GROWTH RESPONSE OF *PINUS TAEDA* TO VARYING LEVELS OF HARDWOOD CONTROL

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(Received for publication 30 March 1995; revision 11 March 1996)

ABSTRACT

A loblolly pine (*Pinus taeda* L.) plantation study was installed across the south-eastern United States by members of the Auburn University Silvicultural Herbicide Cooperative. This study was designed to quantify and model the effects of varying levels of competing vegetation on long-term pine growth. A matrix of initial stand conditions was established encompassing three site index classes, six plantation ages (0–5 years), four hardwood rootstock density classes (class limits vary by age), and absence or presence of herbaceous weed control.

Five 0.13-ha treatment plots, with 0.06-ha measurement plots, were established at each location. Variation among plots was controlled by sampling and matching plots based on pre-treatment pine and hardwood tree and stand attributes. Each plot was selected for no treatment (check), total hardwood control for 1 year, or specific levels of intermediate hardwood control (one-time treatment by basal spray of herbicide). Herbaceous weed control was combined with hardwood control for certain treatments at selected locations to evaluate the impact of herbicides that control both plant components. Establishment of plots began in 1987, and 56 locations were active in 1995.

The first model presented predicted response in pine basal area as a function of age of treatment and hardwood basal area response at age 8. This model expressed the trade-off between hardwood and pine basal area and clearly showed larger pine responses per unit of hardwood control at younger ages of release (1.61 m^2 of pine basal area response per square metre of hardwood control at treatment age 0, *v.* 0.01 m^2 pine basal area response at treatment age 5). The second model predicted age 8 hardwood basal area as a function of sum of hardwood rootstock heights per hectare and number of hardwood rootstocks per hectare from early stand evaluations (ages 1–5). Prediction of age 8 hardwood basal area allowed stands of different ages to be ranked for need of release through projection of long-term yield loss. Pine yield reduction at rotation due to hardwood competition can be estimated for young stands by using this hardwood basal area prediction model in growth and yield models which use an estimate of hardwood basal area at or past age 8.

Keywords: hardwood competition; growth; response surface design; hardwood basal area; sum of hardwood rootstock heights; *Pinus taeda.*

INTRODUCTION

The south-eastern United States encompasses large areas of relatively productive forest land on a wide range of physiographic provinces. For the purposes of production forestry, each province has unique vegetation and other features that require site-specific information to manage commercial tree species properly. The coastal flatwoods have primarily loblolly pine and slash pine (*Pinus elliottii* Engelm.) plantations. The major vegetative competitors are a variety of understorey shrub species and many grasses, forbs, herbs, vines, and other woody and non-woody herbaceous species. Most of the remainder of the south-eastern United States forest land is in the upper, well-drained, coastal plain region, or in one of several inland, heavily weathered, mountain ranges, plateaus, or river bottom regions.

Many of the non-flatwoods areas being managed are planted with loblolly pine or longleaf pine (*Pinus palustris* Mill.) for pulpwood and solid wood products production. If these upland areas are left undisturbed (without fire or other catastrophic occurrences) succession will proceed toward a temperate mixed-hardwood forest dominated by oaks *(Quercus* spp.) and hickories (*Carya* spp.), along with dozens of associated species such as sweetgum (*Liquidambar styraciflua* L.), maples (*Acer* spp.), elms (*Ulmus* spp.), yellow-poplar (*Liriodendron tulipifera* L.), and blackgum (*Nyssa sylvatica* Marsh.), among others. In addition, there is a large complex of sub-overstorey small trees and shrubs such as dogwood (*Cornus florida* L.), persimmon (*Diospyros virginiana* L.), and blueberries (*Vaccinium* spp.). This highly variable complex of species, coupled with vigorous herbaceous vegetation in early stages of stand development, creates a formidable challenge in the regeneration of pine plantations.

Where establishment of a pine plantation is the goal of the landowner, several methods of vegetation management can be practised to ensure establishment and economically acceptable growth of planted pine species. Harvested sites are often prepared before planting with mechanical equipment, herbicides, or a combination of both. The use of pre- and post-emergent herbicides for the temporary control or suppression of competing herbaceous vegetation immediately after planting is becoming more common as longer-term growth response information becomes available. If undesirable competing hardwoods are not controlled with site preparation, pine stands are often "released" or cleaned using herbicides as either liquid or granular broadcast applications or directed spray applications. This release typically is accomplished during the first 2–5 years after planting. There also is growing interest in control of competing hardwoods at mid-rotation (8–18 years after planting), particularly when thinning and/or mid-rotation fertiliser application are employed, both of which tend to enhance competing hardwood growth.

Against this background the research study reported in this paper was developed. There have been several reports that undesirable hardwoods growing in pine plantations have a strong detrimental effect on long-term growth and economic productivity. Glover & Dickens (1985) reported several studies that showed a consistent downward trend of pine basal area and volume production with increasing percentage of the stand basal area in hardwoods. This trend was generally greater than a one-to-one relationship, indicating that one unit of additional hardwood basal area resulted in a loss of more than one unit of pine basal area. Bacon & Zedaker (1987) reported the detrimental effect of varying levels of competition on loblolly pine growth at pine age 3 years. Glover *et al.* (1991) showed that a reduction of hardwood interference, achieved by increasing rates of hexazinone, increased pine growth.

Zutter *et al.* (1988) showed pine growth response to control of hardwoods using glyphosate. Knowe (1992) modelled the effects of hardwood competition on basal area and diameter distributions of loblolly pine plantations and showed a substantial negative impact of hardwood competition on pine basal production. Knowe also showed that adding hardwood competition to a pine stand increased the variance of the diameter distribution. Similar reductions in growth have been shown with the effects of woody competitors on Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) growth and stem morphology (Petersen & Newton 1985; Petersen *et al.* 1988; Harrington & Tappeiner 1991; Harrington & Hughes 1991). What has not been reported is an extensive study that addresses timing and level of hardwood control in existing conifer plantations, with provision for measuring these stands through the rotation.

This study provides data about hardwood levels at six treatment ages and periodically after treatment. Growth and yield models, such as HDWD (Burkhart & Sprinz 1984) and North Carolina State University Loblolly Pine Stand Simulator (Smith & Hafley 1987; Hafley & Smith 1991) predict the long-term effects of hardwood competition on loblolly pine yield, but require hardwood basal area at or past the sapling stage. Eight years is typically the earliest age at which these growth and yield models can be used. The need for pine release is evaluated long before age 8, however. Prediction of hardwood basal area at age 8 and beyond from early stand measures is currently a weak link in young-stand release decisions based on long-term growth and economics. Models developed from this study would allow managing foresters to better evaluate the biological and economic outcome of vegetation control decisions.

METHODS

A loblolly pine plantation study was installed across the south-eastern United States by members of the Auburn University Silvicultural Herbicide Cooperative. The study was designed to quantify and model the effects of controlling competing vegetation on long-term growth of pine. A matrix of initial stand conditions was established encompassing:

- Three site index classes: low ($SI_{25} \leq 16.8$ m), medium (16.8 m< $SI_{25} \leq 19.9$ m), and high ($SI_{25} \geq 19.9$ m);
- Six plantation ages 0–5 years
- Four hardwood rootstock density classes, which vary by age:

Lower class limits (upper limit is lower limit of next class)

Rootstock density class	(No. hardwood rootstocks/ha) Age (years from planting) 0	1	2–3	4–5
A	0	0	0	0
B	1237	1237	1237	1237
C	2470	2470	3705	4940
D	2705	4940	6175	7410

A hardwood "*rootstock*" is defined as a single- or multiple-stemmed hardwood plant that obviously arises from the same root system. That is, a rootstock is a single plant, but possibly with more than one stem.

- Presence or absence of herbaceous weed control.

A complete factorial of treatments was not established due to the large number of plots required. Instead, a hypothesised response surface was generated and *key combinations* of treatments were selected to represent the desired response surfaces. Plots were concentrated at ages 1–3 years, matching the most common operational release ages. Fewer plots were installed at ages 0, 4, and 5 years, but these plots help establish the shape of multi-dimensional response surface models.

Five 0.13-ha treatment plots with 0.06-ha *pine measurement plots* (PMP) were established at each location. Plots were not replicated at each site. The study was not intended to test treatment differences through analysis of variance, but rather to provide data across conditions of the south-eastern region for modelling the effects of design variables on loblolly pine growth response. Within each PMP, eight 2.14-m radius (0.0014-ha) *competition measurement plots* (CMP) were established. Two CMPs were randomly placed within each quadrant of each PMP to ensure a representative unbiased sample of competing vegetation. The CMP sample represented an 18.7% sample of each PMP. In many situations this sample was determined to be insufficient to properly characterise the hardwood rootstocks because of within-plot variation. Therefore, 1 year after treatment and at pine age 5, a single technician performed a 100% tally of all hardwood rootstocks on each 0.06-ha PMP at all locations. The CMPs were measured at the same time, providing an adjustment of CMP measurements during years that a 100% tally was not performed. Starting at pine age 8 and at subsequent measurements, a 100% tally of all hardwoods was made on each plot.

Variation among plots at a location was controlled by an intensive sampling and matching of plots based on pre-treatment pine and hardwood tree and stand attributes. To control site quality and pine stocking among plots, each plot's mean pine total height and density (trees/ha) had to be within ±10% of the mean pine total height and density on the site. To control pretreatment hardwood vegetation abundance, each plot had to have hardwood rootstock density within ±20% of the mean hardwood rootstock density of the five plots, and similar species composition. Past records and soils information were used to place each location into a site index class. Mean hardwood rootstock density was used to place the location into a density class.

Each plot was randomly selected for no treatment (check), total hardwood control for 1 year (with retreatment during the second year), or a specified level of intermediate hardwood control (one-time treatment by basal spray of herbicide). Herbaceous weed control (broadcast spray of sulfometuron methyl) was combined with hardwood control for selected treatments at certain locations to evaluate the impact of herbicides that control both plant components. This aspect of the study will not be addressed in this paper. The targeted percentage control of hardwood rootstocks for each age and hardwood class is given in Table 1. Each individual hardwood rootstock on the treatment plot was visited and randomly selected for either treatment or non-treatment. The specified percentage of hardwood rootstocks was treated with herbicide (triclopyr as Garlon 4E[7] in diesel fuel applied as a basal spray) although that percentage of rootstock kill was not always accomplished. Actual measured rootstock density was used in all analyses.

Establishment of plots began in 1987, with 54 locations being active in 1995. Vegetation measurements and timing of these measurements are summarised in Table 2. At the end of 1994, 53 and 33 locations reached age 5 and 8 years, respectively. A detailed description of each location is not included because of space limitations.

TABLE 1–Target hardwood rootstock control by plantation age and hardwood density class.

Initial, residual hardwood level*	Plantation age at treatment (years)			
	0	1	2–3	4–5
	Target reduction in arborescent species rootstocks (%)			
A, A	0	0	0	0
A, 0	100	100	100	100
B, B	0	0	0	0
B, A	65	65	75	70
B, 0	100	100	100	100
C, C	0	0	0	0
C, B	40	50	50	50
C, A	80	85	90	90
C, 0	100	100	100	100
D, D	0	0	0	0
D, C	30	40	35	30
D, B	55	70	70	65
D, A	85	90	90	90
D, 0	100	100	100	100

* Numeric density depends on age at treatment (*see* text).

TABLE 2–Measurement schedule and observed measurements for loblolly pine and competing vegetation.

Treatment age	Measurement age of pine (years)										
	0	1	2	3	4	5	6	7	8	11	15+5
0	X	X		X		X			X	X	X
1		X		X		X			X	X	X
2			X		X	X			X	X	X
3				X		X			X	X	X
4					X	X	X		X	X	X
5						X		X	X	X	X

Pine measurements: *0.06-ha PMP*: Stem count, total height, condition code, free-to-grow index, crown class (age 8+), dbh (age 5+), height to live crown base (age 8+). *Subsample of 20 pines/PMP*: Height to crown base, diameter 15 cm above ground (through age 5), crown width (through age 8).

Hardwood measurements: *Eight 0.004-ha CMPs per PMP*: Species or species group, height class, crown width (through pine age 8). *100% tally on PMP:* (at 1 year after treatment, age 5, and pine age 8+): Species, height class, dbh (pine age 8+).

Herbaceous measurements: *Four 0.004-ha subplots per PMP:* Clipped, dried, and weighed herbaceous vegetation and percentage cover estimates during first year after treatment. *Eight CMPs per PMP:* Percentage cover at all evaluations.

RESULTS AND DISCUSSION

Because this study was installed across a range of ages and during a 7-year period, a complete analysis at a given pine plantation age cannot be performed until all locations reach that age. Only 33 locations had reached age 8 at the time of this analysis. Results presented in this paper are interim results based on data available in 1995. Response to herbaceous weed control had been dramatic and was commonly evident within 2 years of treatment. Only weak response trends developed at age 5 for levels of hardwood control, however. This was expected since response to hardwood control is expressed over a longer time than response to herbaceous weed control. Locations that had reached plantation age 8 exhibited stronger hardwood control response trends. As more locations reach age 8, 11, and beyond, better and improved predictions of rotation-length response will be obtained. Results of the 33 locations that had reached pine age 8 are the focus of this analysis.

Prediction of Age 8 Pine Response

The response in pine basal area at age 8 was modelled using the form:

Pine basal area at age 8 = Pine basal area of check plot at age 8 + modifiers for hardwood levels at age 8

This model predicts age 8 pine basal area as a function of the check plot basal area plus perturbations in hardwood levels due to treatment. Although specific residual hardwood density classes were targeted at time of treatment, the actual measured residual number of hardwood rootstocks and basal area was used in the analysis. Basal area of the check plot accounts for site quality factors and makes use of the clustering and pretreatment matching of plots at each location. Response differences occurred due to age and success of treatment. Age of treatment was included in the model as a class variable. The model was fit simultaneously for all ages. Herbaceous weed control treatments were not included in this model owing to the limited number of observations at the time and the inability with this approach to account for the interaction of herbaceous weed control with hardwood level and site quality. The result was a common model that differed in only one parameter for each treatment age.

PBA8 = 0.6089 + 0.9603 CKPBA8 + a_1 REHBA8

where: PBA8 = pine basal area at age 8 (m^2/ha)

CKPBA8 = pine basal area of the untreated check plot at age 8

REHAB8 = response in hardwood basal area at age 8 (m^2/ha) (treatment minus check hardwood basal area, therefore REHAB8 is negative for treatments with less hardwood basal area than the check) (standard error of parameter = 0.0282775, p>|t|=0.001)

Parameter estimates for a_1 were:

Treatment age	Number of observations	a_1	Standard error	p>|t|
0	6	−1.609	0.470	0.0008
1	19	−0.787	0.256	0.0025
2	34	−0.678	0.206	0.0013
3	42	−0.823	0.129	0.0001
4	25	−0.145	0.309	0.6391
5	15	−0.010	0.313	0.9735

R^2 = 0.90; mean square = 44.5; CV = 12.4; Root mean square = 6.67. Standard error of intercept = 0.384537, p>|t|=0.1157.

The absolute value of parameter a_1 is the gain in pine basal area for each square metre reduction of hardwood basal area below the check at age 8 (negative parameter times negative hardwood basal area "response" due to treatment results in a positive pine basal area response). When hardwoods were controlled at pine age 0, there was a gain of 1.6 m^2 of pine basal area for each square metre reduction in hardwood basal area at age 8. Increases in pine basal area per unit hardwood basal area controlled were similar for ages 1, 2, and 3 at an average 0.76 m^2. Pine responses for treatment ages 4 and 5 were not significantly different from zero at age 8, but responses were expected to increase with increasing stand age. Patterns of pine response had more time to develop from younger compared with older treatment ages. While pine response to herbaceous vegetation control is usually exhibited very quickly, pine response to control of hardwood vegetation is exhibited more slowly, but the impact continues over the entire rotation.

Pine basal area response at age 8 as a function of hardwood basal area response at age 8 is indicated in Fig. 1. The slope of the relationship decreases with increasing age. This implies that pine response decreases with increasing treatment age for a given change in hardwood basal area due to treatment. These relationships support the notion that when hardwood is controlled at earlier ages in a loblolly pine stand, more pine growth will be observed at a given age, for a given level of hardwood control. Desired stand parameters (basal area, piece size, etc.) can also be achieved at an earlier age. This information, coupled with an economic analysis, can assist forest managers in making pine-release timing decisions.

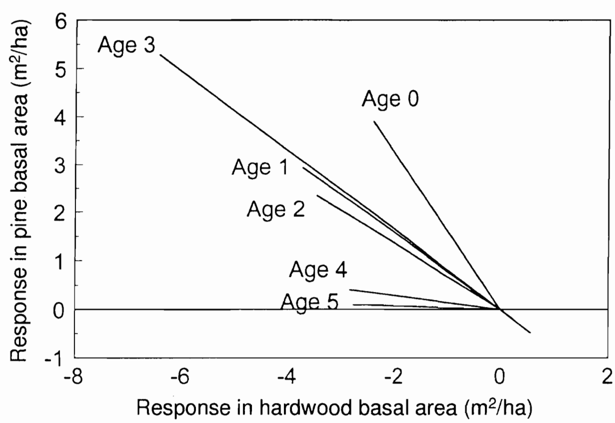

FIG. 1–Predicted response in pine basal area per hectare at age 8 as a function of hardwood basal area response at age 8.

Overall, there was large variation in pine response around predicted values. This model will improve as more sites are added to the age 8 database. However, variation in predicted response will be significantly reduced only by more intense modelling to describe hardwood and pine development at each location. Future models will attempt to include a site variable in the model, such as SI_5 (the mean height of dominant and codominant trees at age 5) and improved expressions of hardwood development and impacts.

Prediction of Age 8 Hardwood Basal Area

Hardwood attributes at time of study establishment on check plots with no hardwood control, and attributes one growing season after treatment on plots with less than 100%

hardwood control treatments, were related to hardwood basal area at age 8. Plots that received herbaceous weed control were not included, leaving 126 plots for this analysis. Several models were examined, but variables that were most important involved measures of the total number of rootstocks present and size of rootstocks. The height of the tallest stem in a single- or multiple-stemmed hardwood rootstock was summed across all hardwood rootstocks on a sample plot to obtain the variable *sum of hardwood rootstock heights*. The following model was judged the best based on model form, mean square error, R^2, and an examination of residuals:

	Parameter value	Standard error	p>|t|	Number of observations
HBA8 =	0.63489	0.122450	<0.0001	—
	+ 0.00056 SH1	0.000121	<0.0001	10
	+ 0.00055 SH2	0.000082	<0.0001	23
	+ 0.00043 SH3	0.000082	<0.0001	23
	+ 0.00038 SH4	0.000046	<0.0001	40
	+ 0.00020 SH5	0.000047	<0.0001	20
	− 0.00015 HRHA	0.000060	0.0122	—

where:

HBA8 = hardwood basal area at age 8 (m^2/ha)

SH_i = sum of hardwood rootstock heights per hectare at age "I" (m/ha), (I=1 to 5, where "I" is evaluation age)

= 0 otherwise

HRHA = number of hardwood rootstocks/ha at evaluation

$R^2 = 0.61$; mean square = 0.7756; CV = 50.6; root mean square = 0.8807.

The effect of number of hardwood rootstocks and sum of hardwood rootstocks at age 3 on hardwood basal area at age 8 is shown in Fig. 2. As the sum of hardwood rootstock heights increases for a given number of hardwood rootstocks, hardwood basal area at age 8 *increases*, indicating larger-sized mean hardwood rootstocks. As the number of rootstocks increases for a given sum of hardwood rootstock heights, hardwood basal area at age 8

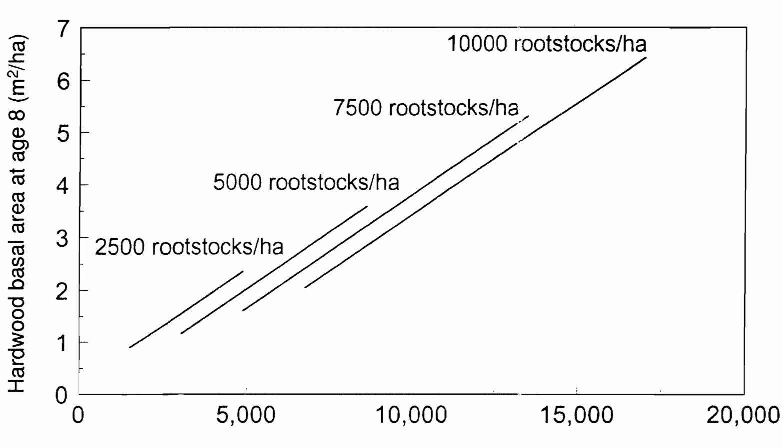

FIG. 2–Example of predicted hardwood basal area at age 8 as a function of sum of hardwood rootstock heights and number of hardwood rootstocks per hectare at age 3 years.

decreases, indicating smaller-sized mean hardwood rootstocks. These relationships are logical, given knowledge of density effects of number of rootstocks on rootstock size.

The effect of evaluation age on the relationship between hardwood basal area at age 8 and sum of hardwood rootstock heights at evaluation age, for a constant 3700 rootstocks/ha, is shown in Fig. 3. For a given sum of hardwood rootstock heights, the hardwood basal area at age 8 is less for older evaluation ages. This relationship is logical, since a given level of hardwood (when expressed as sum of rootstock heights) occurring at an earlier age has more years to grow before age 8 than an older stand.

This model allows prediction of age 8 hardwood basal area per hectare from sample estimates of number of hardwood rootstocks and sum of hardwood rootstock heights per hectare in pine stands at ages 1 to 5 years. The predicted hardwood basal area can be used in a growth and yield model (e.g., HDWD (Burkhart & Sprinz 1984) or NC State Loblolly Pine Simulator (Hafley & Smith 1991)) to predict rotation-length effects of hardwood growing in pine stands. This prediction, along with appropriate costs and incomes, can be used to assist decisions regarding application of herbicides for control of the competing hardwoods.

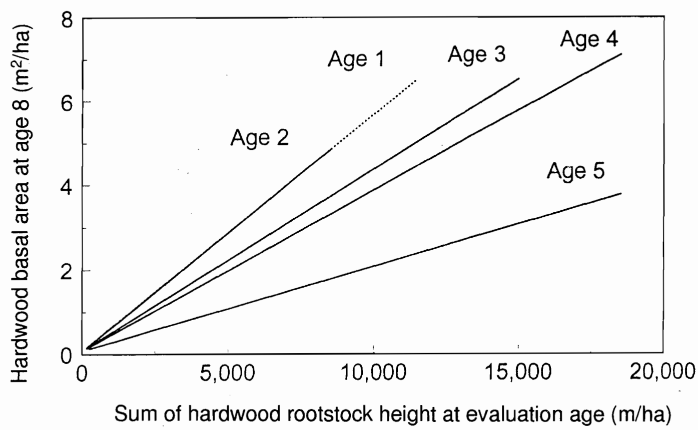

FIG. 3–Relationship between predicted hardwood basal area at age 8 and sum of hardwood rootstock heights at ages 1–5 years, given 3700 hardwood rootstocks per hectare.

CONCLUSIONS

Preliminary analyses of the data from this study suggest that measures of hardwood density (number of rootstocks per unit area) and hardwood size (sum of hardwood rootstock heights per unit area) observed in the first several years of a loblolly pine plantation can be used to predict hardwood basal area per unit area at age 8. This prediction allows forest managers to use existing growth and yield models that incorporate projected long-term effects of hardwood competition for making biologic- and economic-based decisions regarding chemical release of young pine plantations. Based on these data and other studies, response of loblolly pine to control of competing hardwoods can be slow to appear, but there were indications of significant growth enhancement at age 8 from hardwood control. As observations are made on this study site at older ages, the relationships between early hardwood measures and later hardwood basal area, as well as the production trade-off between the hardwood and pine components of these plantations, should become more evident. This information will allow improved growth and yield models to be developed, aiding forest managers to make better silvicultural decisions.

REFERENCES

BACON, C.G.; ZEDAKER, S.M. 1987: Third-year response of loblolly pine growth to eight levels of competition control. *Southern Journal of Applied Forestry 11(2)*: 91–5.

BURKHART, H.E; SPRINZ, P.T. 1984: A model for assessing hardwood competition effects on yields of loblolly pine plantations. *Virginia Polytechnic Institute and State University, Blacksburg, School of Forestry and Wildlife Resources, Virginia Publication FWS-3-84*.

GLOVER, G.R.; DICKENS, D.F. 1985: Impact of competing vegetation on yield of the southern pine. *Georgia Forestry Commission Research Paper 59*. 14 p.

GLOVER, G.R.; ZUTTER, B.R.; MINOGUE, P.J.; GJERSTAD, D.H. 1991: Effect of hexazinone rate and formulation on loblolly pine in broadcast release applications. *Southern Journal of Applied Forestry 15(1)*: 54–61.

HAFLEY, W.L.; SMITH, W.D. 1991: "North Carolina State University Managed Pine Plantation Growth and Yield Simulator, Version 3.2". North Carolina State University, Raleigh, North Carolina.

HARRINGTON, T.B.; HUGHES, T.F. 1991: Predicting average growth and size distributions of Douglas-fir saplings competing with sprout clumps of tanoak and Pacific madrone. *New Forests 5*: 109–30.

HARRINGTON, T.B.; TAPPEINER, J.C.II. 1991: Competition affects shoot morphology, growth duration, and relative growth rates of Douglas-fir saplings. *Canadian Journal of Forest Research 21*: 474–81.

KNOWE, S.A. 1992: Basal area and diameter distribution models for loblolly pine plantations with hardwood competition in the Piedmont and upper coastal Plain. *Southern Journal of Applied Forestry 16(2)*: 93–8.

PETERSEN, T.D.; NEWTON, M. 1985: Growth of Douglas-fir following control of snowbrush and herbaceous vegetation in Oregon. *Down to Earth 41(1)*: 21–5.

PETERSEN, T.D.; NEWTON, M.; ZEDAKER, S.M. 1988: Growth and water relations of Douglas-fir (*Pseudotsuga menziesii*) seedlings under different weed control regimes. *Weed Science 36*: 653–62.

SMITH, W.D.; HAFLEY, W.L. 1987: Simulating the effect of hardwood encroachment in pine plantations. Pp.180–6 *in* Waldrop, T.A. (Ed.) Proceedings, 4th Biennial Southern Silvicultural Research Conference, 4–6 November, Atlanta, Georgia. *USDA Forest Service General Technical Report SE-42*.

ZUTTER, B.R.; MINOGUE, P.J.; GJERSTAD, D.H. 1988: Response following aerial applications of glyphosate for release of loblolly pine in the Virginia Piedmont. *Southern Journal of Applied Forestry 12(1)*: 54–8.