NUTRIENT MANAGEMENT OF SOUTHERN PINES

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Abstract—Fertilization of slash (*Pinus elliottii* Engelm.) and loblolly pine (*P. taeda* L.) stands has increased dramatically over the last two decades. As a cost effective silvicultural tool, fertilization has been successfully applied for increasing forestland productivity. Effective operational use of fertilizers relies on a variety of diagnostic systems to identify site nutrient status and potential responsiveness of candidate stands. General principles of forest nutrition, including guides for implementing fertilization prescriptions, are discussed.

INTRODUCTION

In the southeastern United States the dominant plantation species are slash (*Pinus elliottii* Engelm.) and loblolly pine (*P. taeda* L.), occupying approximately 13 and 30 million acres, respectively (Sheffield and Knight 1982; Sheffield and others 1983). The productivity of these even-aged, single-species plantations can be influenced by a wide spectrum of processes, including soil nutrient supply, genetics, and pest dynamics (fig. 1). Early site occupancy and the development of a large and functioning leaf area represent important strategies for enhancing pine productivity, and fertilization is one of the most cost-effective silvicultural treatments that forest landowners can apply to increase growth rates and financial returns. As many forest soils throughout the South tend to be infertile, fertilizers are commonly applied to southern pine stands at-time-of-planting and at mid-rotation (6 to 15 yr) to enhance and sustain rapid tree growth. Recent statistics suggest that the area of southern pine stands receiving fertilizer additions in 2001 was about 1.3 million acres, down slightly from an annual peak of 1.5 million acres in 1999 (NCSFNC 2002). Levels of financial return associated with fertilizer applications depend on the magnitude and duration of growth responses, costs associated with the fertilizer investment, and product values. It is safe to say that the potential productivity of most sites in the South is not being realized, and that nutrient limitations are largely responsible.

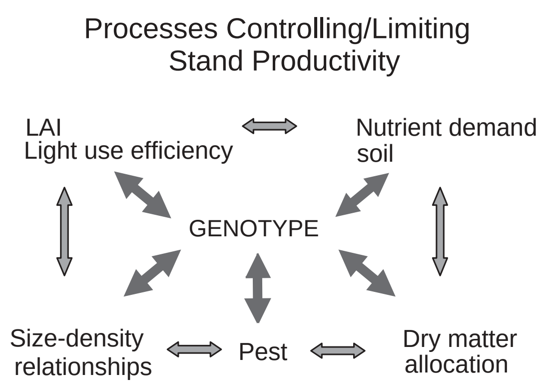

Figure 1—Processes and interactions that affect the productivity of southern pine stands.

Effective operational use of fertilizers requires diagnostic systems, used individually or in combination, which accurately identify site nutrient status, needs, and potential responsiveness. Soil classification, visual criteria, foliage and soil testing, and growth and yield models can all aid decision making. Each of the methods has operational advantages and limitations because of differences in reliability, costs, and technical skills required for application (see Pritchett and Comerford 1981; Jokela and others 1991a; Amateis and others 2000). Understanding stand development dynamics and interactions among silvicultural treatments can also aid interpretations and the evaluation of treatment efficacy (Albaugh and others 1998; Jokela and Martin 2000). This paper addresses issues of soil fertility, growth-limiting nutrients, and fertilizer recommendations for slash and loblolly pine. Although many of the principles discussed in this paper are applicable across the South for these species, emphasis will be placed on lower Coastal Plain sites of Florida and Georgia where both slash and loblolly pine are commonly planted.

PRINCIPAL DIAGNOSTIC TOOLS

Soil Groups

As a diagnostic tool, soil descriptions are commonly used for characterizing and classifying sites as potential candidates for forest fertilization. Soil groupings, based on easily recognizable features, are used to identify sites where available nutrient supplies are low, or where other site factors (for example, moisture availability) influence growth. CRIFF soil groups (A-H), defined using soil drainage, texture and depth of the subsurface soil layers (Fisher and Garbett 1980; see also description in Fox 2004; Jokela and Long 2000) have found application in guiding operational fertilization efforts in the South. Average stand responses to fertilizers differ significantly among soil groups and, in some cases, knowing the soil type (for example, CRIFF A) is adequate for making fertilization decisions and estimating

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Citation for proceedings: Dickens, E.D.; Barnett, J.P.; Hubbard, W.G.; Jokela, E.J., eds. 2004. Slash pine: still growing and growing! Proceedings of the slash pine symposium. Gen. Tech. Rep. SRS-76. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 148 p.

response. In other cases, responses may vary significantly within a soil group, indicating that current groupings oversimplify important factors influencing response, and that additional information is necessary to increase prediction accuracy. Soil maps have been prepared for many industrial lands and they have been broadly integrated and applied to aid management decisions on a variety of issues such as management intensity, fertilization rates, species selection, site preparation, site quality (productivity classes), and disease hazard ratings.

Foliar and Soil Testing

Chemical analyses of soils and foliage have been widely used to evaluate the potential response of sites to fertilizer treatments. These techniques are based on the assumption that a stand will respond to an added nutrient when foliar or soil concentrations fall below established critical levels. The reliability of these techniques increase as the similarity between the candidate stands and reference stands used to derive the relationships increase. Although critical foliage nutrient concentrations have been published for southern pines (table 1), they are not known with any exactness, especially for elements other than N and P. Hence, they are used principally as qualitative guides. Variation in nutrient levels due to foliage age, sampling position within the crown, sampling date and analytical procedures can complicate interpretations, particularly when values are near the critical levels. Standardized sampling (for example, dormant season, upper third of the crown, fully elongated current-year needles) and analysis procedures are, therefore, essential for successful use of either foliar or soil analysis. The critical level concept further assumes that other elements are not limiting. Experience has revealed that multiple nutrient deficiencies can exist on some sites (see discussion below), and that evaluating the balance of nutrients can improve diagnostic capabilities (Comerford and Fisher 1984; Adams and Allen 1985).

Table 1—Foliar nutrient guidelines (minimum) for southern pines

Nutrient	Slash pine	Loblolly pine
	- - - - - - - - - percent - - - - - - - - -	
N	1.0	1.2
P	0.09	0.12
K	0.25 – 0.30	0.30
Ca	0.08 – 0.12	0.15
Mg	0.06	0.08
S	0.08	0.10
	- - - - - - parts per million - - - - - -	
B	4 – 8	4 – 8
Zn	10 – 20	10 – 20
Cu	1.5 – 3	2 – 3
Mn	20 – 40	20 – 40
Fe	15 – 35	20 – 40

Source: Allen (1987); Pritchett and Comerford (1983); Wells and others (1973).

Visual Symptoms and Fertilizer Field Trials

The inherent appeal of using visual symptoms for guiding fertilizer prescriptions reside in the potential simplicity of making quick field diagnoses without the need for laboratory determinations. Foliar discoloration (chlorosis, necrosis), needle twisting, irregular branching patterns (e.g., lack of apical dominance (fig. 2), premature needle fall, and dieback of young shoots are among the variety of symptoms used to describe nutrient deficiencies in conifers (Stone 1968). However, as multiple nutrient deficiencies (for example, N, P, K, micronutrients) are possible in southern pine stands, foliar analyses are often used in conjunction with visual symptoms and soil groups to confirm initial interpretations. To be reliable, visual criteria must be calibrated with stand response data.

Over the last decade, interpretations of what is considered “normal growth” among land managers have also changed dramatically. Prior to the implementation of intensive silvicultural growing systems, that include improved seedling quality, proper planting techniques, superior genotypes, site preparation, competition control and fertilization treatments, expectations were that 3-yr-old trees would average

Figure 2—Copper deficiency in young loblolly pine growing on a sandy Spodosol in north central Florida. Note: deficiency is expressed in lack of apical dominance of the terminal and leading lateral shoots.

about five ft tall. Currently, when using a variety of the treatment combinations listed above, it is not uncommon to have stands average 10 to 12 ft tall during the same time period. These well-established plantations also tend to be quite uniform in height and character across the site.

Experimental field trials have undoubtedly been the most reliable approach for estimating fertilizer responses. The fertilizer rate-growth response relationships commonly used today were largely developed through regional experiments established by cooperative forest research programs involving forest industry and southern universities (for example, University of Florida, North Carolina State University). In addition, operational monitoring plots have been used by many companies to corroborate suspected nutrient deficiencies and to estimate growth responses on a variety of soil types. These "in-house" plots, that include replicated fertilized and non-fertilized treatments (strips), are monitored over time, and their results are incorporated into geospatially based maps.

Response Models

A variety of models (primarily for mid-rotation aged stands) have been developed for slash and loblolly pine that relate tree and stand level responses (for example, dominant height, basal area, stand volume) to fertilization. Predictor variables have included site index, soil drainage class, fertilizer treatment, stand age, number of surviving trees and dominant height at time of treatment (Bailey and others 1989; Martin and others 1999; Amateis and others 2000). Response models, based on site and stand conditions, predict average growth responses for broad site types and can be useful for identifying potentially responsive stands, and selecting appropriate fertilizer treatments. Independent field testing and calibration by users is still required, however, as empirical models may not accurately account for changes in future conditions.

Process-based computer simulation models are also becoming available to aid site-specific fertilizer decisions by forest managers. The SSAND (Soil Supply and Nutrient Demand) model, for example, was recently developed at the University of Florida to diagnose nutrient limitations and determine fertilization regimes necessary to achieve preset stand production goals (Adegbidi and others 2002). With this type of model, the user determines a desired level of productivity. Simulations of soil nutrient supply, based on input variables, are compared with the stand nutrient demand estimates. If stand nutrient demand exceeds soil supply, fertilization regimes can be tested to determine the most efficient treatment for meeting production goals and plant nutrient demands.

RATES OF FERTILIZER APPLICATION

Fertilizer recommendations for southern pine stands have not been determined as precisely as those for agronomic crops. Rapidly growing southern pine stands place high nutrient demands on the soil, especially during the early stages of canopy development. Yet, few estimates of uptake exist for such stands, but these data are critical for quantifying plant nutrient demands and developing fertilizer prescriptions based on soil nutrient supply. Recently, Adegbidi and others (2003) reported that rapidly growing (aboveground biomass ~16 tons per ac) 4-yr-old loblolly pine stands (CRIFF C soils) had accumulated about 175 lbs N per ac and 20 lbs P per ac, with the crown (foliage, branches) being the dominant pools (52 to 59 percent) for these elements. About 23 percent of the N and 29 percent of the P was accumulated in roots. Cation (K, Ca, Mg) accumulations were also highest in the aboveground components (~50 percent). Approximately 77 lbs per ac K, 65 lbs per ac Ca, and 25 lbs per ac Mg had accumulated in the total tree biomass by age 4 yr. In contrast, Colbert (1988) reported that aboveground nutrient accumulations were considerably lower for extensively managed, slow-growing (aboveground biomass ~ 1 ton per ac) loblolly pine stands on similar soils. For example, aboveground accumulations of N, P K, Ca, and Mg at age 4 yr averaged about 9, 1, 3.5, 3, and 2 lbs per ac, respectively. These results clearly indicate that rapidly growing stands place correspondingly higher levels of demand on soil nutrient pools and, in comparison to extensively managed stands, will require more frequent fertilizer additions to sustain high levels of production. Frequent removal of pine straw from the site may also necessitate the need for more frequent additions of fertilizers (Morris and others 1992).

When developing fertilizer prescriptions, practitioners must be aware that past management practices will influence both the timing and rates of future fertilizer treatments. In addition, trees are generally inefficient in terms of fertilizer recovery. For example, Fisher and Binkley (2000) suggested that less than 25 percent of the fertilizers applied to forest stands are taken up by trees, with about 25 percent being immobilized in soil microbes and organic matter, and an equally large but variable pool being lost through volatilization and leaching. Removal of understory vegetation may improve nutrient retention by the trees and additional research is required to determine if low application rates or repeated applications substantially improve fertilizer recovery by trees.

Described below are fertilizer recommendations commonly used across a variety of soil types in the Coastal Plain of Florida and Georgia. Treatment rates are presented for both young and established (after crown closure) stands and it is assumed that the stands have received effective understory competition control treatments at establishment. As with any silvicultural treatment, local conditions may cause results to deviate from those reported here. Therefore, the recommendations listed below should be used as general guides only. For example, as additional nutrient ramping studies are completed with southern pines, the sequence and amount of fertilizers required to sustain desired growth rates may change. Also, variable timber markets will directly affect the economic viability of different treatment regimes.

Phosphorus plus N, and P alone, are the nutrient elements that tend to be the most widely applied to southern pine stands. Application of N alone is not generally recommended in young stands because it often stimulates competing vegetation. In some cases, K and other macronutrients may also limit growth once N and P demands have been met (table 2). The fertilizer rate prescription ratio for southern pines is approximated as 100:10:35 (N,P,K). Similarly, examples of micronutrient deficiencies have been documented

Table 2—Recommended fertilizer application rates (elemental – pounds per acre) for loblolly and slash pine when diagnosed as limiting for growth

Species	Stand phase	N	P	K	Ca, Mg, S, B, Cu, Mn, Fe[a]
Loblolly	At planting	40 – 50	25 – 50	50 – 80	As needed based on foliar analysis (table 1) or other diagnostics
	Canopy closure	175 – 200	25 – 50	50 – 80	As above
Slash	At planting	40 – 50	25 – 50	50 – 80	As above
	Canopy closure	150 – 200	25 – 50	50 – 80	As above

[a] Approximate application rates based on stand needs: 25 to 40 pounds Ca per acre, 25 pounds Mg per acre, 25 to 40 pounds S per acre, 0.5 to 1 pound B per acre, 3 to 5 pounds Cu per acre, 3 to 5 pounds Mn per acre, and 10 to 15 pounds Fe per acre.

Source: Allen (1987), Jokela and others (1991), South and others (2003).

(for example, B, Cu, Mn, Zn) in southern pine stands, and are often induced when intensive silvicultural practices accelerate early stand growth. It should be noted that recommended fertilizer application rates for micronutrients are not known with any exactness and care should be taken to avoid possible toxicities in southern pine stands. For example, elemental application rates of B should not exceed about 1 lb per ac.

CRIFF A AND B SOILS (Very Poorly to Somewhat Poorly Drained - Bays and Wet Savannas)

These soils are typically found in nearly level depressions, stream terraces, and broad wet flats. Excessive soil moisture and lack of available P commonly limit pine growth. Without adequate P nutrition, the pines often are no more than 40-45 feet in height after 25 years, and the stand leaf area is very sparse and consists of short, yellowish needles.

Young Stands

Fertilization with P or a combination of P and N is recommended at planting and growth responses can be dramatic on these soils. Yield differences of 2-3 fold have been documented following fertilization. For example, a 25-yr-old slash pine stand growing in the Panhandle of Florida produced about 4500 ft^3 per ac of wood with fertilization (50 lbs per ac P) compared to 2040 ft^3 per ac without fertilizer additions (Jokela and others 1989). Delaying fertilizer applications on such sites will cause significant growth losses.

If these sites have never had a history of fertilizer applications, approximately 40 to 50 lbs per ac of elemental P and 40-50 lbs per ac of elemental N are recommended rates. The superphosphates are the principal P fertilizers used when only P is required (triple superphosphate (0-44-0) and normal superphosphate (0-20-0). If a combination of N and P is desired, diammonium phosphate - (DAP) (18-46-0) represents an excellent fertilizer choice. An application rate of 250 lbs per ac DAP would, for example, provide an elemental equivalent of 45 lbs per ac N and 50 lbs per ac P. If stands growing on these soils received P applications late in the previous rotation, then 125-150 lbs per ac DAP would be applied at establishment.

When used in conjunction with N + P fertilization, herbaceous weed control treatments can augment pine growth responses on these soils. Results recently showed that volume growth of 8-yr-old loblolly pine stands growing on A group soils averaged 713 ft^3 per ac when no fertilizer or weed control treatments were applied (Jokela and others 2000). In contrast, volume was doubled (1430 ft^3 per ac) when herbaceous weed control was combined with 250 lbs per ac DAP. Volume growth for the fertilizer and herbaceous weed control treatments, when applied alone at planting, averaged 1202 ft^3 per ac and 803 ft^3 per ac, respectively. It is clear that on these soils weed control alone did not elicit much growth response, presumably because of the overarching limitations due to P deficiency.

Established Stands

Fertilizer requirements for older stands are based on the same principles as young stands. However, it is often more difficult to predict the need for fertilizers in older stands because deep root penetration may allow absorption of nutrients from subsoil horizons, even though surface horizons are low in available nutrients. Surface layers of organic debris (for example, pine needles) also serve as a nutrient reservoir, and can release nutrients for the pines as the material slowly decomposes (Polglase and others 1992). Deficiencies of N and P are most pronounced following crown closure. Decomposition processes generally slow down and nutrient availability decreases because they are immobilized in the stem, bark, branches, roots and foliage of the pines and understory plants.

Fertilization with combinations of N and P are recommended for closed canopy stands. The combined elemental treatment gives larger and more consistent responses than either element applied alone. Application rates of approximately 150 - 200 lbs per ac elemental N and 25 lbs per ac elemental P at about age 10 on A group soils and about 6-8 years on the sandier textured B group soils will usually result in growth responses averaging 50 ft^3 per ac per yr or more. Fertilizer responses normally last for about 6 - 8 years. Although N application rates above 200 lbs per ac (with P) can result in higher levels of growth response, they are not generally economically justifiable on most soils. Common fertilizer sources would include DAP, superphosphates, and urea.

Evidence from six fertilizer trials suggested that land managers have flexibility in applying fertilizers either as a single or split mid-rotation fertilizer treatments without impacting the biological magnitudes of response or longevity (Jokela and Stearns-Smith 1993). For example, if 200 lbs per ac N and 25 lbs per ac P was the recommended treatment, it could be applied at age 10 years as a single combined treatment (DAP + urea). Alternatively, 125 lbs per ac DAP (equivalent to 22.5 lbs per ac N + 25 lbs per ac P) could be applied at age 10 years with a follow-up urea treatment (178 lbs N per ac; 395 lbs per ac urea) within 2 years. The split N treatment has the potential to provide economic benefits because a significant portion of the capital costs of fertilizer can be postponed for up to 2 years, and thereby reduce the total carrying costs over the investment period. It should be noted that mid-rotation fertilizer applications that include urea are generally recommended for all soils between January and May to avoid volatilization losses of N. In addition, if the stand is being managed for sawtimber, a second mid-rotation fertilizer application (150-200 lbs per ac N + 25 lbs per ac P) would typically be prescribed the year after thinning to sustain acceptable growth rates until rotation age is achieved. The actual age for the thinning treatment will vary among sites, but commonly occurs when merchantable height of the stand is > 40 ft.

CRIFF C AND D SOILS (Very Poorly to Moderately Well Drained - Flatwoods Spodosols)

The Flatwoods represent one of the most extensive groups of forest soils in the Coastal Plain. The somewhat poorly to moderately well drained C and D group soils (Spodosols) developed in coarse textured sediments (acidic, sand to loamy sand texture) low in native fertility. Nitrogen and P fertilizer additions commonly elicit significant growth response in both slash and loblolly pine stands.

Young Stands

Fertilizer and herbaceous weed control treatments applied alone or in combination at time of planting can significantly increase pine growth on C and D group soils. These soils tend to be deficient in both N and P, although levels of K and micronutrients (B, Mn, Cu and Zn) are also in marginal supply. Broadcast applications of approximately 200 to 250 lbs per ac DAP (40 to 50 lbs per ac elemental N and 40 to 50 lbs per ac elemental P) represents the most common treatment for these soils if the sites have not previously received fertilizer additions. Pre-plant chemical site preparation or herbaceous weed control treatments applied in the spring of the first growing season can also enhance the probability and magnitude of growth responses derived from fertilizer applications. Loblolly pine, because of higher nutrient demands, has generally been more responsive than slash pine to fertilizer and weed control treatment on these soils. For example, 8th year volume response of loblolly pine on C and D group soils averaged 32 percent when 45 lbs per ac N + 50 lbs per ac P was applied at planting (Jokela and others 2000). Growth responses to the combination treatment of fertilizer + herbaceous weed control averaged 52 percent. Slash pine treatment responses were generally smaller in magnitude and averaged 10 percent for the combined treatment.

With the application of more intensive management systems, foresters must recognize that rapid growth rates can result in induced deficiencies (dilution effects) of other elements (for example, micronutrients) on these sandy soils, and periodic monitoring is warranted to avoid subacute deficiencies (fig. 2). Subacute deficiencies of Mn, Cu, B, and Zn on CRIFF B, C and D group soils appear to be easily corrected from a single application of a needed micronutrient at time of planting, and it may suffice for the entire rotation. For example, slash pine responses to Mn additions averaged 32 ft^3 per ac per yr above the control over 16 years (Jokela and others 1991). If deficiencies of K and micronutrients are suspected, on the basis of soil or foliar tests, a mixed fertilizer such as 10-10-10 + micronutrients should be applied at rates of 500 to 600 lbs per ac rather than the DAP treatment. Custom blended fertilizers, that contain both macro- and micronutrients, are also an option.

Established Stands

Older southern pine stands (post crown closure) growing in the Flatwoods are commonly deficient in both N and P. Typically, these sites are fertilized at about age 6 years with 150 lbs N per ac and 25 lbs P per ac. Growth responses average approximately 55 ft^3 per ac per yr when both N and P are applied. Note that the application of N or P alone is not recommended on these soils because growth responses have been largest and most consistent to the combined N + P treatment. Fertilizer responses on these soils commonly persist for 6-8 years. A second mid-rotation application of N and P (200 N, 25 P per ac) may be applied at age 12-13 years to sustain growth through rotation (perhaps following the first thinning). The most common fertilizer sources used for this prescription are a combination of DAP and urea. Where K is deficient, it should be included in the fertilizer program at rates ranging from 50 to 80 lbs K per ac. Common K fertilizer sources would include KCl (muriate of potash), KSO_4 or a mixed fertilizer material. A foliar test should be used to confirm suspected deficiencies of these elements, including micronutrients.

CRIFF E AND F SOILS (Moderately Well to Well Drained - Uplands)

These Coastal Plain soils are found in upland areas and range from relatively deep, moderately well-drained sands to well-drained loamy sands and sandy clays. Many of the existing stands planted on these soils were established on abandoned farmlands, which have been seriously eroded. Unless the site has been in recent agricultural production, these soil groups tend to be naturally deficient in N and P.

Young Stands

These upland soils often receive combinations of mechanical tillage and chemical site preparation treatments. With good initial weed control, pine stands would typically receive N and P fertilization (100-150 N per ac, 25 P per ac) at about age 5 years. In some cases, DAP (200 lbs per ac) applications are made at establishment and the efficacy of fertilizer additions are enhanced when combined with herbaceous weed control. For example, when compared to untreated plots, 8th year loblolly pine volume on E group soils averaged 33 percent more on plots receiving 45 lbs per ac N + 50 lbs per ac P (DAP – 250 lbs per ac), and 53 percent more on plots that received the same fertilizer treatment + herbaceous weed control (Jokela and others 2000).

Established Stands

Nitrogen and P tend to be the most limiting nutrients for loblolly pine on upland sites, although K and micronutrient deficiencies may also exist. Foliar analysis is recommended to delineate deficient areas among older stands (post crown closure). Where a deficiency is indicated, elemental application rates of 200 lbs N per ac and 25 lbs P per ac are recommended, often at about age 12 to13 years (assuming earlier treatment at age 5 to 6 years). On responsive sites, especially those that have a well-developed, shallow, clayey subsoil, volume gains due to fertilization can range from 70 - 90 ft^3 per ac per yr and persist for 6 to 8 years. A second mid-rotation fertilizer treatment may be warranted on sites being thinned and managed for sawtimber production.

CRIFF G SOILS
(Excessively Drained - Sandhills)

Extensive areas of deep sands, with little soil profile development, occur in north Florida, Georgia and the Carolina Sandhills. These soils often formed on former sand dunes and beach ridges. Sand pine (Florida) and longleaf pine are commonly planted on these soils. Management practices that conserve organic matter are recommended for these soils. As water deficits and competition generally limit pine productivity, intensive management that includes fertilizer applications are not generally recommended for these soils.

CRIFF H SOILS
(Very Poorly Drained - Depressions)

Soils of the H group are typically found in isolated, very-poorly drained depressions throughout the savannas and flatwoods (for example, cypress ponds or strands, bottomlands along rivers). They contain high levels of organic matter in the surface horizon, with little or no sand or clay present. Excessive wetness and frequent flooding, due to landscape position, limit their potential for intensive pine plantation management and forest fertilization is rarely recommended.

APPLICATION METHODS

The method of application (in other words, banding vs. broadcast) does not appear to affect growth responses to fertilization. Factors such as equipment availability, costs, terrain, uniformity of spread, and timeliness of the operation should be considered when formulating a prescription. Banding involves selective fertilizer placement, usually 3-4 ft wide over the recently planted row of trees. By comparison, broadcast methods spread fertilizers in swaths across the entire stand. Tractor-mounted spreaders are suitable for easily traversed areas, whereas rubber-tired skidders equipped with fertilizer spreaders or aerial application systems (helicopter, fixed-wing) may be more effective on wet or rough sites. Regardless of the application method, uniformity and rate control are important. Unequal distribution of fertilizers may contribute to irregular growth patterns. Therefore, care should be exercised in applying fertilizers, particularly when micronutrient additions are made because they are applied in only modest amounts across the site.

FERTILIZATION EFFECTS ON SITE AND STAND PROPERTIES

Fertilizer additions can result in both short and relatively long-term changes in site and stand properties. Several long-term experiments have been established and maintained throughout the South, and they have been invaluable in understanding the effects of intensive management on stand dynamics. Results from one such trial series established on a CRIFF C group soil (Spodosols) in north central Florida will be used to illustrate these effects for both slash and loblolly pine. At this location, rotation-long nutrient management (macro- and micronutrient additions) was practiced, along with understory competition control (Jokela and Martin 2000). In general, growth responses to the various nutrient amelioration treatments were immediate, obvious and directly related to the intensity of management inputs (fig. 3). Stemwood growth responses were driven by large increases (2x) in LAI. Without nutrient additions or competition control, slash pine generally outperformed loblolly pine. The opposite was true, however, under an intensive management regime.

Fertilizer induced growth responses were associated with temporary increases in site quality and accelerated patterns of stand development. For example, when measured at age 18 years, site index varied from 58 to 82 for loblolly pine and from 72 to 84 for slash pine for the control (C; bedded and planted) and combination fertilizer plus weed control (FW) treatments, respectively. The levels of basal area supported on this unthinned site were also directly related to management intensity. The upper levels of basal area, hence stand density, accrued on the FW treatment was 193 ft^2 per ac for loblolly pine compared to 82 ft^2 per ac for the control (C) treatment. In contrast, basal area levels for slash pine were lower than loblolly pine on the FW treatment (168 ft^2 per ac), but comparatively higher on the C treatment (97 ft^2 per ac) (fig. 4). Culmination of stemwood mean annual increment for both species occurred at age 13 years for the FW treatment, but had not reached a maximum on the C treatment at age 18 yr. Hence, fertilization not only increased stand yields, but also shortened the rotation length and increased stand value. These effects were especially evident in the diameter distributions for each treatment (fig. 5). Fertilization significantly improved stand value by increasing the proportion of "grade" material produced. For example, the C treatment had 17 percent of the stems in 9-12 inch trees compared to 48 percent for the FW treatment. It should be noted that density control treatments, such as thinning, will be required sooner in fertilized stands to avoid reductions in diameter increment due to overstocking and selfthinning.

CONCLUSIONS

Large gains have been made in the South over the last two decades in identifying responsive sites for forest fertilization. Site classification is central to the wise use of fertilizers in forest stands. The development of cost-efficient, biologically sound fertilizer prescriptions will require integration of site, stand, and economic considerations. To aid site-specific

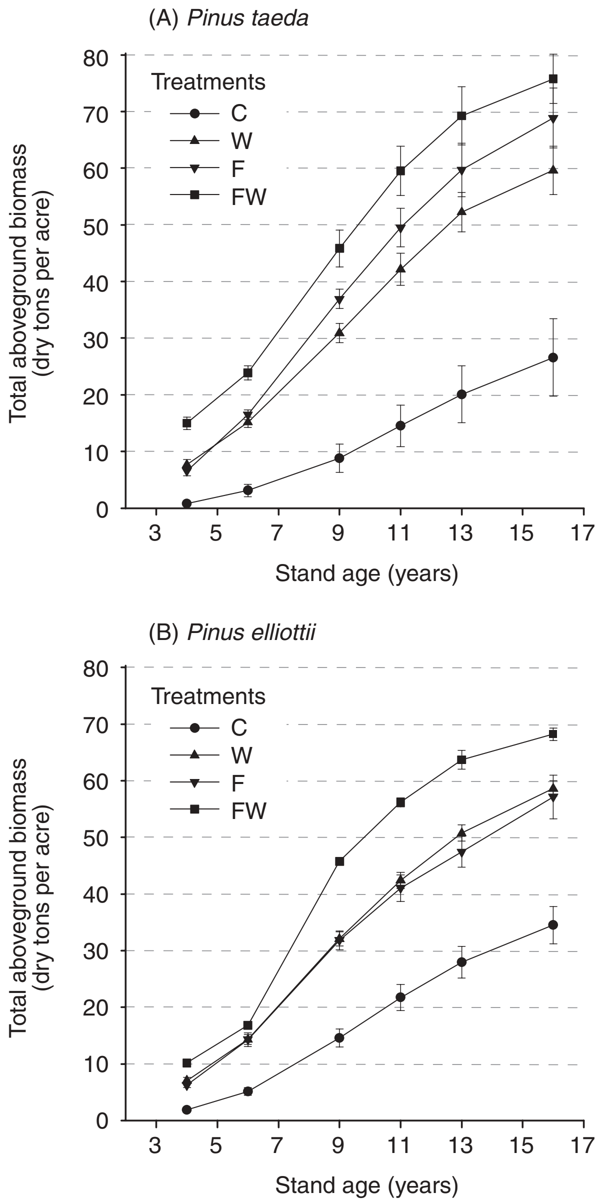

Figure 3—Standing aboveground biomass vs. stand age for control (C), weed control (W), fertilization (F) and combination (FW) treatments for loblolly and slash pine growing on Spodosols in north central Florida. Each point is the mean of three replicate plots, along with standard errors.

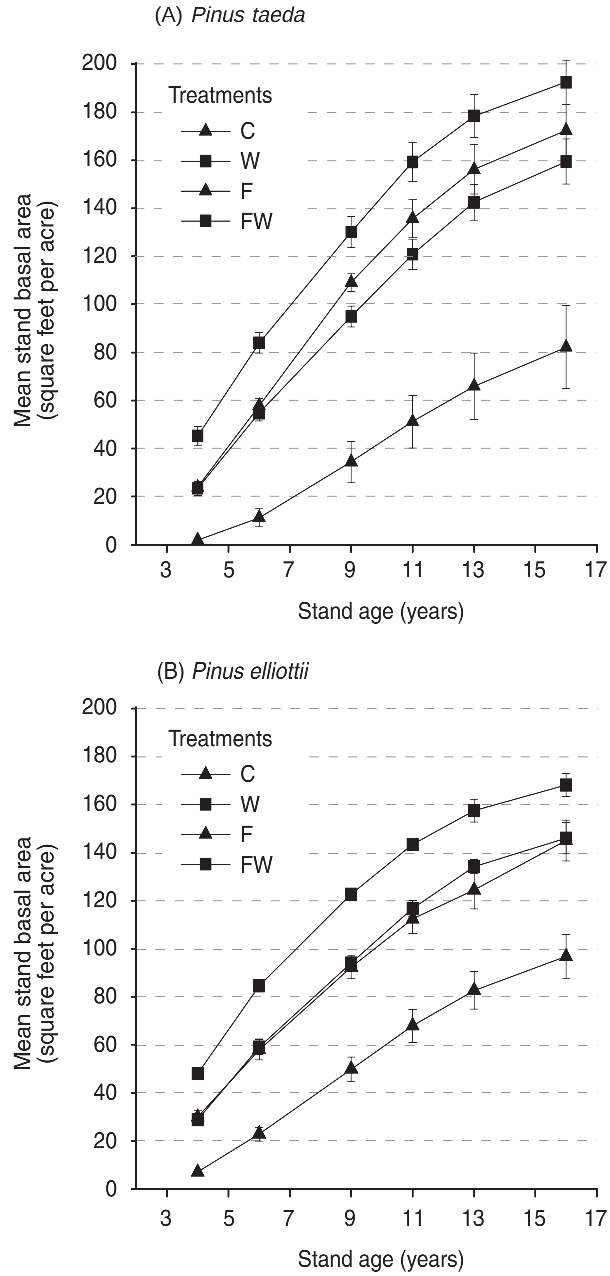

Figure 4—Basal area accretion vs. stand age for control (C), weed control (W), fertilization (F) and combination (FW) treatments for loblolly and slash pine growing on Spodosols in north central Florida. Each point is the mean of three replicate plots, along with standard errors.

fertilizer prescriptions in the future, additional technological advances will be required to improve the accuracy of diagnosing nutritional problems and accurately predicting stand responses. For example, a better understanding of soil nutrient supply (immobilization, retranslocation, mineralization) in relation to stand nutrient demand would aid both the timing and quantity of fertilizer applications necessary to sustain a desired level of growth. Intensive management and rapid growth rates may also induce (dilution) multiple nutrient limitations, especially during the early stages of stand development. As such, multiple element fertilization may be necessary in southern pine stands, and additional research on nutrient balance, especially for elements other than N and P, will be required to support management applications. Finally, in order to achieve continued success in managing the nutrition of southern pine stands, foresters will require not only technical skill for developing prescriptions, but also appreciation of other environmental and silvicultural interactions with forest fertilization (for example, pest management, understory competition, wood properties, water quality).

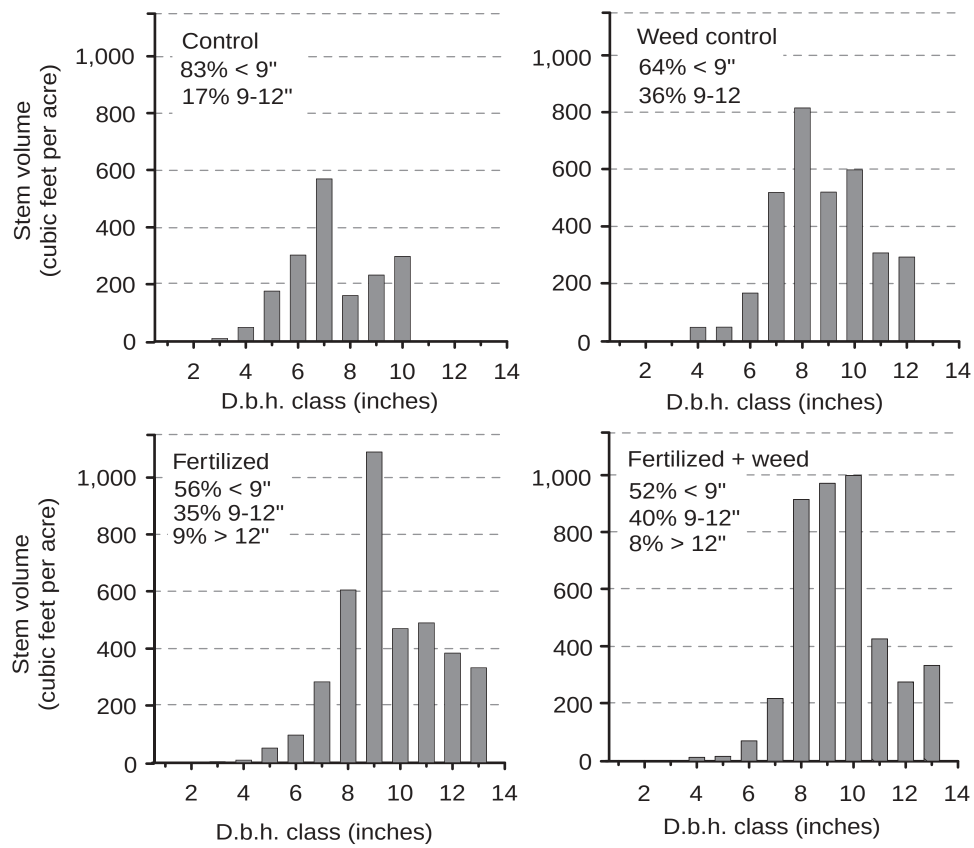

Figure 5—Effects of silvicultural treatments on the distribution of stem volume by diameter class for 18-year-old loblolly pine growing on Spodosols in northcentral Florida. Trees < 9 inches were considered pulpwood; trees 9 to 12 inches were considered chip&saw; and trees > 12 inches were sawlogs.

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