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# Multidecadal Response of Naturally Regenerated Southern Pine to Early Competition Control and Commercial Thinning

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**Multidecadal responses to early competition control are poorly documented in naturally regenerated southern pine stands. This study examined the effects of the following early herbicide treatments in thinned southern pine stands through age 31: (1) no control (CK), (2) herbaceous vegetation control only (HC), (3) woody vegetation control only (WC), and (4) total (woody + herbaceous) vegetation control (TC). Previously reported (through age 13) early competition control effects on net (standing + harvested) pine growth and yield were sustained from ages 15–31, where the CK treatment produced the lowest net volume growth and yield and the WC treatment generated only slightly higher and not significantly different production. Over the decades, mean tree dbh and height were consistently the greatest in the HC and TC treatments, resulting in significantly higher merchantable and sawtimber growth and yield. The pattern of growth-and-yield gains through age 31 were similar to those of other studies, including planted pine stands, indicating the importance of early competition control in the attempt to increase naturally regenerated pine production.**

**Keywords:** Crossett Experimental Forest, herbaceous control, woody control, commercial thinning, Upper West Gulf Coastal Plain

A striking change in silvicultural practices in the southeastern United States over the last few decades has been the widespread adoption of increasingly intensive pine plantation silviculture (Fox et al. 2007), especially across the productive forestlands of the Atlantic and Gulf Coastal Plains. From less than 1 million acres in the mid-20th century, plantations (predominantly of loblolly pine [*Pinus taeda* L.]) in the Southeast now cover about 39 million acres, with additional increases forecast well into the future (Huggett et al. 2013, Klepzig et al. 2014). Most of this pine plantation expansion to date has come at the expense of naturally regenerated pine, oak-pine, and upland hardwood forest types (Hartsell and Conner 2013). Although their coverage has declined from just under 72 million acres in 1952 to 31 million acres in 2010 (Hartsell and Conner 2013), naturally regenerated pine-dominated forests still produce a wide range of ecosystem goods and services at low establishment costs (Jones et al. 2000, Guldin 2011). Various silvicultural strategies can help achieve these different management objectives, including early competition control to promote desired composition and increase growth in even-aged, naturally regenerated pine stands, but long-term research is needed to understand whether the response to such treatments persist throughout the rotation.

Research has consistently shown that the control of noncrop vegetation in southern pines increases both individual tree performance and stand-level growth and yield (e.g., Cain and Mann 1980, Cain 1999, Miller et al. 2003b, Borders et al. 2004, Jokela et al. 2010, Campbell et al. 2013). Most of this work has focused on pine plantations, where combinations of broad-spectrum herbicides are often used with other treatments to manage herbaceous and woody vegetation and accentuate pine growth (e.g., Fox et al. 2007, Jokela et al. 2010). Short-term gains in pine growth associated with early competition control are well documented in plantations (Stewart et al. 1984, Miller et al. 2003b, Campbell et al. 2013), but few studies have documented whether these initial responses continue throughout the rotation (Wagner et al. 2006). This is important, because some research has suggested that competition control response rankings may change over time and could vary by location. For example, the Competition Omission Monitoring Project (COMP) was initiated in the early 1980s at 14 sites across the southeastern United States to test the effects of early control of herbaceous vegetation,

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woody vegetation, and both herbaceous and woody vegetation in loblolly pine plantations (Miller et al. 1991, 2003a, 2003b). From one of the sites with high shrub competition in the COMP study, Zutter and Miller (1998) reported that early herbaceous control only was more effective than controlling only woody vegetation in promoting merchantable wood volume gain through age 11, after which woody control exceeded herbaceous control at age 15; both of these lagged noticeably behind a "total" (herbaceous + woody) control regime. Miller et al. (2003b) reported similar trends in other COMP sites with high shrub and hardwood levels; however, at the low hardwood basal area sites, early herbaceous control trailed only the total control through age 15. At age 20, most of the COMP sites produced a range of pine growth response patterns, some of which were not expected and did not become apparent until late in the study (South and Miller 2007).

Remarkably little long-term, multidecade research has been done on using herbicides and other intensive management techniques to further increase volume growth and yield in naturally regenerated, even-aged southern pine stands. Some inferences about the productivity potential of intensified management in naturally regenerated loblolly and shortleaf pine (*Pinus echinata* Mill.) stands can be made from work in less intensively managed stands. For example, a series of silvicultural trials focusing on methods of cutting in naturally regenerated loblolly and shortleaf pine stands produced substantially different growth-and-yield outcomes and stand structures after 53 years of stand development, due primarily to varying responses to intra- and interspecific competition (Cain and Shelton 2001c). A study of precommercial thinning in even-aged, naturally regenerated loblolly and shortleaf pine stands followed by commercial thinning produced substantial increases in both merchantable and sawtimber yields 25 years after stand establishment (Cain and Shelton 2003). These differences may not be maintained over the long-run, however, as denser stands eventually produce similar or even greater quantities of merchantable and sawtimber volume. Bragg (2013) examined the effects of managing loblolly and shortleaf pine with different basal areas and thinning techniques after 45 years of management. He noted that the highest gross annual increment of the treated stands at age 65 occurred in the stands with the highest target postharvest densities because even though low-density stands produced sawtimber-sized trees considerably faster, the lower stocking eventually limited total stand production.

Multidecadal investigations are especially important in natural pine stands because rotation lengths can exceed 40 years and repeated thinnings are usually applied to increase growth and yield (Cain and Shelton 2003). Given that thinning and competition control may also increase initial yields in even-aged, natural-origin pine stands (Cain 1999), a better understanding of the long-term persistence of early competition control is needed. To address these research needs, a naturally regenerated analog with an experimental design similar to that of the COMP study was installed in 1984 on the Crossett Experimental Forest (CEF) in southern Arkansas to examine early competition control effects in even-aged loblolly-shortleaf pine stands. Results from this study were previously presented at age 5 before precommercial thinning (Cain 1991) and at ages 11 and 13 before the first commercial thinning (Cain 1996, 1999). The current study reports on the combined effects of different early competition control treatments and commercial thinning on the following: individual pine crop-tree size; pine stand growth and yield; and nonpine woody vegetation in the now 31-year-old stands.

## Methods

### Site and Stand Establishment Descriptions

The study is located within two 5-acre clearcuts located 300 ft apart on the CEF. The CEF is located in the Upper West Gulf Coastal Plain, receives approximately 56 in. of rain annually, and currently experiences a frost-free season of about 240 days (Cain and Shelton 2001a). The soil series for the study area are predominantly Bude and Providence silt loams (both are Fragiudalfs), with a site index (base age = 50 years) of about 85–90 ft for loblolly pine (Cain 1991).

Before study installation, the stands were 3-year-old thickets of pines, hardwood sprouts, shrubs, briars, and woody vines that arose after a seed-tree harvest. The pine seed trees were removed immediately before the study was initiated. In August 1983, both areas were mowed with a Hydro-Ax to create a uniform vegetation height of about 2 ft, killing most of the pines taller than this height but leaving the other species on the site. During the fall and winter after mowing, the areas seeded naturally from mature pines that bordered the stands. Data from a seed production study on the CEF showed that the 1983–1984 seed year averaged 1 million sound seeds per acre (Cain and Shelton 2001b). A regeneration survey in the fall of 1984 tallied an average of 13,000 pine seedlings per acre across the study site. It was estimated that >90% of these seedlings were from the 1983–1984 seed crop; any older seedlings that had survived the mowing probably did so because they were too small to be cut down.

### Experimental Design and Treatments

Three competition control treatments plus an untreated check were installed during the summer of 1984. Treatments were replicated four times in a randomized complete block design with blocking based on pretreatment stocking of pine regeneration. Eight treatment plots were established within each of the two 5-acre clearcuts. Each treatment plot was 0.25 acre with a 0.10 acre interior measurement plot. The treatments included: check (CK)—no additional treatment of herbaceous or woody nonpine vegetation after mowing in 1983; woody control only (WC)—all hardwoods, shrubs, and woody vines were controlled annually by single-stem herbicide treatments with 10% Garlon 4E in diesel oil for the first 5 years; herbaceous control only (HC)—forbs, grasses, semiwoody plants, and vines were controlled annually using spot applications of multiple preemergent and postemergent herbicides, including Oust at 0.25 lb of active ingredient (a.i.) per acre, Vantage at 0.70 lb or 1.45 lb a.i. per acre, and/or 2% Roundup for the first 4 years; and total control (TC)—a combination of the herbicides used in the WC and HC treatments to control all nonpine vegetation. Four to 5 years of competition control may be financially infeasible for most landowners but was deemed necessary to ensure that the effects of competitor presence/absence could be observed (Cain 1991).

The treatments were specifically designed as a naturally regenerated complement to the COMP study (Cain 1991, Miller et al. 1991). From the beginning, one of the major differences was that the COMP study planted between 500 and 600 pines per acre, whereas the naturally regenerated stands on the CEF had >13,000 seedlings per acre at establishment and an average of 9,500 pines per acre at age 5. To equalize the stand stocking, precommercial thinning in the CEF stands was necessary to reduce pine density. Before the sixth growing season, 500 dominant and codominant crop pine trees per acre without obvious defect were selected for retention (9.3 × 9.3-ft spacing), and all other pine trees were removed. After thinning, 90% of the pine crop trees were loblolly pine and 10%

Table 1. Quantities of pines removed via two commercial thinnings and one salvage harvest of merchantable trees (≥3.6 in. dbh), conducted through 31 years.

| Treatment | Cut tree dbh (in.)[1] | No. of trees cut per acre | Basal area removed ($ft^2$ $acre^{-1}$) | Harvested volume: Merchantable ($ft^3$ $acre^{-1}$)[2] | Harvested volume: Sawtimber (bd ft $acre^{-1}$)[2] |
|---|---|---|---|---|---|
| First commercial thinning at 14 years[3] | | | | | |
| CK | 5.2 (0.3) | 220 (68) | 34.9 (11.7) | 540 (202) | 259 (518) |
| WC | 5.3 (0.2) | 272 (35) | 44.1 (8.5) | 683 (171) | 129 (259) |
| HC | 5.7 (0.4) | 287 (59) | 53.1 (15.5) | 904 (322) | 0 (0) |
| TC | 6.0 (0.3) | 325 (37) | 67.3 (13.5) | 1,227 (309) | 129 (259) |
| After ice storm thinning at 15 years | | | | | |
| CK | 5.7 (0.6) | 10 (0) | 1.8 (0.4) | 30 (11) | 0 (0) |
| WC | 6.4 (0.3) | 20 (10) | 4.6 (2.2) | 90 (40) | 0 (0) |
| HC | 6.8 (0.0) | 10 (0) | 2.5 (0.0) | 50 (0) | 0 (0) |
| TC | 6.7 (0.0) | 10 (0) | 2.4 (0.0) | 48 (0) | 0 (0) |
| Second commercial thinning at 21 years | | | | | |
| CK | 8.2 (0.8) | 47 (15) | 18.4 (9.0) | 432 (233) | 414 (608) |
| WC | 9.4 (0.6) | 52 (10) | 26.0 (7.4) | 655 (206) | 1,217 (1,392) |
| HC | 9.3 (0.8) | 60 (16) | 29.2 (12.4) | 734 (347) | 1,453 (2,092) |
| TC | 9.9 (0.3) | 70 (8) | 37.7 (6.4) | 971 (179) | 2,747 (1,199) |
| Cumulative total of all thinnings | | | | | |
| CK | 5.6 (1.5) | 272 (75) | 54.1 (17.9) | 986 (371) | 673 (593) |
| WC | 5.9 (1.6) | 340 (26) | 73.5 (7.1) | 1,405 (176) | 1,347 (1,259) |
| HC | 6.2 (1.6) | 352 (56) | 83.5 (18.5) | 1,663 (444) | 1,453 (2,092) |
| TC | 6.6 (1.6) | 397 (33) | 105.7 (11.0) | 2,211 (247) | 2,876 (1,050) |

Data show means by treatment (+1 SD).
[1] Arithmetic mean dbh.
[2] Merchantable volume from all pine trees of ≥3.6 in. dbh; sawtimber volume from all pine trees of ≥9.5 in. dbh expressed in board feet, international 1/4-in. rule.
[3] Sawtimber volume was calculated because there were four 10-in. trees removed in the thinning (lower dbh threshold of 9.5 in.). These trees were probably branchy edge trees and removed to release desirable crop trees.

were shortleaf pine (Cain 1999). A full description of the initial experimental design and treatments up through age 13 can be found in Cain (1991, 1996, 1999).

Three additional intermediate treatments occurred after precommercial thinning, all removing commercial-sized trees, defined as stems ≥3.6 in. dbh (4.5 ft from the base of the tree) (Table 1). At age 14, plots were thinned from below to a residual density of 200 dominant and codominant crop trees per acre. The small amount of sawtimber-sized material removed at this time was limited to a handful of larger, limbier stems along the stand edges that were removed to encourage better formed crop trees; these were included with the pulpwood harvested, rather than being used as lumber. A minor ice storm damaged some trees at age 15 (Cain and Shelton 2002). Trees with glaze damage were salvaged, removing between 0.6% (TC) and 3.7% (WC) of the standing basal area. The most recent harvest was at age 21, when all plots were thinned from below to a residual basal area of 85 $ft^2$ $acre^{-1}$.

### Measurements

Pine crop trees in each 0.10-acre measurement plot were measured every 3 years from age 5 until 15 and then again at ages 18, 22, 24, and 31. Dbh (in.) was measured for all crop trees, whereas total height (ft), height to the crown base (ft), and crown width (ft) in the north-south and east-west directions were measured on 25–30% of trees. Dbh was also measured for all hardwood stems of ≥3.6 in. dbh at age 31.

Four 0.01-acre subplots were established within each pine measurement plot at age 31. Each subplot was centered 20 ft from the measurement plot corners toward the plot center. All woody vegetation taller than breast height was tallied by species and size class (class 1, ≤0.25 in. dbh; class 2, 0.25–1 in. dbh; class 3, 1–3.5 in. dbh).

### Data Analysis

Since height, height to the crown base, and crown width were only measured on a fraction of the crop trees, regression models were developed with data from all inventories to estimate these variables. A preliminary examination of the data detected nonlinear relationships between height and dbh and height to the crown base and dbh. The best fit models of the field data were two-parameter power functions

$$\text{Height} = 8.5024\ \text{dbh}^{0.8158} \tag{1}$$

$$\text{Height to crown base} = 2.1130\ \text{dbh}^{1.1213} \tag{2}$$

The two crown width field measurements (north-south [NS] and east-west [EW]) were used to calculate the quadratic mean crown width as

$$\sqrt{(\text{Crown width}_{NS}^2 + \text{Crown width}_{EW}^2)/2} \tag{3}$$

which represents an unbiased estimate of crown width irrespective of crown shape (Gregoire and Valentine 1995). Crown width models were then fit using ordinary least-squares regression by a model incorporating measured dbh and height

$$\text{Crown width} = 6.2150\ \text{dbh}^{1.0311}\text{height}^{-0.3196} \tag{4}$$

For each crop pine, merchantable volume (cubic feet, for all stems of ≥3.6 in. dbh to a 3.5-in. diameter inside bark [dib] top) and sawtimber volume (board feet, international 1/4 rule, for all stems of ≥9.5 in. dbh to a 7.5 in. dib top) were calculated from models developed for natural loblolly and shortleaf pine on the CEF (Farrar et al. 1984). Net mean annual increment (MAI) was calculated as the cumulative net volume (standing + harvested) divided by the age. Merchantable and sawtimber bole green weight were

**Table 2. Least-squares mean individual tree size by early competition control treatment and age.**

| Treatment | Age 15 | Age 18 | Age 22 | Age 24 | Age 31 |
|---|---|---|---|---|---|
| Average dbh (in.) | | | | | |
| CK | 7.9a | 9.0a | 10.7a | 11.5a | 13.1a |
| WC | 8.5ab | 9.7ab | 11.1ab | 11.9ab | 13.5ab |
| HC | 8.4ab | 9.5ab | 11.2ab | 12.1ab | 14.0b |
| TC | 8.9b | 9.8b | 11.4b | 12.3b | 14.0b |
| Least-squares SE | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 |
| Average height (ft) | | | | | |
| CK | 46.4a | 51.0a | 59.8a | 63.8a | 69.8a |
| WC | 48.1ab | 53.3ab | 60.9ab | 65.3ab | 72.4b |
| HC | 50.6b | 54.5b | 63.6c | 67.7c | 75.0c |
| TC | 51.1b | 54.4b | 62.6bc | 67.0bc | 73.8bc |
| Least-squares SE | 1.0 | 1.1 | 1.2 | 1.3 | 1.6 |
| Average live crown ratio (%) | | | | | |
| CK | 51.6ab | 48.8ab | 44.4a | 44.3a | 42.0a |
| WC | 52.9b | 51.5b | 47.5b | 47.3b | 44.9b |
| HC | 49.0a | 47.9a | 44.7a | 44.5a | 42.1a |
| TC | 49.8a | 49.5ab | 45.7ab | 46.2ab | 42.5ab |
| Least-squares SE | 0.8 | 0.8 | 0.8 | 0.9 | 0.9 |
| Average crown width (ft) | | | | | |
| CK | 15.9a | 17.0a | 19.4a | 20.4a | 22.1a |
| WC | 16.9a | 18.2a | 20.2a | 21.3a | 22.8a |
| HC | 15.7a | 17.3a | 19.7a | 20.9a | 23.1a |
| TC | 16.8a | 18.3a | 20.5a | 21.6a | 23.4a |
| Least-squares SE | 0.3 | 0.3 | 0.4 | 0.5 | 0.6 |

For a given age, different letters indicate significant differences at $\alpha = 0.05$ for the specific variable between treatments.

estimated using models developed by Baldwin (1987). These models were selected because they were developed from pines in the Western Gulf Coastal Plain region and were fit to trees that encompassed the dbh distribution of trees in this study. Merchantable green weight included all pine trees of ≥3.6 in. dbh to a 3.5 in. dib top and sawtimber green weight included all pine trees of ≥9.5 in. dbh to a 7.5-in. dib top. Total aboveground oven-dry live tree woody biomass, including stump, bole, bark, branches, and foliage was calculated for all trees regardless of size using the most recent version of the National Biomass Estimator equations, assuming higher specific gravity (SG ≥0.45) pine (Chojnacky et al. 2014).

All statistical analyses were performed using functions in the "nlme" package (Pinheiro et al. 2013) in the R environment (version 3.0.3) (R Core Team 2013). Repeated mixed-effects analysis of variance (ANOVA) was used to test for treatment, year, and treatment × year effects, with treatment plot as a random effect. Significance among the main effects and interaction were assessed at the $\alpha = 0.05$ level. Data were only analyzed for ages 15–31, the time period following thinnings, as results before this age were reported previously (Cain 1991, 1996, 1999). Residuals were visually inspected for homoscedascity, whereas normality was assessed with qq plots. If residuals were hetereoscedastic, variance was weighted using an identity link function to weight the variance by treatment (Pinheiro and Bates 2000). In all instances, this improved residuals and resulted in a significantly improved model when tested with a log-likelihood test with $\alpha = 0.05$.

# Results

## Treatment Effects on Mean Pine Crop Tree Size

At age 15, mean pine dbh in the TC treatment was 8.9 in. compared with 7.9 in. in the CK treatment, a 13% gain ($P \leq 0.01$). Comparatively, mean dbh was not significantly different among the other treatments ($P \geq 0.09$) (Table 2). The trend continued through age 31, where mean dbh in the TC and HC treatments was 14.0 in. compared to 13.0 in. in the CK treatment ($P \leq 0.01$). Treatment differences in mean height followed a slightly different pattern than mean dbh, where at age 15 heights were 51.1 ft (10% greater) and 50.6 ft (9% greater) in the TC and HC treatments, respectively, compared with 46.4 ft mean height in the CK treatment ($P \leq 0.01$). Height was also 6% and 5% greater in the TC and HC treatments at age 15, respectively, than in the WC treatment ($P \leq 0.02$) (Table 2). From ages 18–31, mean height did not differ between the WC and TC treatments, but it was greater in the HC than in the WC treatment at ages 22–31. For instance, at age 31 mean height in the HC treatment was 75.0 ft, whereas the mean height in the WC treatment was 72.4 ft, representing a 4% gain ($P \leq 0.01$).

Live crown ratio (crown length ÷ height) was maintained above 40% from ages 15–31 in all treatments, with very little difference between treatments (Table 2). At ages 15 and 18, the significant differences were a slightly greater live crown ratio in the WC than in the HC treatment ($P \leq 0.01$), and from ages 22–31 live crown ratio was slightly greater in the WC treatment than in the HC and CK treatments. There were no treatment differences in average crown width from age 15 through age 31 ($P \geq 0.07$). Crown width did increase steadily for all treatments, with crown widths at age 31 averaging about 30–40% greater than they were at age 15.

## Treatment Effects on Pine Stand Growth and Yield to Age 31

Standing pine basal areas at age 15 in the WC and TC treatments were greater than in the CK treatment by 16% ($P = 0.04$) and 25% ($P < 0.01$), respectively (Table 3). The second commercial thinning resulted in no treatment differences in standing basal area at age 22 ($P \geq 0.90$), a pattern that persisted through age 31 where basal area ranged from 137.6 $ft^2$ $acre^{-1}$ in the TC treatment to 144.8 $ft^2$ $acre^{-1}$ in the HC treatment. Stand density index, standing merchantable volume, and standing sawtimber volume all responded similarly to thinning. Comparatively, standing pine trees per acre was 14% lower in the TC than in the CK treatment from age 22 through age 31 ($P = 0.01$). The lack of early woody control in the HC treatment resulted in greater hardwood basal area at age 31 than in the WC and TC treatments.

Net merchantable volume MAI of the TC treatment (224 $ft^3$ $acre^{-1}$ $year^{-1}$) was significantly greater than for the other treatments at age 15 ($P \leq 0.01$), ranging from 21% greater than the HC treatment to 57% greater than the CK treatment (Table 4). After the second commercial thinning, MAI at age 22 was greater in the TC and HC treatments than the CK treatment ($P < 0.01$), whereas MAI among competition control treatments was only different between the TC and WC treatments. By age 31, MAI declined compared with that at age 22 in all treatments (Figure 1) but was still 26% greater in the TC treatment than in the CK treatment.

The rapid merchantable volume growth at age 15 in the TC treatment corresponded to a high net merchantable volume, where yields were 57% ($P \leq 0.01$) and 28% ($P = 0.01$) greater than for the CK and WC treatments, respectively (Table 4). Through age 31, net merchantable yield remained significantly less in the CK and WC treatments than in the TC treatment. Comparatively, yields between the TC and HC treatments after precommercial thinning were not significantly different, and the differences declined with age, where at age 15 the TC treatment had 21% greater yield, but by age 31, the yield was only 6% greater.

Because of a high degree of variability from one replicate to the next, sawtimber volume MAI was not significantly different among

**Table 3. Least-squares mean standing pine and hardwood statistics from age 15 through age 31 in the four different early competition control treatments.**

| Treatment | Age 15 | Age 18 | Age 22 | Age 24 | Age 31 |
|---|---|---|---|---|---|
| Standing pine basal area ($ft^2$ $acre^{-1}$) | | | | | |
| CK | 70.1a | 89.1a | 94.3a | 109.2a | 138.0a |
| WC | 81.1b | 97.2ab | 94.1a | 108.3a | 138.4a |
| HC | 78.8ab | 97.6ab | 93.5a | 109.4a | 144.8a |
| TC | 87.5b | 104.8b | 91.5a | 105.6a | 137.6a |
| Least-squares SE | 3.1 | 4.0 | 1.3 | 1.8 | 3.4 |
| Standing pine stand density index[1] | | | | | |
| CK | 140a | 170a | 167a | 189a | 227a |
| WC | 158b | 180ab | 165a | 184a | 225a |
| HC | 154ab | 183ab | 163a | 185a | 232a |
| TC | 167b | 193b | 159a | 178a | 221a |
| Least-squares SE | 5 | 6 | 3 | 3 | 5 |
| Standing pine trees per acre | | | | | |
| CK | 200a | 195a | 147b | 147b | 145b |
| WC | 200a | 187a | 137ab | 137ab | 137ab |
| HC | 200a | 195a | 135ab | 135ab | 135ab |
| TC | 200a | 197a | 127a | 127a | 127a |
| Least-squares SE | 5 | 4 | 6 | 6 | 6 |
| Standing merchantable volume ($ft^3$ $acre^{-1}$)[2] | | | | | |
| CK | 1,605a | 2,214a | 2,543a | 3,041a | 4,028a |
| WC | 1,941b | 2,491ab | 2,575a | 3,052a | 4,083a |
| HC | 1,866ab | 2,477ab | 2,561a | 3,096a | 4,310a |
| Standing sawtimber volume (mbf $acre^{-1}$)[2] | | | | | |
| CK | 1.9a | 5.2a | 10.4a | 13.8a | 20.6a |
| WC | 2.8a | 6.7ab | 11.4a | 14.7a | 21.4ab |
| HC | 2.4a | 6.6ab | 11.4a | 14.9a | 22.8b |
| TC | 3.4a | 7.6b | 11.8a | 14.9a | 21.7ab |
| Least-squares SE | 0.9 | 0.9 | 1.0 | 1.0 | 1.1 |
| Standing hardwood basal area ($ft^2$ $acre^{-1}$) | | | | | |
| CK | | | | | 7.5ab |
| WC | | | | | 1.1a |
| HC | | | | | 18.2b |
| TC | | | | | 0.8a |
| Least-squares SE | | | | | 4.9 |

Standing values do not include harvested trees. For a given age, different letters indicate significant differences at $\alpha = 0.05$ for the specific variable between treatments.
[1] Reineke's (1933) stand density index.
[2] Merchantable volume from pine trees of ≥3.6 in. dbh. Sawtimber of pine trees of ≥9.5 in. dbh, expressed in board foot, international 1/4-in. rule.

treatments at age 15 ($P \geq 0.32$) (Table 4). As is apparent in Table 2, at 15 years all stands were approaching the minimum dbh threshold for sawtimber but had only inconsistently reached it. Not surprisingly, after being released in the first commercial thinning and the ice storm-related thinning shortly thereafter, by age 18 sawtimber MAI had started to produce statistically significant differences. Although all treatments responded to thinning, the TC treatment had a 42% greater ($P = 0.04$) sawtimber MAI than the CK treatment (431 versus 303 bd ft $acre^{-1}$ $year^{-1}$). This pattern in sawtimber increment was also seen at age 24 (Figure 1). By age 31, even though sawtimber MAI ranged from 685 (CK) to 794 (TC) bd ft $acre^{-1}$ $year^{-1}$, this variable did not statistically differ among treatments ($P \geq 0.18$).

Net sawtimber yields were not different among the treatments until age 22 (Table 4), when the yield in the TC treatment was 31% greater than in the CK treatment ($P \leq 0.01$). By age 31, sawtimber yield was 14% and 16% greater in the HC and TC treatments than in the CK treatment.

Net yields expressed by green weight had a similar pattern of treatment differences over time, where at age 15, net merchantable green weights were 36% and 62% greater in the HC and TC treatments than in the CK treatment (Table 5). By age 31, the yields in the same two treatments were 23% greater ($P \leq 0.01$) than in the CK treatment and 11% greater ($P \leq 0.01$) than in the WC treatment. Starting at age 18, net total aboveground oven-dry biomass remained significantly greater in the HC and TC treatments than in the CK treatment. By age 31, aboveground biomasses in the TC treatment were 14% and 26% greater ($P \leq 0.01$) than in the WC and CK treatments, respectively, whereas biomass of the HC treatment was 19% greater ($P \leq 0.01$) than that of the CK treatment.

#### Nonpine Woody Vegetation at Age 31

Mean density of shade-intolerant and shade-tolerant hardwood species in the size classes of <1 in. dbh were lowest in the CK treatment and greatest in the HC and TC treatments (Table 6). The HC treatment had the greatest density of hardwood competitors of ≥3.6 in. dbh, ranging from 25 more stems $acre^{-1}$ than in the CK and WC treatments and 27 more stems $acre^{-1}$ than in the TC treatment. Very small (<0.25 in. dbh) shrub density was 644 stems $acre^{-1}$ greater in the CK than in the TC treatment; otherwise there were no significant differences in the number of shrubs between treatments.

Considerable variation in the smallest vine size classes makes interpreting differences in these categories problematic, although the HC treatment seems to have been most effective. However, for the medium size classes, representing older vines, the effects of early competition control were still evident at age 31. Medium-sized vines were virtually absent in the TC treatment with only 1 vine $acre^{-1}$, whereas the CK treatment had significantly more with 69 vines $acre^{-1}$. Very few of these woody vines actually grew on the crop

**Table 4. Least-squares mean pine volume growth and yield from age 15 through age 31 in the four different competition control treatments.**

| Treatment | Age 15 | Age 18 | Age 22 | Age 24 | Age 31 |
|---|---|---|---|---|---|
| Net[1] merchantable[2] MAI (ft$^3$ acre$^{-1}$ year$^{-1}$) | | | | | |
| CK | 143a | 154a | 160a | 168a | 162a |
| WC | 175b | 180b | 181ab | 186ab | 177ab |
| HC | 185b | 189b | 192bc | 198bc | 193bc |
| TC | 224c | 219c | 215c | 217c | 203c |
| Least-squares SE | 10 | 10 | 11 | 11 | 12 |
| Net merchantable volume (ft$^3$ acre$^{-1}$) | | | | | |
| CK | 2,145a | 2,769a | 3,530a | 4,027a | 5,015a |
| WC | 2,624ab | 3,241ab | 3,980ab | 4,457ab | 5,488ab |
| HC | 2,770b | 3,406bc | 4,225bc | 4,760bc | 5,974bc |
| TC | 3,363c | 3,934c | 4,733c | 5,206c | 6,306c |
| Least-squares SE | 168 | 170 | 175 | 177 | 186 |
| Net sawtimber[2] MAI (bd ft acre$^{-1}$ year$^{-1}$) | | | | | |
| CK | 142a | 303a | 503a | 603a | 685a |
| WC | 195a | 379ab | 581ab | 669ab | 733a |
| HC | 159a | 369ab | 583ab | 682ab | 782a |
| TC | 234a | 431b | 665b | 740b | 794a |
| Least-squares SE | 54 | 55 | 58 | 60 | 65 |
| Net sawtimber volume (mbf acre$^{-1}$) | | | | | |
| CK | 2.1a | 5.4a | 11.1a | 14.5a | 21.2a |
| WC | 2.9a | 6.8a | 12.8ab | 16.0ab | 22.7ab |
| HC | 2.4a | 6.6a | 12.8ab | 16.4ab | 24.2b |
| TC | 3.5a | 7.8a | 14.6b | 17.7b | 24.6b |
| Least-squares SE | 0.9 | 0.9 | 1.0 | 1.0 | 1.1 |

Growth was expressed as net MAI, which includes standing plus harvested volume. For a given age, different letters indicate significant differences at $\alpha = 0.05$ for the specific variable between treatments.

[1] Net volume included the standing pine volume at age 31 plus previously harvested volume.

[2] Merchantable volume from pine trees of ≥3.6 in. dbh. Sawtimber of pine trees of ≥9.5 in. dbh, expressed in board foot, international 1/4-in. rule.

pines in any treatment regardless of size, although the CK and WC treatments (0.5 and 0.4 vine acre$^{-1}$) had significantly more medium-sized vines than either the HC or TC treatments (0.1 vine acre$^{-1}$).

## Discussion

Multidecadal stand responses to early competition control treatments are rarely examined, even though competition control is a major reason for the exponential increase in global wood production

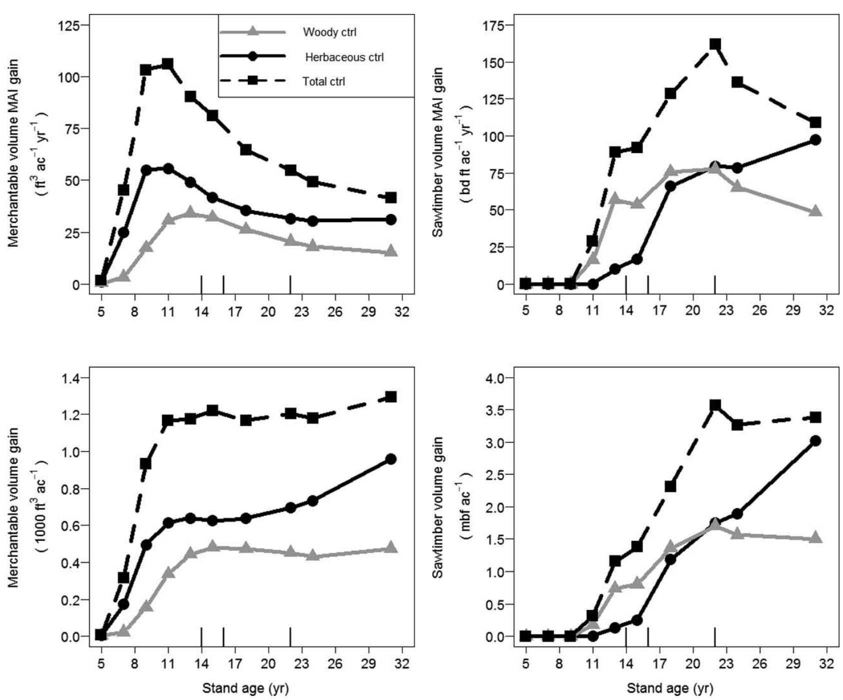


**Figure 1. Changes in net pine volume growth-and-yield gains from the three different competition control treatments relative to the untreated check. Merchantable volume included all trees of ≥3.6 in. dbh and sawtimber volume included all trees of ≥9.5 in. dbh. Net volume included standing plus harvested volume in each size class. MAI was the cumulative volume divided by the age. Sawtimber volume growth and yield are expressed in international 1/4-in. board foot volume. Vertical bars at ages 14, 15, and 21 indicate the timing of commercial wood harvests.**

**Table 5. Least-squares mean pine green weight and dry weight growth and yield from age 15 through age 31 in the four different competition control treatments.**

| Treatment | Age 15 | Age 18 | Age 22 | Age 24 | Age 31 |
|---|---|---|---|---|---|
| Net[1] merchantable[2] green weight MAI (tons $acre^{-1}$ $year^{-1}$) | | | | | |
| CK | 3.1a | 3.6a | 4.0a | 4.4a | 4.5a |
| WC | 3.8b | 4.2b | 4.5ab | 4.8ab | 5.0a |
| HC | 4.2b | 4.5b | 4.9bc | 5.3bc | 5.6b |
| TC | 5.0c | 5.1c | 5.3c | 5.5c | 5.6b |
| Least-squares SE | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 |
| Net[1] merchantable[2] green weight (tons $acre^{-1}$) | | | | | |
| CK | 46.6a | 64.1a | 87.8a | 104.7a | 140.3a |
| WC | 56.8ab | 75.3ab | 98.5ab | 115.5ab | 155.2b |
| HC | 63.6b | 81.4bc | 108.0bc | 126.4bc | 172.3c |
| TC | 75.3c | 91.2c | 115.8c | 132.7c | 173.7c |
| Least-squares SE | 4.5 | 4.7 | 5.1 | 5.4 | 6.2 |
| Net sawtimber[3] green weight MAI (tons $acre^{-1}$ $year^{-1}$) | | | | | |
| CK | 0.5a | 1.3a | 2.3a | 2.9a | 3.5a |
| WC | 0.7a | 1.6ab | 2.7ab | 3.2ab | 3.9ab |
| HC | 0.6a | 1.6ab | 2.8ab | 3.4b | 4.2b |
| TC | 0.9a | 1.9b | 3.0b | 3.6b | 4.2b |
| Least-squares SE | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 |
| Net sawtimber[3] green weight (tons $acre^{-1}$) | | | | | |
| CK | 7.8a | 23.4a | 50.9a | 69.7a | 109.8a |
| WC | 11.0a | 29.7a | 59.1ab | 77.9ab | 120.5ab |
| HC | 9.7a | 29.4a | 61.4ab | 81.6ab | 131.2b |
| TC | 14.1a | 34.0a | 67.1b | 85.2b | 128.8b |
| Least-squares SE | 5.5 | 5.9 | 6.4 | 6.7 | 7.8 |
| Net oven-dry total[3] aboveground biomass MAI (tons $acre^{-1}$ $year^{-1}$) | | | | | |
| CK | 2.9a | 3.1a | 3.2a | 3.4a | 3.4a |
| WC | 3.5b | 3.6b | 3.7ab | 3.8ab | 3.7ab |
| HC | 3.7bc | 3.8b | 3.9bc | 4.0bc | 4.0b |
| TC | 4.4c | 4.3c | 4.3c | 4.4c | 4.2b |
| Least-squares SE | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Net oven-dry total[4] aboveground biomass (tons $acre^{-1}$) | | | | | |
| CK | 43.6a | 55.9a | 71.5a | 82.4a | 105.0a |
| WC | 52.9ab | 65.4ab | 80.8ab | 91.3ab | 115.1ab |
| HC | 55.4bc | 68.1bc | 85.2bc | 97.0bc | 125.4bc |
| TC | 66.6c | 78.1c | 94.8c | 105.3c | 130.8c |
| Least-squares SE | 3.4 | 3.5 | 3.6 | 3.6 | 3.8 |

Growth was expressed as net MAI, which includes standing plus harvested weight. For a given age, different letters indicate significant differences at $\alpha = 0.05$ for the specific variable between treatments.

[1] Net included standing green weight plus green weight removed in harvests.

[2] From Baldwin (1987). Merchantable green weight included pine trees of ≥3.6 in. dbh to an upper diameter of 3.5 in. Sawtimber green weight included pine trees of ≥9.6 in. to an upper diameter of 7.5 in.

[3] From Chojnacky et al. (2014). Total aboveground biomass included stump, bole, bark, branches, and foliage, representing the cumulative tree biological investment in aboveground structures.

(Wagner et al. 2006). The few studies that examined multidecadal responses of planted loblolly pine to early competition control and subsequent thinning have found that initial gains in wood production are sustained to the end of the rotation (e.g., Clason 1989, Glover and Zutter 1993, South and Miller 2007). Our investigation of early competition control and thinning in naturally regenerated loblolly and shortleaf pine also showed substantial long-term productivity gains when herbaceous vegetation was initially controlled, with additional gains when both herbaceous and woody vegetation were controlled. A shorter-term analysis of individual loblolly pine growth and yield comparing naturally regenerated and containerized seedlings with the same total competitor control on a similar CEF site found few differences in production after 12 years, with the primary disparity being the cost of planting (Cain and Barnett 2002). Although our analysis does not include a financial evaluation, we believe the productivity gains from early herbaceous control or herbaceous plus woody control in these naturally regenerated stands can justify the investment, especially given recent advances in herbicides.

#### Determining the Response of Different Competition Control Strategies

It should be noted that the effects of controlling woody competitors often varies by study and is highly dependent on the site's capacity to support competing shrubs and hardwoods. For the relatively productive sites of the CEF, controlling only woody competitors produced modest, often nonsignificant, increases over the untreated check in mean tree size or pine stand growth and yield from age 15 through age 31. In the Southwide COMP study, Miller et al. (2003b) noted that woody control only in some locations with low hardwood basal area (<10 $ft^2$ $acre^{-1}$ at age 15) did not significantly improve productivity over that of their untreated controls. However, their sole location in southern Arkansas (near Warren, approximately 30 miles north of the CEF) was classified as a low hardwood site but displayed a prominent (>20%) increase in merchantable pine volume. The soils of the CEF have a higher site index than those at the Warren COMP site, and nonpine competition tends to be high under most conditions on the CEF: after 31 years, few significant differences in the density of competing shrubs, woody vines, and

**Table 6. Density of shade-intolerant hardwood species, shade-tolerant hardwood species, shrub species, and vine species at age 31 in each of the four competition control treatments by stem size class.**

| Treatment | Size 1 | Size 2 | Size 3 | Size 4 |
|---|---|---|---|---|
| | ........(stem acre$^{-1}$)........ | | | |
| Shade-intolerant hardwood species | | | | |
| CK | 12a | 131a | 94a | 7a |
| WC | 31a | 150a | 87a | 7a |
| HC | 62a | 194a | 94a | 32a |
| TC | 50a | 181a | 44a | 5a |
| Least-squares SE | 15 | 61 | 22 | 9 |
| Shade-tolerant hardwood species | | | | |
| CK | 56a | 187a | 100a | 37ab |
| WC | 62a | 287a | 131a | 5.0a |
| HC | 69a | 200a | 212a | 55b |
| TC | 306b | 806b | 231a | 2.0a |
| Least-squares SE | 42 | 86 | 48 | 14 |
| Shrub species | | | | |
| CK | 931b | 575a | 19a | |
| WC | 575ab | 725a | 25a | |
| HC | 706ab | 406a | 1a | |
| TC | 287a | 544a | 44a | |
| Least-squares SE | 189 | 250 | 24 | |
| Woody vine species | | | | |
| CK | 2,381ab | 512a | 69b | |
| WC | 2,693b | 462a | 19ab | |
| HC | 837a | 300a | 25ab | |
| TC | 2,556ab | 587a | 1a | |
| Least-squares SE | 543 | 117 | 14 | |
| Woody vines on pine trees | | | | |
| CK | 2.8a | 1.7a | 0.5a | |
| WC | 3.3a | 1.5a | 0.4a | |
| HC | 1.0b | 0.7b | 0.1b | |
| TC | 2.9a | 1.9a | 0.1b | |
| Least-squares SE | 0.6 | 0.2 | 0.1 | |

The size classes are as follows: size 1, <0.25 in. dbh; size 2, 0.25–1.0 in. dbh; size 3, 1–3.5 in. dbh; and size 4, >3.5 in. dbh. The average number of woody vines found growing on pine trees is also shown. Different letters within a column indicate treatment differences at $\alpha = 0.05$.

hardwood trees were apparent between the treatments (Table 6). Greater gains in pine production have been observed on other Coastal Plain sites with the control of woody vegetation. For example, at age 20, Balmer et al. (1978) found that controlling understory hardwoods resulted in a 20% gain in merchantable pine volume when basal area was maintained between 60 and 100 ft$^2$ acre$^{-1}$ in commercially thinned, naturally regenerated stands in North Carolina and Virginia. Clason (1993) found that controlling hardwood competition in northern Louisiana increased loblolly pine plantation yields by 27% at age 27, compared with only 9% gains in net merchantable volume at age 31 in this study.

The presence of herbaceous vegetation shortly after stand establishment can have noticeable effects on early pine growth and survival because herbaceous vegetation can deplete surface soil moisture to suboptimal levels for growth (Nelson et al. 1981). Creighton et al. (1987) found that the presence of herbaceous vegetation significantly reduced loblolly pine height and diameter growth from ages 2 to 7 across nine Upper Coastal Plain sites, whereas survival was negatively affected at only three of these sites. Few studies have documented whether the early effects of herbaceous competition control are still evident later in the rotation, especially after crown closure when herbaceous vegetation cover often declines (Cain 1996).

In the current study, herbaceous cover remained above 80% in the CK and WC treatments over the 9-year period after competition control ceased but before the first commercial thin (Cain 1999). The high herbaceous cover in the WC treatment compared with that in the TC treatment noted by Cain (1999) eventually resulted in 22 and 13% lower net merchantable volumes at ages 15 and 31, respectively. This finding is comparable to the results reported in pine plantations across four sites with low hardwood density at age 15, where the lack of herbaceous competition control early in the rotation produced a 21% lower merchantable pine yield (Miller et al. 2003b). By age 20, percent gains compared with those of the untreated control ranged from 0 to 19% at the low hardwood sites, whereas gains at four sites with high hardwood basal area (> 17.4 ft$^2$ acre$^{-1}$) were negative (e.g., yields in the untreated control exceeded those in herbaceous control only), probably a result of increasing competition from hardwoods and shrubs (South et al. 2006). As noted with woody control only, these results are not universal: Clason (1993) found that early herbaceous control had no effect on mean tree dbh or merchantable volume at ages 22 or 27 after commercial removals at ages 13 and 18, which he attributed to a greater influence of hardwood competition.

Total control of competing vegetation immediately after loblolly pine plantation establishment is generally considered synergistic (e.g., Miller et al. 2003b), as this treatment allows the seedlings to gain an initial advantage that is usually sustained through the rotation. For example, projections with a growth-and-yield model of planted pine treated with different types of early competition control suggest that by the end of the rotation at age 25 after two commercial thinnings, total competition control can increase sawtimber yields by 97%, whereas controlling herbaceous vegetation only may result in a 27% gain in sawtimber volume (Miller et al. 1995). Similarly accentuated outcomes were reported for sawtimber volume in planted loblolly pine after total control, including a 37% gain in Louisiana stands at age 27 (Clason 1993) and a 67% increase in yield at the end of a 25-year rotation in unfertilized stands on the lower Coastal Plain of Florida (Jokela et al. 2010).

As silvicultural intensity increases in naturally regenerated loblolly-shortleaf pine stands, merchantable pine yields also increase, probably due to greater initial advantages of trees growing free of competition. When combined with thinnings to regulate crop tree density, early competition control can noticeably enhance pine growth and yield. A comparison across a gradient of management intensities (from no precommercial thinning to precommercial thinning to early competition control plus precommercial thinning) using stands on the CEF clearly demonstrates different outcomes. At the lower end of management intensity, a stand regenerated with a seed-tree harvest, occasionally burned, and first (commercially) thinned at age 14 to 80 ft$^2$ acre$^{-1}$ residual basal area produced a net merchantable yield of 2,580 ft$^3$ acre$^{-1}$ at age 25 (Cain and Shelton 2001c). Cain and Shelton (2003) examined different stands precommercially thinned at age 9, prescribed burned every 2–5 years thereafter, and commercially thinned to basal areas of 85 or 75 ft$^2$ acre$^{-1}$ at ages 17 and 23 and found that net merchantable pine yields at age 25 were 3,486 ft$^3$ acre$^{-1}$ (85 ft$^2$ acre$^{-1}$) and 3,503 ft$^3$ acre$^{-1}$ (75 ft$^2$ acre$^{-1}$). The present study, which combined precommercial thinning and early competition control, found net (harvested + standing) merchantable volumes of 5,206 ft$^3$ acre$^{-1}$ in the TC treatment and 4,027 ft$^3$ acre$^{-1}$ in the CK treatment at age 24.

#### Special Requirements of Naturally Regenerated Loblolly and Shortleaf Pine

By their nature, naturally regenerated southern pine stands, even those intensively managed to maximize their increment and yield, will never have as short a rotation as possible with pine plantations. This is not necessarily because of inadequate yields—this study clearly demonstrates that productivity of intensively managed naturally regenerated loblolly pine stands can approach that of comparably treated plantations. Rather, it is because naturally regenerated stands must be allowed to develop long enough to adequately restock the site with the next generation of quality crop trees. The presence of sufficiently mature seed trees and maintenance of appropriate stocking to final rotation are critical to ensuring adequate seed production. Grano (1957) noted that 13–15 in. dbh pines produced more than 4 times as many cones as 8–10 in. dbh pines, and Baker and Balmer (1983, p. 148) reported that even though widely spaced 25-year-old loblolly pine stands may produce enough seed to regenerate the stand, a 40-year-old stand would produce 3–5 times as many seeds. This requires well-timed thinnings to ensure that stand stocking does not reach the point at which crowns recede, growth performance suffers, and, in extreme conditions, mortality ensues. Thinnings can also be used to improve crop tree quality by targeting suppressed, poorly formed, or diseased individuals and those damaged by logging or natural disturbances (Baker and Balmer 1983, Schultz 1997); such improvements also help ensure better quality seedlings in the future.

The standing merchantable volume at age 31 in all four treatments exceeded 4,000 $ft^3$ $acre^{-1}$ in this study, with a predominance of that volume being sawtimber. These yields may warrant end-of-rotation harvesting and regenerating the next stand if adequate seed was available. However, we observed very few cones in the tops of these pines. This could be due to a variety of factors, including the immaturity of the crop trees, the high stand density, or simply a year of low cone production. Regardless of the cause, the lack of cones suggests that these stands may not adequately restock the stands if harvested now. At this stage in stand development, a thinning to remove 40–50% of the basal area, which currently ranges between 138 and 145 $ft^2$ $acre^{-1}$, will not only produce a large amount of sawtimber but also release remaining crop trees, accentuating their bole growth, crown development, and seed production to the end of the rotation. Compared with pine plantations managed on 25–30 year rotations, we believe that harvesting intensively managed naturally regenerated loblolly-shortleaf pine stands at 35–40 years old represents only a modest sacrifice of time for many small landowners unable or unwilling to invest the large amount of capital needed to establish intensively managed plantations.

## Conclusions

It is apparent that early competition control, when coupled with precommercial thinning and well-timed commercial thins, can produce substantially greater individual pine growth performance and higher merchantable and sawtimber yields over decades. Indeed, our results suggest that intensively managed, naturally regenerated southern pine stands can produce wood fiber at levels approaching those of many pine plantations. Although the responsiveness of naturally regenerated southern pines to intensive competition and stocking control is not surprising, they remain overlooked as silvicultural options. Just as in intensive plantation management, treatments such as precommercial thinnings or early competition control in naturally regenerated southern pine stands require investments that can be justified by more income generated in greater yields of pulpwood and sawtimber in later thinnings and a higher proportion of sawtimber at final harvest (Baker and Murphy 1982, Cain and Shelton 2001c, Cain and Shelton 2003).

This degree of performance in naturally regenerated southern pine stands is fortunate. Even after the major economic downturn from 2007 to 2009, regional, national, and global demands for forest products and other ecosystem services produced by southern pine forests are expected to grow well into the 21st century (Ince and Nepal 2012), especially from developing markets for pellets, later-generation biofuels, cross laminated timbers, and biopolymers (e.g., Ince and Nepal 2012, Mohammad et al. 2012, Abt et al. 2014, Ragauskas et al. 2014). Much of this demand will be satisfied by continued expansion of southern pine plantations. However, plantations will not be installed on every acre possible and production increases must be found elsewhere. Although continued declines in naturally regenerated pine-dominated forests are forecast (Huggett et al. 2013), this type will remain a substantial segment of the commercial forests of the Southeast. Intensifying management of naturally regenerated forests should therefore help with regional economic development and provide options that may not otherwise be provided by plantations.

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