LOBLOLLY PINE GROWTH AS AFFECTED BY YOUNG STAND HARDWOOD AND HERBACEOUS COMPETITION: RESULTS BASED ON THE AUSHC RL-4I STUDY

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ACKNOWLEDGEMENTS

The RL-4I Study was conceived and established by the researchers, technicians and cooperators of the Auburn University Silvicultural Herbicide Cooperative (AUSHC). We at the Plantation Management Research Cooperative appreciate the work that went into establishing and maintaining this study. We also appreciate the opportunity to extend the contribution of these installations into the future. We will rely heavily on study plans, work plans and research papers produced by the AUSHC to describe the history of the RL-4I Study and to build a basis for future measurement and analysis. This information, as well as the past measurement data and analysis programs, was made available to us without reservation or restriction and we acknowledge that future analysis would not be possible without this foundation.

SUMMARY

During the 1984-1985 dormant season, the Auburn University Silvicultural Herbicide Cooperative (AUSHC) began the establishment of a region-wide pine release study in the Piedmont and upper coastal plain regions of the Southeastern United States. The primary objective of the RL-4I study was to quantify the pine growth responses to the degree and timing of woody vegetation control in loblolly pine plantations. Herbaceous weed control treatments were also included at most locations.

A significant number of RL-4I installations had reached at least 15 or 16 years of age by the time of this analysis. Therefore, that snapshot in time was used to examine trends in stand characteristics with respect to post-treatment hardwood level and impact of herbaceous weed control. With respect to post-treatment hardwood level, average dominant heights ranged from 24 to 60 feet across all treatments. Treatment means were between 41 feet for the highest level of hardwood to 46 feet for the complete hardwood control plots. Per-acre basal areas ranged from 36 to 193 ft^2/ac with treatment means from 114 to 133 ft^2/ac. Per-acre green weights ranged from 10 to 129 tons/ac with treatment means from 60 to 76 tons/ac.

Response to herbaceous weed control (HWC) was more variable and some sites appeared to respond negatively. Average HWC basal area response at age 15 or 16 with post-treatment hardwood level 0 ranged from -4 to 21 ft^2/ac with an average of 9 ft^2/ac. Height responses for this group ranged from -1.6 feet to 2.4 feet with an average of 1.1 feet. With post-treatment hardwood level A, basal area responses ranged from -15 ft^2/ac to 25 ft^2/ac with an average of 0 ft^2/ac. Height responses ranged from -2.7 feet to 3.5 feet with an average of 0.3 feet. With post-treatment hardwood level B, basal area responses ranged from 8 ft^2/ac to 44 ft^2/ac with an average of 26 ft^2/ac. Height responses ranged from 0.4 feet to 7.3 feet with an average of 3.9 feet.

Results from past RL-4I analyses were summarized to provide a basis for the current modeling effort. Release treatments carried out prior to age three provided a greater response than later treatments in terms of height and basal area growth. Height response increased with increasing hardwood control prior to age three, but treatments after age three exhibited little or no height response. In general, better sites responded better to hardwood control under all conditions. Both height and per-acre basal area at age eight were positively affected by the herbaceous weed control treatment. As with hardwood control, these affects decreased with increasing treatment age.

The current effort focused on approaches to model the effects of hardwood and herbaceous weed control on per-acre basal area and height growth. In the first approach, a base model and response function were fit to the per-acre basal area data. Response was modeled as a function of site index, years since treatment and whether or not a herbaceous weed control treatment was carried out. The model did not account for the level of hardwood control. In the second approach, the level of hardwood basal area as a proportion of the total basal area at age five was included as an independent variable in a basal area prediction equation. This system also required a separate herbaceous weed control response function and a hardwood dampening function to adjust the response to herbaceous weed control as a function of hardwood level.

Both approaches to modeling basal area produced results that were not encouraging from a statistical standpoint. In some cases the R^2 values were poor and in other cases there were parameter estimates not significantly different from zero. In spite of that, the models produced reasonable-looking results with treatment response trends as observed in the data.

Attempts to directly model the effects of hardwood level and herbaceous weed control on average dominant height growth were essentially ineffective. Past studies indicate that many factors influence height growth response to vegetation control treatments. In light of this, dominant height growth response models were developed using empirical evidence from the RL-4I data. Average dominant height growth responses to herbaceous weed control were calculated by age and post-release hardwood level. These response levels and years to maximum response were used to parameterize a response function. Since response levels appeared to be proportional to hardwood level, a hardwood dampening function was also developed.

The current modeling effort focused on response functions designed to augment existing growth and yield systems for loblolly pine. Future analyses may include an attempt to relate early competition assessments (prior to age five) to a measure useful for inclusion in a growth and yield projection system.

1 INTRODUCTION

Release cutting is described by Smith (1962) as “the act of freeing a young stand of desirable trees, not past the sapling stage, from the competition of undesirable trees that threaten to suppress them”. The most obvious effect of release is the freeing of the crowns of overtopped or suppressed trees. Equally important in young stands, however, is the release of growing space as well as increasing the nutrient and moisture availability in the soil. To achieve these results, release treatments must be effective in killing the competition without facilitating the aggressive sprouting of competing vegetation in the future. Modern herbicides, including both foliar and directed basal applications provide effective options for eliminating or reducing hardwood competition in pine plantations.

During the 1984-1985 dormant season, the Auburn University Silvicultural Herbicide Cooperative (AUSHC) began the establishment of a region-wide pine release study in the Piedmont and upper coastal plain regions of the Southeastern United States. The primary objective of the RL-4I study was to quantify the pine growth responses to the degree and timing of woody vegetation control in loblolly pine plantations (*Pinus taeda* L.) (Lauer and Glover, 1990). Herbaceous weed control treatments were also included at most locations. In 2003, the Plantation Management Research Cooperative (PMRC) assumed responsibility for the RL-4I study. The PMRC objective is to continue the study of pine growth response to hardwood vegetation and to incorporate these responses in plantation growth and yield models.

2 STUDY DESCRIPTION

The emphasis of the RL-4I study was on region-wide inference and application as opposed to site-specific analyses. Therefore, the objective included the modeling of pine growth response over a wide range of site qualities, treatment ages and pre-treatment hardwood levels. Due to the variability in pre-treatment hardwood levels within stands, a response surface approach was used for site selection and treatment allocation. To reduce variability among the five plots at each location, plots were sampled and matched on the basis of pine stocking, pine height and hardwood density prior to treatment.

Allowable pine stocking levels ranged from a maximum of 900 trees per acre to a minimum of 500, 450, 400 and 350 trees per acre for ages of 0,1,2,3 and 4 or 5, respectively. Site classes were defined as low (< 55 feet), medium (55-64 feet) and high (> 64 feet). Hardwood density classes are shown in Table 1. A design matrix was created using site classes, plantation ages and hardwood density classes. Emphasis was given to the medium site index level, plantation ages 1-3 and initial hardwood levels B-D. Numbers of installations by hardwood density class and plantation age at establishment are shown in Table 2.

Table 1. Hardwood density classes by plantation age (rootstocks/acre).

Hardwood Density Class	Plantation Age			
	0	1	2-3	4-5
A	<501	<501	<501	<501
B	501-1000	501-1000	501-1500	501-2000
C	1001-1500	1001-2000	1501-2500	2001-3000
D	>1500	>2000	>2500	>3000

Table 2. Numbers of installations by hardwood density classes and plantation age.

Hardwood Density Class	Plantation Age			
	0	1	2-3	4-5
A	1	2	3	3
B	1	4	10	6
C	1	4	8	0
D	2	9	5	2

Hardwood reduction treatments were allocated based on the pre-treatment hardwood density levels. The reduction levels are shown in Table 3. Herbaceous weed control treatments were not assigned to every location. In general, herbaceous weed control treatments were assigned to a location when there were multiple sites with similar initial conditions.

Table 3. Hardwood percent reduction treatments by initial pine age, initial hardwood class and residual hardwood class.

Initial Pine Age	Initial Hardwood Class	Residual Hardwood Class				
		0	A	B	C	D
0-5	A	100%*	0%	0%	--	--
0-1	B	100%	65%	0%	--	--
2-5	B	100%	75%	0%	--	--
0	C	100%	80%	40%	0%	--
1	C	100%	85%	50%	0%	--
2-5	C	100%	90%	50%	0%	--
0	D	100%	85%	55%	30%	0%
1	D	100%	90%	70%	40%	0%
2-3	D	100%	90%	70%	35%	0%
4-5	D	100%	90%	65%	30%	0%

*100% indicates complete hardwood reduction.

Hardwood control was accomplished during the dormant season when the plots were established. Basal bark applications of triclopyr ester in diesel fuel were used to control hardwoods. Proportional reductions were carried out by randomly selecting rootstocks. The

100% hardwood reduction treatment plots received a second treatment after one year to ensure complete control. Herbaceous control was accomplished with a spring broadcast application of sulfometuron methyl and a direct application of glyphosate in June of the same year. Herbaceous weed control treatments were not repeated.

The establishment phase of the Rl-4I study began in 1984-85 and was completed in 1991. A total of 61 locations were established and by 1999, 52 remained active. Pine and hardwood measurements were scheduled during the dormant season in the year of establishment, two years after establishment and at ages 5, 8, 11, 15 and then every five years to rotation. The most recent measurements were carried out in 2002.

3 MEASUREMENTS AND GROWTH TRENDS

3.1 Plot Averages

Tables 4-9 show average stand characteristics for measurements taken at ages 15 and 16 years of age. Many installations had reached this age range as of the 2002 measurement. The hardwood components were summarized in terms of hardwood basal area (SBA), the number of hardwood stems/acre (NSTEM) and the sum of hardwood stem heights (SHGT).

Table 4. Average stand characteristics for RL-4I control (untreated) plots that had reached age 15 or 16 years by the 2002 measurement.

Variable	Mean	Minimum	Maximum	Std. Dev.
Dom. Height (ft)	44.2	26.7	56.0	6.68
Trees/acre	568	369	758	115
Basal Area (ft^2/ac)	122.3	48.2	197.8	32.34
Avg. Dbh (in)	6.2	3.6	7.5	1.04
Avg. Height (ft)	42.5	24.8	54.6	6.68
Total Volume(ft^3/ac)	2605	680	4847	898
Total Weight (tons/ac)	67.2	15.7	129.3	24.60
SBA (ft^2/ac)	7.2	0.00	31.8	9.87
NSTEM	1742	408	6770	1558
SHGT (ft)	23510	1885	72101	17926
Total Basal Area (ft^2/ac)	129.5	48.2	200.3	32.26

Table 5. Average stand characteristics for RL-4I complete control plots that had reached age 15 or 16 years by the 2002 measurement.

Variable	Mean	Minimum	Maximum	Std. Dev.
Dom. Height (ft)	45.5	24.3	60.0	7.07
Trees/acre	557	356	842	116
Basal Area (ft^2/ac)	133.0	36.2	192.6	35.07
Avg. Dbh (in)	6.5	3.3	8.4	1.12
Avg. Height (ft)	44.0	21.0	58.5	7.33
Total Volume(ft^3/ac)	2910	454	4794	983
Total Weight (tons/ac)	75.7	10.3	128.6	26.96
SBA (ft^2/ac)	0.98	0.00	8.78	1.64
NSTEM	371	32	1274	285
SHGT (ft)	3826	240	13501	3155
Total Basal Area (ft^2/ac)	134.0	36.2	192.9	34.84

Table 6. Average stand characteristics for RL-4I plots with post-treatment hardwood level "A" that had reached age 15 or 16 years by the 2002 measurement.

Variable	Mean	Minimum	Maximum	Std. Dev.
Dom. Height (ft)	45.1	26.7	58.9	6.74
Trees/acre	558	356	764	91
Basal Area (ft^2/ac)	132.6	48.2	197.8	33.13
Avg. Dbh (in)	6.4	3.6	7.9	0.95
Avg. Height (ft)	43.6	24.8	55.5	6.73
Total Volume(ft^3/ac)	2866	680	4847	907
Total Weight (tons/ac)	74.4	15.7	129.3	24.76
SBA (ft^2/ac)	4.3	0.00	23.6	5.92
NSTEM	877	227	3445	676
SHGT (ft)	11887	1885	33156	7891
Total Basal Area (ft^2/ac)	136.8	48.2	200.3	32.36

Table 7. Average stand characteristics for RL-4I plots with post-treatment hardwood level "B" that had reached age 15 or 16 years by the 2002 measurement.

Variable	Mean	Minimum	Maximum	Std. Dev.
Dom. Height (ft)	45.4	34.3	52.1	4.58
Trees/acre	558	376	823	132
Basal Area (ft^2/ac)	126.5	70.2	166.4	24.25
Avg. Dbh (in)	6.4	4.6	7.8	0.91
Avg. Height (ft)	43.9	33.8	50.5	4.52
Total Volume(ft^3/ac)	2721	1206	4006	630
Total Weight (tons/ac)	70.3	29.5	104.7	17.13
SBA (ft^2/ac)	7.1	0.00	31.7	9.18
NSTEM	1642	551	5126	1252
SHGT (ft)	23772	8493	51106	12522
Total Basal Area (ft^2/ac)	133.6	77.3	174.3	23.83

Table 8. Average stand characteristics for RL-4I plots with post-treatment hardwood level "C" that had reached age 15 or 16 years by the 2002 measurement.

Variable	Mean	Minimum	Maximum	Std. Dev.
Dom. Height (ft)	44.0	30.9	54.8	7.34
Trees/acre	534	369	687	112
Basal Area (ft^2/ac)	114.9	62.4	135.7	25.22
Avg. Dbh (in)	6.2	4.5	7.5	1.16
Avg. Height (ft)	42.1	28.6	52.8	7.44
Total Volume(ft^3/ac)	2416	945	3002	689
Total Weight (tons/ac)	62.3	22.5	79.4	19.18
SBA (ft^2/ac)	4.2	0.00	18.0	7.90
NSTEM	2724	2488	2960	334
SHGT (ft)	32081	31012	33150	1512
Total Basal Area (ft^2/ac)	119.2	78.5	153.7	23.75

Table 9. Average stand characteristics for RL-4I plots with post-treatment hardwood level "D" that had reached age 15 or 16 years by the 2002 measurement.

Variable	Mean	Minimum	Maximum	Std. Dev.
Dom. Height (ft)	41.0	32.2	49.8	5.83
Trees/acre	601	422	758	127
Basal Area (ft^2/ac)	118.8	74.8	150.0	28.14
Avg. Dbh (in)	5.9	4.6	7.3	1.02
Avg. Height (ft)	39.3	29.0	48.1	6.20
Total Volume(ft^3/ac)	2351	1229	3476	743
Total Weight (tons/ac)	59.8	29.5	89.7	20.04
SBA (ft^2/ac)	12.5	0.00	31.8	11.94
NSTEM	3066	1587	6770	2135
SHGT (ft)	38065	21660	72101	20830
Total Basal Area (ft^2/ac)	131.2	90.5	163.5	29.45

3.2 Growth Trends

Figures 1-12 illustrate growth trends by treatment in terms of average dominant height, per-acre basal area and per-acre total green weight. To maintain some consistency in the charts, averages by treatment were calculated for those installations measured at ages 8, 11 and 15 years of age. Therefore, not all of the available measurements for each treatment are represented. Growth trends are shown by initial and post-treatment hardwood level, with and without the herbaceous weed control treatment. Legend codes such as B – A + H, for example, refer to the pre-treatment hardwood level (B), the post-treatment hardwood level (A) and H indicates a herbaceous weed control treatment.

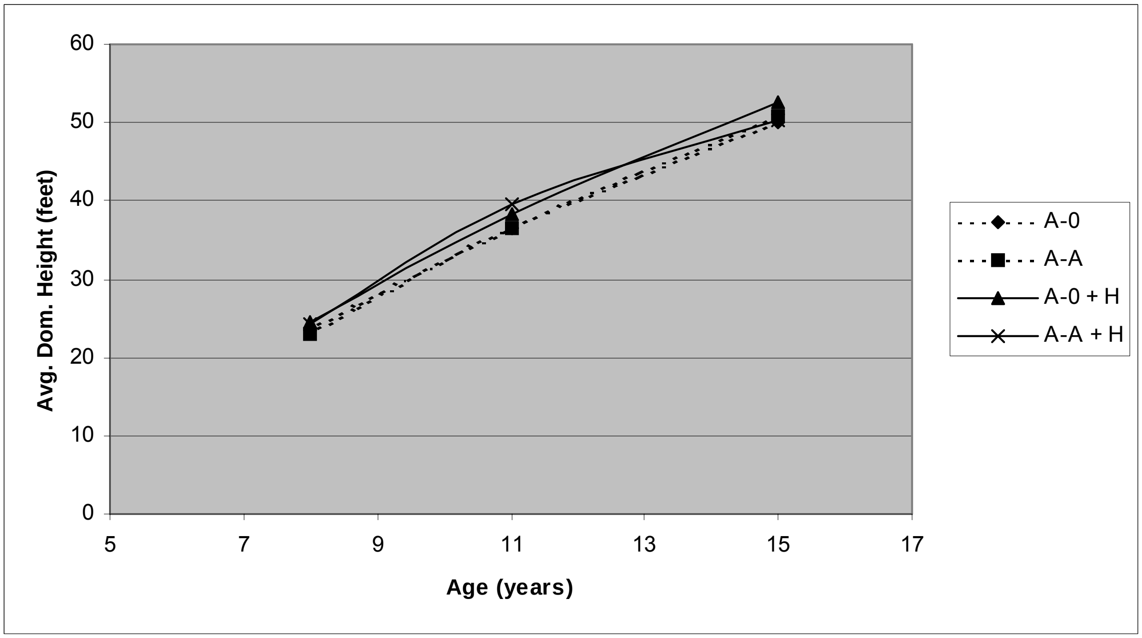

Figure 1. Average dominant height growth by treatment for RL-4I plots with pre-treatment hardwood level "A".

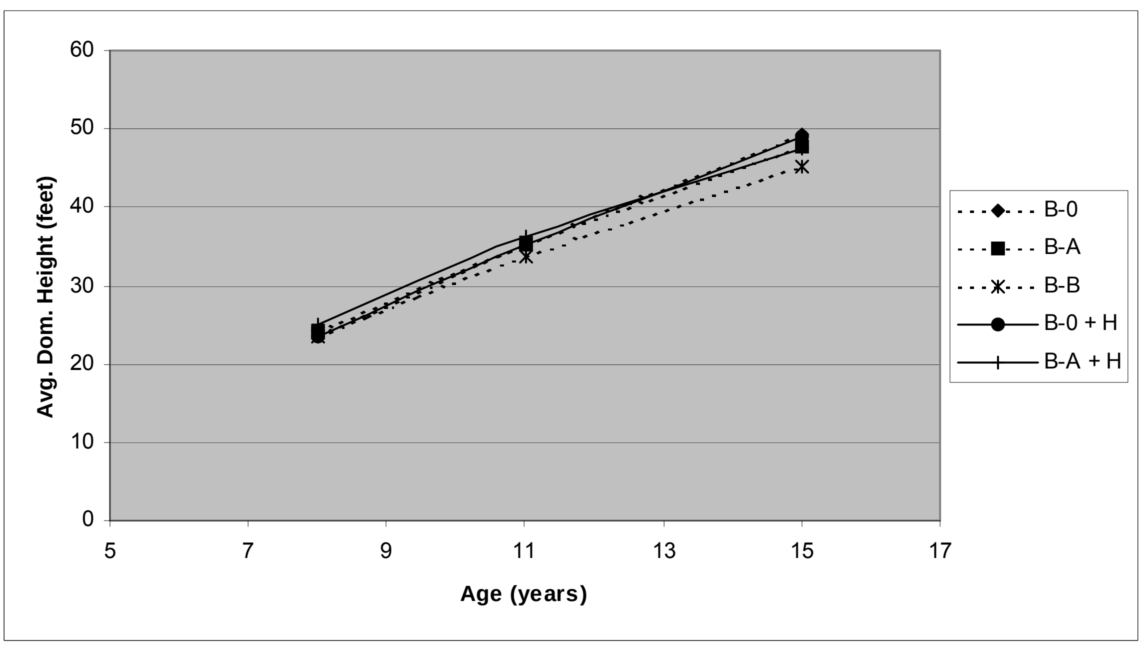

Figure 2. Average dominant height growth by treatment for RL-4I plots with pre-treatment hardwood level "B".

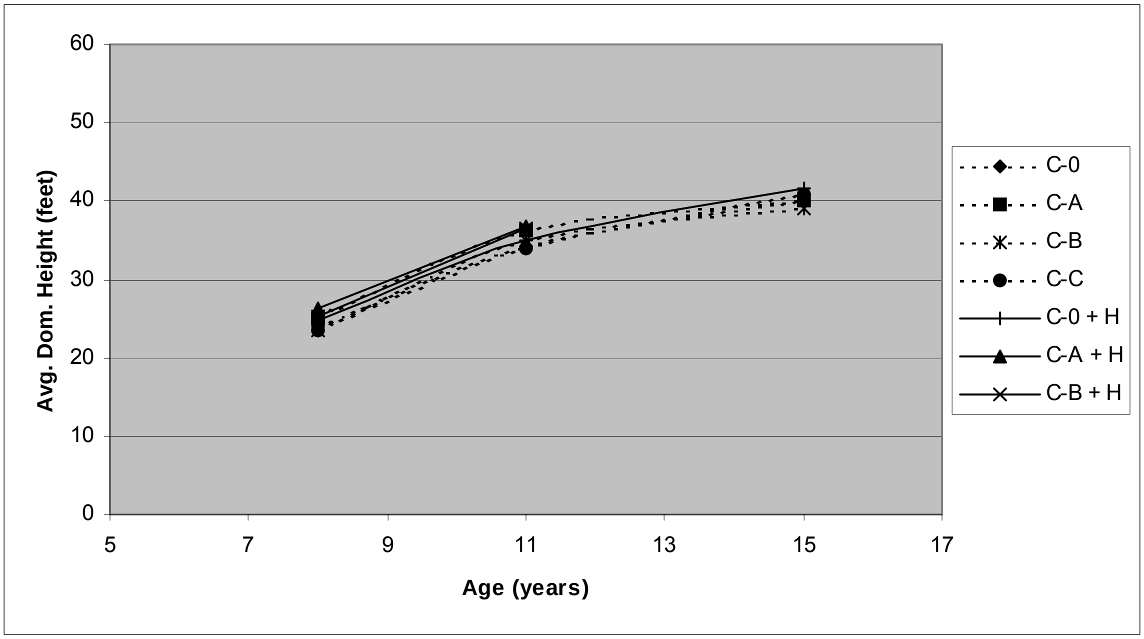

Figure 3. Average dominant height growth by treatment for RL-4I plots with pre-treatment hardwood level “C”.

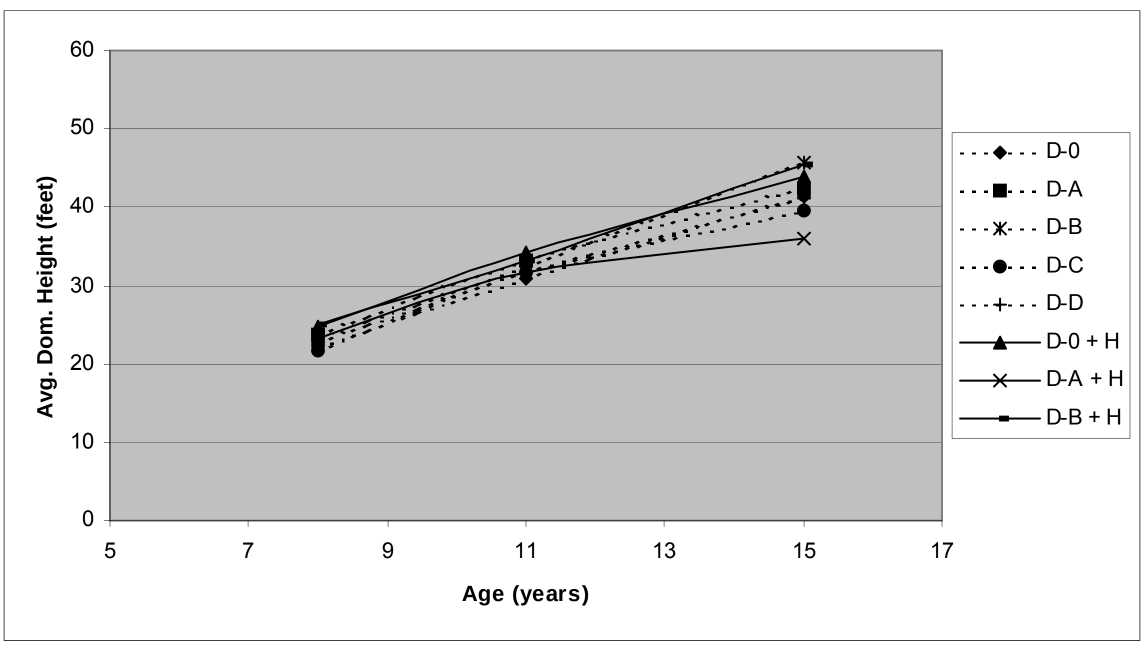

Figure 4. Average dominant height growth by treatment for RL-4I plots with pre-treatment hardwood level “D”.

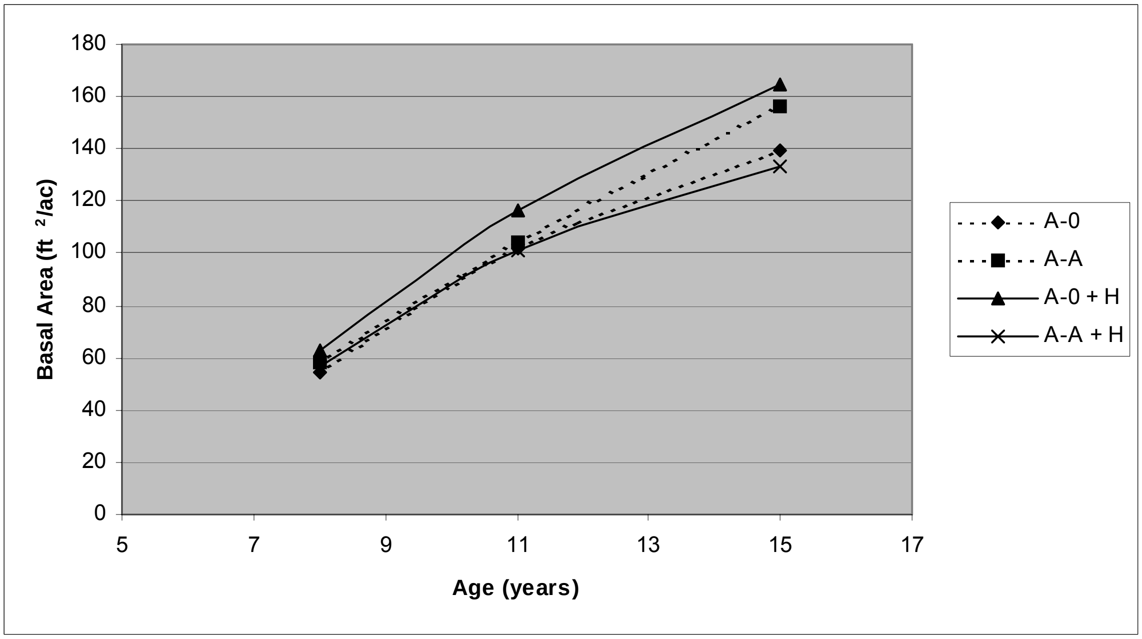

Figure 5. Average per-acre basal area growth by treatment for RL-4I plots with pre-treatment hardwood level "A".

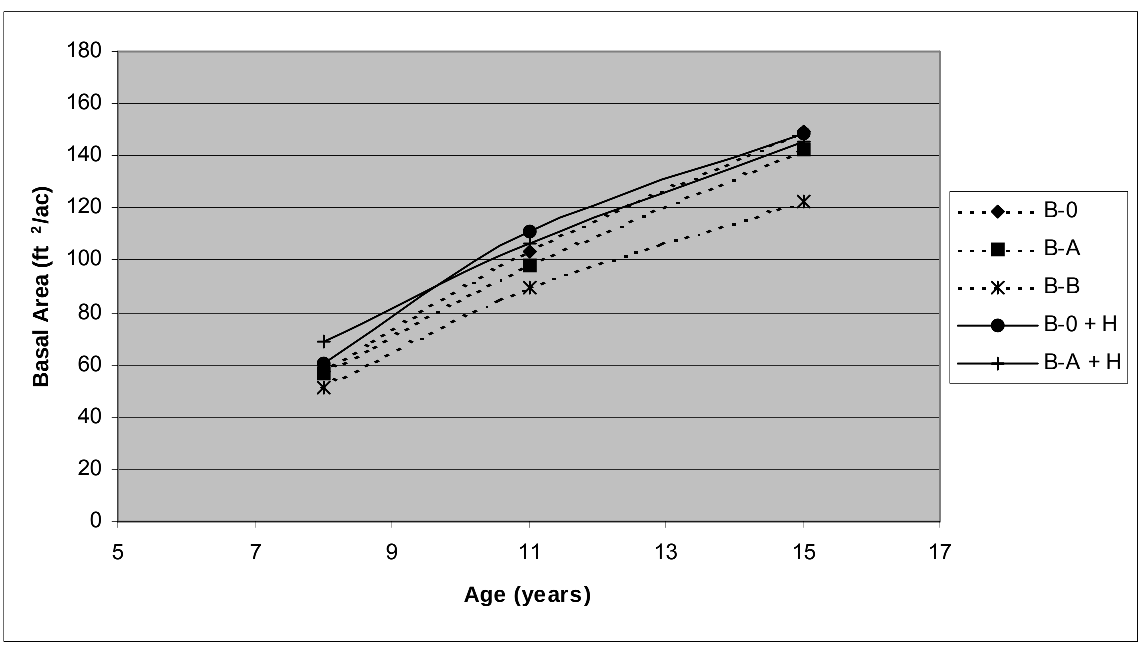

Figure 6. Average per-acre basal area growth by treatment for RL-4I plots with pre-treatment hardwood level "B".

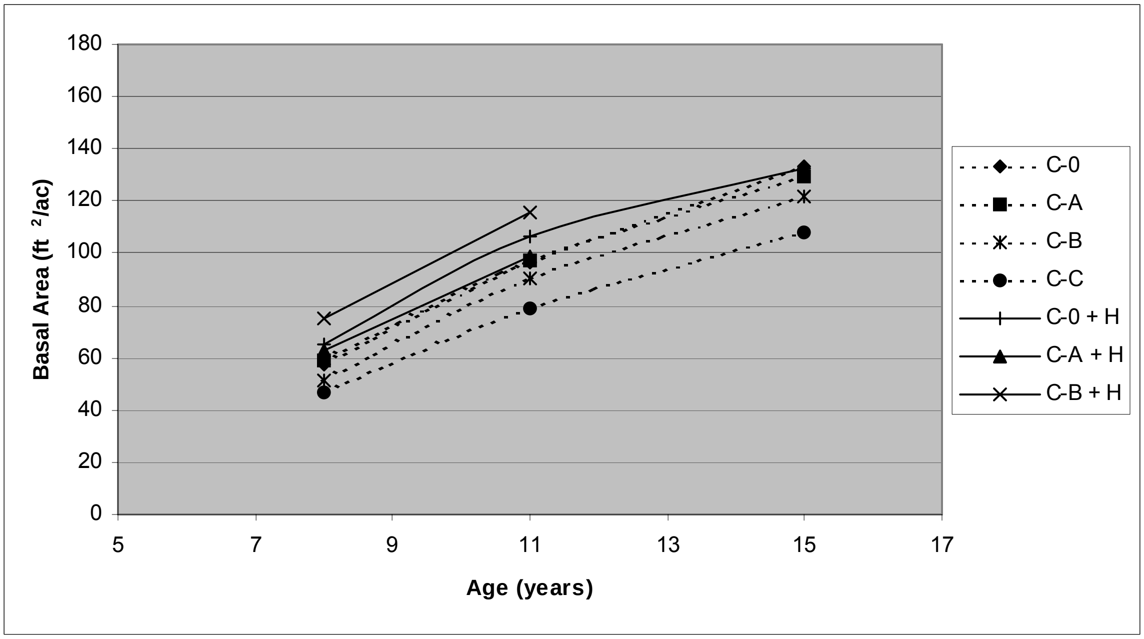

Figure 7. Average per-acre basal area growth by treatment for RL-4I plots with pre-treatment hardwood level “C”.

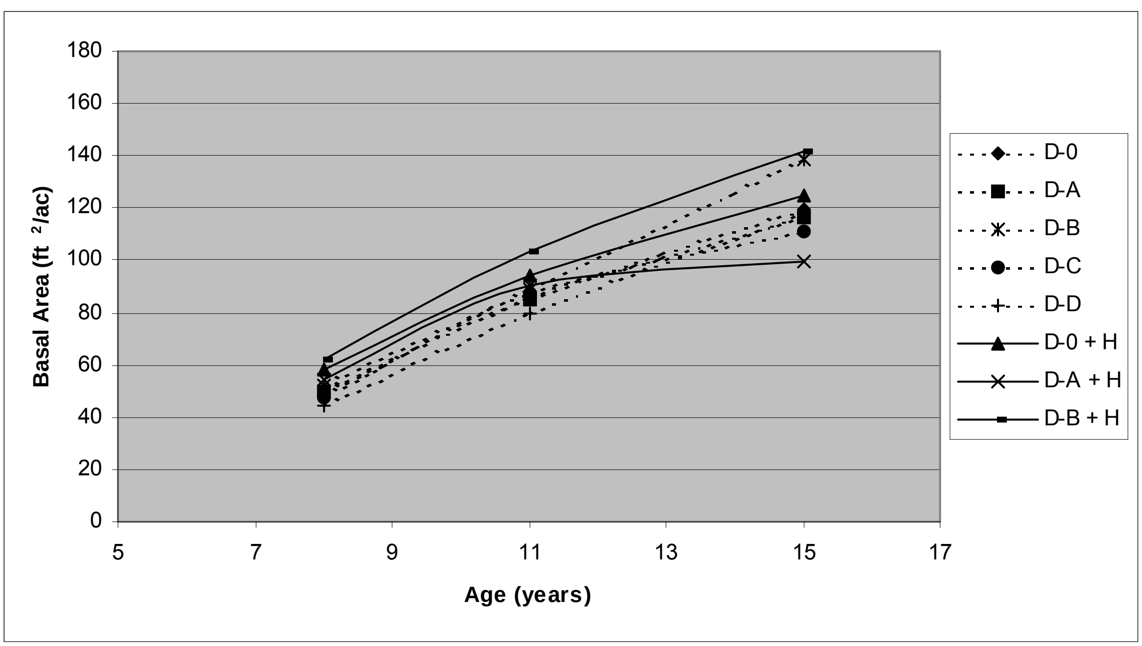

Figure 8. Average per-acre basal area growth by treatment for RL-4I plots with pre-treatment hardwood level “D”.

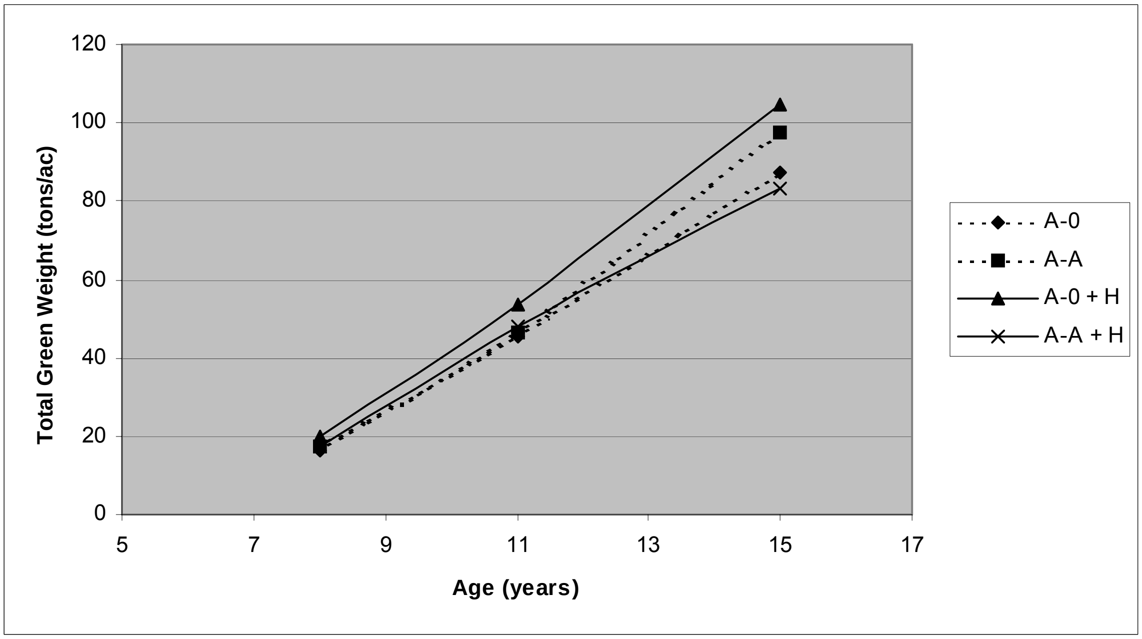

Figure 9. Average per-acre green weight growth by treatment for RL-4I plots with pre-treatment hardwood level “A”.

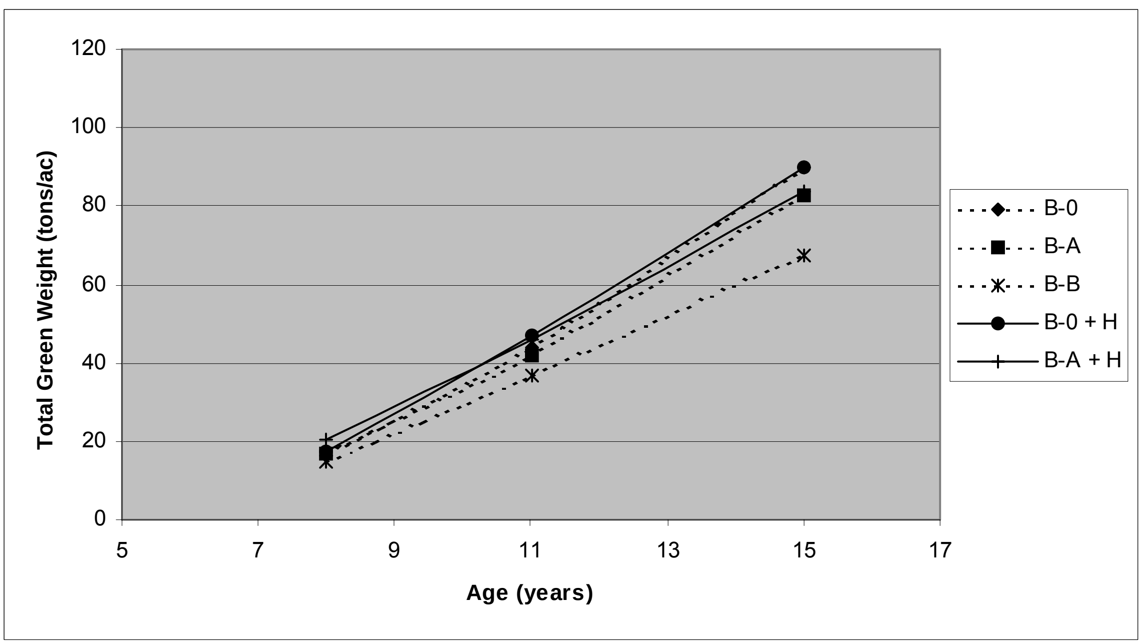

Figure 10. Average per-acre green weight growth by treatment for RL-4I plots with pre-treatment hardwood level “B”.

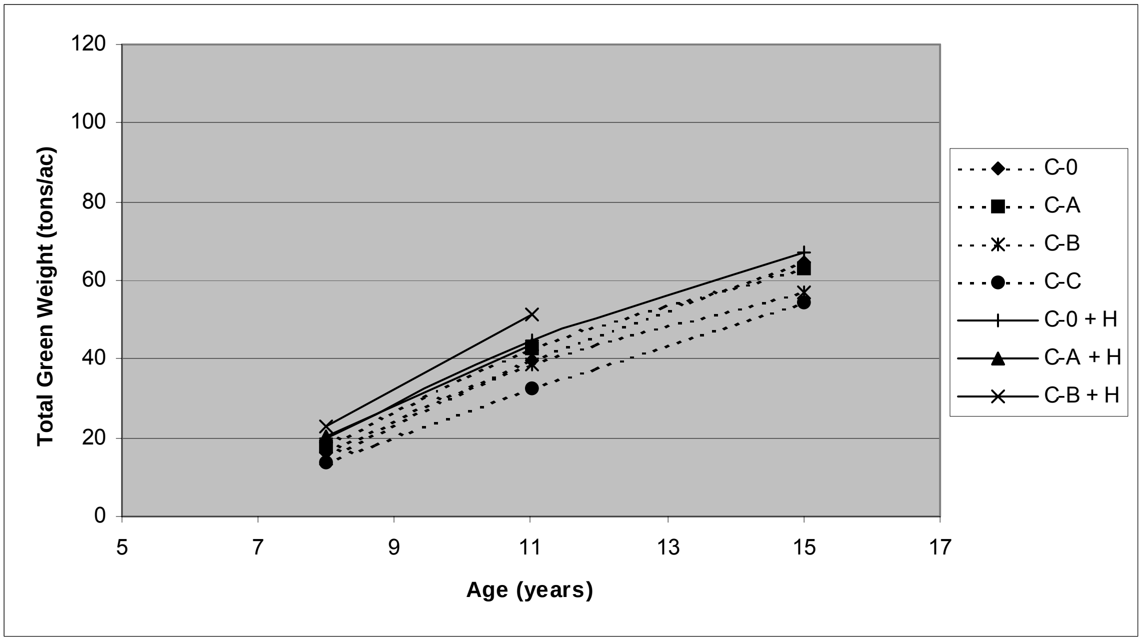

Figure 11. Average per-acre green weight growth by treatment for RL-4I plots with pre-treatment hardwood level "C".

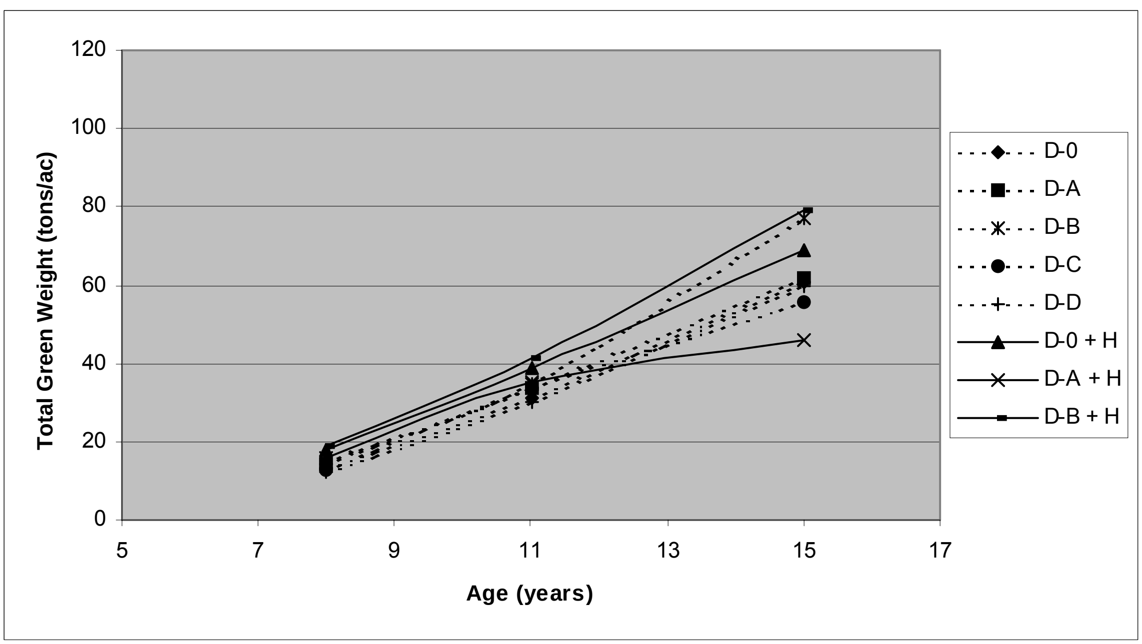

Figure 12. Average per-acre green weight growth by treatment for RL-4I plots with pre-treatment hardwood level "D".

4 MODELING RESULTS

The RL-4I study was designed so that various levels of hardwood competition could be created and the resulting effects of these hardwood levels on pine growth could be modeled. A comprehensive modeling effort requires five discrete steps as described by Lauer *et.al.*, 1999: 1) the development of a stand-level basal area model that relates pine basal area to pine height, pine density and hardwood basal area at specific measurement ages, 2) modeling the relationship of pine stand volume as a function of stand level pine basal area and average pine height, 3) modeling pine height response as a function of hardwood control, 4) modeling pine mortality as a function of hardwood control, and 5) the prediction of later stand hardwood basal area as a function of early hardwood attributes. The effects of the herbaceous weed control treatment are to be included in these modeling steps, as well.

4.1 Past Results

A summary of the results of past modeling efforts will be useful in interpreting the results of the current modeling exercise. Lauer *et.al.*, 1999 (1) first screened potential pine basal area models by fitting to untreated check plots. It was observed that per-acre pine basal areas for stands of a given height and density were not constant across soils and geographic locations. Therefore, a productivity grouping term was included in the models to improve resolution. The next step was to construct a pine basal area prediction model that included the effects of hardwood reduction level and age of release in the treated plots. Results indicated that the amount of hardwood removed prior to age three had minimal impact on age eight pine basal area except that which could be attributed to changes in survival and/or height growth. Release treatments carried out at ages 3-5 resulted in an additional, positive basal area response to the amount of hardwood removed, but it was unclear as to how to estimate the overall negative impact of delaying the release treatment. For stands that were released prior to age three, it was then only necessary to include an estimate of the remaining hardwood level at the age of interest, as follows:

$$\ln(PBA_{ij}) = \mu + L_i + \alpha_1 \ln(TPA_{ij}) + \alpha_2 \ln(H_{ij}) + \alpha_3 HBA_{ij} + \varepsilon_{ij}$$

where *i* designates location, *j* designates plot within location and L_i is the departure from the mean intercept for location *i*. The model explained at least 97% of the variation in pine basal area at ages 8 and 11.

Lack of replication prevented the direct estimation of pine height response due to release at a given location. A modeling approach was used to relate average height response to stand attributes. Results indicated that there was a positive response from herbaceous control that diminished with increasing release age and height response was related to the level of hardwood control. The following model was constructed to fit the observed patterns:

$$HR = c_1 HWC + c_2 AH + c_3 HBAD + c_4 HBAD x AR$$

where *HR* = age eight height response of the tallest 50% of trees,
HWC = 1 if herbaceous control was included, 0 otherwise,
AH = age of herbaceous control (0 for no herbaceous control),
HBAD = age eight hardwood basal area on the control minus the treated plot (an estimate of hardwood basal area removed),
AR = age of release,
c_1, c_2, c_3, c_4 = parameters to be estimated.

The model fit was poor due to the relative magnitude of height response to hardwood control and between-plot variability at age eight. Trends produced by the model indicated that response to herbaceous control was positive, greatest when carried out at age zero, and decreased with increasing treatment age. Height response increased with decreasing hardwood level in stands released prior to age three, but declined with increasing release age from 0 to 2 years. Pine height at age eight in stands released at ages 3-5 years was less than the height of stands released earlier.

To complete the modeling system, an equation was fit to predict pine stand volume at ages eight and 11 as a function of pine trees per acre, basal area and top height:

$$PV = \gamma_0 TPA^{\gamma_1} PBA^{\gamma_2} \exp(\gamma_3 H)$$

where *PV* = pine volume (ft^3/ac),
TPA = pine trees per acre,
PBA = pine basal area (ft^2/ac),
H = average height of tallest 50% of pine trees,
$\gamma_0, \gamma_1, \gamma_2, \gamma_3$ = parameters to be estimated.

Figures 13 and 14 show the basal area and volume response curves at age eight implied by the equations listed above. Responses are due to complete hardwood control and are illustrated as functions of age eight hardwood basal area, year of release and the use of a herbaceous weed control treatment for a given site class.

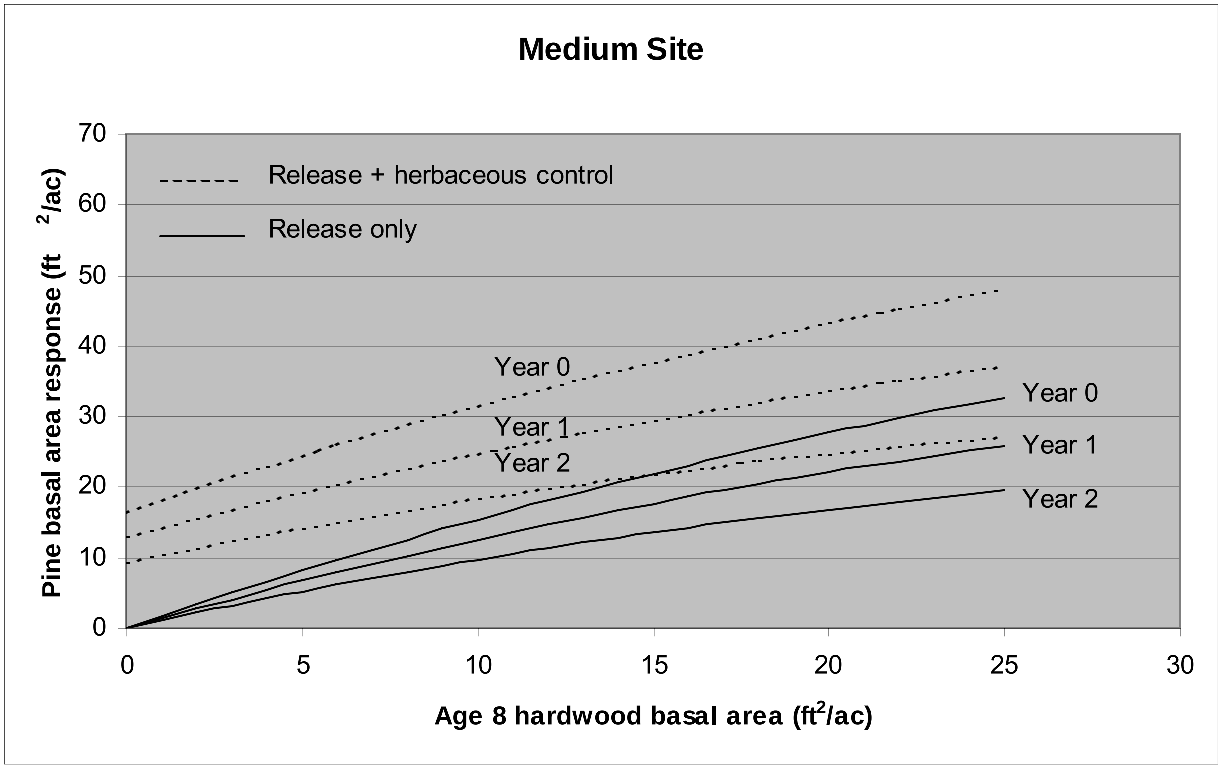

Figure 13. Age eight pine basal area response from complete hardwood control, with and without herbaceous weed control, as related to age eight pine basal area of an untreated stand and year of release.

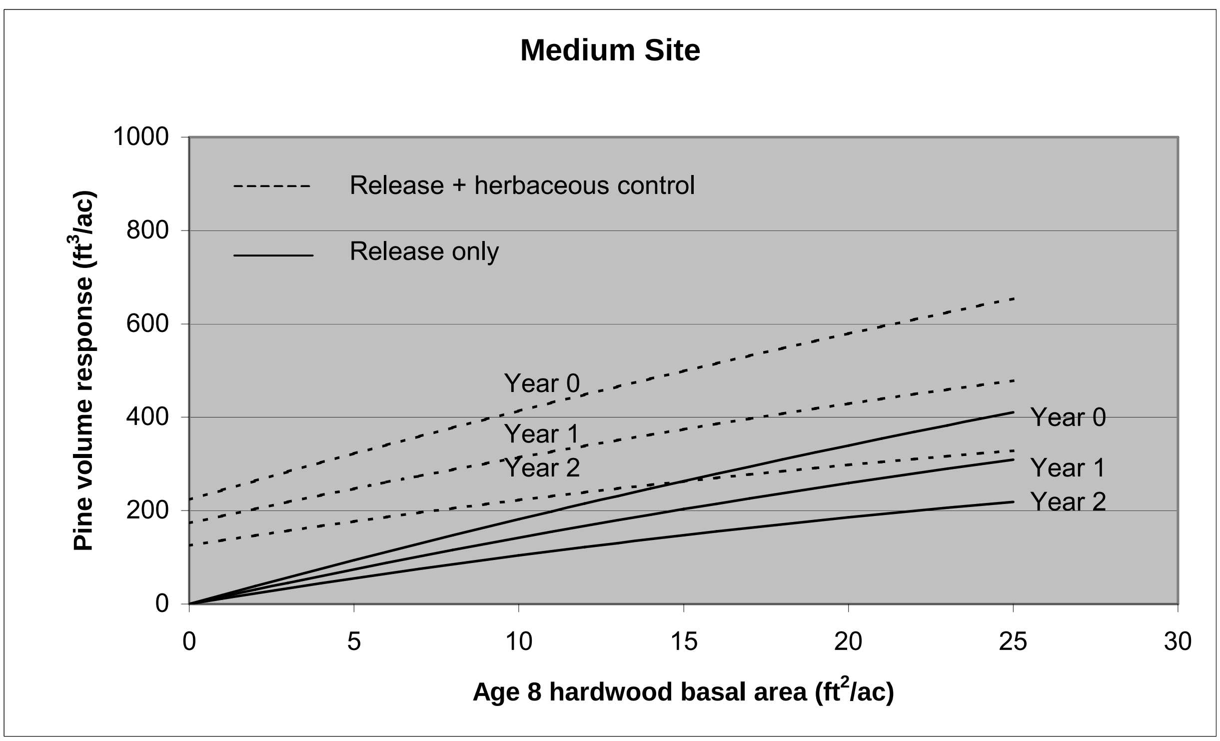

Figure 14. Age eight pine volume response from complete hardwood control, with and without herbaceous weed control, as related to age eight pine basal area of an untreated stand and year of release.

Lauer *et.al*., 1999 (2) developed models to estimate pine responses to release and herbaceous weed control through age 11 for release ages 0-5. The models were constructed to relate response (yield), in terms of per-acre basal area or volume, as functions of potential yield and hardwood basal area at the time of release. The potential yield was defined as the per-acre basal area or volume following complete hardwood control at a given location and release age.

$$\ln(Y_{ij}) = L_i + \alpha_k HBA_{ij} + \beta_k HWC_{ij} + \varepsilon_{ij}$$

Where Y_{ij} = yield for the i^{th} study location and the j^{th} plot at that location,

L_i = an estimate of the potential yield at the i^{th} location following total hardwood control at release age k,

HBA_{ij} = the hardwood basal area at yield age,

HWC_{ij} = 1 if herbaceous weed control was applied, 0 otherwise.

The model form allows for straightforward interpretation of the parameters so that α_k estimates the loss per unit of hardwood basal area at release age k and β_k estimates the response to herbaceous weed control applied after the k^{th} growing season.

Results from fitting of the model indicated that response to release and herbaceous weed control decreased with age of release. To incorporate this trend, the model was restructured so that release age was included as a continuous variable.

$$\ln(Y_{ij}) = L_i + \alpha_0 HBA_{ij} + \alpha_1 LA_i * HBA_{ij} + \beta_1 LA_i * HWC_{ij} + \varepsilon_{ij}$$

Where LA_i = (5 – release age).

Figures 15 and 16 illustrate the trends produced by the models. The curves show the percent loss in basal area and volume site potential at age eight as functions of the year of release and the hardwood basal area that would be present at age eight if no release was done. In general, loss in site potential increased with increasing hardwood basal area present at age eight and increased with year of release. In the worst case, if the release was delayed to age five and there was 30 ft^2/ac hardwood basal area, the loss in pine basal area was 55% and the loss in pine volume was approximately 52%.

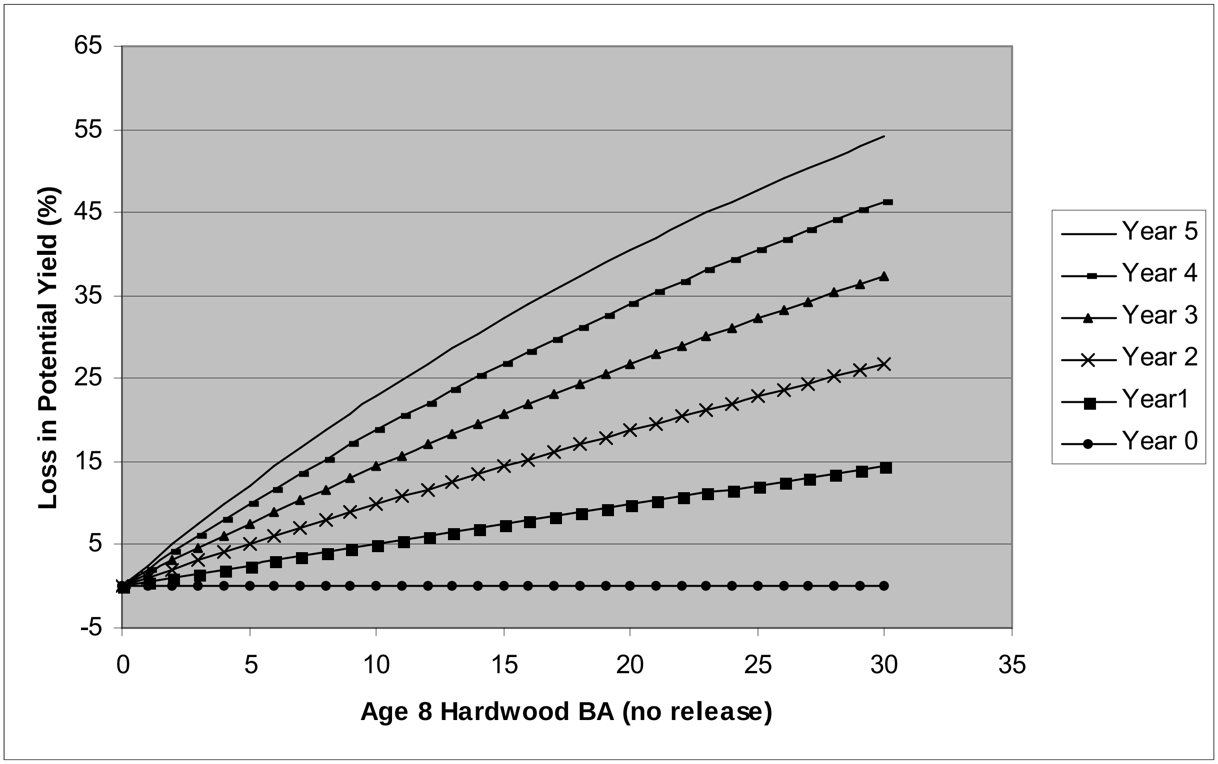

Figure 15. Percent loss in age eight pine basal area as related to age eight hardwood basal area without release and year of release.

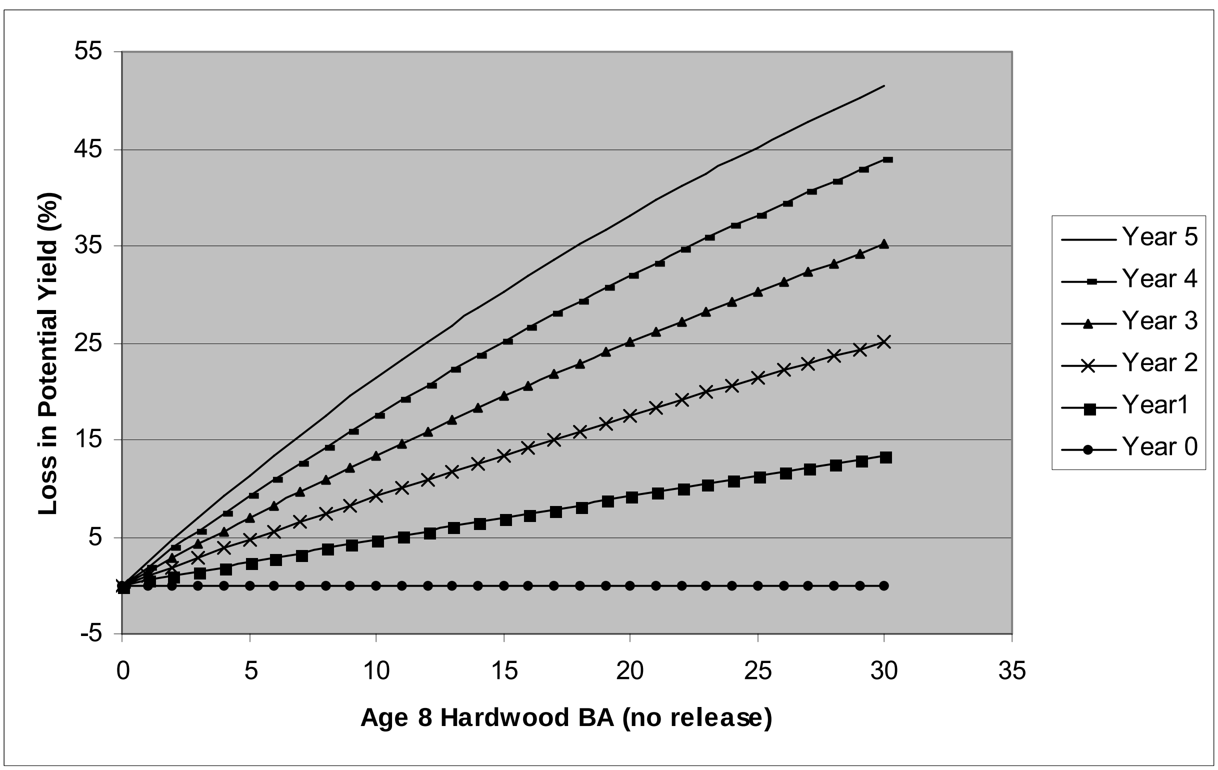

Figure 16. Percent loss in age eight pine volume as related to age eight hardwood basal area without release and year of release.

Previous attempts to model RL-4I dominant height growth produced mixed results. It was observed that "height response and differences in survival were expected to be of small magnitude compared to the plot-to-plot variation of these attributes at a given location" (Lauer, et.al., 1999). A model was fit to estimate dominant height response as a function of herbaceous weed control, age of herbaceous control, age of release and an estimate of woody control in terms of basal area:

$$HR = c_1 HWC + c_2 AH + c_3 HBAD + c_4 HBAD * AR$$

Where *HR* = height response of the tallest 50% of trees,

HWC = 1 if treatment included herbaceous weed control, 0 otherwise,

AH = age of herbaceous control, 0 for treatments without *HWC*,

HBAD = hardwood basal area on the control minus the treated plot,

AR = age of release,

c_1, c_2, c_3, c_4 = parameters to be estimated.

Selected plots were dropped from the fitting process due to various circumstances resulting in suppression of pine height growth. The model was fit to the remaining, age eight RL-4I data. Fitting results were poor but illustrated reasonable trends in height response: 1) response to herbaceous control was positive, 2) response decreased with increasing release age until response was close to zero at release age five, 3) height response increased with decreasing hardwood level in stands released prior to age three, 4) height declined (negative response) following release at ages 3-5 with and without a herbaceous weed control treatment. Figure 17 illustrates the trends implied by the model.

4.2 Current Modeling Results

4.2.1 Per-Acre Basal Area Base and Response Models

Pienaar and Rheney (1995) demonstrated the utility of an additive response function to modify existing basal area and height growth models. This approach was applied to the RL-4I plots to estimate the basal area response to release and herbaceous weed control treatments. First, a base model to predict pine basal area was fit to the untreated check plots.

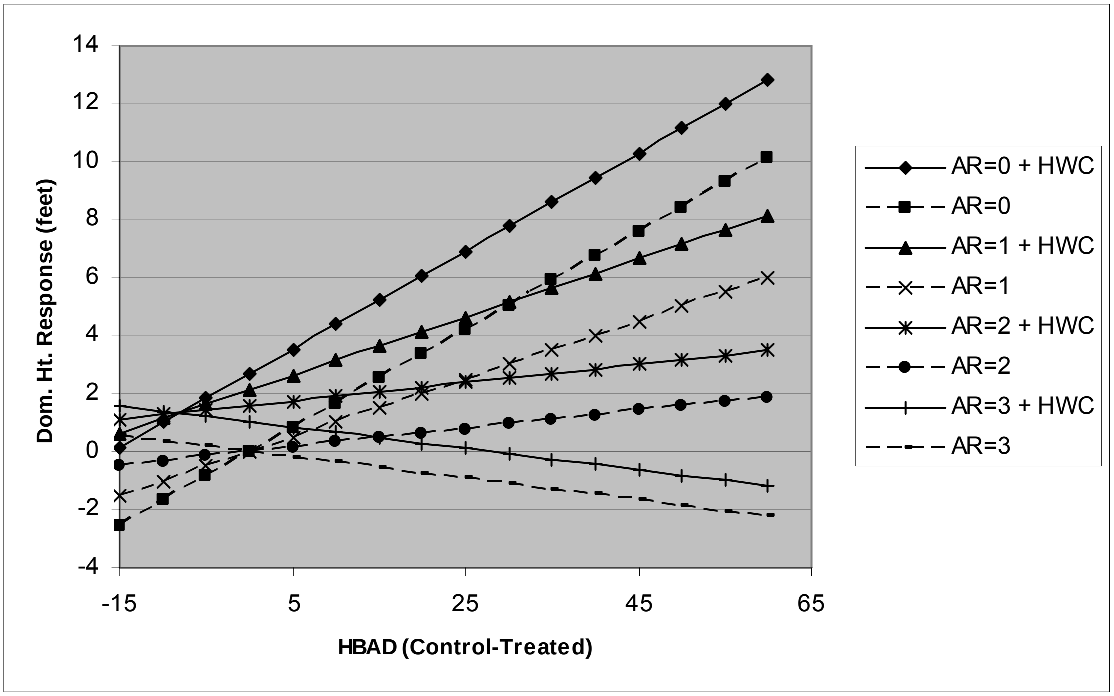

Figure 17. Dominant height response of the tallest 50% of trees as a function of herbaceous weed control and level of hardwood control.

$$\ln(BA) = b_0 + \frac{b_1}{Age} + b_2 \ln(TPA) + b_3 \ln(HD) + b_4 \frac{\ln(TPA)}{Age} + b_5 \frac{\ln(HD)}{Age}$$

Equation	DF Model	DF Error	SSE	MSE	Root MSE	R-Square	Adj R-Sq
lBAb	6	142	6.5431	0.0461	0.2147	0.8434	0.8378

Nonlinear OLS Parameter Estimates

Parameter	Approx Estimate	Std Err	Approx t Value	Pr > |t|
b0	-0.62474	2.0087	-0.31	0.7562
b1	-45.1243	20.0465	-2.25	0.0259
b2	0.251276	0.2339	1.07	0.2844
b3	0.927682	0.2941	3.15	0.0020
b4	3.265985	2.5371	1.29	0.2001
b5	7.653521	2.7594	2.77	0.0063

In addition to the base model, a model is required to predict the response in basal area to hardwood release and herbaceous weed control treatments. Past results and analysis of the data suggest a basal area response pattern that reaches and maintains an asymptotic level some time after treatment. The following generalized model form has that characteristic:

$$R_{BA} = b\left[1 - e^{(-cY_{st})}\right]$$

Where: R_{BA} = basal area response (ft^2/ac),

b = parameter representing the asymptotic response level,

c = parameter representing the rate of increase to the asymptotic response,

Y_{st} = years since treatment.

The RL-4I data indicate that the asymptotic response level may be expressed as a function of site quality and the presence (or absence) of the herbaceous weed control treatment. The rate of increase to the asymptote may be expressed as a linear function of the age of release. The base response function and these observed relationships result in the following basal area response function for RL-4I:

$$R_{BA} = \left(b_0\, zHWC + b_1 SI\right)\left\{1 - e\left[-\left(c_0 + c_1 Age_t\right)Y_{st}\right]\right\}$$

Where: $zHWC$ = 1 if herbaceous weed control was applied, 0 otherwise,

SI = base age 25 site index,

Age_t = age of release treatment.

This model was fit to the RL-4I dataset with the following results:

Equation	DF Model	DF Error	SSE	MSE	Root MSE	R-Square	Adj R-Sq
BARESP	4	610	112131	183.8	13.5580	0.1446	0.1404

Nonlinear OLS Parameter Estimates

Parameter	Approx Estimate	Std Err	Approx t Value	Pr > |t|
b0	18.57614	8.0739	2.30	0.0217
b1	0.241049	0.1040	2.32	0.0207
c0	0.101437	0.0694	1.46	0.1446
c1	-0.0124	0.0111	-1.11	0.2658

Fitting results for the base model and the response model do not look encouraging. Although the R-Square for the base model was 0.84, three of the six parameters were not significantly different from zero at the $\alpha = 0.05$ level. For the response function, the R-Square value was only 0.14 and two of the four parameters were not significantly different from zero. Despite the shortcomings in statistical terms, the models produce reasonable-looking results. Figures 18-20 show the basal area response patterns implied by the model for different site indexes, herbaceous weed control treatments and release ages. Figures 21-23 show the basal area curves produced by the base model with the predicted treatment responses added.

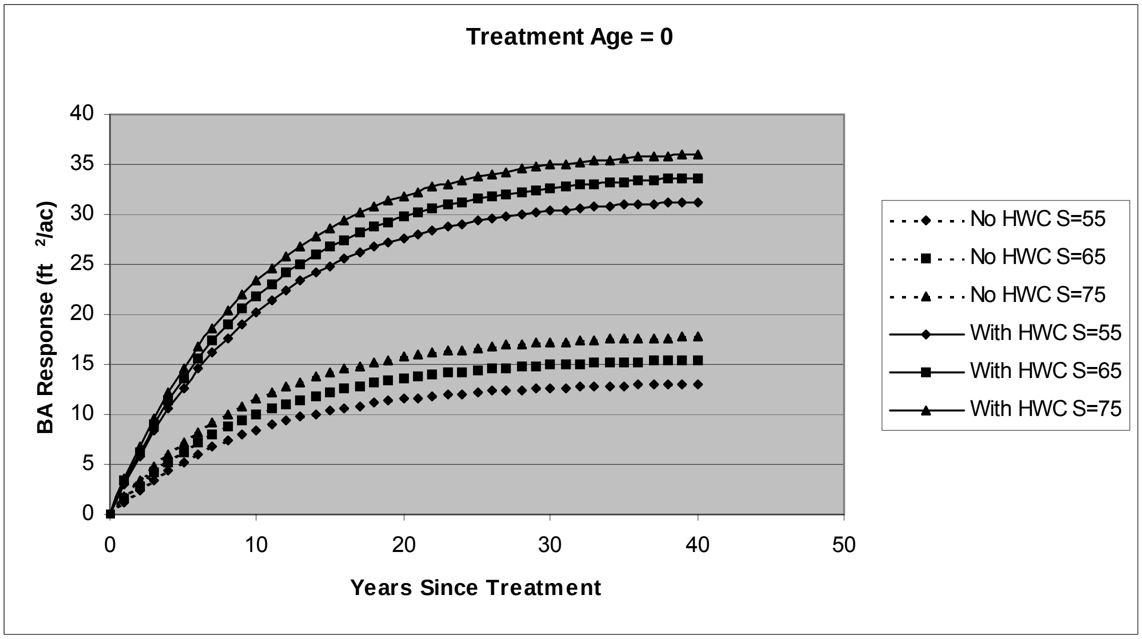

Figure 18. Implied basal area response curves for release age zero, with and without herbaceous weed control for various site indexes.

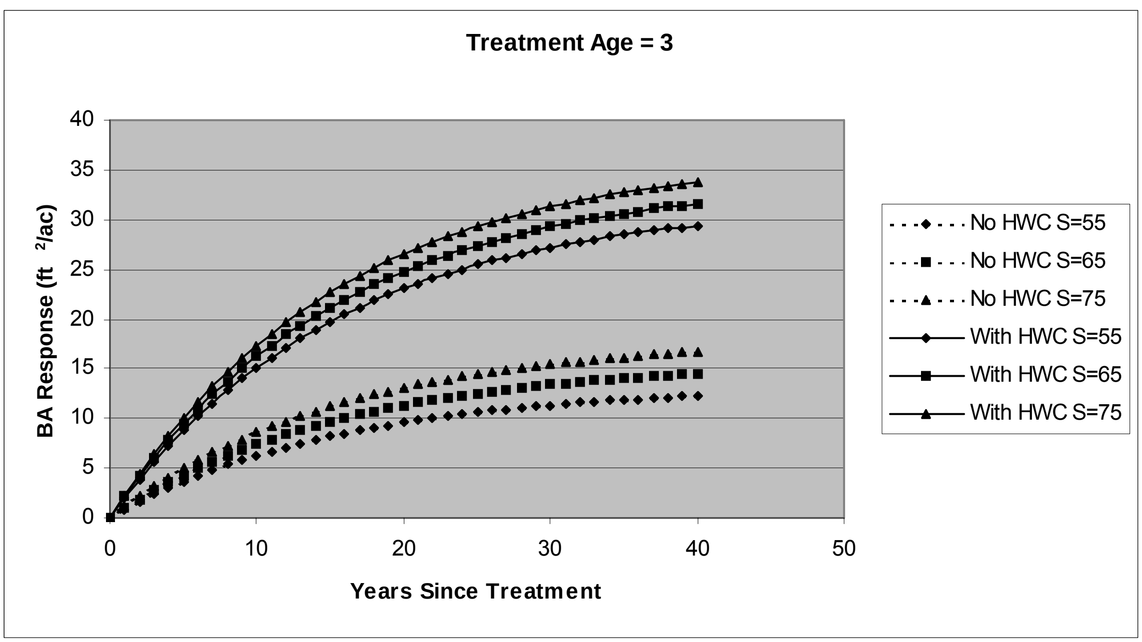

Figure 19. Implied basal area response curves for release age three, with and without herbaceous weed control for various site indexes.

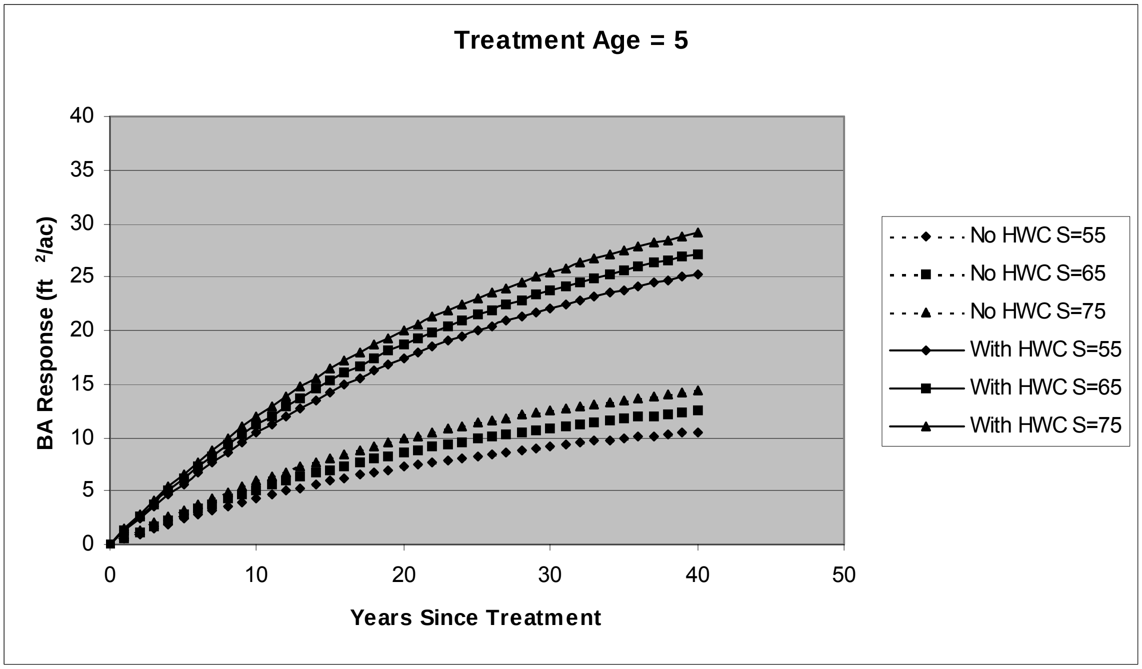

Figure 20. Implied basal area response curves for release age five, with and without herbaceous weed control for various site indexes.

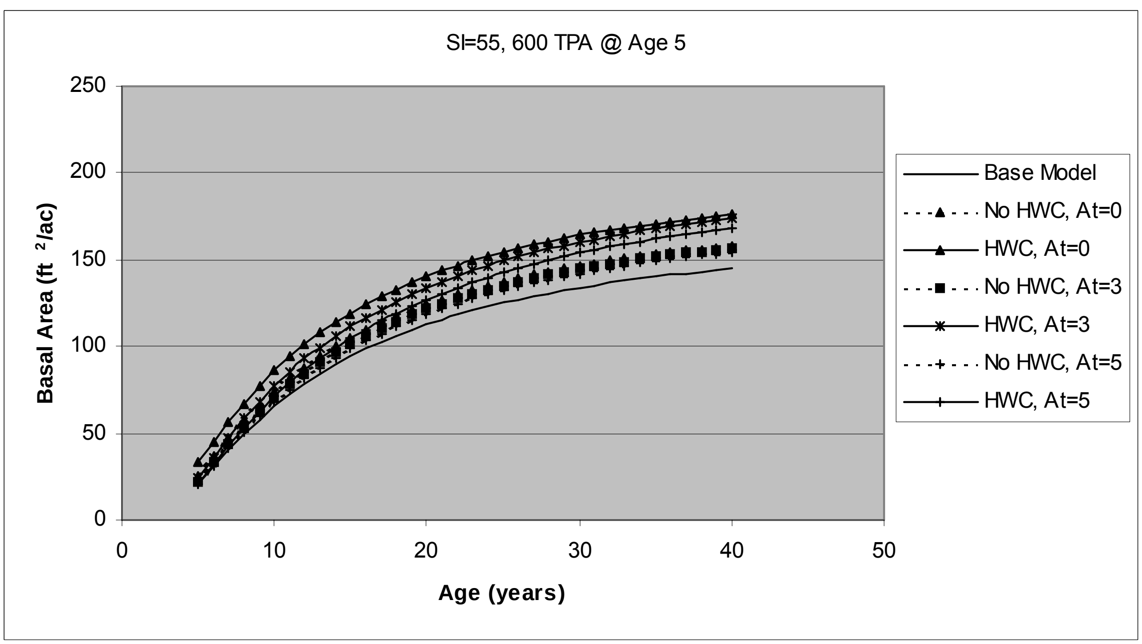

Figure 21. Implied basal area growth curves for site index 55, 600 TPA at age five, with various release ages with and without herbaceous weed control.

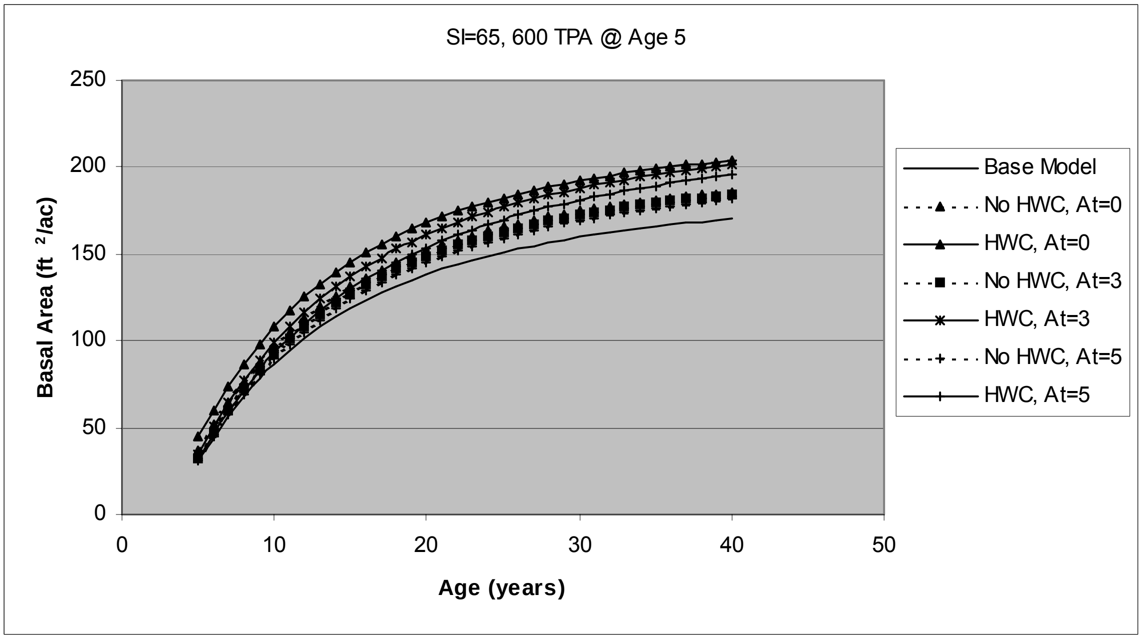

Figure 22. Implied basal area growth curves for site index 65, 600 TPA at age five, with various release ages with and without herbaceous weed control.

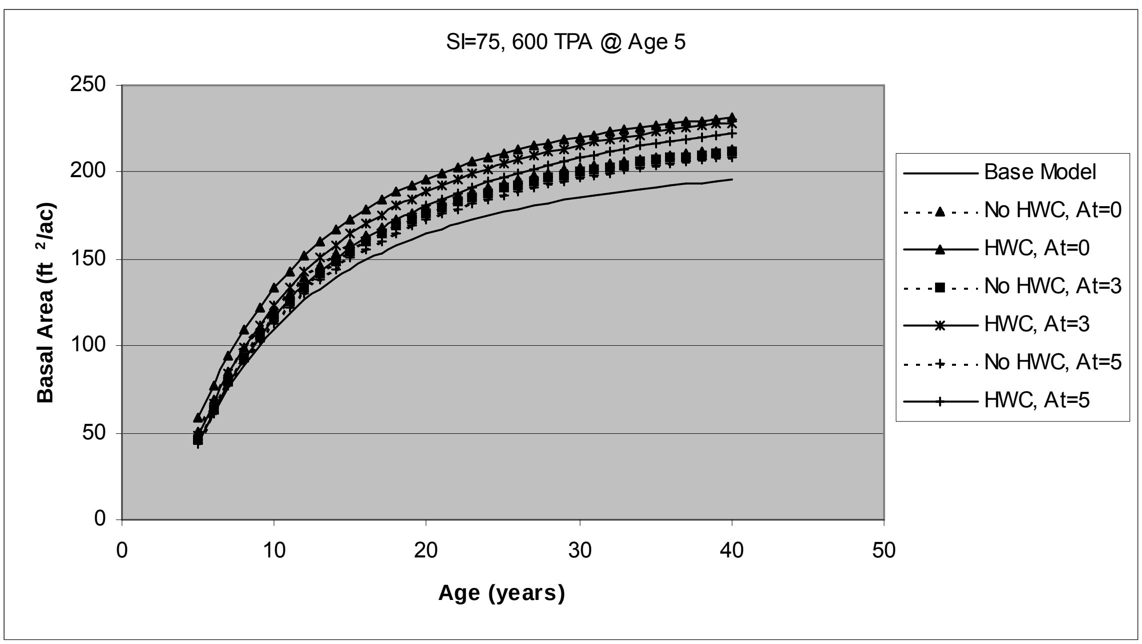

Figure 23. Implied basal area growth curves for site index 75, 600 TPA at age five, with various release ages with and without herbaceous weed control.

4.2.2 Per-Acre Basal Area Model Including the Effect of Hardwood

Another approach to model pine basal area development is to explicitly include a measure of hardwood density in the pine basal area prediction function as in Harrison and Borders (1996):

$$\ln(BA) = b_0 + \frac{b_1}{Age} + (b_{31} + b_{32} HDWD_5)\ln(HD) + b_4 \frac{\ln(TPA)}{Age} + b_5 \frac{\ln(HD)}{Age}$$

Where $HDWD_5$ = hardwood basal area as a proportion of total basal area (pine + hardwood) at age five.

The above equation was fit to all plots that did not receive the herbaceous weed control treatment. This was done to avoid confounding of the herbaceous weed control response with the basal area growth including the effect of hardwood.

Equation	DF Model	DF Error	SSE	MSE	Root MSE	R-Square	Adj R-Sq
lBAb	6	505	16.2279	0.0321	0.1793	0.8743	0.8731

Nonlinear OLS Parameter Estimates

Parameter	Approx Estimate	Std Err	Approx t Value	Pr > |t|
b0	1.882391	0.5103	3.69	0.0002
b1	-57.3277	4.8819	-11.74	<.0001
b3	0.732233	0.1361	5.38	<.0001
b3z	-0.29517	0.0282	-10.47	<.0001
b4	7.868078	1.2583	6.25	<.0001
b5	4.902963	0.3860	12.70	<.0001

4.2.3 Herbaceous Weed Control Response Function for Per-Acre Basal Area

A separate response function to account for the effect of herbaceous weed control (HWC) is required to complete the basal area prediction system. An analysis of the observed HWC response was carried out to determine the magnitude of HWC responses. Observations were created by pairing plots by treatment age, measurement age and initial hardwood level. One plot in the pair had HWC and the other did not. Differences in the average basal areas of the treated and untreated plots represent the HWC response. The average HWC response level was 9.3 ft^2/ac and occurred 9.5 years after treatment. These observations are consistent with the patterns shown in Figures 17-19. Response levels due to HWC, 10 years after treatment, were in the range of 7-11 ft^2/ac, depending on the treatment age. Based on these observations and results from other studies, it is hypothesized that the maximum response level to HWC has not been reached 9.5 years after treatment and the maximum basal area response level is somewhat higher than 9.3 ft^2/ac. Using the methodology developed by Pienaar and Rheney (1995), we can construct a HWC response function that fits our hypothesized pattern, as follows:

$$R_{BA} = b_1 Y_{st} e^{-b_2 Y_{st}}$$

Where: R_{BA} = basal area response (ft^2/ac),

b_1 = function of maximum response level so that Max(R_{BA}) = $(b_1/b_2)e^{-1}$,

b_2 = function of the number of years after treatment when the maximum response will be attained so that Max(Y_{st}) = *(1/b2)*,

Y_{st} = years since treatment.

If we assume that the maximum response in basal area to herbaceous weed control is 12 ft^2/ac and the maximum occurs 14 years after treatment, the resulting parameters are computed as follows:

b_2 = 1/Max(Y_{st}) = 1/14 = 0.0714

$b_1 = b_2$ Max(R_{BA})/e^{-1} = (0.0714 * 12)/0.36787944 = 2.3290.

Based on the RL-4I data and previous results, it is also clear that we must account for the age of treatment in determining the basal area response level. This can be accomplished by making the maximum response level a simple linear function of treatment age, as follows:

$b_1 = 2.5 – 0.2 * Y_t$

Where Y_t = Year of treatment.

Table 10 shows the maximum basal area response levels, attained 14 years after treatment, as a function of the year of treatment.

Table 10. Maximum basal area response levels for different HWC treatment ages.

Year of Treatment	Max BA Response (ft^2/ac)
0	12.88
1	11.84
2	10.82
3	9.78
4	8.76
5	7.72

Evidence from previous studies (Bacon and Zedaker, 1987; Miller *et.al*, 2003) also indicates that the expected basal area response from herbaceous weed control tends to decrease as the level of hardwood increases. This trend was not explicitly observed in the RL-4I study, possibly because HWC was always carried out in conjunction with hardwood release. The use of a "hardwood dampening" function (Borders, *et.al.*, 2004) is suggested to account for the effect of hardwood density on the herbaceous weed control response. The dampening function is to be used as a multiplier on the predicted HWC response and produces values less than 1, except in the case where no hardwood is present and the full HWC response would be realized.

$$H_{DAMP} = e^{\left(-b_1 HDWD^{b_2}\right)}$$

Where: H_{DAMP} = hardwood dampening multiplier,

HDWD = hardwood basal area as a proportion of total basal area (pine + hardwood).

As defined by (Borders, *et.al.*, 2004), the b_1 parameter is 0.25 and the b_2 parameter varies in a linear fashion from 0.25 (S = 50) to 0.75 (S = 80).

The basal area development curves implied by the basal area prediction equation and the response function are shown in figures 24-32.

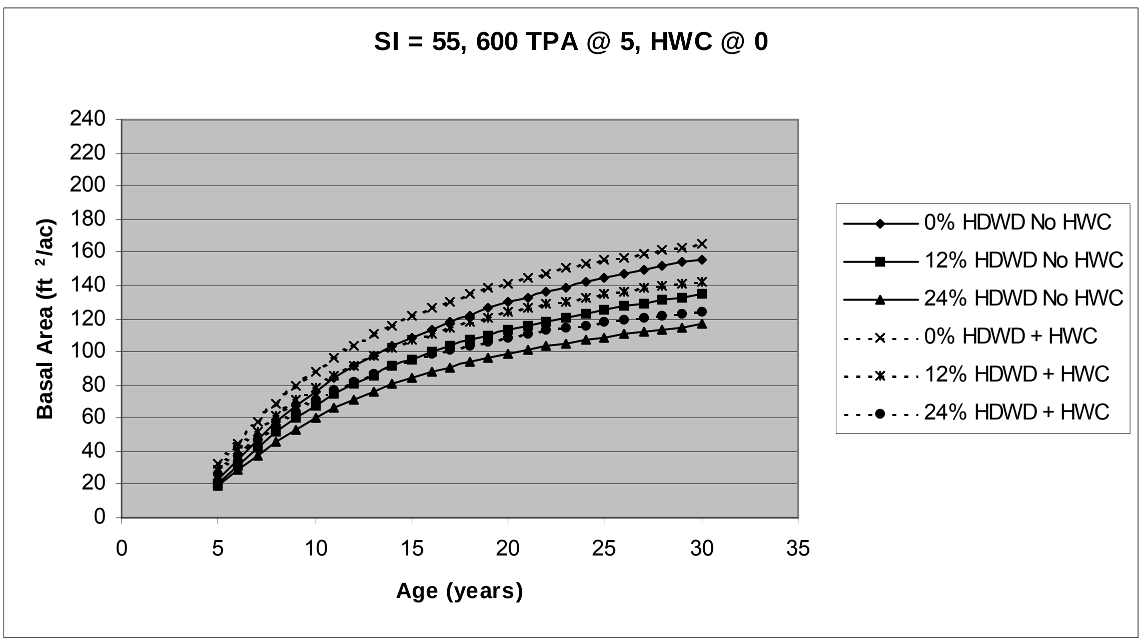

Figure 24. Basal area development curves for site index 55, 600 TPA at age five, with and without herbaceous weed control at age zero for various levels of hardwood competition at age five.

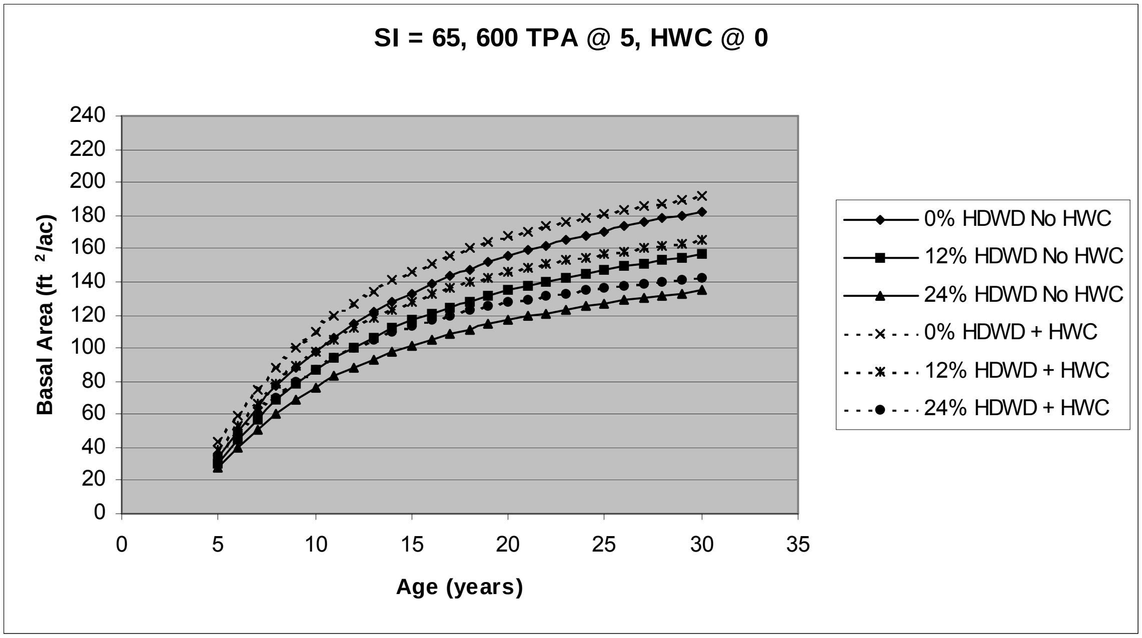

Figure 25. Basal area development curves for site index 65, 600 TPA at age five, with and without herbaceous weed control at age zero for various levels of hardwood competition age five.

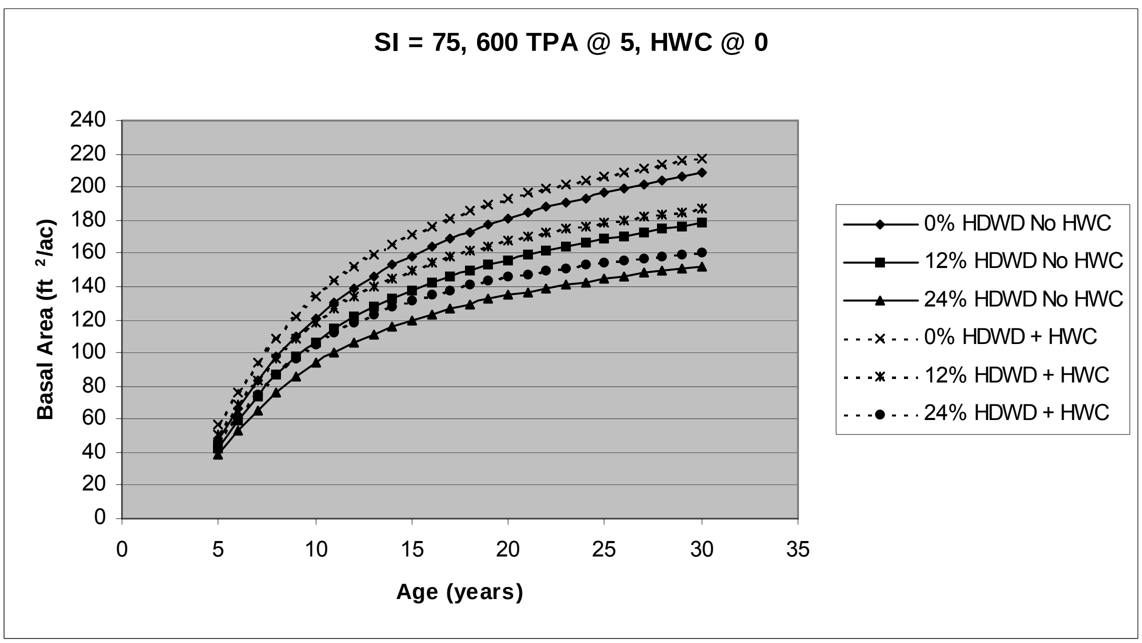

Figure 26. Basal area development curves for site index 75, 600 TPA at age five, with and without herbaceous weed control at age zero for various levels of hardwood competition at age five.

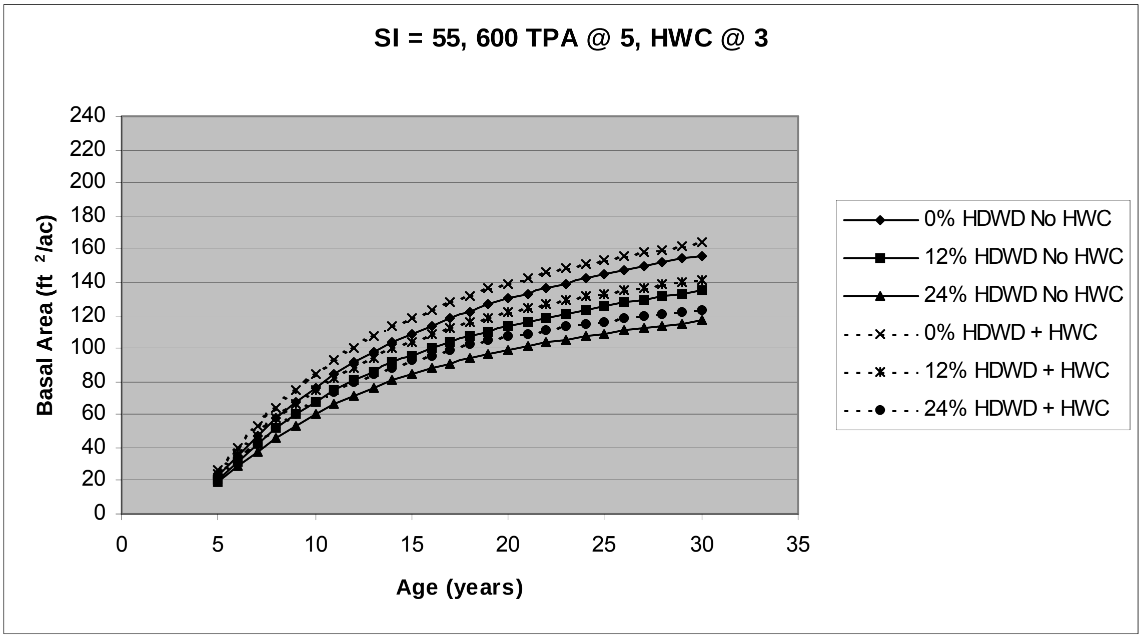

Figure 27. Basal area development curves for site index 55, 600 TPA at age five, with and without herbaceous weed control at age three for various levels of hardwood competition at age five.

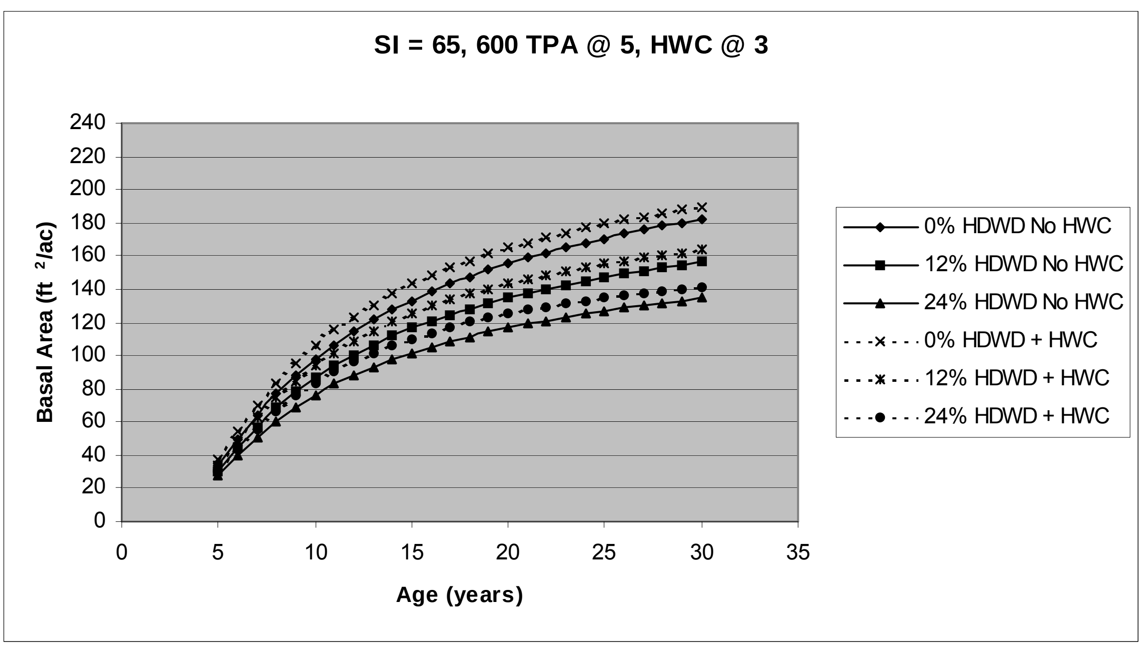

Figure 28. Basal area development curves for site index 65, 600 TPA at age five, with and without herbaceous weed control at age three for various levels of hardwood competition at age five.

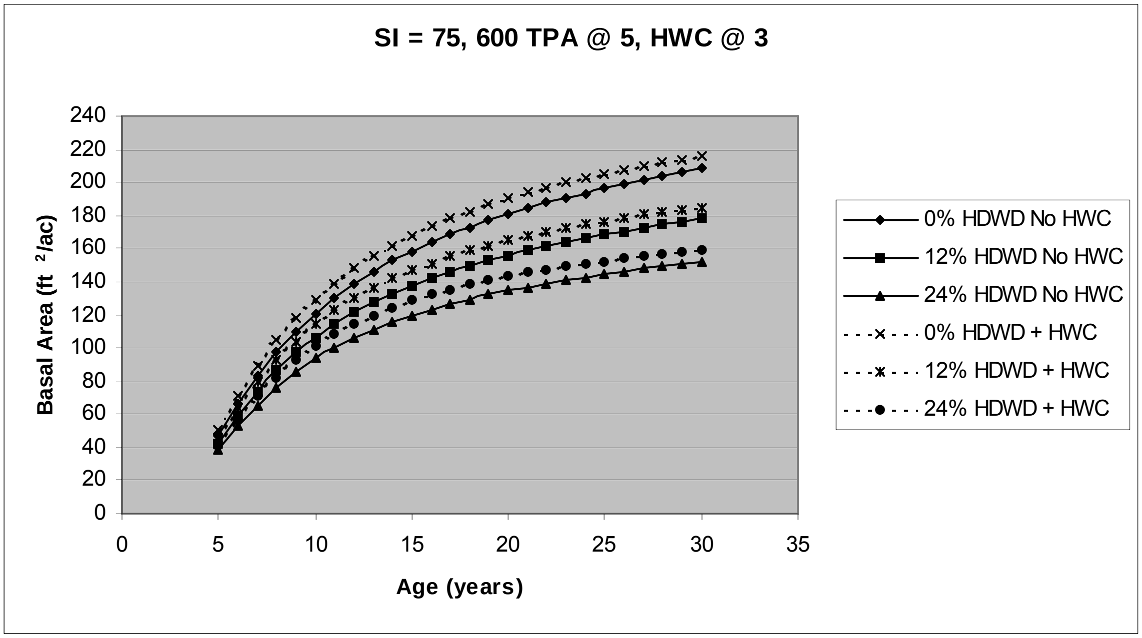

Figure 29. Basal area development curves for site index 75, 600 TPA at age five, with and without herbaceous weed control at age three for various levels of hardwood competition at age five.

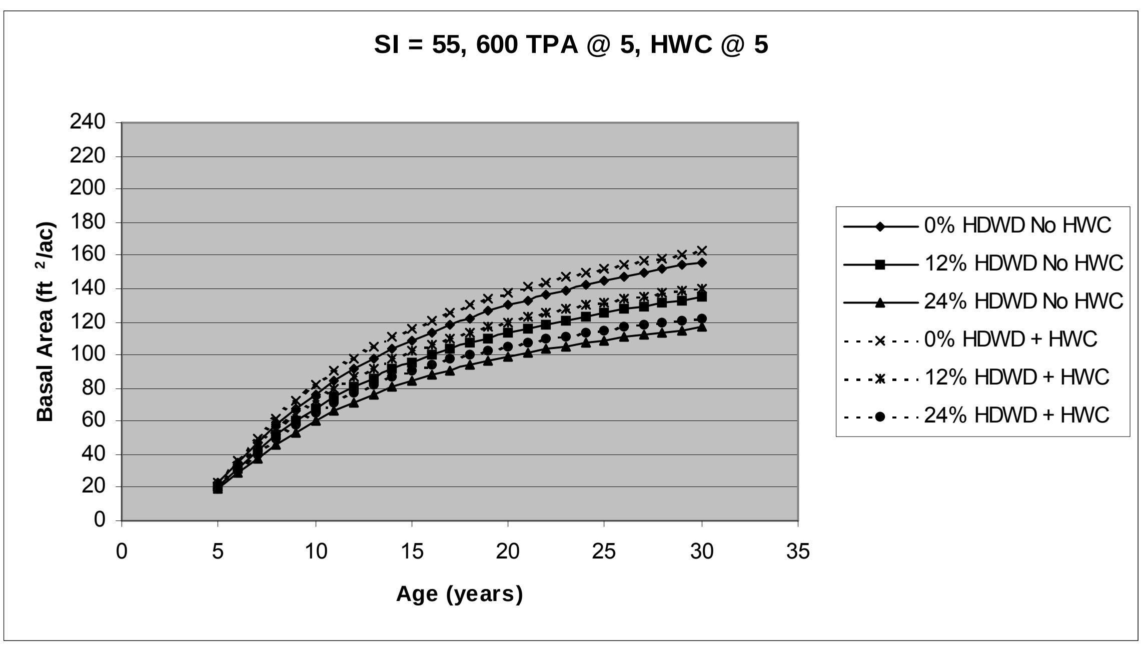

Figure 30. Basal area development curves for site index 55, 600 TPA at age five, with and without herbaceous weed control at age five for various levels of hardwood competition at age five.

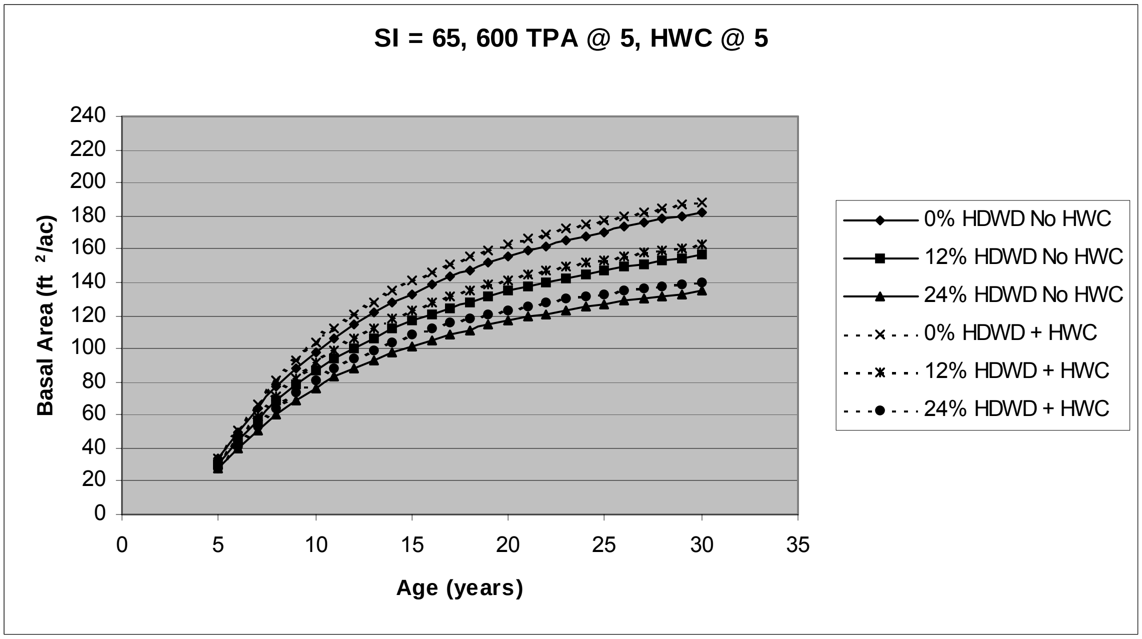

Figure 31. Basal area development curves for site index 65, 600 TPA at age five, with and without herbaceous weed control at age five for various levels of hardwood competition at age five.

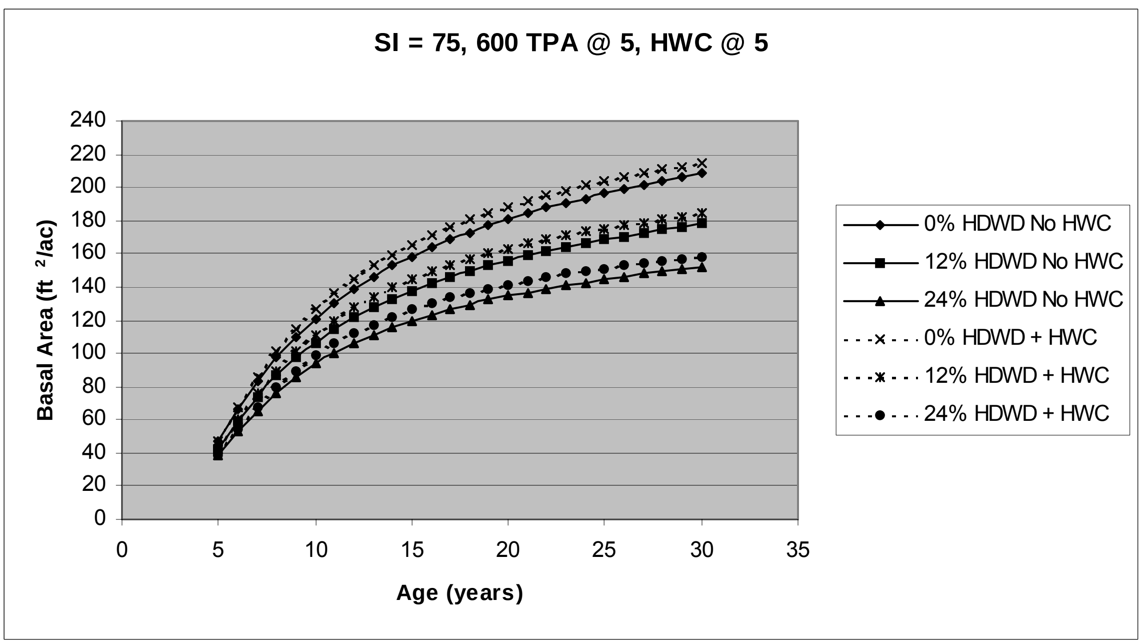

Figure 32. Basal area development curves for site index 75, 600 TPA at age five, with and without herbaceous weed control at age five for various levels of hardwood competition at age five.

4.2.4 Dominant Height Growth

In the current analysis, an attempt was made to separate the effects of herbaceous weed control and release treatments on average dominant height growth. In terms of modeling, this effort was essentially unsuccessful. Differences in site quality and situations where the dominant height growth responses did not adhere to expected trends caused the resulting models to exhibit unreasonable behavior. There are many factors that may contribute to disparate response to vegetation control treatments in terms of average dominant height. Borders *et.al.*, 2004 cite the underlying site productivity, type and amount of herbaceous vegetation and type and amount of woody competitors as factors that influence response to herbaceous weed control. In terms of operational herbaceous weed control treatments, there is also the application method and timing to consider.

For the RL-4I study, dominant height response values were calculated as the difference between treated and untreated plots at each age. Average response values were calculated by post-treatment hardwood level at each age beginning at age eight. The data were plotted and response "guide curves" were created for the different post-treatment hardwood levels. The maximum response to herbaceous weed control appears to consistently peak at the 11-year post-treatment measurement. Maximum response levels were 2.4 ft. with complete hardwood control, 2.0 ft. with A-level post treatment hardwood and 1.7 ft. with B-level post treatment hardwood. With this information, response models can be constructed according to the method of Pienaar and Rheney, 1995:

$$R_{HD} = b_1 Y_{st} e^{-b_2 Y_{st}}$$

Where: R_{HD} = dominant height response (ft),

b_1 = function of maximum response level so that Max(R_{BA}) = $(b_1/b_2)e^{-1}$,

b_2 = function of the number of years after treatment when the maximum response will be attained so that Max(Y_{st}) = *(1/b2)*,

Y_{st} = years since treatment.

Figure 33 shows the response patterns implied by the maximum response levels attained 11 years after treatment. It is clear from the parameterization of the herbaceous weed control response model (and from the graph) that the response levels are proportional with respect to hardwood level. It should be possible, therefore, to use the hardwood dampening function to adjust the response models according to the observed pattern.

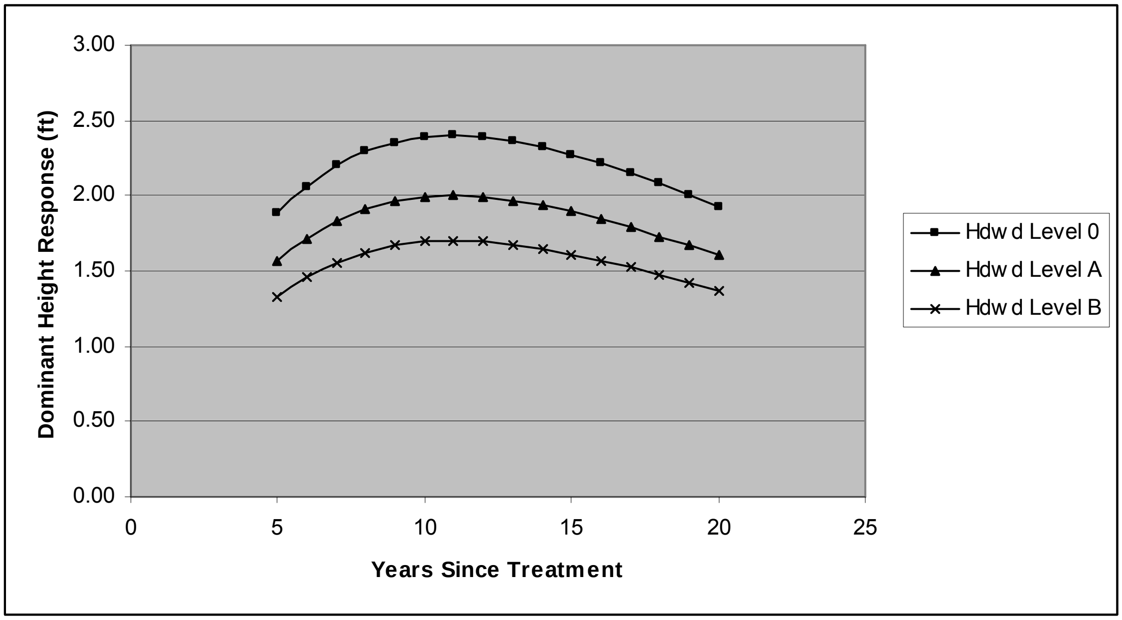

Figure 33. Average dominant height response due to herbaceous weed control for various levels of post-treatment hardwood.

The proportion of response of the post-treatment hardwood levels A and B relative to the complete control can be calculated from the maximum response levels:

Prop. Response A = 2.0/2.4 = 0.8333

Prop. Response B = 1.7/2.4 = 0.7083

Recall the form of the hardwood dampening function discussed earlier:

$$H_{DAMP} = e^{\left(-c_1 HDWD^{c_2}\right)}$$

Where: H_{DAMP} = hardwood dampening multiplier,

HDWD = hardwood basal area as a proportion of total basal area (pine + hardwood).

Since there are two parameters in the dampening function and two levels of hardwood, we should be able to calculate the parameters that will result in the same adjustment. Given that the average hardwood levels are 6% and 12% for post-treatment levels A and B, respectively:

$$e^{\left(-c_1 0.06^{c_2}\right)} = 0.8333$$

$$e^{\left(-c_1 0.12^{c_2}\right)} = 0.7083$$

After some algebra we solve for the c_2 parameter which turns out to have a value of 0.9196. We substitute c_2 into one of the equations and solve for c_1 which has a value of 2.4236. With the two equations, it is possible to calculate responses due to herbaceous weed control and hardwood level on average dominant height:

$$R_{HD} = 0.5931 Y_{st} e^{-0.0909 Y_{st}} * e^{-2.4236\, HDWD^{0.9196}}$$

5 DISCUSSION AND CONCLUSIONS

During the 1984-1985 dormant season, the Auburn University Silvicultural Herbicide Cooperative (AUSHC) began the establishment of the RL-4I study. The primary objective of the study was to quantify the pine growth responses to the degree and timing of woody vegetation control in loblolly pine plantations with and without herbaceous weed control treatments.

Early modeling work on the RL-4I data established relationships that could be successfully represented for stand development through age eight. The overall amount of hardwood removed in a release treatment carried out prior to age three had little effect on age eight pine basal area. Release treatments carried out after age three resulted in less pine basal area response. Herbaceous weed control treatments resulted in positive dominant height growth response that diminished with increasing treatment age. The response to herbaceous weed control was also related to amount of hardwood present after the release treatment.

The current modeling effort focused on developing pine basal area and dominant height growth response models. Basal area response due to release and herbaceous weed control was modeled as an asymptotic function of site index, age of release and years since treatment. This response function represents the average level of pre and post-treatment hardwood levels. Fit statistics for the base and response models were not encouraging but the models produced reasonable growth trends. A different approach to basal area response modeling produced similar results. In this case, the current hardwood level was used in a basal area prediction model. The addition of a response function, also modified by the level of hardwood completed the system.

Attempts to directly model average dominant height growth as modified by release and herbaceous weed control treatments were not successful. An alternative approach was taken where trends in height growth responses were analyzed and used to parameterize response functions. The resulting system can modify an existing height/age projection model with the addition of a herbaceous weed control response. The response is calculated as a function of the level of hardwood and years since treatment.

The models resulting from the RL-4I analysis can be used to validate and/or augment existing growth and yield systems. Growth and yield systems with flexible treatment response modules could benefit from the effects of hardwood and herbaceous weed control treatments as reported here. Future analysis of this data will focus on further augmentation of existing systems. For example, these data could be used to relate early competition assessments (prior to age five) to a quantity or index useful for future growth and yield projections.

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