Twenty-Five Years of Intensive Forest Management with Southern Pines: Important Lessons Learned

Eric J. Jokela, Timothy A. Martin, and Jason G. Vogel

ABSTRACT

A commitment to long-term forest research provides the basis and opportunity to understand developmental processes and stand dynamics over an entire rotation. The southeastern United States has undergone a significant evolution in forest management practices over the last 60 years, especially in regard to the intensification of pine plantation silviculture. However, few studies have examined production relationships for an entire rotation. This article reviews results from a rotation-length experiment that tested factorial combinations of understory competition control and sustained fertilizer additions on the productivity and stand dynamics of loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliottii* var. *elliottii*) in north central Florida. After 25 years, fertilizer and competition control treatments increased site index (base age, 25 years) from 64 to 87 ft in loblolly pine and from 75 to 88 ft in slash pine. In addition, these cultural treatments increased total stand stem volume accumulation by 1.8–2.2-fold compared with the control treatments for slash and loblolly pine, respectively; the proportion of volume in high-value product classes such as chip-n-saw (C/S) and sawtimber was also increased in both species (e.g., 39% in C/S and sawtimber in the loblolly pine control treatment versus 74–87% in the fertilizer and/or weed control treatments). Overall, results from this study, as well as others in the region, highlight the overriding importance of soil nutrient supply on long-term productivity of southern pine stands.

Keywords: loblolly pine, slash pine, fertilization, weed control, long-term research, production dynamics

Rotation long investigations examining the effects of silvicultural treatments on growth and stand dynamics are rare but essential for improving our ability to assess biological growth potential, understand growth strategies, and determine responsiveness of stands to management inputs. The southeastern United States has undergone a significant evolution in forest management practices over the last 60 years, especially in regard to pine plantation silviculture (Fox et al. 2007b). Management systems for loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm. var. *elliottii*) plantations now routinely include elements of mechanical and chemical site preparation, fertilization, herbaceous weed control, density management, and deployment of planting stock that has been genetically improved for growth, form, and disease resistance. Changes in stand productivity resulting from these management practices have been dramatic (Jokela et al. 1989, 2004; Allen et al. 2005, Adegbidi et al. 2005, Chmura et al. 2007). For example, southern pine plantations established in the 1950s, which produced less than 90 ft^3 ac^{-1} per year, have been replaced with 21st century plantations capable of producing in excess of 400 ft^3 ac^{-1} per year on some sites (Fox et al. 2007b). Over this same time period, total acreage of southern pine plantations has increased from about 2 million ac in the 1950s to greater than 32 million ac today. Compared with other forested regions of the United States, the South constitutes about 30% of the nation's forestland, but accounts for about 60% of the total removals nationwide (Wear and Greis 2002).

Ownership patterns of forestlands in the South have also changed significantly during the last 10 years. In particular, large divestitures of forestlands have occurred among the vertically integrated forest products companies. For example, forest indus-

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Eric J. Jokela (ejokela@ufl.edu) is professor, Timothy A. Martin (tamartin@ufl.edu) is associate professor, and Jason G. Vogel (jvogel@ufl.edu) is postdoctoral research associate, School of Forest Resources and Conservation, University of Florida, Gainesville, FL 32611. *The authors thank the members of the Forest Biology Research Cooperative for their long-term support.*

try lands have declined from 40 million ac in 1999 to about 20 million ac in 2005 (Wear et al. 2007). Several factors may have contributed to these changing forestland ownership patterns, including selling lands to reduce corporate debt, increasing tax efficiency, deriving higher value from developed land use, increasing shareholder returns, and reduced demands for domestically produced timber products (Wear and Newman 2004, Clutter et al. 2005, Wear et al. 2007).

Much of the productive lands originating from the vertically integrated forest products companies have been purchased by timberland investment management organizations (TIMO) and real estate investment trusts (REIT). In the case of TIMOs, which act as fiduciaries for timberland pension and other related closed-end funds, the investment horizons typically vary from 10 to 15 years. It has been argued that in rapidly urbanizing areas, monetizing real estate opportunities of lands managed by TIMOs and REITs under Highest and Best Use objectives may result in increased parcelization and reduced forest tract sizes (Wear et al. 2007, Bliss et al. 2008). Another implication of increased divestiture of forest industry lands will be greater dependence on TIMOs, REITs, and nonindustrial private landowners for meeting dimension lumber, pulp and paper, and wood energy supply needs. The long-term consequences of these changes will undoubtedly result in the use of intensive forest management systems, especially on those highly productive lands kept in forest production.

In an effort to better understand intensive forest management, the Intensive Management Practices Assessment Center (IMPAC) was established in Gainesville, Florida in 1976 as a research cooperative that included participating scientists from the University of Florida, US Forest Service, and forest industry. One research experiment emanating from this program was established in 1983. That study focused on assessing the biological growth potential of southern pines and examining why comparable seed sources deployed in the southern hemisphere grew several times faster than at comparable latitudes in Florida (Swindel et al. 1988). The goal was to examine various management practices for maximizing tree growth rates and to determine which practices were ecologically, environmentally, and economically feasible (US Forest Service 1987).

In this article, we synthesize rotation-long growth data from the IMPAC growth potential experiment and address the effects of silvicultural treatments on processes affecting the productivity of loblolly and slash pine stands. To accomplish this objective, we examine and compare patterns of mean annual increment, basal area development, mortality, and volume distribution among product classes for four silvicultural treatments over a 25-year period. A secondary objective is to discuss the broad forest management implications and lessons learned from this rotation-long investigation.

Materials and Methods

The study used data collected over a 25-year period from the IMPAC experiment located about 6 mi north of Gainesville, Florida (29°30′N and 82°20′W), at an elevation of about 148 ft. Mean annual precipitation and temperature averages about 53 in. and 69.8°F, respectively. The soils are somewhat poorly drained Ultic Alaquods (Pomona fine sands) and the soil nutrient reserves are inherently low (Martin and Jokela 2004a). In a typical profile, the spodic horizon occurs at 8–20 in. and the argillic horizon occurs at 35–47 in.

The study was established in January 1983 as a 2 × 2 × 2 factorial of species (loblolly and slash pine), complete and sustained weed control, and annual fertilization arranged in a randomized split-plot (whole plot = species) design. This experimental design resulted in four treatments within each species: control (C), weed control only (W), fertilizer only (F), and fertilizer + weed control (FW). Complete establishment details and relevant site and treatment descriptions are reported in Swindel et al. (1988), Colbert et al. (1990), and Martin and Jokela (2004a). Briefly, the entire area was site prepared using a single-pass bedding treatment and hand planted with genetically improved (first generation, open pollinated) 1-0 bareroot stock. A balanced fertilizer regime (macro- and micronutrients) was applied annually for the first 10 years to the F and FW treatments (stopped in May 1993). Fertilizers were applied in narrow bands (12-in. semicircle) around the base of each tree or planting location. During the first 10 years, 32.1 lb ac^{-1} of N, 12.8 lb ac^{-1} of P, and 28.3 lb ac^{-1} of K plus micronutrients were applied annually. The fertilizer treatments were annually resumed during the 16th–18th growing season (1998–2000). To put the fertilizer treatment history into perspective, the quantities of N, P, and K added between the 16th and 18th growing season was 650, 78, and 100 lb ac^{-1}, respectively. Total nutrient additions over the life of the study for the F and FW treatments were (lb ac^{-1}): 971 N, 206 P, 383 K, 96 Ca, 64 Mg, 64 S, 3.7 Mn, 4.8 Fe, 0.8 Cu, 3.6 Zn, and 0.8 B. Although these later levels of nutrient additions were well above "operational norms," the study design called for a "fully nonlimiting" nutrient environment. Understory vegetation was controlled in the W and FW plots using herbicides and mechanical methods from ages 1 to 10 years. Canopy development prevented understory encroachment on those plots thereafter. The C plots did not receive fertilizer or competition control treatments over the course of the study. None of the treatment plots received thinning treatments.

Treatment plots were 0.20 ac in size, with interior measurement plots being 0.06 ac (40 trees). An untreated two-row planted buffer separated all plots. Diameter and height data were collected 13 times over the 25-year study period. Volume estimates were derived from inventory data and equations developed for site prepared plantations of slash and loblolly pine (Bailey et al. 1982, 1985). Analysis of variance for a split-plot design was used to test for species and treatment effects on growth metrics, and the *P* values for all pairwise comparisons adjusted using the Tukey-Kramer procedure for multiple comparisons. All statistical analyses were conducted using the SAS statistical package (SAS Institute, Inc., 1996).

Results

Impressive growth responses to the applied silvicultural treatments were evident for both species over time for this experimental location (Colbert et al. 1990, Jokela and Martin 2000, Martin and Jokela 2004a, 2004b; Figure 1). At age 25 years, site index was determined using average total height of dominant and codominant trees defined as the upper quartile of all trees within each treatment plot. Site index$_{\text{(base age 25 years)}}$ for loblolly and slash pine were C, loblolly = 64 and slash pine = 75; W, loblolly = 74 and slash pine = 86; F, loblolly = 86 and slash pine = 86; and FW, loblolly = 87 and slash pine = 88. Loblolly and slash pine differed significantly in site index ($P = 0.044$). The main effects of W ($P < 0.05$) and F ($P < 0.01$) were significantly greater than C in both species. In addition, pairwise comparisons of site index among treatments for

Figure 1. Contrast in tree size between the untreated buffer (right, equivalent to the C treatment) and FW treatment (left) for loblolly pine. (Photo by Eric J. Jokela.)

loblolly pine indicated that the W treatment was significantly less than the F and FW treatments.

During early stand development, basal area accretion was closely related to the intensity of the imposed silvicultural treatments. The FW treatment for loblolly pine accrued the highest levels of basal area, peaking at about 190 $ft^2\ ac^{-1}$ at age 16–18 years, and then declining to 170 $ft^2\ ac^{-1}$ by age 25 years (Figure 2). With the exception of the C treatment, that was still slowly aggrading at age 25 years (loblolly C = 110 $ft^2\ ac^{-1}$), basal area for the F treatment reached maximum levels at about age 16 years (170 $ft^2\ ac^{-1}$), and the W treatment peaked at age 20–22 years (170 $ft^2\ ac^{-1}$). By age 25 years for loblolly, only the FW treatment differed significantly (P = 0.05) from C. A similar story was generally apparent for slash pine, with basal area for the FW (180 $ft^2\ ac^{-1}$) and F (150 $ft^2\ ac^{-1}$) treatments peaking at age 18 years and then declining to 150 and 120 $ft^2\ ac^{-1}$, respectively, at age 25 years (Figure 3). A notable exception to these trends was the W treatment for slash pine, which was still aggrading over time, reaching 180 $ft^2\ ac^{-1}$ at age 25 years. This later peak was significantly greater ($P < 0.05$) than the C, F, and FW treatment basal areas at age 25 years, and the FW treatment continued to have a significantly greater ($P = 0.035$) basal area than the C treatment.

Diameter distributions for both species reflected the intensity of silvicultural treatments, with increased skewness toward larger trees in the F and FW treatments (Figures 4 and 5). Average diameter for the C, W, F, and FW treatments at age 25 years were 6.1, 7.9, 9.1, and 9.0 in. for loblolly pine; corresponding average diameters by treatment for slash pine were 7.2, 8.6, 9.1, and 10.1 in.

In general, stem mortality by dbh class from age 18 to 25 years was more apparent on those plots receiving fertilizer additions (Figures 4 and 5), although all treatments showed greater mortality in the lower diameter class trees, a reflection of increased self-thinning over time. At age 25 years, cumulative mortality rates for the C, W, F, and FW treatments for loblolly pine were 15, 28, 48, and 37%, respectively (Figure 6). Slash pine cumulative mortality tended to be higher than loblolly pine, especially for the C (38%), F (58%), and FW (59%) treatments (Figure 7). As expected, mortality levels on the treated plots became especially pronounced as the stand basal area approached 130–175 $ft^2\ ac^{-1}$, apparently in response to the upper limits of stocking supported at this site and the diminished levels of light received by the lower crown class trees (Dean and Jokela 1992, Dean and Baldwin 1993). Also evident was increased incidence and severity of fusiform rust (*Cronartium quercum* [Berk.] Miyabe ex Shirai f. sp. *fusiforme*) and pitch canker (*Fusarium circinatum* Nirenberg & O'Donnell) related mortality on the fertilized plots (data not shown). Both pathogens are endemic to this region and tend to become more pronounced in stands receiving intensive management inputs that enhance site fertility (Blakeslee et al. 1999, Schmidt 2003, Lopez-Zamora et al. 2007). Interestingly, the stockability or basal area carrying

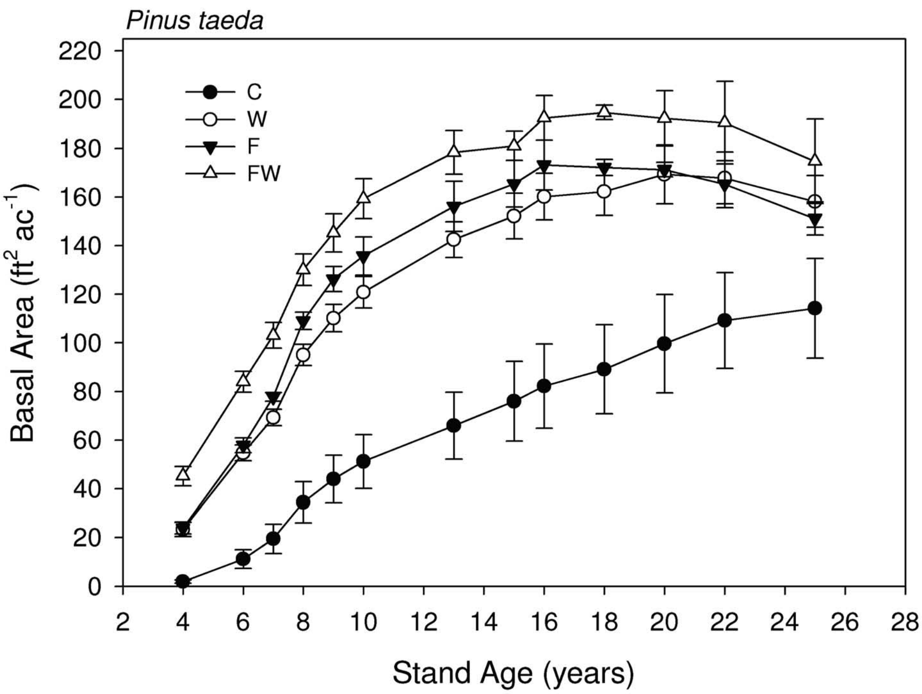

Figure 2. Basal area accretion by silvicultural treatment for loblolly pine growing on a Spodosol in north central Florida.

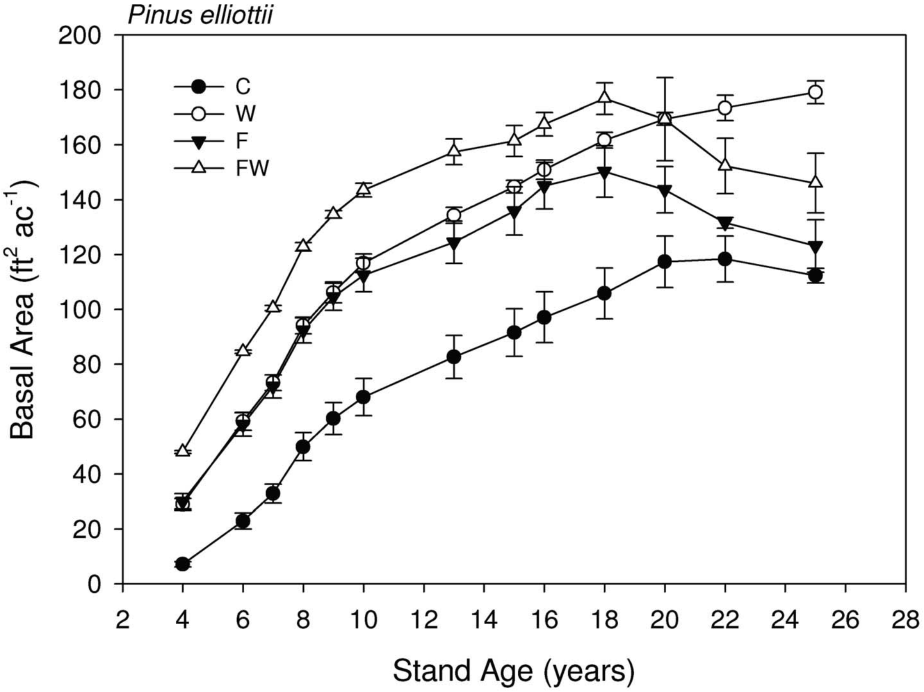

Figure 3. Basal area accretion by silvicultural treatment for slash pine growing on a Spodosol in north central Florida.

capacity appeared to be increased on the W, F, and FW treatments before significant density-related mortality occurred. By comparison, density-related mortality on the C treatment plots began to occur at about 120 ft^2 ac^{-1} for both species (Figures 6 and 7). These results clearly reinforce the role of nutrient and density management as silvicultural tools for producing higher value, larger dimension trees, and minimizing competition-related growth reductions and mortality losses.

Significant differences among treatments in standing crop volume were still detected at age 25 years. For loblolly pine, stand volumes ranged from 2,370 ft^3 ac^{-1} for the C treatment to 5,250 ft^3 ac^{-1} for the FW treatment (Figure 8). Patterns of volume accumulation for slash pine were somewhat different than loblolly pine. The W treatment sustained higher levels of standing crop volume (5,130 ft^3 ac^{-1}) than either the C (2,800 ft^3 ac^{-1}) or the F (3,660 ft^3 ac^{-1}) treatments. As previously discussed, however, increased mortality associated with plots receiving heavy fertilizer applications at age 16–18 years is likely responsible. Slash pine, being a lower nutrient-demanding species than loblolly pine, did not tolerate the fertilizer treatments as well, especially under unthinned conditions.

Culmination in mean annual volume increment (m.a.i.; ft^3 ac^{-1} per year) for loblolly pine was quite different among silvicultural treatments (Figure 9). For loblolly pine, m.a.i. for the FW treatment peaked at about 250 ft^3 ac^{-1} per year at 14 years and then declined thereafter. In contrast, the F and W treatments culminated at age 16 years at approximately 230 and 200 ft^3 ac^{-1} per year, respectively. The m.a.i. of the C treatment continued to slowly increase over time, reaching 100 ft^3 ac^{-1} per year at age 25 years.

Treatment responses for m.a.i. in slash pine were generally similar to loblolly pine, with the F and FW plots culminating at about age 18 years at 180 and 220 ft^3 ac^{-1} per year, respectively. Similar to that found for basal area, m.a.i. for the W treatment culminated at about age 23 years at 230 ft^3 ac^{-1} per year. Results for both species suggest that if maximizing volume (fiber) production was the primary management objective, the rational age to harvest the stands and replant would have been around 16 years for loblolly pine and about 18 years for slash pine. With the C treatment, biological rotation age for both species appeared to be about 23–25 years.

Merchandising the stand into product classes is an essential step in performing financial analyses that guide management decisions. In this analysis, the distribution of stem volume by dbh class was examined among treatments for both species. Product classes were defined as follows: trees falling in the 4- to 8-in. dbh classes were classified as

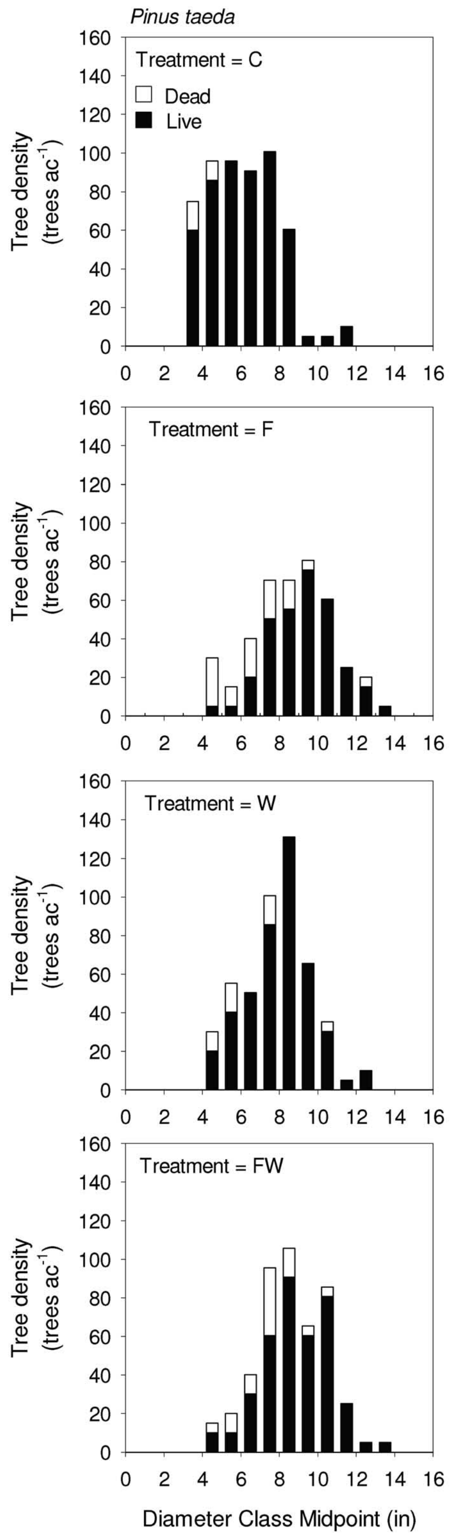

Figure 4. Distribution of stems per acre by diameter class and silvicultural treatment for loblolly pine at age 25 years (note that mortality by dbh class that occurred from age 18 to 25 years is depicted by the non-shaded portion of the histogram).

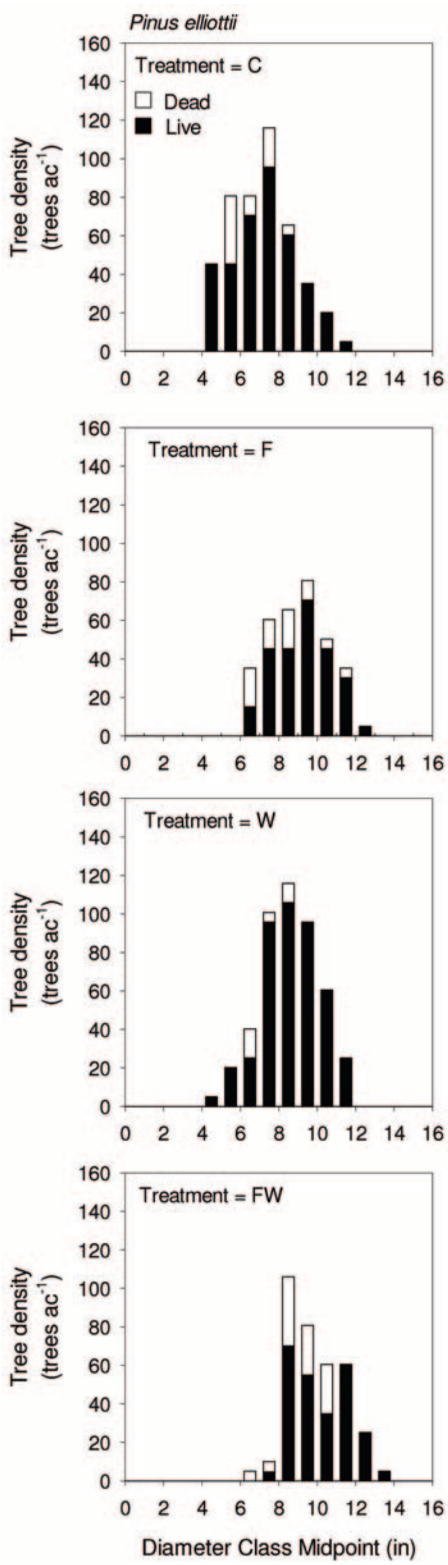

Figure 5. Distribution of stems per acre by diameter class and silvicultural treatment for slash pine at age 25 years (note that mortality by dbh class that occurred from age 18 to 25 years is depicted by the non-shaded portion of the histogram).

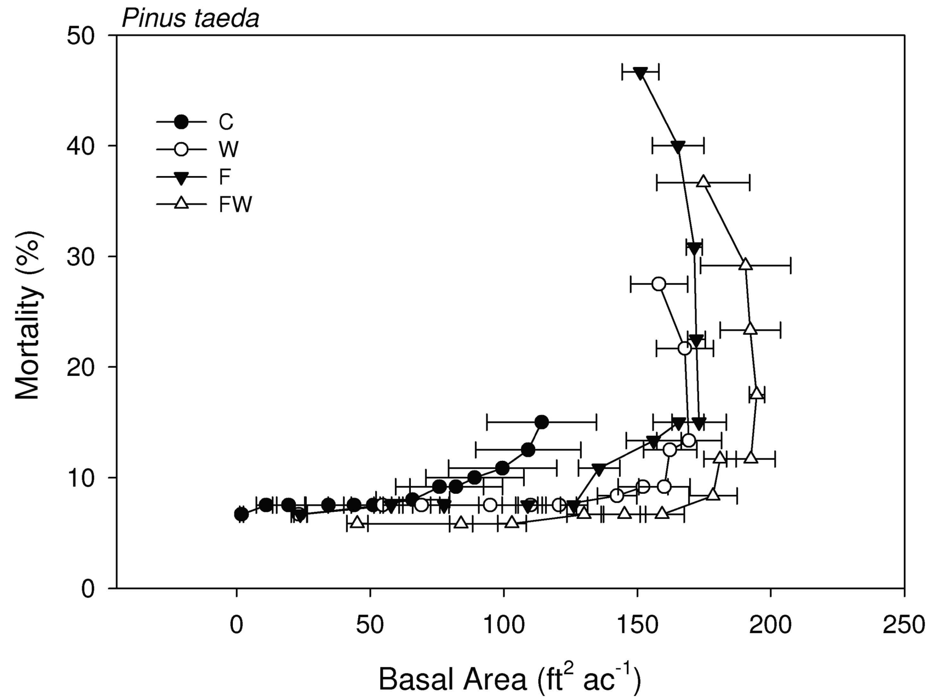

Figure 6. Cumulative mortality among silvicultural treatments as affected by stand basal area for loblolly pine.

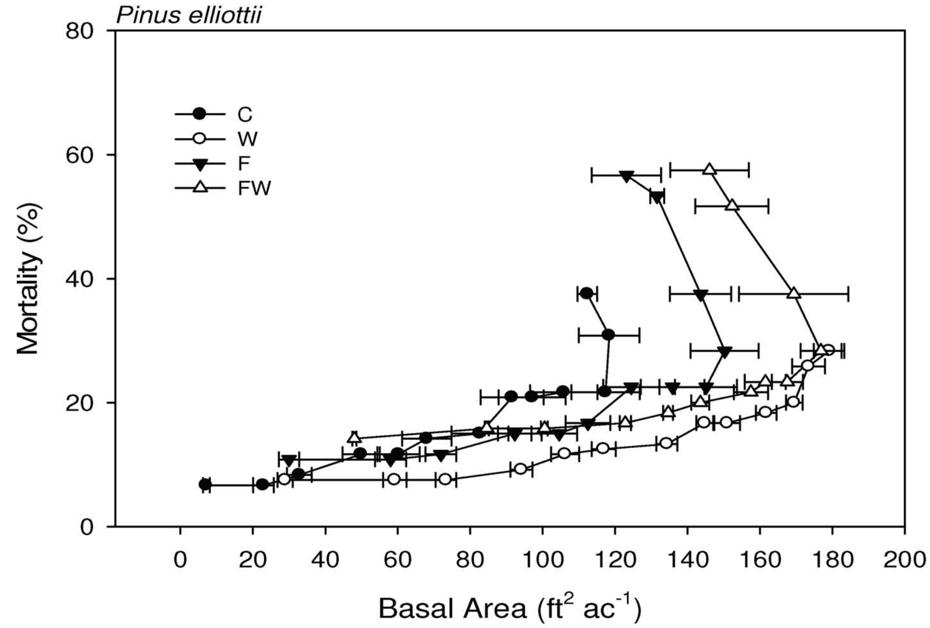

Figure 7. Cumulative mortality among silvicultural treatments as affected by stand basal area for slash pine.

pulpwood, trees in the 8- to 12-in. dbh classes were classified as chip-n-saw (C/S), and trees >12 in. were classified as sawtimber. No additional wood quality variables were assessed in this analysis.

Large differences in the relative proportions of pulpwood and "grade" products were apparent among treatments and between species (Figures 10 and 11). With loblolly pine, the F (4,650 $ft^3\ ac^{-1}$) and FW (5,250 $ft^3\ ac^{-1}$) treatments produced the greatest standing volume, as well as the greatest proportion of stems making C/S and sawtimber grades (about 62–65% C/S and 21–25% sawtimber). The W treatment, with nearly 4,000 $ft^3\ ac^{-1}$ of volume, produced 65% C/S and 9% sawtimber. The C treatment produced about 55% less volume (2,370 $ft^3\ ac^{-1}$) than the FW treatment, and was dominated by pulpwood-sized trees

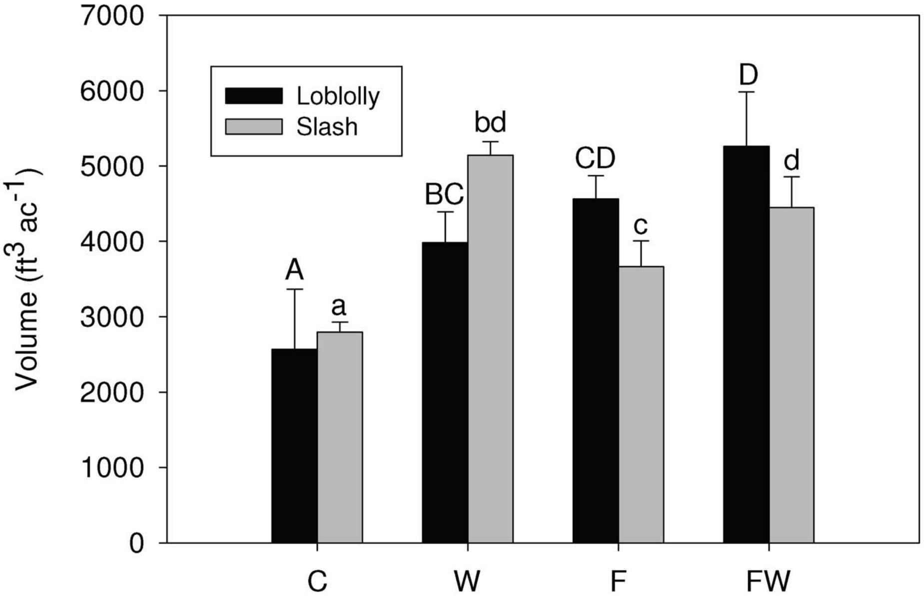

Figure 8. Differences in standing crop volumes among silvicultural treatments for slash and loblolly pine at age 25 years (note that within a species, means not followed by the same letter are significantly different [$P < 0.05$]).

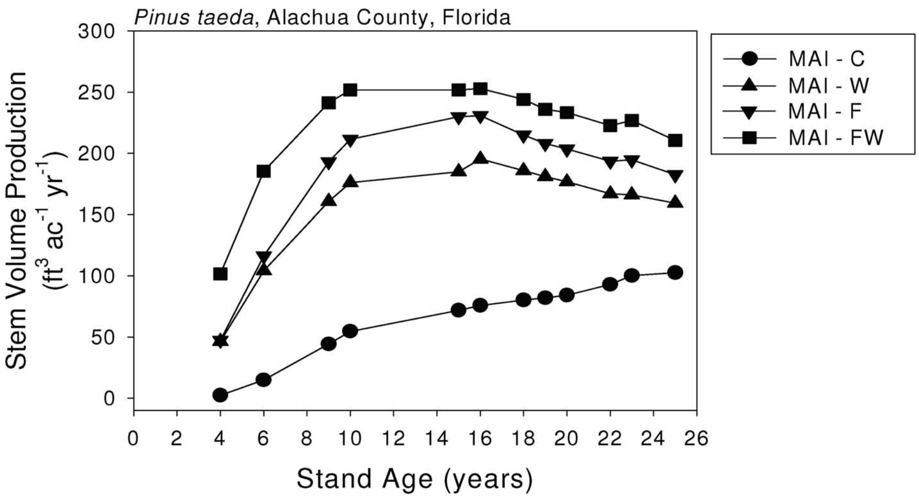

Figure 9. Trends over time in m.a.i. among silvicultural treatments for loblolly pine.

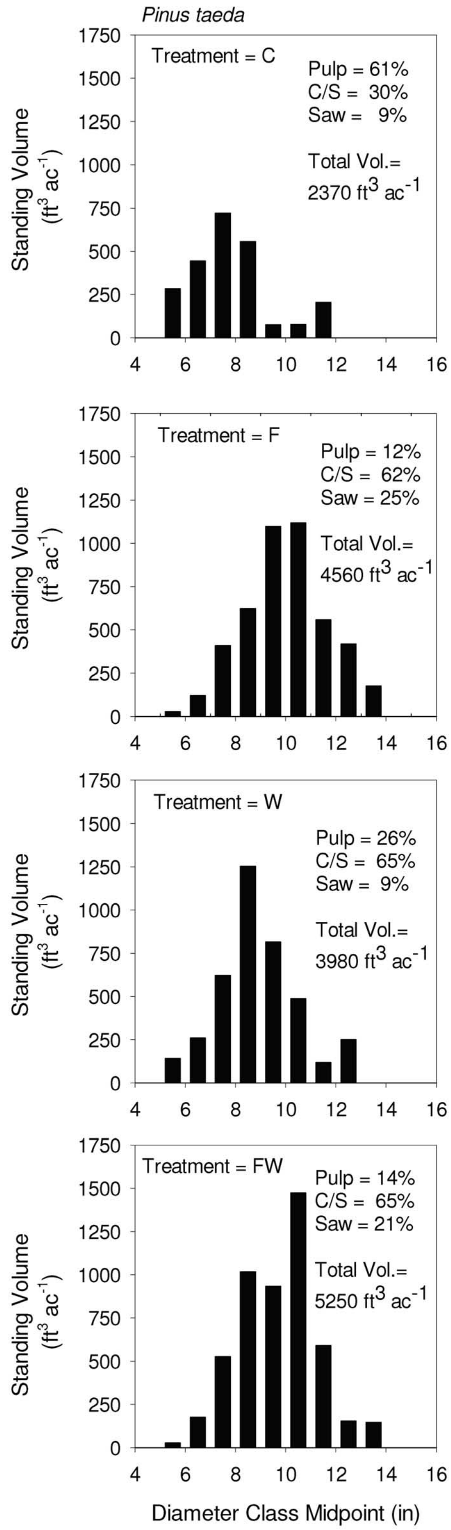

Figure 10. Distribution of stem volume by diameter and product class for loblolly pine managed under a range of silvicultural treatments at age 25 years.

(61%), with lesser amounts of grade material (30% C/S and 9% sawtimber).

For slash pine, the greatest absolute amount of standing volume at age 25 years was present in the W-treated plots (5,130 ft^3 ac^{-1}). However, in comparison to the FW treatment, it contained more volume in C/S (71% versus 32%) and less volume in sawtimber (11% versus 50%). For example, the W treatment produced about 564 ft^3 ac^{-1} of sawtimber at age 25 years compared with 2,225 ft^3 ac^{-1} in the FW treatment. Such differences likely not only reflect the positive effects of fertilization on diameter and volume growth, but also a "thinning" response associated with increased density-dependant mortality in the fertilizer-treated plots.

Discussion

A commitment to long-term forest research provides the basis and opportunity to understand developmental processes and stand dynamics over an entire rotation. To this end, the IMPAC experiment has been exceedingly informative in quantifying and understanding the production ecology of loblolly and slash pine and their responsiveness to a wide range of silvicultural treatments. The specific treatments imposed in this experiment created a strong nutritional gradient and the growth potential of both species was clearly reflective of this gradient (Figure 1). The large differences in site index documented among treatments speaks volumes to the importance of not asking the old

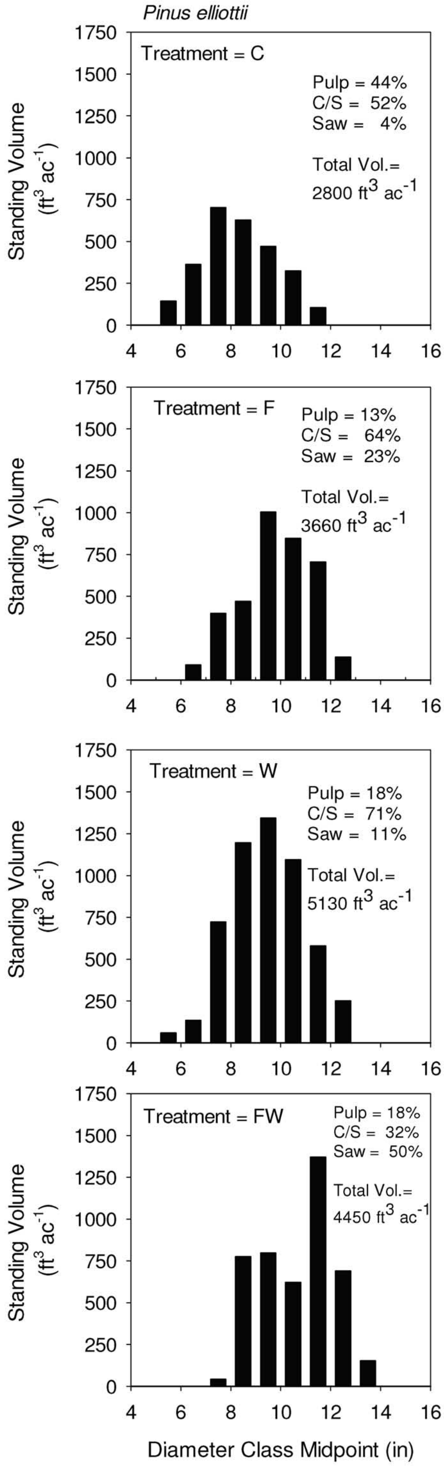

Figure 11. Distribution of stem volume by diameter and product class for slash pine managed under a range of silvicultural treatments at age 25 years.

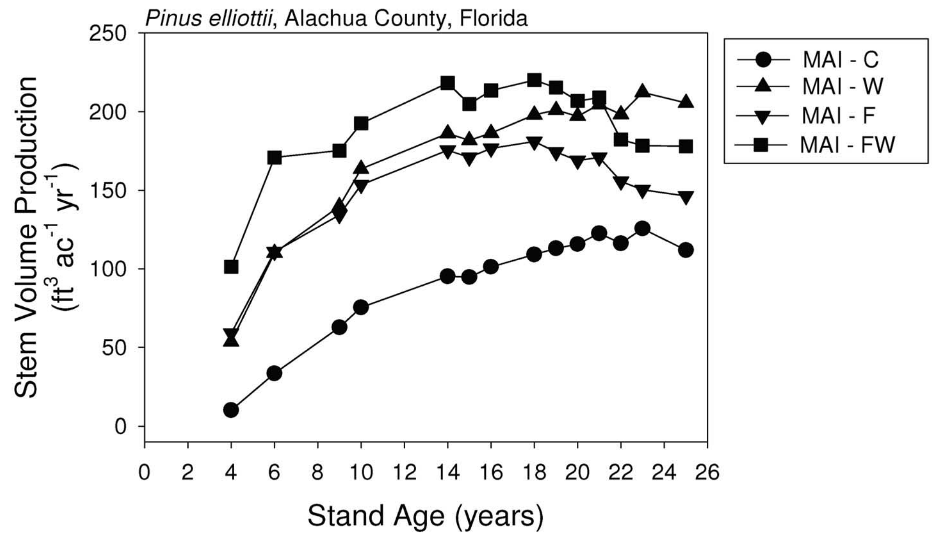

Figure 12. Trends over time in m.a.i. among silvicultural treatments for slash pine.

question of what the inherent site quality class would be for a given locale, but rather what level of site quality could be achieved using various genetic, site preparation, fertilization, and weed control treatments (Stone 1984)?

Nutrient limitations, especially for N and P, are common throughout much of the southeastern Coastal Plain (Pritchett et al. 1961, Pritchett and Comerford 1982, Fox et al. 2007a). The acreage of southern pine stands receiving fertilizer additions has increased from about 200,000 ac in 1990 to over 1.2 million ac in 2004; rates of fertilizer application for these intensively managed plantations typically range from 150 to 200 lb ac^{-1} of N and 25 to 50 lb ac^{-1} of P, applied one to three times over the course of a 18- to 25-year rotation (Albaugh et al. 2007, Fox et al. 2007a). The magnitudes of growth responses associated with the F, FW, and W treatments reinforce the notion that competition for soil nutrients represents one of the major growth-limiting factors on these soils (Neary et al. 1990). In a nutrient-limited environment such as this, reducing the competitive effects of understory vegetation with herbicide applications redirects soil nutrient supply to the pines in a manner similar to fertilizer additions. Water limitations, in contrast, are generally less problematic on these somewhat poorly drained soils (Swindel et al. 1988). Elsewhere within the region, including deep well-drained sands, nutrient limitations have been shown to have a stronger influence on forest productivity than water availability (Albaugh et al. 2004, Samuelson et al. 2004, 2008; Allen et al. 2005).

Not only did the silvicultural treatments increase total standing volume (i.e., up to 2.2-fold at age 25 years), but they also increased the proportion of trees making valuable product grades, especially for loblolly pine and the fertilized plots. For example, without thinning, the highest percentages of volume produced in the C/S and sawtimber categories occurred in the F and FW treatments for both species (Figures 10 and 11). In contrast, total volume accumulated in the W treatment for slash pine exceeded the F and FW treatments at age 25 years. However, this treatment produced comparatively less total sawtimber volume. Such results reflect differences in nutritional requirements between species (loblolly > slash pine) and the role that fertilizers play in changing product classes in this region. Although a detailed economic analysis was beyond the scope of this article, the results further emphasize the need for foresters to evaluate and understand the costs, growth responses, and ultimate product values (stumpage) and financial returns that accrue from various management decisions. Refinements in both growth and yield and process-based models that account for differences in soil conditions, genetic sources of plant materials, site preparation needs, and responsiveness to various management inputs will ultimately aid in the goal of making more site-specific silvicultural prescriptions.

Stand density levels, expressed as basal area, increased for both loblolly and slash pine as the silvicultural treatment intensities increased (Figures 2 and 3). Basal area accretion for the F and FW treatment plots for both species tended to culminate at age 16–18 years, and the values were in general agreement with the upper limits of stocking reported for these species within their native range. For example, Jokela et al. (2004) found in a regional analysis that upper stocking levels of loblolly pine in the southern United States were surprisingly uniform, with a maximum basal area of about 195

ft^2 ac^{-1}. They suggested that the lack of significant regional variation in upper stocking limits indicated that genetic and climatic limitations may be less important than soil nutrient supply as factors influencing potential biological productivity and maximum basal area accretion in this region.

In contrast, increasing evidence suggests that considerable variation in growth performance can exist for southern pines when grown outside of their native range, including Hawaii and southern hemisphere countries such as Brazil, Argentina, and South Africa (Burns and Hu 1983, Borders and Bailey 2001). For example, basal area accretion levels for loblolly pine have been reported as high as 370–435 ft^2 ac^{-1} in Hawaii (DeBell et al. 1989, Harms et al. 1994, 2000). These researchers hypothesized that competition-related mortality was much lower in Hawaii than the southeastern United States, and that higher soil fertility levels and solar radiation intensities in Hawaii allowed for greater retention of photosynthetically active leaf area that facilitated high growth rates compared with plantations growing in South Carolina. From a research perspective these observations suggest that the genetic growth potential of loblolly and slash pine is not likely being achieved within their native range. Comparative studies conducted between hemispheres that contrast soils, climate, ecophysiology and stand development patterns would prove insightful in understanding genetic versus environmental controls on southern pine growth potential.

In addition, although nutrient management was essential for maintaining high production levels, it was also evident that rotation long density management could have minimized competition-related growth reductions and mortality losses. Judicious use of thinnings, beginning as early as age 10–12 years, and accompanied by midrotation fertilizer applications (e.g., 200 lb ac^{-1} of elemental N and 25 lb ac^{-1} of elemental P) represents a cost-effective means for producing higher value, large dimension trees. The lack of an apparent fertilizer response, as expressed in m.a.i. after retreatment from ages 16 to 18 years for both species (Figures 9 and 12), suggests that the F and FW plots were most likely density limited.

One of the many challenges facing foresters and the profession in the 21st century is related to the efficient production of high-quality lumber and fiber products. Precision forestry is a term frequently used in this context and it can have various meanings, ranging from using advanced technologies to inventory trees and measure wood quality traits to developing site-specific management systems that match genotypes to sites and deliver precise ameliorative treatments to augment nutrition and control competing vegetation (Dyck 2003). An interesting and related result from the IMPAC experiment was that spot fertilizer treatments were used with much success to enhance growth and site quality. Although not directly compared with the more traditionally used broadcast fertilizer application technique at this site, the growth responses associated with the spot applications were similar in magnitude to published estimates for broadcast applications (Fisher and Garbett 1980, Jokela and Stearns-Smith 1993, Adegbidi et al. 2002, Will et al. 2002, Fox et al., 2007a) It follows that precise, localized applications of fertilizers to a planting spot and root zone may enhance plant nutrient uptake, especially for less mobile nutrients such as phosphorus.

Although it is clear that fertilizer additions and understory competition control can significantly improve volume growth, there is some evidence that intensive forest management practices could have negative effects on wood quality (Clark et al. 2004). In a recent analysis conducted on similar site types, Love-Myers et al. (2009) reported that midrotation fertilization treatments caused significant short-term reductions in latewood-specific gravity in both slash and loblolly pine, but that trees returned to specific gravity patterns consistent with unfertilized trees within 2 or 3 years.

Results from the IMPAC experiment also have some other broad and specific implications for how forests may be managed for carbon sequestration, or as a source of biofuels or biomass energy. Increasing forest carbon density (mass of carbon per unit ground area) is a potentially effective tool for mitigating atmospheric CO_2 buildup (Jandl et al. 2007, Canadell and Raupach 2008), and using forest biomass as a fuel may provide significant levels of fossil fuel offsets for specific regions of the United States (Argow 2009, Bowyer 2009, Kimbell et al. 2009). For carbon sequestration at IMPAC, the increases in stand volume associated with the F treatment corresponded to increased carbon storage in the summed forest floor, roots, and aboveground vegetation; however, because of lower root and forest floor mass, weed control resulted in no net carbon gain in these summed components despite the stand volume being larger than the control (Jason Vogel, University of Florida, unpublished data, 2009). In considering energy generation derived solely from tree biomass, the F, W, and FW treatments would have provided a similar yield at age 25 years, but the FW treatment produced "thinnable" stand densities earlier in the rotation for both species. These examples highlight that in a future where carbon sequestration and biofuels are important forest products, silvicultural approaches will be needed that account for all components of forest biomass as they interact over the course of a rotation. Regardless of the products, effective and efficient forest management in the 21st century will depend heavily on integrated systems that incorporate proper application and timing of a wide range of technologies, including forest tree improvement, genotype deployment, competition control, density control, and nutrient management.

Finally, the IMPAC experiment will continue to provide future opportunities for learning and refining silvicultural systems in the context of meeting societal goals for practicing sustainable management. In 2009 the entire IMPAC study was harvested and all plots were remonumented with the goal of following the growth and development patterns over a second rotation. The entire experiment will be replanted with a single full-sib loblolly pine family that is responsive to silvicultural treatments. One-half of the study will remain untreated to quantify any legacy or "carryover" effects of past silvicultural treatments on second rotation site productivity. A second objective will focus on examining the sustainability of intensive forest management systems. To address this question, the other half of the experiment will receive the same historical silvicultural treatments to their respective plots, and various ecosystem metrics such as aboveground carbon gain and soil carbon dynamics will be monitored over time. More than most enterprises, forest management is a long-term undertaking. Although short-term studies will always have their place, long-term, multirotation studies such as IMPAC are uniquely suited to provide the scientific underpinning of sustainable forest management.

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