state of Virginia are categorized into frill treatments, injections, stump treatments, and aerial and soil applications for site preparation and conifer release (Chappell and Hipkins 1982 and Haywood 1981). Chemicals registered for use in conifer release include glyphosate (N-(phosphonomethyl)glycine), picloram (4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid) plus 2,4-D and hexazinone (3-cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2,4 (1H,3H)-dione). Recommendations for use include application of glyphosate aerially or by ground methods at 27 - 36 kg/ha. A dilute solution of picloram and 2,4-D should be applied utilizing a low pressure backpack sprayer with a directed spray while hexazinone should be applied at 9 - 27 kg ai (active ingredient)/ha.

A recently introduced herbicide, triclopyr ([(3,5,6-trichloro-2-pyridinyl)oxy] acetic acid), is currently being tested for use in conifer release (Fitzgerald et al. 1980). Byrd et al. (1977) found that this herbicide gave good control of hardwoods with foliar applications. In addition, basal bark applications with a three percent solution of triclopyr in a diesel oil carrier resulted in excellent control of several hardwood species in the Pacific Northwest (Warren 1980). Because of the precise control possible in the basal bark application, the ease of application and the effectiveness of triclopyr, it was chosen as the hardwood control chemical in this study.

Another recently introduced chemical, sulfometuron (2-[[[[(4,6-dimethyl-2-pyrimidinyl)amino]carbonyl]amino] sulfonyl]benzoic acid), has proven effective in the control of herbaceous vegetation in young pine plantations. From studies conducted throughout the Southeast, Gjerstad and Nelson (1983) reported that sulfometuron consistently controlled a variety of weeds at 0.22 and 0.45 kg/ha. In addition, toxicity due to the herbicide was not apparent on pines growing on finer textured soils, though some chlorosis and stunting occurred on coarser soils. A study testing the use of several herbaceous herbicides in a one-year-old loblolly pine plantation reported that sulfometuron gave good control of many weeds including woody vines, and reported a significant pine diameter growth response (Michael 1985). The effectiveness of sulfometuron in weed control and the apparent pine tolerance were the primary reasons for being selected as the herbaceous herbicide in this study.

Even though herbicides vary in price, general estimates for the cost of chemical weed control in pine plantations are reported in the literature. These estimates vary between $74 and $124 per ha (1981 dollars) for release, depending upon the chemical used, the method of application, and intensity of treatment (Balmer et al. 1978 and Klopatek and Risser 1981). Generally conifer release herbicides can be applied with ground application techniques using simple equipment, such as knapsack sprayers, which could be available to the small-tract woodland owner. This combination of relatively low price and simple equipment makes chemical weed control more feasible for the private non-industrial owner which was why ground application techniques were used in this study.

Growth and Yield Modeling

Numerous studies have involved the development of models to predict the growth and/or yield of various tree species. The majority of these models were developed for pure, even-aged stands of southern pine and have usually focused on stands greater than 8-10 years of age (Farrar 1979). These models have been of three different levels of resolution, the whole stand, size-classes within the stand, and the individual tree.

<u>Whole Stand Models</u>

The earliest whole stand models, or stand average models, were yield tables for stands of "normal" stocking. These yield tables were developed from temporary plots using graphical techniques and provided the per hectare yield of wood as a function of age and site quality (U.S. Forest Service 1929). However, the assumption of a vaguely defined standard density was inadequate and inflexible, leading to unsatisfactory predictions for the stands with non-normal densities.

This led to the use of multiple regression techniques to develop variable density yield tables (MacKinney et al. 1937). The first such tables (MacKinney et al. 1937) used the Pearl-Reed growth function while MacKinney and Chaiken (1939) used a logarithmic equation with age, site quality, and a stand density index as independent variables. This general equation form has been the basis for several more recent stand average growth and/or yield models for southern pine. (Schumacher and Coile 1960, Coile and Schumacher 1964, Burkhart et al. 1972a, 1972b).

Diameter Distribution Models

Another approach to growth and yield modeling developed uses diameter distribution models. Diameter distribution models provide estimates of trees per unit area by diameter, usually dbh, classes. This method assumes that the diameter distribution of a stand can be characterized by a probability density function (pdf). Several different probability distributions have been used to describe the diameter distributions of forest stands.

The actual diameter distribution was originally assumed to follow the pattern of a geometric series, and reverse J-shaped curves were also tested in early studies (Meyer and Stevenson 1943 and Meyer 1952). Bennett and Clutter (1968) obtained reliable and consistent estimates of slash pine yield using the beta distribution as the basis for the construcion of yield tables. The beta parameters were predicted from stand attributes, age, site index, and density. Several subsequent studies also used the beta probabilty distribution function to develop models in southern pine stands (Lenhart and Clutter 1971, Lenhart 1972, Burkhart and Strub 1974). Use of the beta distribution has one disadvantage, however, since the cumulative distribution function (cdf) does not exist in closed form and the pdf must be numerically integrated to obtain the proportion of trees in each diameter class.

Another distribution useful for describing diameter distributions is the Weibull pdf, which was first used in a model by Bailey (1972). This distribution was found to have several desirable properties. The pdf is flexible in shape, the parameters are relatively easily related to stand characteristics, and the cdf exists in closed form (Bailey and Dell 1973). The Weibull distribution has been used to construct models for loblolly pine plantations (Smalley and Bailey 1974a and Feduccia et al. 1979) and other southern pine plantations (Smalley and Bailey 1974b, Lohrey and Bailey 1976, Dell et al. 1979).

Several other distributions have been tested for use in diameter distribution models. Hafley and Schreuder (1977) compared six of the most commonly used distributions. These distributions were normal, lognormal, gamma, Weibull, beta, and Johnson's S_B. In terms of flexibility , the S_B was the most flexible followed by the beta, Weibull, gamma and lognormal. The normal distribution has only one shape, and therefore, limited flexibility, but was included for comparative purposes. The S_B was consistently better for fitting the diameter distributions, followed by the beta and the Weibull. However, for practical purposes, there were no differences between the theoretically and computationally complex S_B and the beta and Weibull distributions.

Diameter distribution models were originally all constructed using equations to predict the parameters of the chosen pdf from stand attributes. Values for the parameters were estimated for each sample plot, usually using maximum likelihood procedures. Regression equations were then developed relating the parameter values to the age, site quality, and density of the plot. These equations were referred to as parameter prediction equations and commonly had R^2 values of 0.3 or less. This suggested a problem with model specification, or a weak relationship between the parameters and the stand attributes (Frazier 1981).

Hyink (1980a, 1980b) and Hyink and Moser (1983) introduced an alternative method to parameter prediction, the method of moments which predicted stand attributes of interest and used these estimates to "recover" the parameters of the distribution. This method used the first two non-central moments of the distribution to develop a system of two equations with two unknowns. The first two non-central moments of x, in this case dbh, were expressed as:

$$E(x) = \int_0^\infty x \; f(x;\, b,\, c) \; dx$$

$$E(x^2) = \int_0^\infty x^2 \; f(x;\, b,\, c) \; dx$$

These non-central moments were estimated by the mean stand diameter and the mean squared diameter. For a two-parameter Weibull, the first two central moments were estimated to give the system of equations:

$$\overline{x} = b\,\Gamma\,(1 + 1/c)$$

$$\overline{x^2} = b^2\,\Gamma\,(1 + 2/c)$$

The estimated variance of the distribution was given by:

$$s^2 = \overline{x^2} - \overline{x}^2 = b^2\,[\Gamma(1 + 2/c) - \Gamma^2(1 + 1/c)]$$

The coefficient of variation was estimated by:

$$c.v. = s/\overline{x} = \frac{[\Gamma(1 + 2/c) - \Gamma^2(1 + 1/c)]^{\frac{1}{2}}}{\Gamma(1 + 1/c)}$$

which was a function of c only. Therefore, with the estimates of the mean diameter and mean squared diameter, it was possible to solve for c. This value for c was substituted back into the equation for the mean diameter to obtain a value for b. This method has been used to develop models for southern pine plantations (Matney and Sullivan 1982, Cao 1981, Frazier 1981).

Individual Tree Models

An alternative method of growth and yield modeling focuses on the growth of individual trees. These models were developed more recently than whole-stand models and often are elaborate computer simulation models. The elaborate models simulate the growth of individual trees and aggregate these to provide estimates of stand growth and yield (Burkhart et al. 1981). In addition, some studies have developed individual tree growth equations based on theoretical growth relationships.

Aggregate Models. The earliest of individual tree models were developed in coniferous forests of the western United States (Newnham 1964, Newnham and Smith 1964, Lee 1967). These models were based on the idea that diameter growth increment for trees in plantations was equal to open-grown diameter growth reduced by an amount based on competition. Growth was incremented every five years from 10 to 100 years of age and mortality was assigned as a function of diameter growth. The models were tested and gave reasonable results.

Mitchell (1975) developed a simulation model based on branch elongation and crown extension of individual trees. The model allowed for the crown to expand and contract asymmetrically in a three-dimensonal space based upon restrictions imposed by competitors and internal growth processes. Stem volume was predicted from regressions based on crown size and tree height.

Daniels and Burkhart (1975) developed an individual tree growth model for loblolly pine. Potential annual height and diameter growth was simulated as a function of age, site, size, and adjusted with the use of a competition index. In addition, tree growth was adjusted by random components representing genetic and/or microsite variability. Mortality was based on tree size and competition.

Theoretical Growth Equations. The use of modified Chapman-Richards growth equations for describing the growth of individual stems has been explored (Pienaar and Turnbull 1973 and Martin and Ek 1984). The equations developed assumed that the increase in physical dimensions of trees was related to the internal anabolic and catabolic processes of the trees. The anabolic rate was assumed to be proportional to the photosynthetic area, which has an allometric relationship to a physical dimension, such as diameter or volume, while the catabolic rate was simply proportional to the physical dimension. These relationships were represented mathematically as:

$$\text{anabolic rate} = cD^m$$

$$\text{catabolic rate} = c_1 D$$

where D was the physical dimension and c, c_1, and m were the appropriate constants (Pienaar and Turnbull 1973). The anabolic rate equation was extended to include an index of site quality. The potential rate of surplus production was obtained by subtraction. This potential rate was assumed to be modified by the environment based upon the amount of competition present (Martin and Ek 1984). The actual equation fitted by Martin and Ek (1984) was:

$$\Delta D = e^{-b_1 C}(b_2 S^{b_3} D^{b_4} - b_5 D)$$

where:

D = the physical dimension

C = competition index

S = site index

b_i = non-linear regression coefficients

Martin and Ek (1984) used this model to test the efficacy of different competition indices, and compared this model to an empirically-derived regression equation. Diameter and height growth were predicted using data from red pine (Pinus resinosa Ait.) stands, of 20 to 58 years of age, in the Lake States region. For diameter growth models, the empirical model performed better than the Chapman-Richards equation. Competition indices significantly improved model fit for all model forms, and distance-independent indices resulted in better fit than the distance-dependent indices tested.

Eventhough the literature on growth and yield modeling is extensive, there are limited numbers of studies dealing with stands less than 8 to 10 years of age. This led to the inclusion of model development in this study.

Competition Measures

The need for the development of measures of competitive stress have been long recognized in forestry. To be practical these competition indices should be easy to measure and calculate. Such quantitative measures of competition could be used in the determination of the proper timing of silvicultural activities such as weeding, cleaning and thinning. They could also aid in decisions about the intensity of these operations since competition indices can give the manager an indication of the spacing of trees required to optimize the production of a given area. Competition indices have become very useful in simulation models which predict stand growth and estimate the effects of silvicultural treatments.

In quantifying competitive stress, measures of crown size have been used as indicators of the competitive status of an individual. In an early study, Krajicek et al. (1961) reasoned that crown size would be an excellent indicator of competition for light and would also give an indication of root competition based on a hypothesized relationship between crown size and root area. By comparing the crown/dbh relations of open-grown trees, which are not affected by competition, with trees under competitive stress in a forested stand, a competition index was developed. This index was expressed on an individual tree basis as maximum crown area (MCA) and on an entire stand basis as the crown competition factor (CCF), the sum of the MCA's. No attempt was made, however, to account for the spatial distribution of trees.

In loblolly pine plantations, Strub et al. (1975) compared diameter growth and crown competition factor (CCF). They found that the age at which diameter growth of the average tree in a stand was reduced to less than the growth of the average open grown tree corresponded to canopy closure or a CCF of 100.

Based on the relationship of dbh to crown size of trees, competition indices have been developed from dbh (Gerrard 1969) and basal area (Steneker and Jarvis 1963). However, several difficulties were inherent in the use of diameter or basal area alone as a competition index. Most notably, is the difficulty in defining the radius within which competitors should be measured. In addition, a decision must be made of whether to include the size and crown class of the subject tree in the description of the spatial distribution of the competitors (Opie 1968). This led Opie (1968) to define zones of influence as the total area over which a tree obtains or competes for site factors. These zones of influence were considered to be essentially circular in shape with a radius that was roughly proportional to the dbh of the subject tree. In evaluating competition, the area of zone overlaps between a subject tree and its competitors was summed. A further modification of this measure, the Competitive Influence-zone Overlap (Bella 1971), weighted the importance of each zone overlap by the size of the competitor. The subsequent summation of these weighted areas gives an index of the amount of competitive influence to which an individual is subjected. A similar index developed by Arney (1973) used the equivalent open-grown crown radius to define the radius of a tree's influence zone.

In a comparison of several competition indices and their correlation with annual loblolly pine growth, simple indices which chose competitors with angle gauges gave better correlations with growth than more elaborate indices utilizing fixed radius plots (Daniels 1976). These simplified indices are easier to measure and less costly to compute which will enhance their application in the field.

In a somewhat different approach, Moore et al. (1973) developed an index which hypothesized polygons of influence around each tree. This polygon or Area Potentially Available (APA) was constructed from lines placed perpendicular to lines drawn between the subject tree and each neighbor. The distance at which this line was placed was based upon a ratio of the square of the dbh of the subject tree and the sum of the squared diameters of the competitor and the subject tree. The authors cite three desirable characteristics of this polygon. The area between the two trees is divided in proportion to relative tree size and the formula is sensitive to changes in relative tree size over time. Plus, in contrast to the overlap indices, the area available to a tree is mutually exclusive from that of another tree. In trials, the APA accounted for sixty to seventy percent of the variation in basal area growth of three species in a forested stand.

Hatch et al. (1975) developed an index of competition based on the amount of crown surface area exposed to sunlight. This index was intended to overcome two shortcomings of zone overlap indices, namely the lack of consideration of the spatial pattern of trees surrounding the subject tree and that the vertical development of the subject tree in relation to its competitors is only indirectly considered. The index was computed as the ratio of the directly exposed surface area of the crown of the subject tree when light was restricted by each competitor and the distance from the crown to dbh for the subject tree. This ratio was weighted by the ratio of the basal areas of the subject tree and each competitor. Unfortunately, only those competitors which were immediate neighbors of the subject tree influenced the index. Thus, use of this index would imply that competition for light is more limiting than competition for moisture and nutrients. This shortcoming in combination with the inherent difficulty in measuring exposed crown surface make this an unattractive index for use.

Most competition indices were developed for use in mature monoculture forests. However, studies of growth in regenerating mixed species stands have used these indices or developed similar ones. A study of brush competition in a ponderosa pine (Pinus ponderosa Dougl. ex Laws.) plantation expressed brush volume as an index value obtained for each plant by multiplying crown height times crown area (Bentley et al. 1971). In general, pine height growth decreased with an increase in the brush volume index, however, use of the index had limitations in comparing the competitive effects of two brush covers consisting of different brush species. Glover (1982) selected several variables to represent different aspects of competition in young loblolly pine plantations. In a detailed multiple regression analysis, these variables were used as predictors of pine size and growth. By comparing several models, the sum of the hardwood groundline basal area, the number of hardwood rootstocks per square meter, and the sum of hardwood heights, were found to be the best predictors of pine size and growth. Prediction was improved when these variables were weighted by the inverse of the distance to the pine. These results indicate that hardwood basal area, the number of rootstocks per square meter, and the sum of the hardwood heights may be functional as competition indices in young loblolly pine plantations when weighted by the distance to the pine.

Burkhart and Sprinz (1984) developed a model to assess the effects of hardwood competition on yields in loblolly pine plantations. Working in stands that had attained canopy closure, the competition index used was the percentage of basal area within the stand that was in hardwoods. The index was used to modify the potential growth, represented by growth in old-field plantations. When tested with an independent data set, the model performed adequately, indicating that the percentage of basal area in hardwoods may be a useful index of competitive stress.

Leaf Area Indices

Purely mathematical attempts to evaluate crown size by calculating crown area have limitations. Crown area estimates usually use averages of crown diameter, measured perpendicularly, combined with height measurements and assumptions of a cylindrical or cone-shaped crown. This is a crude approximation of crown size. Evaluating the leaf surface area of a crown would be a much more precise measure of the functional portion of the crown.

Leaf area can be estimated from sapwood basal area or cross-sectional area (Grier and Waring 1974, Rogers and Hinkley 1979, Waring et al. 1978, Johnson et al. 1985). Leaf areas have been shown to be sensitive to environmental conditions, especially moisture availability (Grier and Running 1977, Gholz et al. 1976, Waring et al. 1978). Therefore, Waring et al. (1980) proposed that leaf area indices could be a good measure of competitive stress, however, no studies have directly studied this hypothesis.

It is hypothesized that leaf area would be an excellent measure of the competitive status of a plant because of its direct relationship to resource use (Zedaker 1983). The leaves are the photosynthetic and transpiring surfaces of the plant. Therefore, leaf area could be used to more precisely define the areas of influence around trees, leading to more accurate evaluations of competition that would include all facets of competition, not just competition for light. In addition, development of the sapwood basal area to leaf area relationships of individual species will be useful in the derivation of weighting factors for the determination of differential resource use by the different species. The slope of the basal area to leaf area regression for each species can serve as a weighting factor which, though not previously included, may increase the precision of the definition of the zone of influence. These proposals were investigated in this study.

Summary

There is a need for research in the quantification of competition in loblolly pine plantations to increase the knowledge of the competition-release-growth response relationships in these plantations. In spite of the large number of release studies in loblolly pine stands, there is a noticeable absence of studies that actually evaluate the competitive stress caused by both the hardwood and herbaceous competing vegetation. Few studies have evaluated the growth response of plantation loblolly pines to different levels of competition control or attempted to determine the best timing or intensity of release. Finally, the use of chemical release treatments using simple ground application techniques ensures that results of this study will be beneficial to the small-tract private woodland owner, in contrast to many previous studies which used sophisticated equipment and techniques.

Objectives

The objectives of this study were:

1) to quantify interspecific competition in young loblolly pine plantations by evaluating the growth of the pines and competing hardwood and herbaceous vegetation.

2) to evaluate the growth response of young loblolly pines to different levels of release from competing vegetation and to determine the best timing and intensity of release.

3) to develop predictive models for the growth response to release of young loblolly pine plantations.

LEAF AREA PREDICTION EQUATIONS FOR YOUNG SOUTHEASTERN HARDWOOD STEMS

Introduction

During establishment, southern pines are subject to intense competition from hardwood sprouts for light, water, and nutrients essential to growth (Newbold 1979). Quantification of this competition and its effects is necessary for effective management of these plantations. Since leaf area is directly related to resource use, it has been proposed as a sensitive index to the competitive status of a plant and a method of weighting species by competitive ability (Zedaker 1983).

Although leaf area is difficult to measure directly in the field, several studies have indicated a strong relationship in woody plants between leaf area and stem area, an easily measured variable. Whittaker and Woodwell (1967) established a relationship between stem diameter, at breast height (1.37 m), and leaf area for forest trees. Several subsequent studies have determined that sapwood cross-sectional area, at breast height, is a more accurate predictor of leaf area, or leaf weight, for mature trees of both coniferous and broadleaf species (Grier and Waring 1974, Kaufmann and Troendle 1981, Rogers and Hinckley 1979, Snell and Brown 1978, Waring et al. 1978). Recently, Johnson et al. (1985) found that leaf area of young loblolly pines (*Pinus taeda* L.) was strongly linearly related to root collar cross-sectional area. However, the relation of leaf area to stem cross-sectional area has not been determined for hardwoods competing with the pines.

The objective of this study was to develop equations predicting leaf surface area from root collar cross-sectional area for hardwood species found in young pine plantations in the South. The study was also designed to compare the relationship of leaf area and basal area between species and between single- and multiple-stemmed individuals within species.

Materials and Methods

In order to obtain species common throughout the southeast, sampling was conducted in two different areas of the Virginia Piedmont. The lower Piedmont was represented by a site, harvested five years previously, near Keysville in Charlotte County, while two sites (harvested two and six years previously) were in the Appomattox-Buckingham State Forest of the upper Piedmont. Sampling occurred in early August to assure maximum canopy development.

Thirty-six individuals each of sixteen southeastern hardwoods were sampled (Table 1). To compare the relationship between individual stems and sprout clumps, thirty samples were of multiple-stemmed sprout clumps while six of the individuals sampled were single-stemmed. Individuals were selected to cover the entire range of sizes expected in stands harvested from one to six years previously. An even size distribution in sampling was ensured by selecting sprouts from three height classes, with ten multistemmed and two single-stemmed individuals selected in each class. The height classes were: 1) less than one meter; 2) between one and two meters; 3) and taller than two meters.

Total height and two crown diameters, the widest diameter from bud to bud and the perpendicular diameter, were recorded to the nearest cm for each individual. Root collar diameters were recorded to the nearest 0.1 mm for each stem of the sprout. For individuals less than two meters tall, the entire sprout was harvested. For individuals over two meters tall, a subsample was taken that included at least 25% of the groundline basal area. Total weights for these individuals were expanded from subsample weights based on the proportion of subsample basal area to total basal area. Samples were oven dried at 65°C to a constant weight.

Table 1. Specific leaf area and slope, coefficient of determination (R^2), and root collar area ranges for predictive equations for common hardwood species on the Virginia Piedmont.

Species	Specific leaf area (cm^2/g)	Slope[1] (m^2/cm^2)	R^2	Range of root collar area (cm^2)
Acer rubrum L. red maple	339	0.597	0.97	0.09-66.87
Carya spp. Nutt. hickories	256	0.833	0.96	0.43-25.33
Cercis canadensis L. eastern redbud	228	0.463	0.98	0.75-62.31
Cornus florida L. flowering dogwood	401	0.709	0.94	0.07-43.46
Fraxinus spp. L. ash	223	0.342	0.93	1.98-66.45
Liquidambar styraciflua L. sweetgum	221	0.447	0.93	0.45-52.42
Liriodendron tulipifera L. yellow-poplar	413	0.738	0.97	0.97-84.42
Nyssa sylvatica Marsh. black gum	276	0.336	0.92	0.41-47.30
Prunus serotina Ehrh. black cherry	236	0.515	0.90	0.29-46.88
Quercus alba L. white oak	261	0.468	0.97	0.25-82.73
Quercus coccinea Muenchh. scarlet oak	241	0.358	0.92	0.14-36.75
Quercus falcata Michx. southern red oak	221	0.373	0.97	0.15-92.34
Quercus prinus L. chestnut oak	274	0.522	0.87	0.28-33.59
Quercus stellata Wangenh. post oak	221	0.385	0.97	0.13-88.03
Rhus spp. L. sumac	251	0.597	0.94	0.15-15.57
Ulmus alata Michx. winged elm	277	0.444	0.90	0.93-26.95

1. Equation: Leaf Area = Slope*Root Collar Cross-sectional Area
   with: Leaf Area in m^2 and Root Collar Cross-sectional Area in cm^2

Foliage (leaves and petioles) was then separated from stems and component weights recorded.

Specific leaf area (cm^2/g; all sides) was determined with subsamples of five leaves selected from each of the upper, middle, and lower thirds of the crown, of each individual. Leaves were selected to avoid insect damage and holes but, since specific leaf area was calculated, it was assumed that the area to weight relationship remained constant and any loss to insect damage, where unavoidable, would not change the relationship. Samples were stored in coolers to minimize weight loss due to respiration. Leaf area was determined for each fresh sample with an area meter (Hayashi Denko Co., Tokyo, Japan), and oven dried weights were recorded. Specific leaf area was calculated for each sample and averaged by species.

Results and Discussion

Specific leaf areas (all sides) ranged from 221 to 413 cm^2/g for the species sampled (Table 1). These compare favorably with values reported for broadleaf species (100 to 800 cm^2/g; Kaufmann and Troendle 1981 and Waring and others 1977), and are greater than values for coniferous species (90 to 220 cm^2/g ; Gholz et al. 1976, Kaufmann and Troendle 1977, Johnson et al. 1985).

Plots of the data indicated that leaf area and root collar cross-sectional area were linearly related, with normal variance structure. Linear regressions were significant ($P < .05$) for all species and the intercept values were not significantly different from zero. Coefficients of determination (R^2) ranged from 0.87 to 0.98 and the slope coefficients ranged from 0.334 to 0.833 m^2/cm^2 (Table 1). Equations were compared, by species, with F-tests (Swindel 1970), and slopes were significantly different ($P < .05$) for all species except southern red oak (Quercus falcata Michx.) and post oak (Q. stellata Wangenh.). A comparison of equations for single- and multiple-stemmed individuals within each species indicated no significant differences in slopes. Therefore, the equations apply to seedling and root sprouts as well as stump sprouts.

The fit of the regression equations is similar to those reported previously. For linear equations, Kaufmann and Troendle (1981) , Rogers and Hinckley (1979), and Johnson et al. (1985) reported R^2's ranging from 0.93 to 0.99. Two studies which have used natural logarithmic transformation of the data prior to regression reported R^2's from 0.86 to 0.98 (Snell and Brown 1978 and Waring et al. 1977).

The slope coefficients also compare well with those reported for other species. In linear equations relating sapwood area at breast height to leaf dry weight and leaf area, respectively, Kaufmann and Troendle (1981) reported a range of slope coefficients from 0.19 to 1.88 m^2/cm^2 for mature individuals of one broadleaf and three coniferous species, while Waring et al. (1977) found a slope of 0.427 m^2/cm^2 for bigleaf maple (Acer macrophyllum Pursh.).

For young loblolly pine, Johnson et al. (1985) found a slope coefficient of 0.271 m^2/cm^2, which is smaller than those for the hardwood species. This seems to support a hypothesis, suggested by Kaufmann and Troendle (1981), that the slope of the sapwood area-leaf area regression is related to shade tolerance, with a larger slope for more shade tolerant species, since loblolly pine is less shade tolerant than most of the competing hardwood species measured.

The significant differences between the slopes for the different species supports the value of using leaf area as an index of competitive ability. Most competition indices used in forestry were developed for single species plantations and are based on the basal areas of the competitors. This approach has been used in the evaluation of competition in young loblolly pine plantations, where

Bacon and Zedaker (1985) and Glover (1982) have determined that hardwood basal area is an important variable in explaining pine growth. In mixed species stands, however, the effect of one species will differ from that of another because species may utilize resources differently. Since leaves are the surfaces that intercept sunlight and transpire water, it has been suggested that leaf area is a measure of resource utilization (Grier and Running 1977), and that the slopes of the leaf area to stem cross-sectional area regressions can be used as indicators of relative competitive ability (Zedaker 1983). Therefore, the use of leaf area in competiton indices may increase the ability to quantify the effects interspecific competition in mixed stands.

THIRD YEAR GROWTH RESPONSE OF LOBLOLLY PINE TO EIGHT LEVELS OF COMPETITION CONTROL

Introduction

Throughout the South, unwanted hardwood and herbaceous vegetation invades, and sometimes dominates, forest lands following harvest (Knight 1977). Interspecific competition from this weedy vegetation severely limits the growth and development of loblolly pine (Pinus taeda L.) (Cain and Mann 1980, Loyd et al. 1978, Nelson et al. 1981). While numerous studies have established a pine growth response with competition control (Stewart et al. 1984 and Walstad 1976), few have evaluted the effect of removing different amounts of the surrounding vegetation, or compared release treaments at different plantation ages. Clason (1978) created four different levels of competition in a seven-year-old loblolly pine plantation, by removing hardwood and/or herbaceous vegetation. After five years the treatments resulted in significantly larger diameters and volume than the check. Knowe et al. (1985) reported differential growth with different intensities of weed control, but only treated newly planted seedlings, and concentrated on herbaceous weed control. Removal of competition has been shown to improve growth but recommendations on how much release is necessary or when the release should be performed for a maximum growth response have not been formulated. Therefore, the objective of this study was to compare the growth response of young loblolly pines to release from different amounts of woody and herbaceous vegetation at different plantation ages.

Methods

Site Descriptions

The study was installed in 1983 at three different sites on the Virginia Piedmont and included plantations of three ages at each site. All sites were being converted from hardwood stands to pine plantations and had been chopped and burned for site preparation following harvest. Two of these sites were located in Buckingham County, and the other had one age in Charlotte County and two in nearby Halifax County. The Buckingham sites were located on silt loams of the Tatum and Manteo series. The Tatum series soils (clayey, mixed, thermic Typic Hapludults) are fairly deep and well-drained, while the Manteo series soils (loamy-skeletal, mixed thermic Lithic Dystrochrepts) are shallow and excessively drained. The site in Charlotte County was located on a Georgeville silt loam, a fairly deep, well-drained soil, while the Halifax sites were on the gravelly phase of an Orange silt loam, a fairly deep, poorly drained soil. Soils of the Georgeville series are clayey, kaolinitic, thermic Typic Hapludults and soils of the Orange series are fine, montmorillonitic, thermic Albaquic Hapludalfs.

Design and Treatments

Plantations beginning their first, second, and third growing seasons were divided into 0.1 ha plots for the application of eight release treatments in a split-plot design. These randomly assigned treatments controlled four different amounts of the hardwood vegetation, removing all, two-thirds, one-third or none of the woody stems, in combination with either total or no control of the herbaceous vegetation.

All vegetation control was provided by chemical means, using backpack sprayers. Woody stems were treated with a basal bark spray of a 4% solution (v/v) of the ester formulation of triclopyr [Garlon 4 (TM)], in diesel oil, applied in June 1983. Herbaceous vegetation was also controlled in June with a broadcast spray of sulfometuron [Oust (TM)] at 0.42 kg ai/ha in a water carrier. An additional late season application of a directed spray of a 1% (v/v) solution of glyphosate [Roundup (TM)] in water was required, in August, to ensure control of the herbaceous vegetation for an entire growing season.

<u>Pine Measurements</u>

Pine growth response to release was evaluated with measurements before treatment and at the end of the first, second, and third growing seasons after treatment. Growth measurements were taken on twenty-five systematically located, and uniquely numbered, seedlings in each treatment plot. Measurements included the total height, height to the base of the live crown, and diameter measurements at groundline, 15 cm above groundline, base of the live crown, mid-crown, breast height (1.37 m) and 2 m. These data were used to calculate current stem volume and volume growth using Smalian's formula by dividing the stems into a series of cylinders between the diameter measurements (Avery and Burkhart 1983).

<u>Hardwood and Herbaceous Vegetation Measurements</u>

The surrounding vegetation was assessed around five systematically selected seedlings of the twenty-five in each treatment plot. Every fifth seedling was selected, starting with the one assigned the same number as the treatment plot. The hardwood vegetation was measured in assessment plots centered around the pines with a radius of 1.5 m or one-and-a-half times the height of the pine up to a 3 m maximum. Groundline diameters were recorded for all stems of every hardwood rootstock taller than 0.5 m within the plot. The hardwood vegetation was also assessed in 1.5 m radius plots around an additional three randomly selected subject pines per treatment plot. Information from these fixed radius plots was combined with the other five plots to estimate hardwood basal area and numbers of rootstocks per hectare. Assessment occurred before treatment and at the ends of the first, second, and third growing seasons following treatment.

The herbaceous vegetation was evaluated within a 1 m^2 frame centered over the pine. Percent cover was ocularly estimated, by cover class, for all herbs and grasses within the frame. In a double sampling scheme, nearby plots were destructively sampled and regressions developed to predict herbaceous biomass from cover class. The herbaceous vegetation was evaluated in the late summer of the first, second, and third growing seasons following treatment.

Results and Discussion

Hardwood and Herbaceous Vegetation Response

Pre-treatment hardwood evaluation indicated that the amount of hardwood vegetation was the same on all treatment plots, except for a few significant differences in the numbers of rootstocks per hectare in stands beginning their third growing season (Table 2). Three years after treatment there were some differences in both groundline basal area and numbers of rootstocks between the treatments. These defined a trend of decreasing basal area and rootstocks with increasing intensity of treatment, although the differences were not always significant. There was also a general trend of more basal area in treatments with herbaceous weed control, indicating a growth response in the hardwoods to release from the herbaceous competition.

The initial effect of treatment on the hardwood vegetation is indicated in the percent reduction of hardwood basal area and numbers of rootstocks over the first growing season (Table 3). While the total woody control treatments did not completely eradicate the hardwood vegetation, they did remove about 90% of the hardwood rootstocks and from 88-98% of the groundline basal area. The intermediate treatments also did not remove exactly one-third or two-thirds of the hardwood vegetation, but did result in

Table 2. Groundline basal area and number of rootstocks per hectare of hardwood vegetation before and after treatment in loblolly pine plantations on the Virginia Piedmont[1,2]

	Treatment Age (yrs) 0		1		2	
	Pre-treatment	3 yrs after	Pre-treatment	3 yrs after	Pre-treatment	3 yrs after
			Groundline basal area (m^2/ha) Rootstocks per ha			
Herbaceous + woody control:						
Total woody	0.036a 3488A	0.031b 3937AB	0.039a 4009A	0.050b 3428BC	0.102a 14904AB	0.094b 4619B
2/3 woody	0.034a 5488A	0.045ab 4528AB	0.069a 4288A	0.090a 4888ABC	0.056a 9616B	0.098b 6617AB
1/3 woody	0.047a 5397A	0.066ab 4688AB	0.037a 3688A	0.015a 4108ABC	0.071a 18683A	0.172a 9057A
Herbaceous control only:	0.039a 3379A	0.087a 5597A	0.050a 4668A	0.124a 5147AB	0.090a 10935B	0.147a 7207AB
Woody control only:						
Total woody	0.037a 4678A	0.012b 2319B	0.046a 3819A	0.027b 2749C	0.082a 12725AB	0.078b 3749B
2/3 woody	0.037a 5898A	0.072a 3878AB	0.037a 4439A	0.065ab 6197A	0.095a 16754A	0.118ab 6978AB
1/3 woody	0.032a 5217A	0.090a 6138A	0.071a 5459A	0.091a 6298A	0.069a 11135B	0.111ab 7247AB
Check:	0.049a 5958A	0.092a 5298A	0.071a 3638A	0.092a 5758A	0.069a 11755AB	0.169a 9895A

1. Basal area means within columns followed by the same lower case letter are not significantly different at the 0.05 level (Duncan's MRT).
2. Rootstock means within columns followed by the same capital letter are not significantly different at the 0.05 level (Duncan's MRT).

Table 3. Average percent reduction of hardwood basal area per hectare and rootstocks per hectare, by woody control treatment, over the first growing season in loblolly pine plantations of the Virginia Piedmont.

	Percent Reduction[1]		
	Treatment Age (yrs)		
Treatment	0	1	2
	Groundline basal area (m^2/ha) / Rootstocks per ha		
Total woody control	98 / 90	96 / 91	88 / 90
2/3 woody control	40 / 79	48 / 59	58 / 45
1/3 woody control	35 / 56	26 / 26	34 / 28

1. Percent reduction =

$$\frac{\text{pretreatment value* - value at end of first growing season}}{\text{pretreatment value*}}$$

* pretreatment value adjusted to reflect the change in the treatments without woody control.

different levels of release. The one-third woody control treatment removed 26-35% of the hardwood basal area and the two-thirds woody control removed 40-58% of the basal area.

The effect of treatment on the herbaceous vegetation was evident in the first growing season where the treatments with herbaceous weed control averaged only about half of the herbaceous biomass found in the treatments without herbaceous control (11,698 vs. 21,943 kg/ha). By the third season, however, this difference was smaller. (18,839 vs. 23,253 kg/ha).

Pine Response

There were no significant differences in pine survival between treatments after the first and third growing seasons following treatment (Table 4). This indicated, initially, that there was no herbicide-related mortality, and that, through the third season, there was no competition-induced mortality. Overall, pine survival over three seasons was good, ranging from 92-97% in the oldest plantations, 77-91% in the plantations treated at the beginning of their second growing season, and 69-89% in the youngest plantations.

The pines exhibited relatively little differential height growth between treatments after three growing seasons (Table 5). In the stands treated at the beginning of the third

Table 4. Survival of loblolly pine seedlings, by treatment, after the first and third seasons following treatment, in plantations of the Virginia Piedmont[1,2]

	Treatment Age (yrs)					
	0		1		2	
	First season	Third season	First season	Third season	First season	Third season
	Seedling Survival (%)					
Herbaceous + woody control:						
Total woody	83a	75A	93a	87A	97a	97A
2/3 woody	93a	84A	96a	91A	100a	97A
1/3 woody	92a	89A	99a	85A	97a	97A
Herbaceous control only:	80a	78A	100a	91A	96a	93A
Woody control only:						
Total woody	76a	76A	95a	83A	100a	92A
2/3 woody	93a	82A	96a	89A	96a	92A
1/3 woody	72a	69A	95a	79A	96a	95A
Check:	84a	81A	93a	77A	96a	93A

1. First season means within columns followed by the same lower case letter are not significantly different at the 0.05 level (Duncan's MRT).
2. Third season means within columns followed by the same capital letter are not significantly different at the 0.05 level (Duncan's MRT).

Table 5. Average pine height, groundline diameter (GLD), and volume growth response, by treatment, over three growing seasons in loblolly pine plantations on the Virginia Piedmont[1]

Treatment	Treatment Age (yrs) 0 Height growth (m)	0 GLD growth (cm)	0 Volume[2] growth (cm^3)	1 Height growth (m)	1 GLD growth (cm)	1 Volume[2] growth (cm^3)	2 Height growth (m)	2 GLD growth (cm)	2 Volume[2] growth (cm^3)
Herbaceous + woody control:									
Total woody	1.24b	3.12a	634ab	1.73bcd	4.52a	2517a	2.08a	4.85a	4057ab
2/3 woody	1.46a	3.38a	759a	2.00a	4.47a	2555a	2.05ab	4.57ab	4451a
1/3 woody	1.39a	3.05a	616ab	1.94ab	4.27ab	1975b	1.84bc	3.86de	3153bc
Herbaceous control only:	1.21bc	2.54b	487bc	1.89abc	3.96bc	1752bc	2.00ab	4.06cd	3592abc
Woody control only:									
Total woody	1.04de	2.64b	433cd	1.54d	3.51cd	1367c	1.89abc	4.32cd	3190bc
2/3 woody	1.07cde	2.46b	380cd	1.68cd	3.89bc	1816bc	1.94abc	3.99cde	3631abc
1/3 woody	1.03e	1.98c	293d	1.66cd	3.66cd	1747bc	1.73c	3.84de	2764c
Check:	1.20bcd	2.39b	393cd	1.62d	3.30d	1275c	1.93abc	3.58e	2912c

1. Means within columns followed by the same letter are not significantly different at the 0.05 level (Duncan's MRT)
2. Volume growth calculated using Smalian's formula.

year, none of the treatments exhibited a growth response significantly different than the check. In the first and second year stands, only the treatment combining herbaceous control with two-thirds or one-third woody control resulted in significantly better pine growth. The lack of a differential response was not surprising, since height growth is known to be relatively insensitive to competition. This result was differed from Knowe et al. (1985) who reported a significant difference in height, after four years, with all of their treatments, but was similar to those reported by Clason (1978) with no significant differences in height after five years.

There was, however, a definite differential response in the groundline diameter growth (Table 5). In all ages, the two-thirds woody plus herbaceous control and the total control treatments resulted in significantly better growth than the check. This trend was similar to those previously reported (Clason 1978, Loyd et al. 1978, Cain and Mann 1980). The importance of herbaceous control is shown in the first and second year seedlings where all of the herbaceous control treatments resulted in significantly better growth than the treatments without herbaceous control. This concurred with the findings of studies that controlled only the herbaceous vegetation (Nelson et al. 1981 and Knowe et al 1985).

Volume growth also exhibited a differential response to treatment (Table 5). In all ages, both the total control treatment and the two-thirds woody plus herbaceous treatments resulted in significantly greater growth than the check. For seedlings treated at the beginning of either their first or second growing season, the treatment combining one-third woody control with herbaceous control also resulted in significantly better growth than the check. The magnitude of the response was not as large as that found by Nelson et al. (1981) with annual weed control over three years, but may be more comparable to operational results since a single season of weed control was used.

Viewing the change in volume as the percent increase in growth by treatment over the check, indicated that the best response was obtained with seedlings treated at the beginning of their second growing season in the field (Table 6). The two-thirds woody plus herbaceous control treatment exhibited the best response overall with a 100% increase in growth over three growing seasons. Response to this same treatment resulted in an increase of 93% in the youngest seedlings and only a 53% increase in the oldest seedlings. The greater response by the two-year-old seedlings indicates that the beginning of the second season may be the best time to perform release treatments.

Table 6. Percent increase in pine volume growth, by treatment and age, over check.

Treatment	Treatment Age (yrs) 0	1	2
	Percent Increase		
Herbaceous + woody control:			
Total woody	61	98	39
2/3 woody	93	100	53
1/3 woody	56	55	8
Herbaceous control only:	24	37	23
Woody control only:			
Total woody	10	7	10
2/3 woody	-3	42	25
1/3 woody	-26	37	-5

Graphing the relationship between stem volume and age for three treatments from the plantations that received treatments before the second growing season, reinforces the importance of hardwood and herbaceous vegetation control (Figure 1). At the end of the third growing season following treatment, seedlings in the two-thirds woody treatment plots had an average of 150% of the volume for the check, while the addition of herbaceous control resulted in a doubling of the volume over the check. The growth curves were still diverging after the third season, indicating that the benefits of the release treatments last for more than one or two seasons. If this trend continues for several more years, the application of release treatments may significantly shorten rotation length.

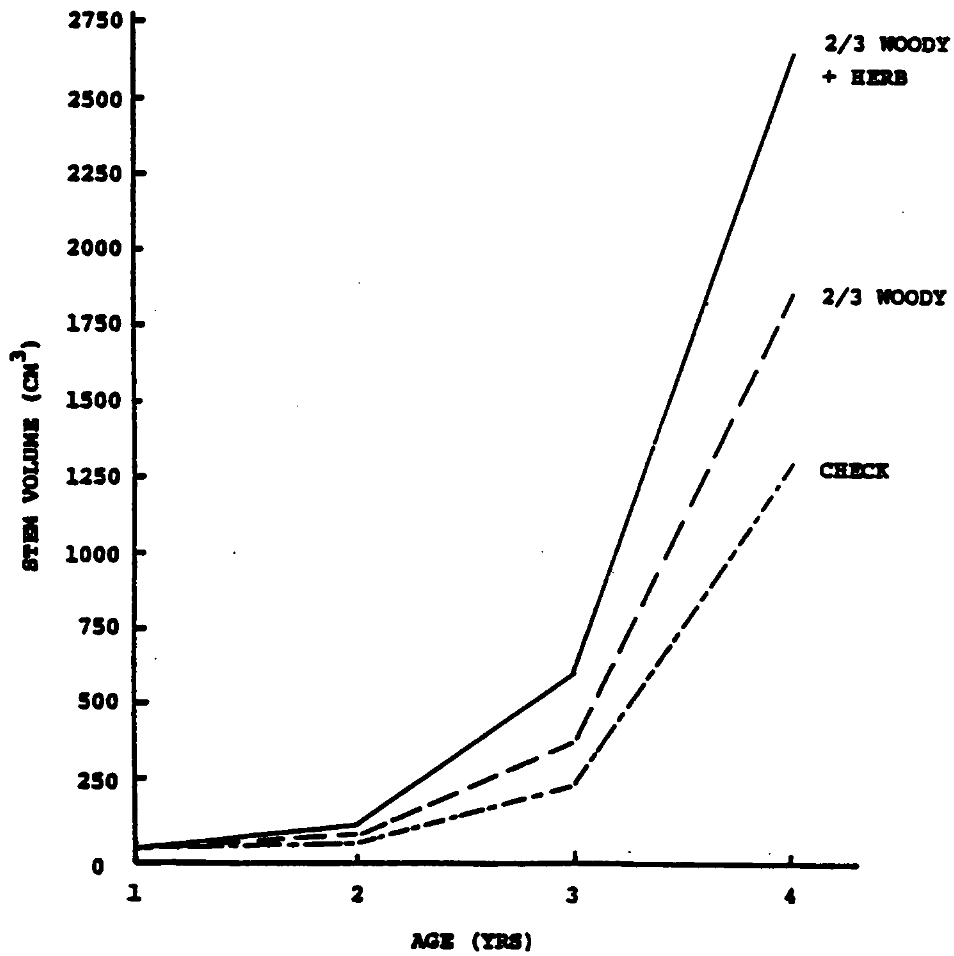

Figure 1. Loblolly pine stem volume growth curves for seedlings on Virginia Piedmont sites subjected to three different treatments at the beginning of their second growing season.

GROWTH, YIELD, AND COMPETITION MODELING IN YOUNG LOBLOLLY PINE PLANTATIONS

Introduction

Numerous studies have involved the development of mathematical models that predict the growth and/or yield of various tree species. These models have been of three levels of resolution, the whole stand, size-classes within the stand, and the individual tree. The majority of these models were developed for pure, even-aged stands of older than 8-10 years of age, with an emphasis on stands of southern pines (Farrar 1979). The techniques that have been developed have rarely been applied to very young (< 10 years) stands, so few growth and yield models exist for the early years of coniferous plantations.

Unwanted hardwood and herbaceous vegetation invades, and sometimes dominates, forest lands following harvest (Knight 1977). Interspecific competition from this weedy vegetation limits the growth of the coniferous crop seedlings (Cain and Mann 1980, Loyd et al. 1978, Nelson et al. 1981). Removal of this competition results in a growth response, but few studies have evaluated the magnitude of response based upon the amount of surrounding vegetation removed. The development of equations which predict the amount of conifer growth based upon the competition present can indicate the magnitude of growth increase with competition control treatments. Therefore, the objective of this study was to use modeling techniques developed for mature stands to construct predictive equations for the volume and volume growth of young loblolly pines at the whole stand, size-class, and individual-tree levels. The stand-level and size-class models were used to test the significance of adding interspecific competition measures to the models containing normal stand attributes. The individual-tree level equations were used to compare distance-dependent and distance-independent competition indices, and to compare the use of empirical equations to theoretically-based equations.

Modeling Techniques

Whole Stand Models

The introduction of multiple regression techniques to model tree growth and yield (MacKinney et al. 1937), allowed for the development of variable density yield tables. MacKinney and Chaiken (1939) developed a logarithmic equation with age, site quality, and a stand density index as independent variables. This general form of equation has been the basis for several additional stand growth and/or yield models (Schumacher and Coile 1960, Coile and Schumacher 1964, Burkhart et al. 1972a, 1972b) and was used as the basic form for stand-level models of young pine plantations in this study. The equations used in this study related the natural logarithm of the three year volume and volume growth per hectare to the usual stand attributes, age, site quality, and stand density, with the addition of measures of competition from other species.

Diameter Distribution Models

Another approach to stand level growth and yield models involved the development of diameter distribution models, which provided estimates of trees per unit area by diameter at breast height (dbh) classes. This method assumed that the diameter distribution of a stand can be characterized by a probability density function (pdf). The Weibull pdf has been successfully used to model the diameter distributions of mature forest stands (Bailey 1972, Smalley and Bailey 1974a, Feduccia et al. 1979) and was chosen for use in this study.

The two-parameter Weibull distribution was used for two different methods of diameter distribution modeling. This distribution was simplified from the three-parameter Weibull by the assumption that the location parameter, 'a', was equal to zero, since the pines were very young. The probability density function (pdf) and cumulative distribution function (cdf) for the two-parameter Weibull are:

$$f_X(x;\ b,\ c) = \begin{cases} (c/b)\ (x/b)^{c}\ \ \exp\ \{\ -\ (x/b)^{c}\ \}, & \\ \qquad x,\ b,\ c > 0; & \\ 0, \qquad \text{otherwise}; & \end{cases}$$

$$F_X(x) = 1 - \exp\{\ -\ (x/b)^{c}\ \},$$

where:

x = tree groundline diameter

b = scale parameter

c = shape parameter

<u>Parameter Prediction</u>. The parameters for the two-parameter Weibull distribution were estimated from the plot data using a maximum likelihood program developed by Zutter et al. (1982). Regression equations were developed which predicted these parameters based on plot attributes. The regressor variables included, the inverse of age; average height of dominants and codominants; and number of pines per hectare. In addition, interspecific competition variables were included in the models, where significant. The

equations were then used to predict the parameters for each plot. The predicted parameters were used in the cdf to determine the frequency of trees within each 1 cm diameter class for each plot. This predicted distribution was compared to the actual distribution with the Kolmogorov-Smirnov goodness-of-fit test (Massey 1951).

Parameter Recovery. The parameter recovery method was based on the method of moments (Hyink and Moser 1983). Regression equations to predict the mean diameter ($\bar{D}$) and mean squared diameter ($\overline{D^2}$) were initially developed separately. However, when the coefficient of variation was calculated a negative value was sometimes obtained. Therefore, it was necessary to condition the term $\overline{D^2} - \bar{D}^2$ to be greater than zero. This was accomplished by predicting $\ln(\overline{D^2} - \bar{D}^2)$ and $\bar{D}$ and then solving for $\overline{D^2}$.

These estimates of $\bar{D}$ and $\overline{D^2}$ were used to recover the diameter distributions, by plot, with a computer program using the secant method for finding roots of non-linear equations (Burk and Burkhart 1984). These predicted and actual distributions were compared using the Kolmogorov-Smirnov goodness-of-fit test (Massey 1951).

Kolmogorov-Smirnov Goodness-of-fit Test. The diameter distribution methods were evaluated by comparing the predicted or recovered distributions to the actual distributions, by plot, using the Kolmogorov-Smirnov goodness-of-fit test (Massey 1951). The Kolmogorov-Smirnov test statistic is:

$$k = \text{maximum} \mid F_o(x) - S_n(x) \mid$$

where:

$F_o(x)$ = the hypothesized cumulative distribution function defined by the predicted or recovered parameters

$S_n(x)$ = the actual distribution of the groundline diameters of the n trees on the plot

The statistic k is used to test the hypothesis:

$$H_o: F_o(x) = H(x)$$

$$H_1: F_o(x) \neq H(x)$$

where H(x) is the unknown population distribution function.

This hypothesis is tested at a specified significance level, however since the parameters were estimated from the sample, the significance level can not be computed exactly (Massey 1951). The effect is a lowering of the critical value with estimation of the parameters, therefore the more stringent significance level of 0.10 was used.

Individual Tree Models

An alternative method of growth and yield modeling focused on the growth of individual trees. Individual tree models simulated the growth of individual trees and aggregated the trees to provide estimates of stand growth and yield. The earliest individual tree growth models were developed in coniferous forests of the western United States (Newnham 1964, Newnham and Smith 1964, Lee 1967), and were based on the idea that diameter growth increment for stand-grown trees was equal to open-grown diameter growth reduced by an amount based on competition. Daniels and Burkhart (1975) developed an individual tree growth model for loblolly pine. Potential annual height and diameter growth was simulated as a function of age, site, size, and adjusted with the use of a competition index.

In this study, the volume growth of individuals over a single growing season was also predicted as a function age, site, and size, and adjusted with the use of an interspecific competition index. The actual equation form fitted was:

$$VG = b_0 + b_1(1/AGE) + b_2(Hd) + b_3(V) + b_4(HERB) + b_5(C)$$

where:

VG = volume growth over a single season (dm^3)

V = volume at the beginning of the season (dm^3)

AGE = years since planting

Hd = average height of dominants and co-dominants (m)

HERB = presence (1) or absence (0) of herbaceous weed control

C = interspecific competition index

b_i = linear regression coefficients

The use of a modified Chapman-Richards growth equation for describing the growth of individual stems has been explored (Pienaar and Turnbull 1973 and Martin and Ek 1984). Equations developed were based on assumed relationships between internal growth processes and physical dimensions, and the modifying effects of the external environment. Martin and Ek (1984) used this model to test the efficacy of different competition indices, and compared this model to an empirically-derived regression equation with data from red pine (*Pinus resinosa* Ait.) stands of 20 to 58 years of age. Similar comparisons were attempted in this study, and the equation used was:

$$VG = e^{-b_1 C}(b_2 \, Hd V^{b_4} - b_3 V)$$

where:

VG = stem volume growth over a single season (dm^3)

V = stem volume at the beginning of the season (dm^3)

C = competition index

Hd = average height of dominants and codominants (m)

b_i = non-linear regression coefficients

Data Base

The data were from a study designed to test the effects of competition control on the growth of young loblolly pine in plantations on the Virginia Piedmont. Plantations beginning the first, second and third growing seasons at each of three sites were divided into eight 0.1 hectare treatment plots, for a total of 72 plots. The eight treatments involved the removal of different amounts of the surrounding hardwood and herbaceous vegetation.

Pine growth response to release was evaluated with yearly measurements of twenty-five systematically located, and uniquely numbered, seedlings in each treatment plot. Growth measurements of these pines, included total height, height to the base of the live crown, and diameter measurements at groundline, 15 cm above groudline, base of the live crown, mid-crown, breast height (1.37 m), and 2 m. These data were used to calculate current stem volume and volume growth using Smalian's formula (Avery and Burkhart 1983). Pine leaf areas were estimated with an equation developed by Johnson et al. (1985). Counts of numbers of pines per plot allowed for the estimation of stem volume, volume growth, basal area, and leaf area per hectare.

The surrounding hardwood vegetation was assessed around five systematically located pines among the twenty-five subject trees within each treatment plot. Every fifth seedling was selected, starting with the one with the same number as the treatment plot. These pines served as the centers of competition assessment plots with radii of 1.5 m or one-and-a-half times the height of the pines taller than a meter, up to a 3 m maximum. The distance and bearing from the pine were recorded for each hardwood rootstock taller than 0.5 m within the assessment plot, along with species and groundline diameters of each stem of the rootstock. Hardwood leaf areas were estimated, by species, using equations relating groundline basal area to leaf area (Bacon and Zedaker 1986). In addition, the hardwoods were assessed in 1.5 m radius plots around an additional three randomly selected subject pines in each treatment plot. Information from these fixed radius plots was combined with the individual tree plots to provide estimates of hardwood groundline basal area and leaf area per hectare, for the stand level equations.

Data from both the second and third growing seasons were used in this analysis. Therefore, for the stand level equations there were a total of 144 plots, and for the individual tree equations a maximum of 720 trees.

Competition Indices

Growth and yield models of older stands (> 10 years) have commonly included measures of the amount of intraspecific competition affecting the trees. In stand-level models, this measure was the stand density, often just the number of trees, or the basal area, per unit area. Individual-tree level models have included more elaborate indices that were either distance-dependent, if the distance between the subject tree and competitor was needed, or distance-independent, if per unit area measures were used (Munro 1974). Since most models have been developed for pure stands, very few have included measures of interspecific competition. Recently, however, Burkhart and Sprinz (1984) developed a model that incorporated the effects of hardwood competition on the growth of loblolly pine in stands following canopy closure.

In very young plantations, before canopy closure, the effects of interspecific competition should be more important than intraspecific competition since the pines are planted at wide spacings and are not yet interacting. Therefore, the competition indices developed in this study were based on the hardwood vegetation surrounding the pines. In plantations on sites converted from hardwood stands, the pine seedlings will be affected by of many different species of hardwoods. To account for the possible differential resource use by the competitors, and potentially different intensities of competition, the competition indices were calculated with leaf area, in addition to basal area.

For the stand level equations competition measures of the herbaceous and hardwood competitors were used. The herbaceous competition variable was a categorical variable indicating the presence or absence of herbaceous weed control. The variable had a value of 1 for plots receiving herbaceous weed control and a value of 0 for plots without herbaceous weed control. Several hardwood variables were evaluated in the equations. These included the amount of hardwood groundline basal area per hectare, the hardwood leaf area per hectare, and the percentages of the woody groundline basal area or leaf area per hectare in hardwoods at the end of the third growing season following treatment. The percentage of hardwood basal area in the canopy was shown to be important in predicting yields in older loblolly pine plantations (Burkhart and Sprinz 1984), so these similar variables were used.

Two types of competition indices were compared in the individual tree level models, distance-dependent and distance-independent indices. Two distance-dependent indices were calculated, each based on both leaf area and basal area. One was a modification of an index developed by Heygi (1974), using basal areas and leaf areas instead of the dbh used by Heygi. This modified Heygi's index first determined for each competitor of a subject tree the sum of the subject tree basal, or leaf, area and competitor basal, or leaf, area. This sum was divided by the distance between them and the resulting value summed for each competitor of the subject tree to obtain the index. The other distance-dependent index was an area potentially available (APA) index similar to that used by Moore et al. (1973). The APA index calculated the area of a polygon around the subject tree defined by perpendiculars of lines drawn between the subject tree and each competitor. The distance at which these perpendiculars were placed was based upon the ratio of the basal areas, or leaf areas, of the subject tree and each competitor. A computer program was developed which calculated the areas of these polygons based on the areas of triangles. The distance-independent indices used were simply the percentage of the woody basal area, or leaf area, in hardwoods in each competition assessment plot.

Regression Analysis

Multiple linear regressions were fitted for all models except the modified Chapman-Richards equations, which were fitted with non-linear regression techniques. All possible models were evaluated on the basis of the Prediction Sums of Squares (PRESS) and mean squared error (MSE) statistics. The PRESS statistic gives an indication of the model's predictive ability and the model with the lowest PRESS statistic should also predict well for independent data (Draper and Smith 1981 and Green 1983). The significance of the addition of competition variables to stand-level models was tested with partial F-tests.

Results and Discussion

Whole Stand Average Models

The best stand-level growth and yield equations resulted from the addition of the competition measures to the usual stand attributes (Table 7). The best equation for three year growth related the natural logarithm of the relative volume growth (volume growth/initial volume) to the stand attributes (inverse of age, average height of dominants and co-dominants, and the number of pine stems per hectare) with the addition of the herbaceous variable and the percentage of woody basal area in hardwoods. This equation had an R^2

Table 7. Stand-level equations for volume and volume growth, and parameter prediction and parameter recovery equations for diameter distribution models, for loblolly pine plantations of the Virginia Piedmont.

Subject	Equation
Relative volume growth[1] (m^3/ha)	$\ln(RVG) = -11.73 + 27.58(1/AGE) + 0.350(Hd) + 0.13(N) + 0.435(HERB) - 0.585(PBAH)$
	$R^2 = 0.895$ MSE = 0.2923 PRESS = 23.007
Volume (m^3/ha)	$\ln(V) = -0.959 - 7.176(1/AGE) + 0.612(Hd) + 0.13(N) + 0.356(HERB) - 0.766(PBAH)$
	$R^2 = 0.934$ MSE = 0.1156 PRESS = 8.928
Parameter prediction	$b = 1.369 - 3.969(1/AGE) + 1.498(Hd) + 0.571(HERB) - 0.604(PLAH)$
	$R^2 = 0.916$ MSE = 0.3278 PRESS = 48.937
	$c = 3.003 + 1.215(Hd) + 0.5808(HERB) - 1.957(PLAH)$
	$R^2 = 0.557$ MSE = 1.6317 PRESS = 244.192
Parameter recovery	$\bar{D} = 0.977 - 3.341(1/AGE) + 1.458(Hd) + 0.552(HERB) - 0.681(PLAH)$
	$R^2 = 0.914$ MSE = 0.3044 PRESS = 45.478
	$\ln(\overline{D^2} - \bar{D}^2) = -0.148 - 2.957(1/AGE) + 0.993\ln(Hd) - 0.324(N) - 0.581(PLAH)$
	$R^2 = 0.692$ MSE = 0.1839 PRESS = 27.772

where:

b = scale parameter
c = shape parameter
$\bar{D}$ = mean pine groundline diameter (cm)
$\overline{D^2}$ = mean squared diameter (cm^2)
AGE = plantation age (yrs)
Hd = average height of dominants and co-dominants (m)
N = number of pine stems per hectare (x 100)
HERB = presence (1) or absence (0) of herbaceous weed control
PBAH = percentage of woody basal area per hectare in hardwoods
PLAH = percentage of woody leaf area per hectare in hardwoods

1\. Relative volume growth = $\dfrac{\text{volume growth over three seasons}}{\text{initial volume}}$

of 0.874 and the partial F-tests for the competition variables were significant, indicating that they contributed to the regression. The competition variables explained 20% of the variance remaining when added to the model containing just the usual stand attributes. The equation for yield related the natural logarithm of the volume per hectare present three growing seasons after treatment to the same variables as the growth equation. The R^2 was 0.934, and the partial F-tests were again significant. The competition variables explained 30% of the remaining variance.

For both equations the best hardwood variable was the percentage of basal area in hardwoods per hectare. This variable was a larger number with a greater number of hardwoods, so the negative signs on the coefficients of this variable indicate less volume, or volume growth, with more hardwood competition. Similarly, the positive sign on the coefficients of the herbaceous variable indicate greater growth with herbaceous weed control. The significance of these variables, and the amount of remaining variance explained, indicate the strength of the relationship between pine growth and the amount of surrounding vegetation.

Diameter Distribution Models

Parameter Prediction. The best parameter prediction equations also included both pine and competition variables (Table 7). In both cases, the competition measures significantly contributed to the regressions, as indicated by partial F-tests. The coefficients for the competition variables were as expected, with the presence of herbaceous weed control having a positive sign and the percentage of the total woody leaf area in hardwoods having a negative sign. The R^2's for these equations were 0.916 for the equation predicting the scale parameter and 0.557 for the shape parameter equation, both much higher than the R^2 values of from 0.1 to 0.3 reported by Frazier (1981) as typically occurring.

The results of the goodness-of-fit test indicated that the predicted distributions were mostly not significantly different from the actual distributions (Figure 2). with only 10% (15 out of 144) of the distributions significantly different. Many of the plots with significantly different predicted distributions had actual distributions (Figure 3). which are difficult to fit with the Weibull function. The number of significantly different distributions was somewhat higher than the 3-5% reported for older stands (Frazier 1981 and Little 1983), probably due to the small number of diameter classes per plot (as few as three).

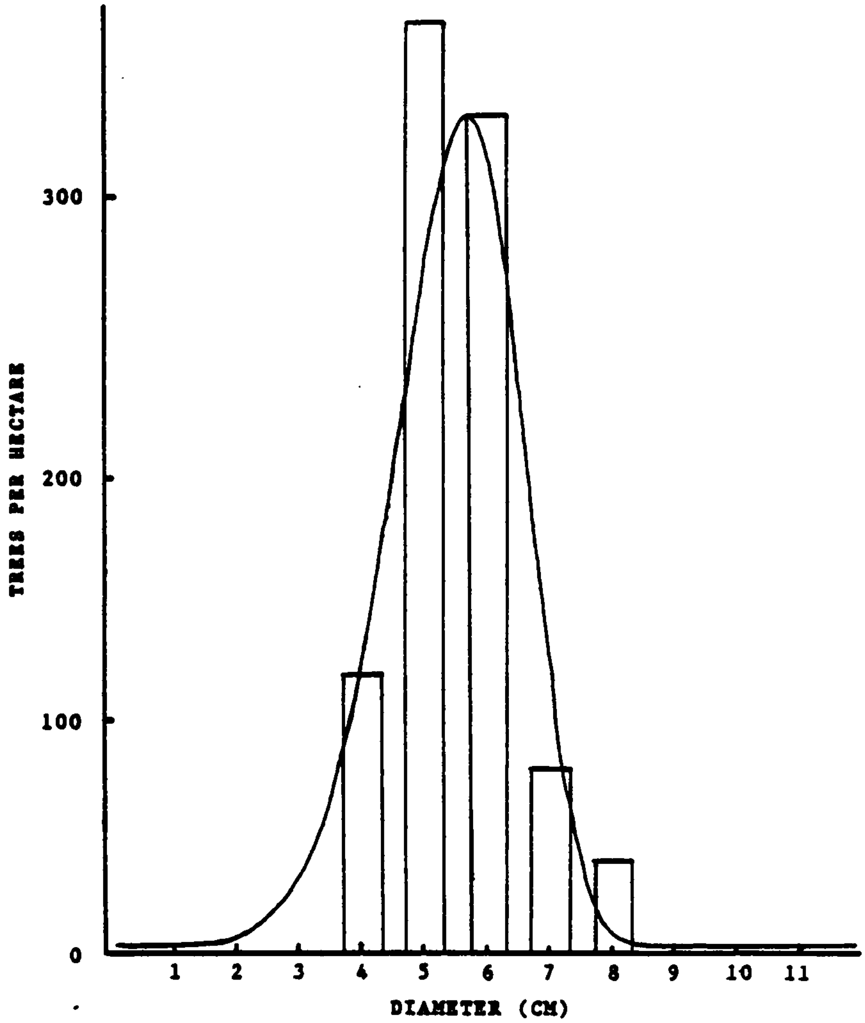

Figure 2. Representative plot of Virginia Piedmont loblolly pine seedlings with a predicted distribution that was not significantly different than the actual distribution.

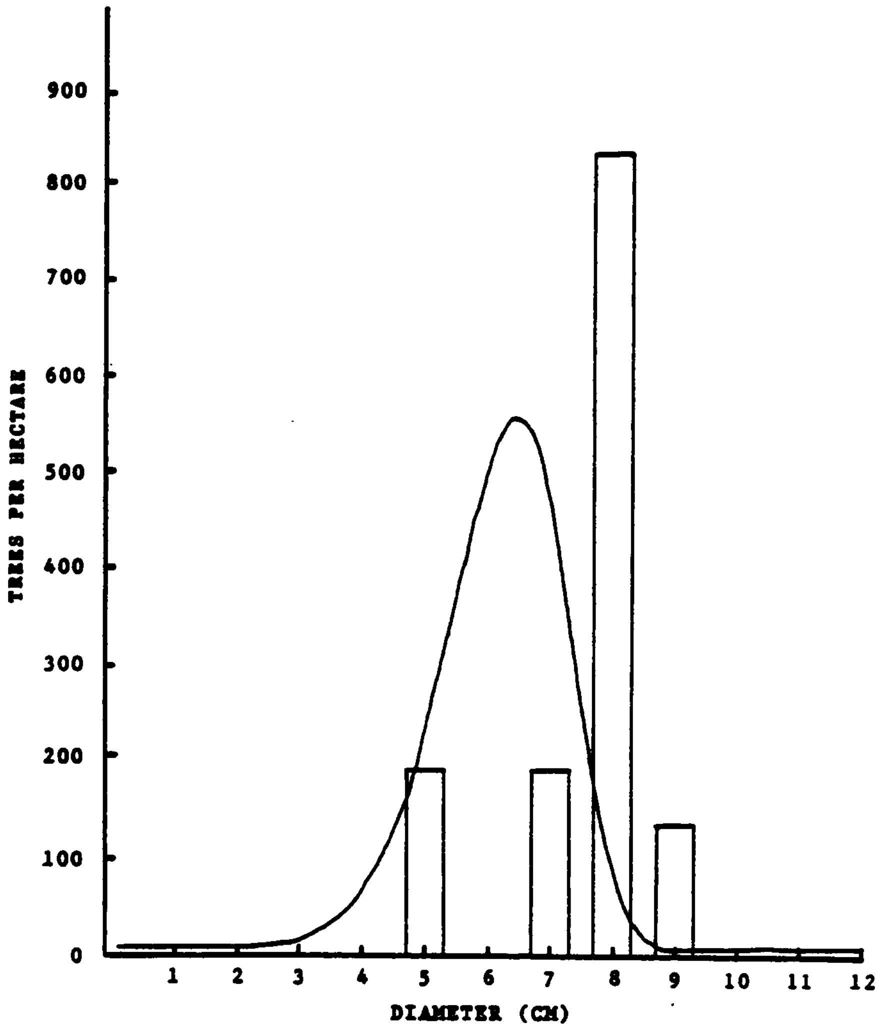

Figure 3. Representative plot of Virginia Piedmont loblolly pine seedlings with a difficult-to-fit actual distribution and the significantly different predicted distribution.

Parameter Recovery. The best equations for the mean diameter and mean squared diameter also included both pine and competition variables (Table 7). The competition variables significantly contributed to the regressions and had coefficients with the expected signs. The R^2's for these equations were high, 0.914 for the mean diameter equation and 0.692 for the equation predicting the variance of diameters. These compare favorably with the R^2's of 0.92 and 0.26 obtained by Frazier (1981) for the mean diameter and variance of diameters for older loblolly stands.

The goodness-of-fit test indicated that 9% (13 of 144) of the predicted distributions were significantly different that the observed distributions. Again, many of the plots where the distributions were significantly different had actual distributions which were very difficult to fit (Figure 3).

Individual-Tree Models

Comparisons of the competition indices in the empirically-based individual-tree growth equations indicated that the distance-independent indices resulted in the best equations, although there was very little difference between all of the equations (Table 8). The equations using the percentages of basal area and leaf area in hardwoods had the lowest PRESS

Table 8. Regression statistics for individual-tree growth equations, for loblolly pine plantations of the Virginia Piedmont, using different competition indices.

Index	Empirical equations			Chapman-Richards equations	
	PRESS	MSE	R^2	PRESS	MSE
Percent of basal area per plot in hardwoods	187.8	0.3117	0.819	183.2	0.3005
Percent of leaf area per plot in hardwoods	188.2	0.3122	0.819	183.3	0.3006
APA[1] based on leaf area	189.6	0.3139	0.819	188.5	0.3094
APA[1] based on basal area	190.9	0.3139	0.819	189.1	0.3104
Modified Heygi index based on leaf area	191.2	0.3153	0.818	192.9	0.3172
Modified Heygi index based on basal area	190.9	0.3145	0.819	193.2	0.3175
No competition index	192.4	0.3189	0.816	191.8	0.3171

1. Area Potentially Available index

statistics and the lowest mean square error, followed by the area potentially available (APA) indices and the modified Heygi's indices. In all cases, however, the competition indices significantly contributed to the explanation of the variation in volume growth. These results were similar to those reported by Martin and Ek (1984), who also found that distance-independent indices performed better than distance-dependent ones.

The distance-independent indices also performed best in the modified Chapman-Richards equations (Table 8). Again, there was little difference between the leaf area- and basal area-based indices, and the APA indices were better than the Heygi indices. In fact, the models with the modified Heygi indices were not as good as the model without a competition index. This was because of the perhaps erroneous assumption that competition is inversely related to the distance between competitors and that the effect remains constant over all distances. The use of basal area instead of diameter may also have reduced the effectiveness of this index.

When compared to the empirical equations, based upon the mean squared errors and PRESS statistics, the modified Chapman-Richards equations were slightly better, with a best PRESS statistic of 183.2 as compared to 187.8 and a best mean squared error of 0.3005 to 0.3117. This finding was different than the results reported by Martin and Ek (1984) of a better fit with empirically-based equations.

IMPLICATIONS AND CONCLUSIONS

After three growing seasons, loblolly pine seedlings exhibited a differential growth response to removal of surrounding vegetation. Seedlings in plantations treated before the beginning of the second growing season after treatment showed the greatest response to release, suggesting that this is the best time for release treatments. The definite drop in response of seedlings that were treated before the beginning of the third growing season after planting indicates the adverse effect of delaying release treatments.

The growth response to the treatment combining control of two-thirds of the woody stems with herbaceous control was comparable to the total weed control treatment, indicating that complete eradication of the surrounding vegetation is not necessary. The importance of herbaceous weed control was shown in the two youngest plantations, where treatments combining herbaceous and woody weed control resulted in significantly better volume growth than the corresponding treatments without herbaceous control.

While this study was not designed to directly compare the effects of competition for different limited resources, the results indicate that competition for moisture was most important. The importance of competition for water was indicated in both the effects of herbaceous weed control and the comparison of the total woody and two-thirds woody control treatments. Herbaceous vegetation was never tall enough to substantially shade and therefore adversely affect photosynthesis of the pine seedlings, yet its removal increased growth, probably through an increase in available moisture with a decrease in transpiring surface. The similar results between the total control and two-thirds woody control treatments again indicated the importance of water over light. The presence of shading may have reduced the amount of water loss through evapo-transpiration, which compensated for the decrease in light due to shading and the additional water loss due to more vegetation.

There were no significant differences in seedling survival, between treatments and within ages, after either the first or third seasons following treatment. This indicates, initially, a lack of herbicide-related mortality, and, at least through the third season, a lack of competition-related mortality. As the stands mature, however, an increase in competition-related mortality will probably occur as pines suppressed for several years begin to die.

Growth curves of treated seedlings diverged from those of untreated or less intensively treated seedlings, even three years after treatment. This suggests that the effects of vegetation removal lasted for more than a single season, and may indicate long-term benefits. Long-term studies are needed, however, to determine if the growth difference will persist through the rotation.

The results also indicated that growth and yield modeling techniques developed for older stands (> 10 years) and larger trees can be applied to young trees (< 10 years) with satisfactory results. Stand-level growth and yield equations were improved with the addition of interspecific competition variables. The presence or absence of herbaceous weed control and the percentage of woody basal area in hardwoods were the best predictors of all competition variables tested. The interspecific competition variables, however, explained less than a third of the variation remaining after the usual stand attributes were included in the equations, leaving a great deal of variation unexplained. Several factors not addressed in this study were probably responsible for the unexplained variation; these include microsite differences, genetic differences and planting variations. Inclusion of variables for these factors could increase the ability to explain differential growth in pine seedlings.

Both the parameter prediction and parameter recovery methods of diameter distribution modeling resulted in equations with comparable, if not better, fits than those reported for older stands. Also, interspecific competition variables were significant contributors to these equations, with the percentage of woody leaf area in hardwoods per hectare as the best hardwood variable. In all cases the competition variables indicated that greater interspecific competition lowered pine growth and yield.

Distance-independent competition indices performed better than distance-dependent indices in both the empirical and theoretically-based individual-tree equations. This was, perhaps, another indication of the importance of competition for moisture, which is less distance-dependent than competition for light.

The use of leaf area as the basis for the indices, a potential weighting factor to indicate differential competitive abilities of species, did not consistently, or significantly, improve the explanation of individual tree volume growth. The lack of improvement of leaf area over basal area in the competition indices indicated that leaf area, by itself, did not reflect differential resource use. Species most likely have differential rates of resource use per unit leaf area, explaining the failure of leaf area alone. Inclusion of rates of resource use per unit leaf area would probably result in a better weighting factor for the differential competitive abilities of species.

Overall, the theoretically-based modified Chapman-Richards equations performed slightly better than the empirically-based equations. This gives some indication of the importance of incorporating knowledge of the biological system in modeling attempts.

Since the equations developed were derived from a limited data base, they can not be directly applied over a large geographical area. However, the success of these attempts indicates that the development of growth and yield models for young conifer plantations is feasible. The development of a larger data base, covering a larger geographical area and including a range of conifer species, site quality, surrounding vegetation, and treatments, would allow for regional generalization. Monitoring studies, such as this, for several more years will provide important information for a period of stand development where very little data exist. This type of data will indicate whether the trends found in this study will continue through to canopy closure.

Such expansion of the data base could lead to studies of optimization of growth, through vegetation management, during plantation establishment and the years prior to canopy closure.

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