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Growth response analysis after early control of woody competition for 14 loblolly pine plantations in the southern U.S.

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Abstract

Only a few growth and yield programs allow users to model the effects of hardwood competition on yields from pine plantations. Several of these programs were developed with the assumption that reducing hardwood competition would consistently produce a Type 2 growth response where pine volume gains increase over time. However, the actual response is not always a Type 2 response. To determine growth response types resulting from woody control treatments, plot volume data were analyzed from 14 trials (on 13 sites) measured over a period of 2 decades (The COMProject). The "age-shift" method of growth analysis and regression analyses were used to classify the types of responses. After 20 years, stand volumes of loblolly pine (*Pinus taeda* L.) were increased after woody control at 13 of 14 trials when compared to no controls. At four trial locations the age gain ranged from 0.7 to 1.6 years and the growth response was classified as a pseudo-Type 1 response (i.e., pine growth was increased while the total above-ground biomass of the mixed-stand was not altered by the species shift). At nine trial locations a true Type 2 response was observed (i.e., increase in total above-ground biomass of the pine dominated mixed-stand) and the age gain ranged from 0.9 to 5.1 years. At a site in Louisiana, woody control on two similar blocks resulted in a reduction in both early and mid-rotation pine volumes (termed a Type E response) while two other blocks resulted in an early reduction that changed to a mid-rotation volume increase (termed a Type F response). Thus, four types of growth response were associated with woody control treatments.

Keywords: *Pinus taeda*; Weed control; Hardwoods; Herbicides; Age-shift

1. Introduction

Snowdon and Waring (1984) defined two basic growth responses (Types 1 and 2) that occur after silvicultural treatments. However, Snowdon (2002) does not specifically define a response type that separates the response of "crop trees" from "non-crop trees." Therefore, we see a need for terminology that provides a further clarification of these response types, especially for regions where hardwood competitors coexist in stands with conifer crop trees. This need is important for growth and economic modeling in an era when hardwood pulpwood values are increasing relative to pine pulpwood.

A Type 1 growth response (Fig. 1) does not increase the maximum carrying capacity but the establishment phase is shortened, resulting in an "age-shift" gain or "time-gain." In this paper we use equivalent volumes per hectare to estimate the amount of time the establishment phase is shortened. For example, South et al. (2006) reported that a 2–5 years "age-shift" gain was obtained by controlling herbaceous competition during the loblolly pine establishment phase (when hardwoods were not present). A pseudo-Type 1 response (Fig. 2) could be possible when there appears to be an age-shift for pine with hardwood component present but the effect is simply due to a shift of species (i.e., the treatment does not increase the stand volume or biomass) (South et al., 2006). To date, there have been no reports of either a Type 1 or pseudo-Type 1 growth response from the suppression of hardwood competition.

Some growth and yield programs model the effect of hardwood competition as a Type 2 growth response (e.g. Fig. 3). In some cases, this approach could result in an over-estimation of treatment response. For example, on some sites a Type 1 growth response might produce less than half the pine volume response as a Type 2 response. Also, if the total volume or above-ground dry biomass of both pines and hardwoods is

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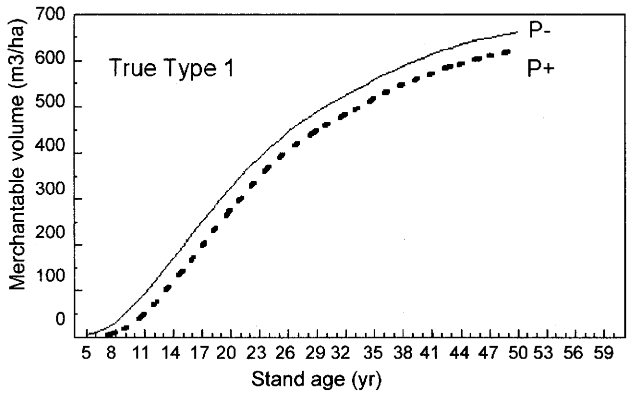

Fig. 1. An example of Type 1 treatment response from controlling herbaceous competition in a loblolly pine plantation established on an agricultural field. The stand with a delay in development contain herbaceous plants and pine (P+). The stand with no herbaceous plants (P−) is represented by the solid line. The carrying capacity of both stands is the same at age 70 years. The solid curve was generated with the NCSU Managed Pine Plantation Growth and Yield Simulator (Smith and Hafley, 1987).

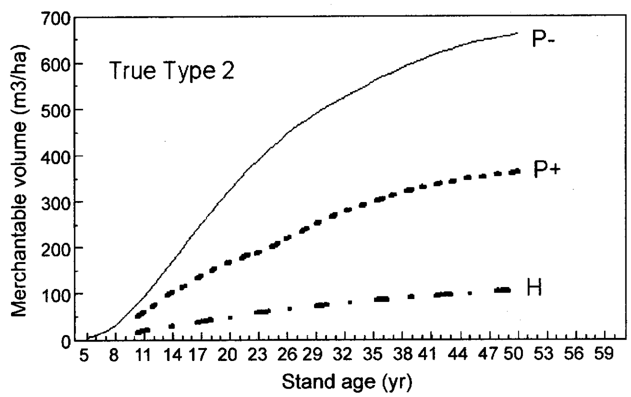

Fig. 3. An example of a Type 2 treatment response from controlling hardwoods in a loblolly pine plantation. The multi-species stand contains hardwoods (H) and pine (P+). The stand with no hardwoods contains only pine (P−). The total biomass (Mg ha^{-1}) of pine (P−) at age 50 years is higher than the total biomass of P+ and H. The P and P+ curves were generated with the NCSU Managed Pine Plantation Growth and Yield Simulator (Smith and Hafley, 1987). After age 12, the average specific gravity of pine is assumed to be 0.48 and the hardwood specific gravity is assumed to be 0.55. The PVI/HVR ratio (i.e., pine volume gain divided by hardwood volume decline) varied from 3.2 at age 20 to 2.8 at age 50.

approximately equivalent for stands with and without hardwoods, then the pine response should be classified as a "pseudo-Type 2" response. This occurs when the suppression of hardwoods simply results in a shift in species composition and a different ratio of pine to hardwood yields (e.g. Fig. 4). It is proposed that to qualify as a true Type 2 response, the maximum carrying capacity of the site must be increased by the silvicultural treatment.

Several other growth responses have been found and previously defined (Table 1). A Type C (a.k.a. Type 3) response occurs when an initial gain eventually turns into a loss in total stand volume (Morris and Lowery, 1988; Richardson, 1993; Kyle et al., 2005). Growth loss might occur when site resources are shifted away from crop species to competing species (Mead and Gadgil, 1978; South et al., 2006). A Type D response occurs when an initial gain occurs but there is no gain or loss at harvest (Table 2). A Type E response occurs when there is an initial reduction in volume and the reduction persists until harvest or specified age (VanderSchaaf and South, 2004). A reduction in long-term pine growth could occur when a toxic material is applied to the soil or an aggressive invasive plant species infests the stand after early treatment.

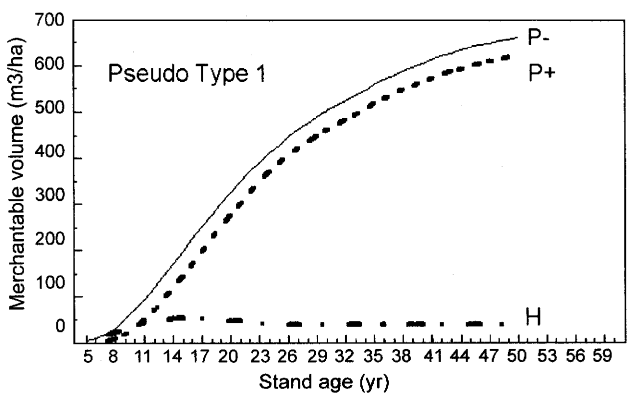

Fig. 2. An example of pseudo-Type 1 treatment response from controlling hardwoods in a loblolly pine plantation on a cutover site. The multi-species stand contains hardwoods (H) and pine (P+). The stand with no hardwoods contain only pine (P−). The total biomass (Mg ha^{-1}) of the pine stand containing hardwoods (P+) is approximately the same as that for the stand with no hardwood (P−). The average tree specific gravity of pine in this case is assumed to be the same for both pines and hardwoods. For this example, the PVI/HVR ratio (i.e., pine volume gain divided by hardwood volume decline) was fixed for all ages at 1.0. The solid curve was generated with the NCSU Managed Pine Plantation Growth and Yield Simulator (Smith and Hafley, 1987).

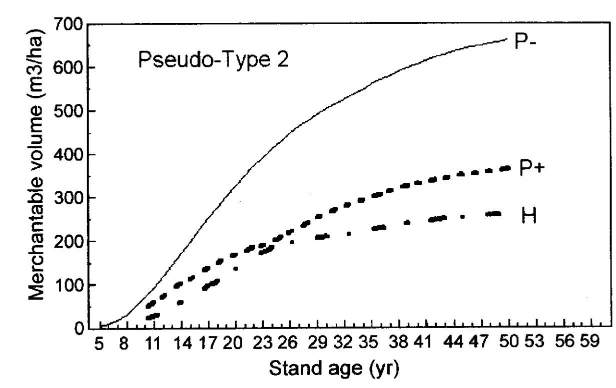

Fig. 4. An example of a pseudo-Type 2 treatment response from controlling hardwoods in a loblolly pine plantation. The multi-species stand contains hardwoods (H) and pine (P+). The stand with no hardwoods contain only pine (P−). The total biomass (Mg ha^{-1}) of the pine stand containing hardwoods (P+) is approximately the same as that for the stand with no hardwood (P−). The average tree specific gravity of pine is assumed to be 0.48 after age 12 and the hardwood specific gravity is assumed to be 0.55. The P and P+ curves were generated with the NCSU Managed Pine Plantation Growth and Yield Simulator (Smith and Hafley, 1987). The H curve was generated assuming hardwood suppression would not result in an increase in total dry biomass (Mg/ha). The PVI/HVR ratio (i.e., pine volume gain divided by hardwood volume decline) was fixed for all ages at 1.15.

Table 1
Examples of various growth responses in loblolly pine stands

Growth response	Pine volume gain at age 5 years	Pine volume gain at harvest	Maximum carrying capacity[a] (when CAI = 0)	Response explained solely by a species shift?
Type 1	Positive	Positive	No change	No
Pseudo-Type 1	Positive	Positive	No change	Yes
Type 2	Positive	Positive	Increased	No
Pseudo-Type 2	Positive	Positive	No change	Yes
Type C	Positive	Negative	Decrease	No
Type D	Positive	No gain	No change	No
Type E	Negative	Negative	Decrease	No
Type F	Negative	Positive	No change	No

[a] Includes both pine and hardwood biomass (Mg/ha): CAI = current annual increment.

The "age-shift" method of growth analysis can be used to classify the type of growth response expected from establishment treatments (Mason and Milne, 1999; South et al., 2006). If the age-shift estimate increases over time, then the response is a Type 2 or pseudo-Type 2. In contrast, if the age-shift estimate is positive and remains about the same over time, then the response is classified a Type 1 or pseudo-Type 1. When the age-shift estimate declines and eventually becomes negative, the response is classified as Type C. A persistent initial loss is referred to as a Type E. Previous forest vegetation management research has not addressed the following questions: (1) does suppression of hardwoods in pine plantations always result in a true Type 2 response and never a pseudo-Type 2; (2) does suppression of hardwoods ever produce a Type 1 or pseudo-Type 1 response, or Type C or E or others? The main objective of this paper is to test whether the responses that occur after woody control treatments in loblolly pine (*Pinus taeda* L.) plantations by year 20 are predictably true Type 2 responses or some other response type, and to determine the age-shifts by year 20.

2. Materials and methods

Data used in this analysis came from the region-wide network of the Competition Omission Monitoring Project (COMProject) (Miller et al., 2003a,b). A factorial experimental design was utilized at 13 sites in seven southern U.S. states and across four physiographic provinces ranging from latitudes 30° to 37°N. The studies were established on medium to high productivity sites that ranged in site index (base age 25 years) from 17 m (Appomattox, VA) to 25 m (Bainbridge, GA). Soil and site location details have been previously reported (Miller et al., 1995, 2003a).

Each study involved treatments that were replicated at least four times in a randomized complete block design. Treatment plots were generally 0.1 ha, and interior measurement plots were 0.036 ha. Planting spots were on a 2.74 m × 2.74 m grid (1329 ha^{-1}) except at Pembroke, GA (1396 ha^{-1}) and Arcadia, LA (1537 ha^{-1}), where seedlings were operationally machine planted. All sites were planted with genetically improved seedlings. Except when planting machines were used, two seedlings were hand-planted at each planting spot. Seedling

Table 2
Hypothetical examples of six growth responses (Mg ha^{-1} of all merchantable trees) from silvicultural treatments

Stand age (years)	Base plantation	Type 1 response	Type 2 response	Type C response	Type D response	Type E response	Type F response
5	2	12	12	12	12	1	1
10	26	95	95	94	34	24	23
15	95	183	183	179	100	85	95
20	183	256	257	248	183	164	185
25	256	305	308	292	256	230	260
30	305	342	348	325	305	274	311
35	342	374	384	351	342	308	352
40	374	395	411	368	374	336	388
45	395	409	430	376	395	356	–
50	409	428	453	389	409	368	–
55	428	439	469	395	428	385	–
60	439	441	476	397	439	395	–
65	441	442	482	398	441	397	–
70	442	442	482	398	442	398	–

All responses are compared to the base plantation (with a maximum carrying capacity of 670 Mg ha^{-1}). The total standing biomass of the trees at year 70 is not affected by a Type 1 or D response but it is increased with a Type 2 response. Type 1 response in this example is equivalent to a 5-year "age-shift." Types C and D responses initially produce a growth increase but in the long-term, Type C results in a decrease in standing biomass, Type D has no effect on standing biomass at harvest (e.g. ages > 19 years). The Type E response reduces standing biomass at all ages. The Type F response results in an initial growth loss but eventually increases standing biomass.

volume (i.e., volume of a cone) was determined by randomly selecting 100 seedlings immediately after planting (50 at Appomattox, VA) and measuring groundline diameter and height for each seedling. After the first growing season, one seedling was thinned using random generated selections when two seedlings survived at a spot. Each interior measurement plot consisted of 49 permanently tagged pines and was surrounded by two border rows.

Four treatments were installed at each site, but only two treatments were involved in this analysis: the "no control treatment" (NC) and "woody control treatment" (WC) that contained herbaceous competition. NC plots contained a mixture of woody and herbaceous competition since, after initial site preparation that cut all above-ground woody stems, no further vegetation control treatments were applied. In WC treatments, foliar and basal sprays, as well as basal wipes, were applied to hardwoods and woody shrubs in a manner to minimize injury to pines and herbaceous plants. At Tallassee (glyphosate), Appomattox (triclopyr ester), and Bainbridge (picloram), herbicide treatments were applied to WC plots prior to planting pines.

Pines were measured annually for total height for the first 11 years and then again at ages 15 and 20 years. Diameters at breast height (DBH) were measured on all pines starting in year 4. In year 8, all hardwood rootstock stems exceeding 4.5 ft in height within each measurement plot were recorded by species, DBH class (1.25 cm classes) and height class (i.e., classes were 30 cm intervals through 3.66 and 1.52 m intervals thereafter). Hardwood heights were measured to the nearest 30 cm in years 15 and 20. Merchantable pine tree volume outside bark (to a 10 cm top) was calculated according to equations by Tasissa et al. (1997). Total hardwood volume outside bark was calculated according to equations by Clark et al. (1986). Tree volumes were expanded to an area basis by multiplying the appropriate expansion factor for the measurement plot.

2.1. Analyses

Three plots out of the 212 total plots were deleted from the dataset before analysis due to past land use practices that yielded exceptionally poor productivity, a southern pine beetle infestation, or excessive ice damage (one each at Camp Hill, AL; Monticello, GA; Appomattox, VA, respectively). In addition, two blocks affected by wildfire were deleted at the Tallassee, AL location. A treatment by block interaction was observed for year 20 pine volume at the Jena, LA site. An analysis that included all four replications would have violated the assumption of no treatment by block interaction (Neter and Wasserman, 1974). The presence of a block by treatment interaction can invalidate the analysis of variance and could adversely affect the comparison of treatment means (Montgomery, 2001). Therefore, the Jena, LA site was split into two studies (each with two WC plots and two NC plots). Jena-14 represents blocks 1 and 4, where average seedling height at age 20 years was 16.8 m for NC plots. Jena-23 represents blocks 2 and 3 where average seedling height of NC plots was 19.0 m.

The age-shift in pine productivity due to controlling woody competition was determined by comparing mean pine volumes on WC plots to volumes on NC plots. The age-shift for year 8 was determined by comparing the x-coordinate for the WC plots at age 8 years with the mean for NC plots (South et al., 2006). For example, assume the coordinates were $x = 8$ years; $y = 39\ m^3\ ha^{-1}$ for the WC and $x = 10.47$ years; $y = 39\ m^3\ ha^{-1}$ for the no control treatment. The age-shift in this example would be 2.5 years since all age-shift values were rounded to the nearest 0.1 year. For each site, age-shifts were calculated for years 8–15 and, when appropriate, for ages greater than 16 years. When the final age-shift estimate was within 0.5 year of the age 8 years estimate, the response was classified as Type 1. When the age-shift estimate at years 16–20 was 0.6 year or greater than that age 8 years, the response was classified as Type 2. A Type D response would be declared if the age-shift estimate was positive at age 8 years and zero at age 20 years.

To test the hypothesis that age-shift value increases from ages 8 to >15 years, linear regressions of age-shift versus age were calculated for each location ($N = 6$). A t-test was then used to determine whether the slope of the regression line was significantly different from zero ($\alpha = 0.10$). When the slope was not significantly different from zero, the response was classified as Type 1. The growth response was classified as Type 2 when the slope was positive and significantly different from zero. The response was classified as Type C or E when the slope was negative and statistically significant. It was considered a Type C response if the age-shift at year 8 was positive and a Type E if it was negative at year 8.

To test whether a growth response was a pseudo-Type 2 response, a ratio of pine volume increase (PVI) to hardwood volume reduction (HVR) was calculated. This ratio was then compared with a ratio determined by dividing the hardwood specific gravity (HSG) by the pine specific gravity (PSG). For example, an HSG/PSG ratio of 1.3 would occur if the HSG were 0.59 and the PSG were 0.46. Methods use to determine cross-sectional, weighted wood PSG for each site and treatment were reported previously (Clark et al., 2006). The ovendry HSG was estimated for each site and was based on the predominating hardwood species (Bendtsen and Ethington, 1975). A pseudo-Type 2 response would be declared when the PVI/HVR ratio was similar to the HSG/PSG ratio.

To test the hypothesis that herbicide treatment had no effect on initial survival, the following equation was used: Y = (number of planting spots with no live planted seedlings 1 year after planting/total number of planting spots) × 100. A paired t-test (with one pair for each of the 14 sites) was used to test the effect of treatment on the response variable.

3. Results

Early woody control increased merchantable pine volume at all locations, except the Jena-23 plots (Fig. 5). For sites with a positive volume response, suppression of woody plants increased pine volume an average of $47\ m^3\ ha^{-1}$ (range = 14–114 $m^3\ ha^{-1}$). However, the response tended to decline as site productivity increased (Fig. 6). Age-shift gains after year 15 ranged from 0.7 years at Bainbridge, GA to 5.1 years at Appomattox, VA (Table 3). These increases in pine

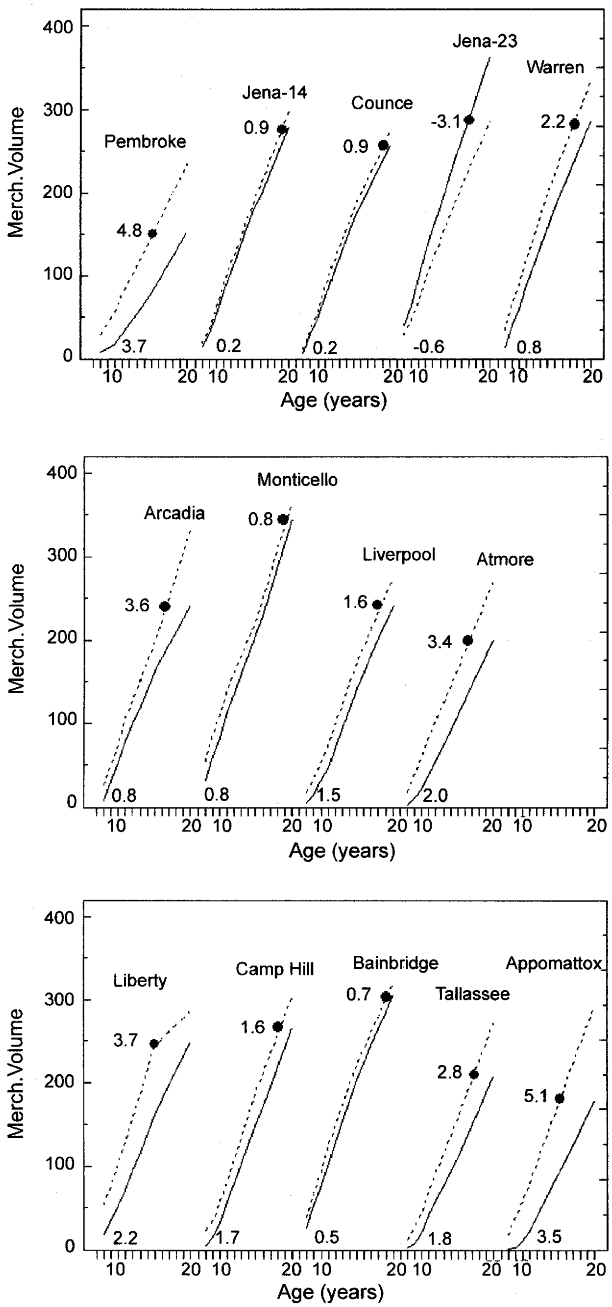

Fig. 5. The average response for controlling woody plants on merchantable loblolly pine volume production (m^3 ha^{-1}). Solid line: plots with woody plants; dashed line: plots without woody plants. Numbers at the bottom of each graph indicate age-shift determined at age 8 years. Numbers at the top of the graph indicate age-shift determined at the age indicated by the black dot.

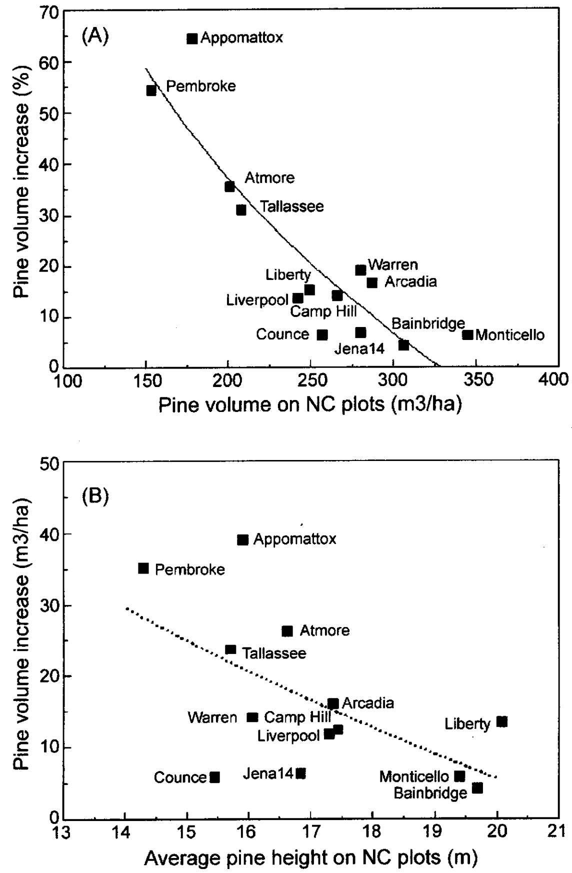

Fig. 6. The relationship between site productivity and volume gains due to controlling woody competition. The equation for the solid line in (A) is: $Y = 433 - 74.7(\ln X)$; $R^2 = 0.81$, $n = 13$, $p < 0.001$. The equation for the dashed line in (B) is: $Y = 207 - 67.2(\ln X)$; $R^2 = 0.36$, $n = 13$, $p = 0.03$.

volume resulted from a reduction of hardwood volumes of 2–43 m^3 ha^{-1} at year 20, which ranged from 15 to 59% of total stand basal area. Except for Bainbridge and the Jena-23 plots, the increase in pine volume exceeded the reduction in hardwood volume (due to herbicide treatment).

For the regression of age-shift over stand age, a significant positive slope was detected at nine locations, indicating in a Type 2 response (Table 4). Slopes were not significantly positive at four locations and were judged to be Type 1 responses while a significant negative slope occurred on the Jena-23 plots indicating a Type E response. On the sites with a Type 1 response, the age-shift ranged from 0.7 to 1.8 years (Table 3) with an overall average of 1.2 years.

For the Type 2 sites, the PVI/HVR ratio ranged from 1.3 to 35 (Table 3). For most of these sites, the ratio was greater than 2.5. The Liberty site exhibited a ratio of 1.3 which was the lowest of all Type 2 sites. For sites exhibiting a Type 1 response, the PVI/HVR ratio ranged from 0.4 to 1.8.

Seedling mortality was increased slightly by the herbicide treatment ($p = 0.027$). Mortality was greatest at the Liberty site and was minimal at the Bainbridge, Liverpool, Camp Hill and Counce sites. Overall, the number of planting spots with one or two live seedlings was slightly greater (89%) on NC plots than on WC plots (85%) that were treated with herbicides and experienced increased early herbaceous competition.

4. Discussion

Treating pine plantations to control woody competition often increases volume production of pines. In many operational applications, both woody and herbaceous competition is reduced when broad spectrum herbicides such as imazapyr and glyphosate are applied after planting. Controlling both herbaceous

Table 3
Age-shift response resulting from controlling woody plants in *Pinus taeda* plantations

Site	Age-shift year 8 (years)	Age-shift year 15 (years)	Age-shift 16–20 years (years)	Year change from age 8 to 16–20 (years)	Response	Pine volume in no control plots, age 20 ($m^3 ha^{-1}$)	Hardwood volume in no control plots, age 20 ($m^3 ha^{-1}$)	Hardwood volume reduction (HVR), age 20 ($m^3 ha^{-1}$)	Pine volume increase (PVI), age 20 ($m^3 ha^{-1}$)	PVI/HVR
Pembroke*	3.7	4.7	4.8 (16)	1.1	Type 2	153	2.6	2.4	82.8	34.5
Appomattox	3.5	4.8	5.1 (16)	1.6	Type 2	178	48.2	42.5	113.8	2.7
Atmore	2.0	3.0	3.4 (17)	1.4	Type 2	201	19.3	19.1	71.4	3.7
Tallassee	1.8	2.5	2.8 (17)	1.0	Type 2	208	40.0	36.3	79.8	2.2
Liverpool	1.5	1.8	1.6 (19)	0.1	Pseudo-Type 1	242	18.7	18.3	32.9	1.8
Liberty	2.2	4.4	3.7 (17)	1.5	Type 2	249	31.5	28.8	38.4	1.3
Counce	0.2	0.6	0.9 (20)	0.7	Type 2	257	6.0	5.7	16.2	2.8
Camp Hill	1.7	1.7	1.6 (19)	−0.1	Pseudo-Type 1	266	32.7	31.0	37.7	1.2
Arcadia*	0.8	1.8	3.6 (17)	2.8	Type 2	280	17.0	15.2	91.3	6.0
Jena-14	0.2	0.4	0.9 (20)	0.7	Type 2	280	5.4	1.9	6.5	3.4
Warren	0.8	1.9	2.2 (18)	1.4	Type 2	287	16.0	13.2	47.4	3.6
Bainbridge	0.5	0.8	0.7 (20)	0.2	Pseudo-Type 1	306	38.4	31.9	13.5	0.4
Monticello	0.8	0.8	0.8 (20)	0.0	Pseudo-Type 1	345	17.2	17.2	21.6	1.3
Jena-23	−0.6	−1.9	−3.1 (20)	−2.5	Type E	363	9.0	5.5	−76.0	−13.8

Estimates of age-shift used total volumes at years 8, 15 and 16–20 (appropriate years in parentheses). Hardwood volume reduction (HVR) and pine volume increase (PVI) are based on woody control plots. Sites with an asterisk (*) were "single-planted".

plants and woody plants will generally increase pine volume growth until mid-rotation more than just controlling only one competitive component (Shiver and Martin, 2002; Miller et al., 2003b; South et al., 2006). In the present analysis, we focus only on determining the effect of woody competition suppression on the type of growth response of pines and pines plus hardwoods. It has been often assumed that hardwood suppression would result in a Type 2 growth response on 100% of pine sites. However, our current analyses suggest that a Type 2 response could occur on two thirds of the sites in the southeastern U.S., if the sampling of sites in this study is assumed to be representative.

4.1. Type 2 growth response

A true Type 2 growth response occurs when hardwood competition is suppressed and the total carrying capacity in dry

Table 4
Treatment response, woody species and soil classification of the COMP sites

Site	Slope, b	$P > \|T\|$	Growth response	Woody competition[a]	Soil classification
Jena-23	−0.211	0.0001	Type E	Sweetgum, Chinese tallow, dogwood	Fine-loamy, siliceous, Thermic Typic Paleudults
Monticello	−0.015	0.3600	Type 1	Yellow poplar, sweetgum	Clayey, kaolinitic, Thermic Rhodic Kandiudults
Liverpool	0.007	0.6579	Type 1	Blackgum, sweetgum	Fine-silty, siliceous, Thermic Typic Fragiudults
Bainbridge	0.010	0.5024	Type 1	Sweetgum, yellow poplar	Fine-loamy, siliceous, Thermic Typic Kandiudults and Clayey, kaolinitic, Thermic Typic Kandiudults
Camp Hill	0.016	0.6321	Type 1	Water oak, yellow poplar, sweetgum	Clayey, kaolinitic, Thermic Typic Kanhapludults and Clayey, kaolinitic, Thermic Typic Kanhapludults
Jena 14	0.049	0.0100	Type 2	Sweetgum, may haw hawthorn	Fine-loamy, siliceous, Thermic Typic Paleudults
Counce	0.049	0.0023	Type 2	Scarlet oak, blackgum	Fine-silty, mixed, Thermic Typic Hapludults
Arcadia	0.115	0.0002	Type 2	Sweetgum, white oak	Clayey, mixed, Thermic Aquic Hapludults
Tallassee	0.121	0.0694	Type 2	Sweetgum, water oak	Fine-loamy, siliceous, Thermic Typic Kanhapludults
Atmore	0.131	0.0042	Type 2	Sweetgum, water oak	Fine-loamy, siliceous, Thermic Typic Kandiudults
Pembroke	0.139	0.0029	Type 2	Sweetgum, redbay	Sandy, siliceous, Thermic Ultic Haplaquods and Loamy, siliceous, Thermic Arenic Paleaquults
Appomattox	0.165	0.0447	Type 2	Virginia pine, yellow poplar	Clayey, kaolinitic. Thermic Typic Kanhapludults, Clayey, mixed, Thermic Typic Hapludults and Fine, montmorillonitic, Thermic Typic Hapludalfs
Liberty	0.218	0.0134	Type 2	Sweetgum, yellow poplar	Fine-loamy, siliceous, Thermic Typic Hapludults and Coarse-silty, mixed Thermic Fluvenic Dystrochrepts
Warren	0.218	0.0021	Type 2	Sweetgum, black cherry	Loamy-skeletal, siliceous, Thermic Typic Hapludults and Coarse-loamy, siliceous, Thermic Fragiaquic Paleudults

Treatment response category determined by the slope of the regression equation [age-shift = intercept + b (stand age)]. When the slope b is not significant ($\alpha = 0.10$; $N = 6$) then the treatment response is classified as Type 1. When the slope is both significant and positive then the treatment response is Type 2. Types C and E growth response curves occur when the slope is both significant and negative.

[a] Scientific names of woody competition: sweetgum, *Liquidambar styraciflua*; Chinese tallow, *Triadica sebifera*; dogwood, *Cornus florida*; yellow poplar, *Liriodendron tulipifera*; blackgum, *Nyssa sylvatica*; water oak, *Quercus nigra*; mayhaw hawthorn, *Crataegus aestivalis*; scarlet oak, *Q. coccinea*; white oak, *Q. alba*; redbay, *Persea borbonia*; Virginia pine, *Pinus virginiana*; black cherry, *Prunus serotina*.

Mg/ha is increased (when the mean annual increment reaches zero). This type of response occurs when the absolute gain in stand biomass increases over time. This gain occurs either when there is a shift to a more productive genotype (i.e., planting loblolly pine seedlings instead of spruce pine (*Pinus glabra* Walt.) seedlings), or when a silvicultural treatment produces a permanent change in soil properties (e.g. Kyle et al., 2005).

Many plantation managers accept the view that certain improved genotypes will produce a Type 2 growth response (Buford, 1986). It is also possible that some genotypes result in a Type 1 growth response. Classifying silvicultural treatments as producing either Type 1 or 2 before the carrying capacity has been reached (i.e., when the current annual increment (CAI) for volume is zero) carries a degree of risk. For loblolly pine, the CAI might not reach zero until after age 50 years (Burkhart et al., 2003). Although we are confident that changing genus of a plantation can affect the carrying capacity of a site, absolute proof that the suppression of hardwood competition causes a Type 2 response will not be obtained unless growth is monitored until the CAI reaches zero. Therefore, we propose that suppression of hardwood plants can produce a pseudo-Type 1, Type 2, or pseudo-Type 2 response. From our 20-year data, it appears that a true Type 2 response might occur in two thirds of loblolly pine plantations (Table 3).

Occasionally, a pseudo-Type 2 growth response will occur when the PVI/HVR ratio is similar to the HSG/PSG ratio. At the Liberty site, the herbicide treatments increased pine production by 38 m^3 ha^{-1} while reducing hardwood volume by 29 m^3 ha^{-1}, which resulted in a PVI/HVR ratio of 1.3. By year 15, the specific gravity of the pines at this site did not vary by treatment and averaged 0.48 (Clark et al., 2006). If the specific gravity of the hardwoods was 0.63 then the total tree biomass of the site would not be increased by killing hardwoods (i.e., the HSG/PSG ratio and the PVI/HVR ratio would both be 1.3). However, since the specific gravity of sweetgum is about the same as loblolly pine and the specific gravity of yellow poplar (*Liriodendron tulipifera* L.) is less than pine (Bendtsen and Ethington, 1975), it appears this response qualifies as a "true" Type 2 response.

4.2. Pseudo-Type 1 growth response

Initially, we assumed hardwood suppression would result only in a Type 2 response similar to that illustrated in Fig. 7. Therefore, we did not expect a pseudo-Type 1 response to occur on two Piedmonts sites (Camp Hill and Monticello) and two Middle Coastal Plain sites (Bainbridge and Liverpool). When averaged over these four sites, the yield-over-age plots (Fig. 8) were similar to the hypothetical example provided in Fig. 4.

We examined several variables but were not able to determine which factors were responsible for producing a pseudo-Type 1 response. There are several factors that were evident before age 5 years that could have contributed to a lower response at these locations. It is known that seedling size can affect early growth (South, 1993; South and Rakestraw, 2002) and at these four locations, initial seedling volumes ranked in the lowest seven sites and all were below the

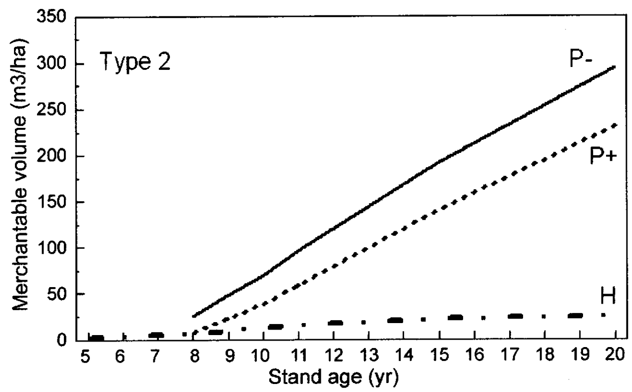

Fig. 7. The average pine response curves for controlling hardwoods at Counce, Warren, Arcadia, Atmore, Liberty, Appomattox and Tallassee. WC plots contain hardwoods (H) and pine (P+). NC plots with almost no hardwoods contain pine (P−). At age 20 years, the PVI/HVR ratio (i.e., pine volume gain divided by hardwood volume reduction) was 2.6 (i.e., 63.3/24.4).

COMProject average. Liverpool, Monticello, and Bainbridge seedling volumes were less than half that of the largest seedlings planted at Counce and Arcadia. At Bainbridge, Camp Hill, and Jena, height growth at age 2 years was the least of all sites.

The Bainbridge study was established on one of the more productive sites (Table 3; Fig. 6). However, the response at the Bainbridge site is slightly different from those observed at the other pseudo-Type 1 sites. Hardwood suppression at Bainbridge significantly increased pine volume but reduced the total volume production (pines plus hardwoods) at age 20 years by 18.4 m^3 ha^{-1}. This resulted in a PVI/HVR ratio that was less than 1.0 (Table 3). The PVI/HVR ratio of 0.4 was unexpected and the reason why this value is so low is not known.

It is generally believed that a Type 2 growth response will result in more volume gain at harvest than a Type 1 response. This belief is often driven by hypothetical figures that almost always show greater gains from Type 2 responses (Snowdon and Waring, 1984; Snowdon and Khanna, 1989; Snowdon, 2002). In one figure, the difference between a Type 1 and Type 2

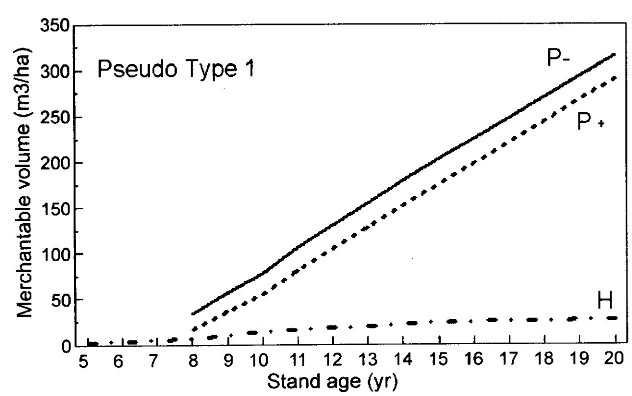

Fig. 8. The average pine response curves for controlling hardwoods at Monticello, Liverpool, Camp Hill and Bainbridge. WC plots contain hardwoods (H) and pine (P+). NC plots with almost no hardwoods contain pine (P−). At age 20 years, the PVI/HVR ratio (i.e., pine volume gain divided by hardwood volume reduction) was 1.0 (i.e., 26.4/26.7).

response was presented as a 30× difference in volume gain (South et al., 2006). However, just because a Type 2 treatment will result in a greater volume gain when the carrying capacity is eventually reached (i.e., when CAI = 0), this does not mean that a Type 1 treatment will produce less volume at time of harvest (which might occur three decades before CAI = 0). For example, at the Warren site, an herbaceous weed control treatment (a Type 1 response) produced more pine volume than controlling hardwoods. At some point in time after age 20 years, the volume gains from a Type 2 response will have to exceed the gains from a Type 1 response but this could be a moot point if harvest is conducted at age 20 years.

4.3. Type E response

The negative growth response to hardwood suppression at the Jena site was unexpected. The soil and topography at the Jena locations was variable and therefore blocks were not located adjacent to each other. Blocks 1 and 4 were located slightly north of blocks 2 and 3. Height growth of plots with suppression of woody plants was similar (Jena-14 averaged 17.4 m and Jena-23 averaged 17.7 m). However, the rate of pine growth varied in no control plots (i.e., 16.8 m for Jena-14 and 20.2 m for Jena-23). The faster growth of pines on no control plots at Jena-23 produced an unexpected block by treatment interaction. The rapid growth of pines in NC plots made it appear that volume and height growth were slowed by treating woody competition with herbicides. On average, the 5-year heights of pines on control plots at Jena-23 (4.4 m) were taller than all other sites except Bainbridge (Miller et al., 1995).

This site was visited after realizing that the Jena site was the only COMProject site where pine diameter and volume on WC plots was less than those in NC plots (Miller et al., 1991). During this visit it was noted that, because of a drain, block 3 had been oriented in a line with the WC plot upslope (on one end of the block) and the NC plot was located downhill (at the opposite end of the block). It was noted that pines in this NC plot were growing on a better micro-site and 5-year heights averaged 5.1 m (only two blocks at Bainbridge had greater 5-year growth). For block 3, pines growing in the NC plot at Jena were 0.44 m taller after 2 years and were 1.46 m taller 20 years after planting (than pines growing in WC plots). Although we have considered several biological reasons for a Type E response, we believe the block by treatment interaction at the Jena site was simply due to the location of two NC plots. Therefore, the reason for the Type E response at Jena-23 is believed to be an artificial effect due to orienting one block down a slope.

4.4. Type F response

In this paper, we propose a new type of growth response. The Type F curve observed at Jena-14 represents a case where a silvicultural treatment has a short-term negative response but a long-term positive response. The response starts out with a negative growth pattern (Miller et al., 1995) and then, over time, switches to a positive growth response (Table 3). We do not know what caused the negative growth response but it might be related to either an increase in herbaceous competition or perhaps to inadequate protection of pines from contact with herbicides. Herbicide treatments did not reduce initial stocking at Jena-23 but at Jena-14, the treatments likely increased first-year mortality (an estimated 18% for untreated plots and 30% for treated plots). Researchers who are "lumpers" might call this a Type 2 response. However, we prefer the Type F terminology since it might produce either a Type 1 or Type 2 response. This is not the first time a Type F curve has been documented in the literature.

5. Conclusion

Some forest managers rely on growth and yield models to demonstrate that suppressing hardwoods is financially worthwhile. In most cases, these models assume suppressing hardwoods will result in a Type 2 growth response and that pine volume gains from weed control will be greater on more productive sites. On a majority of sites, the COMP data supports the modeling of hardwood suppression as a Type 2 growth response. By age 20 years, controlling hardwoods on a typical Type 2 site produced an additional 61 m^3 ha^{-1} of pine. However, forest managers should be aware that hardwood suppression does not always produce a Type 2 response. On sites where a pseudo-Type 1 response occurs, a growth and yield model will likely overestimate the potential gains from controlling hardwoods. On some sites the gain in pine volume might be less than half that observed from Type 2 sites.

Perhaps more importantly, the assumptions used in developing growth and yield models need to be reexamined in light of evidence indicating gains are inversely related to site productivity. No doubt, suppression of hardwood sprouts on a fertile bottomland site is required if a manager hopes to establish a successful pine plantation. However, the results presented here cast doubt on the assumption that volume gains obtained by suppressing hardwoods are always greater on more productive sites.

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