Chapter 14

Fertilization of Southern Pines at Establishment[1]

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Abstract
14.1 Introduction
14.2 Nutrient Requirements
14.3 Economic Justification for Fertilization
14.4 Identifying Fertilizer-Responsive Sites
14.5 Fertilizer Technology
14.6 Silvicultural Interactions With Fertilization
14.7 Other Considerations in Fertilization
14.8 Conclusions
References

Abstract

Fertilization is a silvicultural practice used for increasing forestland productivity in the southern U.S. Effective operational use of fertilizers requires diagnostic systems, used individually or in combination, that accurately identify site nutrient status, needs, and potential responsiveness. Interactions of fertilization with other silvicultural practices such as site preparation and genetic tree improvement, and impacts of fertilization on pests, wood quality, and the environment, must be accounted for if fertilizer prescriptions are to be biologically effective and economically justified. This chapter introduces important concepts of forest nutrition and provides guidelines for fertilizing young, intensively managed southern pine plantations.

14.1 Introduction

Fertilization is a silvicultural practice used for increasing forest productivity, typically in intensively managed plantations of loblolly *(Pima taeda* L.) and slash *(Pinta elliottii* Engelm.) pine, in the southern United States (U.S.). Most trees are fertilized at the time of planting or at midrotation. As of 1987, over 0.5 million ha of loblolly pine and 0.3 million ha of slash pine had been fertilized [2], most by forest industry. Operational fertilization programs for other pine and hardwood species are virtually nonexistent.

Industrial forest research programs and the university-industry cooperatives located at the University of Florida (CRIFF, Cooperative Research In Forest Fertilization) and North Carolina State University (NCSFNC, North Carolina State Forest Nutrition Cooperative) have developed much of the fertilizer technology in this region [4, 24]. Operational fertilization recommendations have been developed from 20+ years of research and extensive field trials [3, 11, 85, 87, 112].

General principles of forest nutrition, practices used in diagnosing nutrient deficiencies, and guides for implementing fertilization prescriptions are discussed in this chapter. Attention is focused on forest fertilization near time of planting (trees <5 years old) for slash and loblolly pine because information is most abundant and operational fertilization programs are most common for these species in the South.

14.2 Nutrient Requirements

14.2.1 Stand Demand Versus Supply

Nutrient requirements within trees are principally met by uptake from the soil and mechanisms of internal transfer (remobilization). Nutrients in young stands may be limiting when nutrient levels within the rooting zone are insufficient to meet growth demands of trees. This assumes, however, that other site resources for tree growth (e.g., water, temperature, and light) are adequate. The quantity of nutrients in the soil and amount taken up by plants depend on factors including the concentration (activity) of nutrient ions in soil solution, rates of soil weathering, inputs from and losses to biological and atmospheric sources, amounts and turnover rate of organic matter, moisture content, soil texture and structure, extent and morphology of a seedling's root system, and mycorrhizal associations.

The demand for soil nutrients varies according to tree species and stage of stand development. However, demand usually is greatest when crowns are rapidly expanding, typically just before culmination of current annual volume increment. Relatively large quantities of nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca) are required at this time (Fig. 14.1). As stand development proceeds and wood formation becomes dominant, net uptake of these elements is greatly reduced, depending on genotype, initial stand density, tree mortality, or intermediate stand treatments such as thinning.

In one study, nutrient uptake for slash pine peaked by

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[1] Florida Agricultural Experiment Station Journal Series No. 10044.

M.L. Duryea & P.M. Dougherty (eds), Forest Regeneration Manual, pp. 263–277.

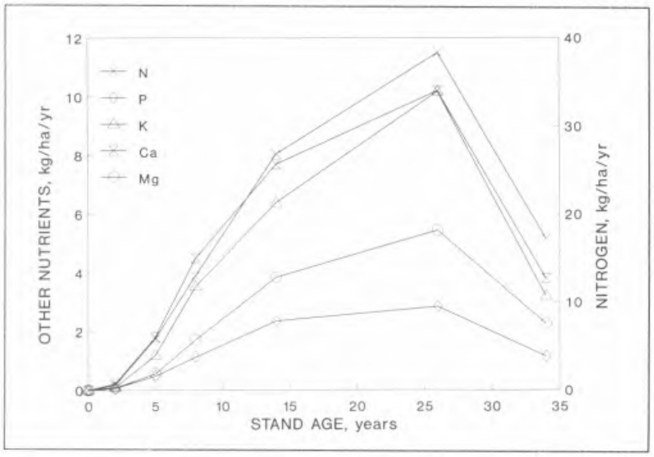

Figure 14.1. Annual levels of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) required for producing new slash pine foliage and twigs (adapted from [37]).

age 8 years and then decreased steadily [37]. These researchers hypothesized that P nutrition becomes the major limitation to pine production on many sites in the Lower Coastal Plain. Slow litter-decomposition rates and low availability of soil P for plant uptake require that trees rely on internal redistribution of nutrients to sustain growth. If these processes cannot supply adequate nutrition, needles will be lost prematurely and productivity will subsequently decline.

Nutrient availability, at least in the short term, is greatest immediately following outplanting or other site disturbances that increase rates of litter decomposition and the release of organic-bound nutrients for uptake or leaching. In newly established stands, the need for fertilization may arise when levels of available soil nutrients are low and the soil volume exploited by roots is still small. Such a situation characterizes many poorly drained Lower Coastal Plain sites with low levels of native P. Moreover, as weed control treatments become more common and early growth rates and nutrient demands of crop trees increase, fertilizers may be necessary for maximum tree growth on all but the most fertile sites. It follows that forest stands are likely to respond to nutrient amendments after the initial flush of soil nutrients declines, but before internal cycling contributes substantially (if ever) to meeting a stand's potential nutrient demand.

14.2.2 Influence of Harvesting and Site Preparation on Nutrient Supply

For all but the most infertile soils, disturbances associated with harvesting and site preparation will increase the availability (through mineralization of organic residues and exposure of fresh mineral surfaces) of nutrients, particularly N, to levels in excess of those normally required by young seedlings [18, 34, 44, 78, 111]. Increased nutrient availability is evidenced on many sites by the luxurious early growth of herbaceous, grassy, or woody species that may compete with selected crop species for moisture, light, and nutrients. In many instances, rapid regrowth of what is considered competing vegetation may actually help retain nutrients on a site for later recycling and use by the crop species [26, 48]. Accelerated leaching of nutrients has been observed where regrowth of competing vegetation was controlled [111].

In the South, P is the most common nutrient limiting seedling growth because of low concentrations in soil solution, poor root-system development, or both. Typically, P deficiencies can be overcome by fertilization; however, artificial drainage can promote rooting and, in turn, increase the total quantity of P taken up by trees from the soil [63]. Where native P levels are adequate or P reserves are available in subsurface horizons, drainage or bedding may be all that is needed to accelerate early root growth and enhance the availability of P to seedlings [115].

Removing nutrient-rich forest floor and surface mineral soil during windrowing or piling may increase nutrient deficiencies [73, 78]. For example, intensive slash-disposal practices may aggravate P deficiencies on P-poor sites and substantially reduce early seedling growth [105]. Deficiencies of other nutrients, particularly N, resulting from windrowing typically do not become apparent until later in the rotation (after crown closure) because of enhanced mineralization and N availability following such disturbances.

14.3 Economic Justification for Fertilization

Fertilization represents an investment expected to generate a return — increased stand volume and value resulting from accelerated stand development — at some future point (see also chapter 2, this volume). However, value of the return depends on many factors, including responsiveness of the site (see 14.4.1); final tree size and product mix; stumpage price; tax treatment; fertilizer and capital costs; and strategic considerations including wood supply, land ownership, timber markets, confidence in treatment/risk analysis, and desire for future management flexibility.

Marginal investment analyses, using discounted cash flows, provide a means for comparing investment returns from various silvicultural practices. These analyses are particularly useful for short-term investment periods where little uncertainty exists concerning product mix and price structure. Determining the value of long-term investments, such as those associated with fertilization at planting, often depends upon response potential and strategic considerations.

Growth projections and economic analyses conducted on 13-year data from nine loblolly pine stands that were bedded, fertilized with P, or both indicated that these treatments can substantially increase volume production and the proportion of sawtimber-sized trees [36]. In this example, the net present value for the combined treatment (bedding and fertilization) was 2 and 3 times higher than that for either treatment applied alone. In such cases, the high probability of response and associated large potential gains in volume make fertilization and other early cultural treatments that improve site quality an attractive long-term investment. As more valuable products are included in the product mix (e.g., pulpwood, "chip and saw," and sawtimber) or as the value of pulpwood increases where demand is heavy, returns on fertilization investments may be even greater.

14.4 Identifying Fertilizer-responsive Sites

14.4.1 Biological Responsiveness

A stand's responsiveness to fertilization depends on how well the availability (supply) of nutrients meets the stand's existing or potential demand. The length of the response period varies according to the kind and amount of fertilizer applied, soil and climatic conditions, site preparation techniques used, and growth patterns of the species. For N, the period of maximum response is usually 1 to 3 years but may last up to 9 years. Trees are generally less efficient in utilizing added N than other nutrients, such as P or K, which are cycled more conservatively within the system [96]. Nitrogen not absorbed by trees may be immobilized in microbial tissues and understory vegetation or lost from the system through leaching and volatilization (gaseous losses).

For P, the period of response may last the entire rotation if native available P is limiting. Four reasons explain sustained P responses. First, the added P from fertilization may contribute significantly to the site's total P capital, elevating P availability throughout the rotation. Second, much of the added P enters and is cycled within the organic components of the site. Third, the added P may stimulate root proliferation and better utilization of native soil nutrient supplies which would remain unavailable to unfertilized stands. Finally, the added P may react with hydrous oxides of iron (Fe) and aluminum (Al) to form insoluble compounds that resist leaching, yet remain available for plant uptake.

On some poorly drained southeastern Coastal Plain soils, slash and loblolly pine responses to P fertilization have been dramatic, making the difference between a commercial stand and no stand at all [36, 84]. Volume gains averaging 3.5 m^3/ha/yr for 15 to 20 years are common, with individual responses exceeding 10 m^3/ha/yr in some cases. Amelioration of P deficiencies at time of planting has increased site index (dominant height) 2.5 to 4.5 m, or more, at 25 years. Although the largest responses to P fertilization have been associated with poorly drained Lower Coastal Plain soils, accumulating evidence indicates that many well-drained, uncultivated Coastal Plain sites are P responsive [2], especially when fertilization is combined with other cultural treatments (Fig. 14.2).

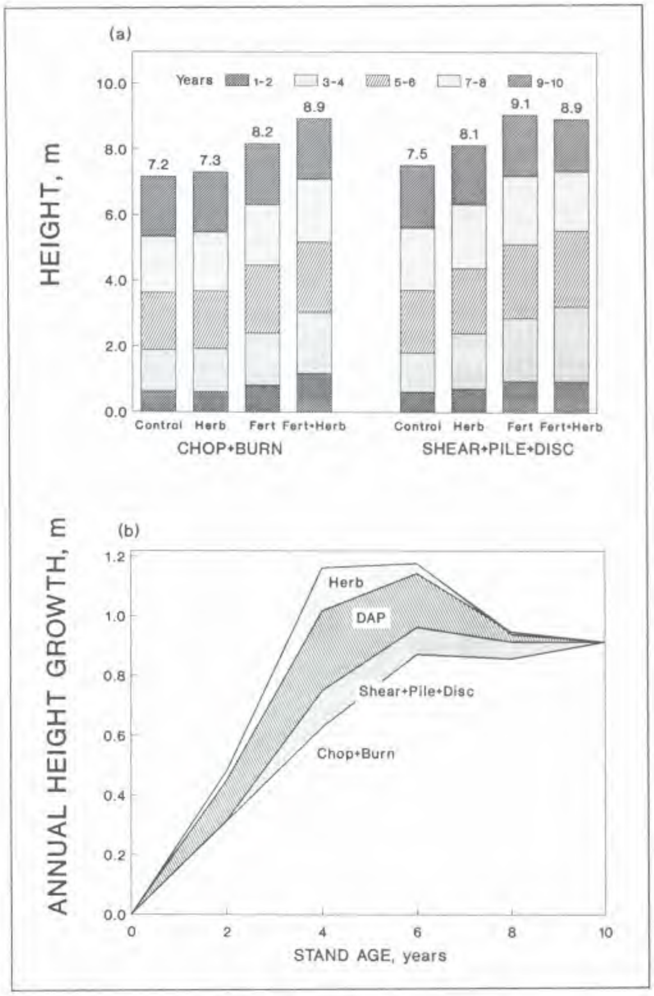

Figure 14.2. Effects of varying intensities and combinations of site preparation (chop and burn; shear, pile, and disc), fertilization (fert. 280 kg/ha of DAP, diammonium phosphate), and weed control (herb, 2 years banded application of VELPAR) on cumulative 10-year height growth (a) and annual height growth (b) of loblolly pine, relative to untreated controls.

Deficiencies and responses to fertilization with other nutrients are less common. On some sites, additional volume gains are possible if P is supplemented with N and (or) K [35, 62, 83, 97]. Isolated responses to added micronutrients, such as manganese (Mn), have been reported where N, P, and K have been supplied in sufficient quantities [25].

Over the past 20 years, considerable research has been conducted to develop reliable diagnostic techniques for identifying sites responsive to fertilization. Typically, fertilizers are applied only to sites where forest managers are certain that dollar investments will significantly enhance growth [30]. Limiting fertilization to only a few hectares, however, could be costly in terms of lost potential stand volume and value.

Numerous diagnostic techniques including soil classifications, soil and foliage testing, visual criteria such as symptoms and indicator plants, greenhouse and field trials, and empirical response models have been developed to help managers decide whether or not to fertilize. All have

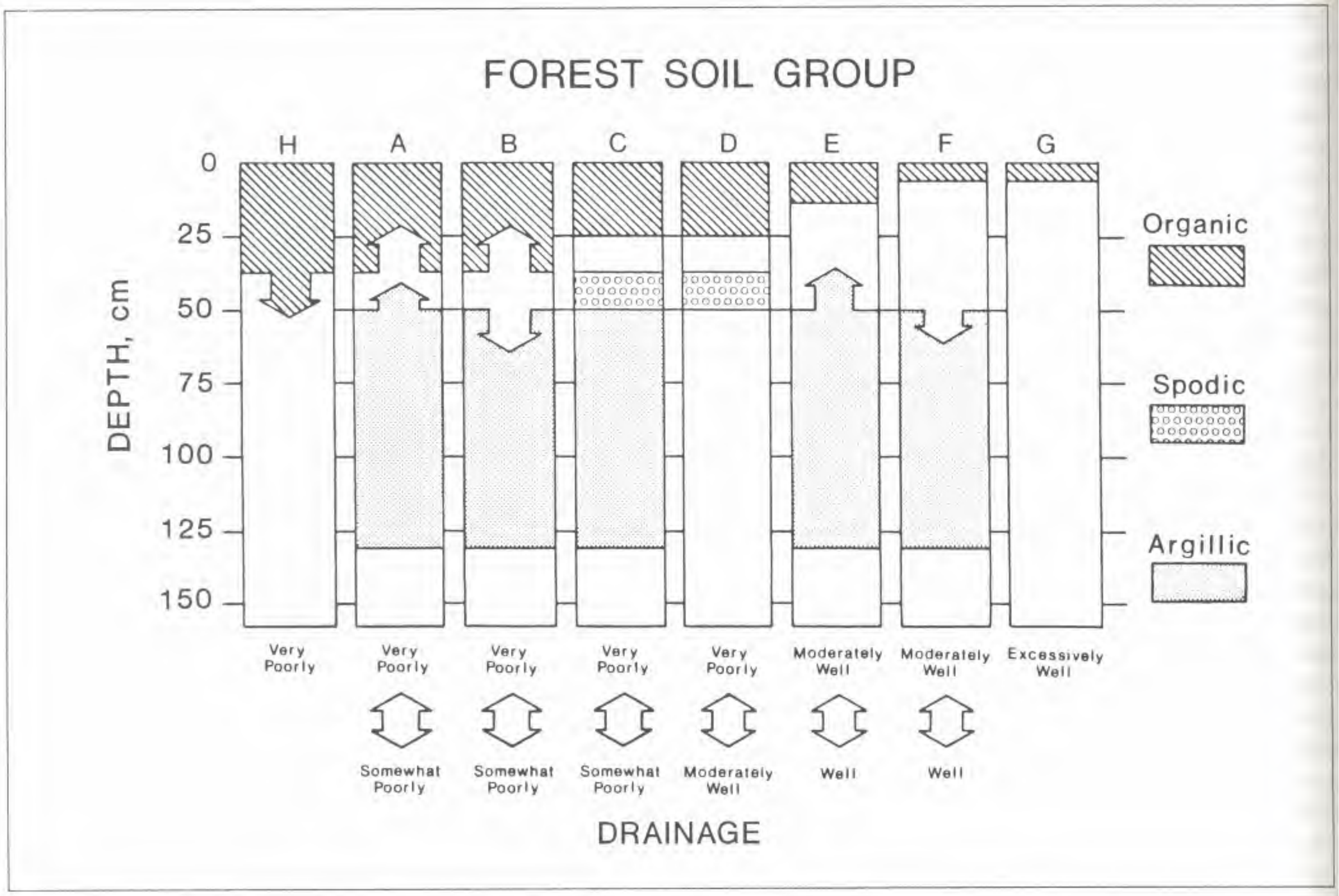

Figure 14.3. Forest soil classifications, by soil group (see Table 14.1 for more detail) and drainage condition, used for determining fertilization requirements of southeastern Coastal Plain sites (adapted from [22]).

operational advantages and limitations because of differences in reliability, implementation cost, and technical skills required for application [51]. The most common and useful diagnostic techniques are described below.

14.4.2 Soil Classifications

Soil groupings, based on easily identifiable landscape and soil physical properties, are used to identify sites where available nutrient supplies are low, or where other site factors (e.g., moisture availability) influence growth (see also Chapter 10, this volume). Such a classification scheme was developed for the southeastern U.S. by grouping soil series on the basis of drainage conditions and subsoil characteristics [31] (Fig. 14.3).

Average stand response to fertilizers differs significantly among soil groups (Table 14.1). In some cases, simply knowing the soil type (e.g., poorly drained clay) is adequate for making fertilization decisions and estimating response. In other cases, responses may vary significantly within a soil group [54], indicating that additional information is necessary to increase prediction accuracy.

Stands growing on soil groups A, B, and C (Fig. 14.3, Table 14.1) have generally responded most consistently and continuously to fertilization at planting [24]. Phosphorus, applied alone or in combination with N, bedding, or weed control, is most effective for these soils. Stands growing on the other soil groups (D-H) generally do not respond

Table 14.1. Response, according to soil group (see also Figure 14.3), as measured by volume gain over a 25-year-rotation, of southeastern Coastal Plain loblolly and slash pine stands fertilized with phosphorus at planting (adapted from [31]).

Soil group	Taxonomic subgroup	Volume gain, $m^3\ ha^{-1}\ yr^{-1}$
A	Typic, Albic, Plinthic, and Umbric Aquults	2.8–7.0
B	Arenic and Grosarenic Aquults, Aquents, and Aquepts	1.4–5.3
C	Ultic Aquods and Humods	1.1–2.8
D	Typic, Aeric, and Arenic Aquods and Humods	0–1.8
E	Typic and Plinthic Udults	0–3.5
F	Arenic and Grosarenic Udults, Umbrepts, and Ochrepts	0–3.5
G	Psamments[1]	–
H	Medisaprists and Histic Humaquepts	0–4.2

[1] Fertilizer not recommended because of limited response potential.

positively enough to warrant fertilization at establishment, although individual sites may benefit. However, any of these soil groups previously planted in row crops will not require fertilization because residual soil nutrient levels are usually adequate to meet the demands of young pine stands.

14.4.3 Soil and Foliage Tests

Chemical analyses of soil and foliar tissues have been commonly used by agronomists and foresters alike for both diagnosing nutrient deficiencies and identifying fertilizer needs. Soil tests provide an estimate of soil nutrient supply and foliage tests an integrated index of soil supply and stand demand. Both techniques assume that a stand will respond to added nutrients when concentrations in soil or foliage fall below established "critical levels," such as those in Table 14.2 for loblolly [113, 114] and slash [85] pine. These critical levels and indexes are entirely empirical and were derived from field and greenhouse experiments. With the exception of that for P, they have not been well calibrated with field trials and should be used only as a guide for identifying the likelihood of a response. Their reliability will increase as similarity (e.g., environment and site conditions, genetics, stage of stand development) between the candidate stand and the reference stand used to derive the relationships increases.

Wells et al. [113] reported that predicting loblolly pine P responses from soil and foliage analyses varied among physiographic regions in the Southeast. Height growth responses were significantly correlated with foliar P levels in the Lower Coastal Plain, but not in the Upper Coastal Plain and Piedmont. Similarly, height growth responses were not correlated with extractable soil P levels in the Lower Coastal Plain, although responsive stands could be identified on the basis of soil acidity and drainage class. In the Upper Coastal Plain, P responses were significantly correlated with levels of extractable soil P (0- to 20-cm depth; Mehlich I-P), acid saturation, and pH.

Soil and foliage analyses have additional limitations that reduce their prediction accuracy. Variation in nutrient levels due to foliage age, sampling position within the crown or soil profile, sampling date, and analytical procedure is well documented and often complicates interpretations when measurement values are near critical levels. Soil tests especially are poor indicators of N availability and likely response to N fertilization [14, 52, 83]. Both aerobic and anaerobic incubation and resin-bag estimates of N availability were poorly correlated with loblolly pine growth and fertilizer response [55].

The "critical level" concept assumes that other nutrients or environmental conditions would not limit growth once the deficient element was applied. Experience indicates, however, that as forest management practices intensify, multiple nutrient deficiencies become more common. Evaluating the supply and the balance of nutrients in relation to stand demand over time may improve the diagnostic capabilities of both soil and foliage tests [1, 23, 109]. For these techniques to be most successful, however, standardized sampling and analysis procedures are essential.

14.4.4 Visual Symptoms and Indicator Plants

Visual symptoms and indicator plants have been used to a limited degree for diagnosing nutrient deficiencies. The appeal of these techniques resides in their simplicity: they allow diagnosis without laboratory testing. Symptoms such as foliar discoloration, needle twisting or fusing, premature needle fall, resin exudation, crooking, and dieback of young shoots are common visual evidence of nutrient deficiency [56, 98]. Likewise, presence, absence, or nutrient content of a particular species (or, in some cases, habitat type) reflects the level of some site factor important for tree growth; pitcher-plants (*Sarracenia* spp.), for example, are frequently associated with wet Coastal Plain soils that are highly responsive to P fertilization. Neither visual symptoms nor plant indicators have found wide operational application in the South, largely because considerable growth potential may be lost before the evidence is recognizable. To be reliable, visual evidence must be calibrated with stand response data from field trials. To date, few such relationships have been quantified.

14.4.5 Greenhouse and Field Trials

Greenhouse trials, in which seedlings are grown in controlled environments and with nutrient solutions of varying compositions, have proven useful for determining ionic preference by species [61], for identifying symptoms of deficiencies and toxicities, and as preliminary screens for nutrient response [110]. However, because long-term field responses and greenhouse results are poorly correlated

Table 14.2. Approximate critical levels or ranges for macro-nutrients in two southern pine species (adapted from [2, 85, 113, 114].

Component	Species	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
Current-year foliage, %	Slash	0.8–1.2	0.08–0.09	0.25–0.30	0.08–0.12	0.04–0.06
	Loblolly	1.10	0.10	0.35	0.12	0.07
Surface soil (0–20 cm), ppm	Slash[1]	–	4–6	8–12	25–40	6–10
	Loblolly[2]	–	5–6	–	–	–

[1] Double acid extractable.

[2] Mehlich II extractable.

[66], greenhouse trials are not a common basis for operational fertilizer decisions.

Experimental field tests undoubtedly represent the most reliable technique for diagnosing nutrient deficiencies and estimating fertilizer response because they closely simulate operational practices. However, field tests are costly, time-consuming, and relatively impractical for broad-scale application. Most fertilizer recommendations available today are based on field trials but have been tested only under limited conditions. University-industry research cooperatives (e.g., CRIFF, NCSFNC) have provided a cost-effective mechanism for extending the database derived from field tests to new and varying site conditions. Likewise, such data are essential for calibrating soil or foliage tests.

14.4.6 Response Models

Numerous attempts have been made to develop models that relate tree response to fertilization (volume or height growth) to variables such as site index, soil properties, foliar nutrient concentrations, and fertilizer quantities [13, 29]. Most of the models developed have been for established stands and are empirical, representing a wide range of statistical sophistication [6]. In one instance, Kushla and Fisher [54] used multiple regression analysis to "fine-tune" fertilizer-response predictions within individual CRIFF soil groups. Soil properties such as available water, extractable cations, cation exchange capacity, and total N were the most useful for predicting stand response.

As with soil classifications, response models based on stand conditions can predict average response for broad site types. However, users should field test and calibrate these models because they may not accurately account for changes in future conditions [53].

14.4.7 Choosing the Diagnostic Technique

In summary, considerable gains have been made in diagnosing nutrient deficiencies and predicting fertilizer response for young southern pine plantations. Forest managers today have a wide variety of qualitative and quantitative techniques available to aid decision making for forest fertilization. A survey of industrial organizations with operational fertilization programs in the South indicated that an integrated approach, based on a combination of diagnostic methods, was most popular when prescribing fertilizer treatments [51]. Soil groups, soil analyses, soil drainage classes, and knowledge from local experimental field trials were cited as the most reliable methods available. In the early stages of diagnosis, forest managers should rely on multiple sources of information for best results [65] but discriminate among techniques, evaluating them carefully, even skeptically. Stone [99] reminds us that when such techniques fail to yield predictable results, the methods rather than their application are often faulted incorrectly.

14.5 Fertilizer Technology

14.5.1 Fertilizer Materials

The fertilizer materials used in silviculture are less varied than those used in agriculture. Dry solids (crushed, granulated, or bulk blends) predominate; coarse, dry materials uniform in particulate size can be evenly spread in wide swaths from ground equipment or aircraft. Liquids, though equally useful from a nutritional standpoint, are not well adapted to aerial application because lower nutrient analyses increase the mass of material that must be handled.

14.5.1.1 Nitrogen fertilizers

Trees absorb essentially all of their nitrogen from the soil solution in the ionic forms of nitrate (NO_3) or ammonium (NH_4+). The N in all of the fertilizers materials listed in Table 14.3 (except urea and organic residue) is in a form immediately available when in contact with soil moisture. Urea is rapidly converted to NH_4+ by urease, an enzyme common in soils, and is available within a few days or weeks. Organic residue, on the other hand, may require long periods for microbes to convert the N to an available form, and generally is too low in N content for efficient use in forestry (other than in nurseries). For sources providing readily available N, considerations such as ease of spreading and cost per unit of N determine material choices.

Currently, urea is most commonly used when N only is desired because it is competitive in price, is high in N (45%), and can be formulated into large granules adapted to wide spreading swaths. Volatile losses of ammonia (NH_3), however, have been noted from surface-applied urea. High surface-soil pH, high levels of urease activity, warm temperatures, and moist soil conditions without adequate precipitation to dissolve and wash urea into the soil favor these losses, which have been reported as high as 20 to 30% [79]. Generally, far less N than this is lost through volatilization. In at least one study [69], ammonium nitrate proved superior to urea in pine fertilization. However, comparisons of N sources in the southeastern U.S. [7, 33] indicate little or no difference in the effectiveness of urea and ammonium nitrate.

Diammonium phosphate (DAP) is most often the product of choice when both N and P are desired because it has good physical properties and contains both N and P in high percentages. Anhydrous ammonia, a gas at normal temperature and pressure, may be used in forest nurseries but is otherwise restricted to agriculture where it is injected into the soil. The other fertilizer materials listed in Table 14.3 are periodically available and can be used as N sources, but are not commonly applied to southern pines.

All of the N fertilizers (Table 14.3) that include ammonium forms (except potassium nitrate) slightly acidify the soil. Because southern pines are adapted to acidic soils and generally grown where soil pH is low, this effect is not viewed as an important consideration in selecting N fertilizers.

14.5.1.2 Phosphorus fertilizers

Pines absorb most of the P they require in the phosphate form 11,PO4; therefore, fertilizers containing P must dissolve for the nutrient to be absorbed. Soil solution levels of B,PO$_4$- required by southern pines for adequate nutrition are low, which makes a slow dissolution rate acceptable in most cases.

All of the P fertilizers listed in Table 14.3 are successfully used in fertilizing young southern pine plantations [86]. The "superphosphates" are the principal P fertilizers used in forestry when only P is required. They are made by reacting rock phosphate (RP) with either sulfuric acid or phosphoric acid to produce ordinary superphosphate and triple superphosphate, respectively. A combination of factors, including high analysis, good physical properties, and solubility, makes the superphosphates the most common P sources applied to young loblolly and slash pine plantations in the South (Fig. 14.4). DAP is an excellent material, providing some N as well as P; it has good physical properties, is completely water soluble, and is usually competitively priced. RP, successfully used on southern pines in several experiments, can only be recommended with reservation. The soils must be quite acid and the RP ground very fine for solution to proceed rapidly enough to supply the needed H$_2$PO4. Difficulty in handling and spreading the finely ground material, and concern about its insolubility, have restricted its use.

Table 14.3. Nitrogen (N) and phosphorus (P) fertilizers used in forestry.

Material	Common analysis[1]	Comments
	Nitrogen	
Urea	45-0-0	Available in coarse granules; subject to volatilization.
Organic residue	(Variable)	Not used on commercial scale because of large bulk; low N content.
Ammonium nitrate	33-0-0	Hydroscopic.
Diammonium phosphate (DAP)	18-46-0	Important as P source when N is also desired.
Potassium nitrate	14-0-46	Not generally available in the U. S.
Anhydrous ammonia	82-0-0	Must be injected into soil; not generally used in forestry.
Ammonium sulfate	21-0-0-24S	Hydroscopic; sulfur source.
	Phosphorus	
Concentrated superphosphate	0-44-0	Common P fertilizer; water soluble.
Normal superphosphate	0-20-0	Contains significant $CaSO_4$; production in U. S. reduced.
DAP	18-46-0	Water-soluble N and P source.
Rock phosphate	0-?[2]	Little or no water-soluble P; low plant availability.

[1] Analysis expressed as required by most state fertilizer regulations: % total nitrogen, % available P_2O_5, % soluble K_2O (Note: $P_2O_5 \times 0.436$ = % P; $K_2O \times 0.833$ = % K). Percentages vary slightly because of purity and process technology.

[2] Rock phosphate contains 30 to 35% P_2O_5, but fertilizer labeling rules require that it be "available" (weak acid or water soluble). In rock phosphate, little if any P is weak acid or water soluble.

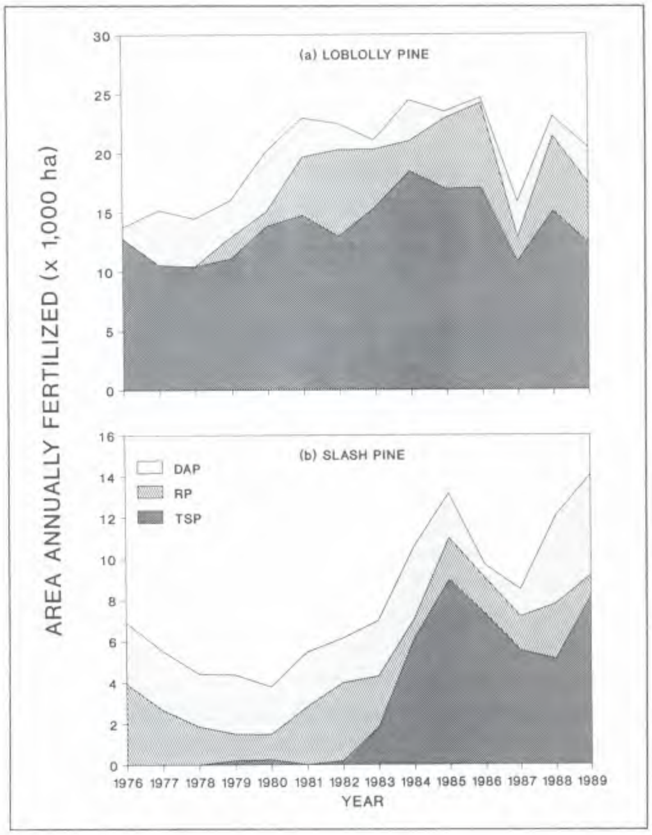

Figure 14.4. Area of loblolly (a) and slash (b) pine operationally fertilized at planting with phosphorus (TSP, triple superphosphate; RP, rock phosphate; DAP, diammonium phosphate) by forest industry in the southern U.S.

14.5.1.3 Potassium and other fertilizers

Potassium chloride (sometimes called potash or muriate of potash) commonly has a fertilizer analysis of 0-0-60. Used directly or blended with other materials, it, and minor amounts of potassium sulfate and potassium nitrate, provide essentially all of the K fertilizer used in forestry and agriculture. When K is needed, cost and convenience determine the fertilizer material to be used because all are soluble in water and equally available to plants.

The demonstrated need for other fertilizers in the nutritional management of southern pines has been limited to micronutrients such as boron (B), copper (Cu), zinc (Zn), and Mn. These can be purchased as simple salts, chelates (organic compounds), or fritted (silicate compounds) materials. The limited experience available indicates that these forms are all equally effective in alleviating micronutrient deficiencies.

14.5.2 Rates and Timing of Application

Fertilizing newly established pines (< 5 years old) on responsive sites produces a faster growing, more competitive young tree. Phosphorus plus N, and P alone, are the elements most widely applied to young southern pines. Nitrogen alone has not been recommended. Application timing of P plus N is important. Nitrogen is relatively mobile in soils, and some may be lost if applied before planting; moreover, N often stimulates competing vegetation. For those reasons, and in order to provide nutrients to the pines as early as possible, P plus N should be applied after planting in late spring or early summer of the first year. The more time pines have to absorb the increased supply of nutrients and outgrow competing vegetation, the better their growth response will be. Phosphorus is less mobile in soil than N, and timing of application is less critical when P is applied alone, but early application is usually best. Phosphorus can be applied before planting if other considerations favor such timing. Availability of micronutrient metals such as Zn, Cu, and Mn is long-lasting and timing is not critical.

Application rates of fertilizers for young southern pines have not been determined as precisely as those for agronomic crops. As previously described (see 14.4), the diagnostic tools used in forestry so far only provide general guidelines, although growth responses are likely to be significant when fertilizers are applied on the appropriate sites.

Where P is needed for young stands and rates have been tested, response usually is near maximum at application rates of 35 to 90 kg/ha (30 to 80 lb/ac) of P. Where rates have not been tested, current recommendations are 45 to 55 kg/ha (40 to 50 lb/ac) of P. (Note that P fertilizer analyses are given in terms of P_2O_5; therefore, rates of approximately 100 to 125 kg/ha of P_2O_5 are recommended.) Likewise, when N is applied to young stands, 45 to 55 kg/ha (40 to 50 lb/ac) of N is recommended; at that stage of stand development, higher rates of added N could stimulate the understory enough to compete with the pine seedlings and reduce pine growth. When P plus N is needed, DAP is an attractive fertilizer because it supplies N and P in the ratio (1:1) usually recommended for young pines. When trees are fertilized at midrotation, levels recommended for P are similar to those used at establishment, but levels recommended for N are considerably higher (e.g., 150 to 200 kg/ha).

Potassium fertilization is not widely recommended for southern pines, but mounting evidence indicates that K is frequently limiting on sites fertilized with P and N. The current recommendation for K is 90 kg/ha (80 lb K or 100 lb K_2O/ac). Although information available on micronutrients is limited, the following rates would be appropriate if soil type, foliar analysis, or other evidence suggests one or more is needed: Mn, Cu, and Zn at 3 to 6 kg/ha, and B at 1 kg/ha.

14.5.3 Application Methods and Uniformity

Application method (i.e., banding vs. broadcast and surface vs. incorporation) apparently does not affect seedling growth response to fertilization. Banded application systems involve selective fertilizer placement, usually 1 m wide over the planted row of trees. Broadcast methods, by comparison, spread granulated fertilizers in swaths 15 to 30 m wide. Once applied, fertilizer can be incorporated into the soil during site preparation, using discing or bedding plows. In easily traversed areas, tractor-mounted spreaders are suitable for applying fertilizers. Where terrain is wet or rough, however, rubber-tired skidders equipped with fertilizer spreaders or aerial application systems (helicopters or fixed-wing aircraft) may prove more effective.

Whatever the method, uniformity of application and rate control are important. Irregular growth patterns may result from unequal distribution of fertilizers. Balloons, suspended from three-wheeled, all-terrain vehicles that traverse the area to be fertilized, are often used as markers to assure uniform distribution of aerially applied fertilizer. Likewise, numerous open-top containers are placed across the treatment area to calibrate and measure the uniformity of fertilizers applied with aerial or ground systems. Because tests indicate that numerous application methods are equally effective in producing growth response, factors such as equipment availability, terrain accessibility, cost, uniformity of spread, and timeliness of the operation should be considered when formulating a prescription.

14.6 Silvicultural Interactions with Fertilization

Maximum returns from fertilizer applications will be realized when they are properly integrated with other silvicultural activities such as site preparation and weed control, genetic tree improvement, and prescribed burning. Unfortunately, many of these interactions are only poorly understood, and will require additional research for the development of cost-effective silvicultural systems.

14.6.1 Site Preparation and Weed Control

Site preparation probably has a more pronounced impact on stand nutrition [12] than any other silvicultural practice including fertilization (see also chapters 13 and 18, this volume). As previously mentioned (see 14.2.2), scalping or windrowing can reduce a site's nutrient capital [73], nutrient availability [111], and potential for productivity [100]. On the southeastern Coastal Plain, the effects of P depletion can be mitigated rather easily and cost-effectively with P fertilization; however, improving tree growth following N losses may be more costly. Fertilization does not compensate for poor management practices. Moreover, it has been argued that if moderate levels of fertilization can increase growth, why should foresters tolerate any unnecessary site nutrient losses [99]. Thus, care should be taken to minimize the negative impacts of excessive site preparation and other silvicultural activities on a site's nutrient capital.

Both site preparation and weed control can influence fertilizer response by (1) changing the composition and quantity of vegetation competing for moisture, light, or nutrients, (2) influencing the release or immobilization of nutrients, (3) changing the physical quality and quantity of the rooting volume, and (4) removing or redistributing site nutrient reserves. Because many site resources affect tree growth, interactions may be both positive and negative.

One of the best examples demonstrating the benefits of combining silvicultural treatments is bedding and P fertilization on poorly drained Lower Coastal Plain sites [36, 64, 106]. Combining loblolly pine growth data from five poorly drained sites with clay-textured soils, Gent et al. [36] found that at age 12, average height on control plots was 5.2 m, with gains of 2.3 m (bedded), 3.1 m (fertilized), and 4.9 m (bedded and fertilized) on treated plots (Fig. 14.5). These results suggest that the effects of bedding and fertilization are additive for poorly drained soils.

Equally large gains in early stand growth are possible by combining intensive site preparation, weed control, and fertilization [20, 95, 116]. On an intensively prepared site in Louisiana, a complete fertilizer (N, P, K) applied at planting, along with operational control of herbaceous and woody plants for the first 4 years, increased loblolly pine volume production at age 5 to 25.9 m^3/ha, compared to 11.8 m^3/ha without treatment [107].

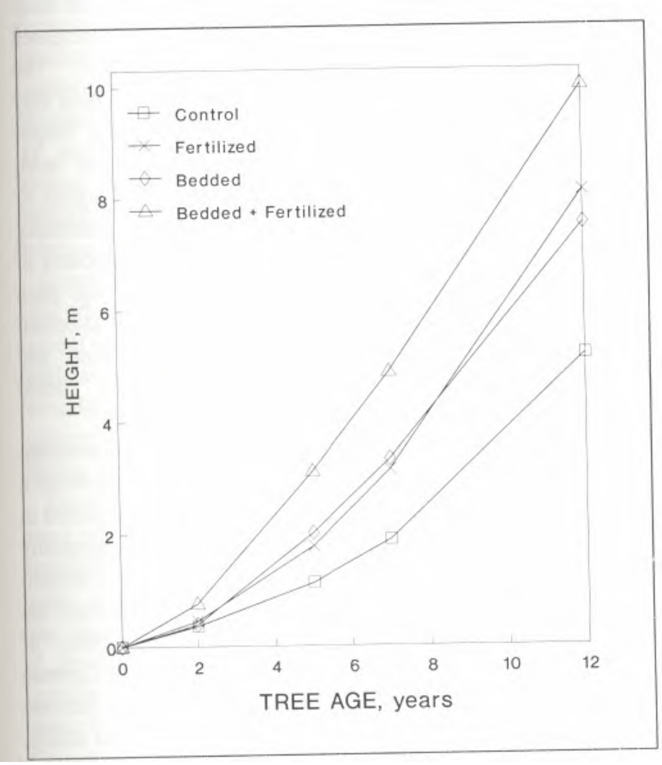

Figure 14.5. Effects of bedding and fertilization on cumulative mean height growth for five poorly drained sites with clay soils on the Lower Coastal Plain of North Carolina (adapted from [36]).

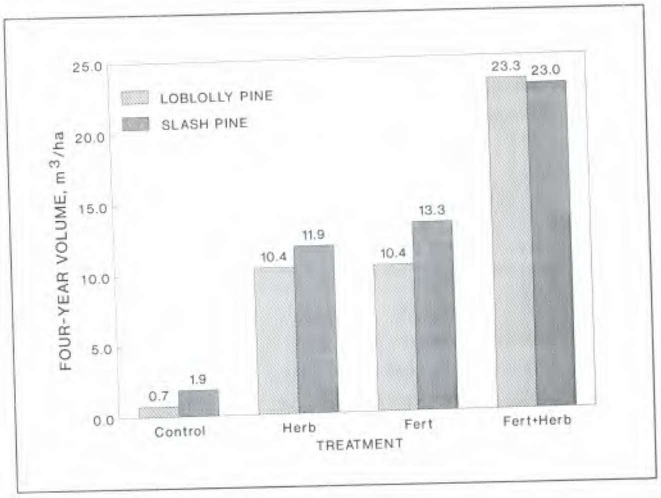

Figure 14.6. Effects of complete, sustained weed control (herb), repeated, annual fertilization (fert), and a combination of the two (fert+herb) after four growing seasons on volume growth of loblolly and slash pine growing on a flatwoods site in north-central Florida, relative to untreated controls (adapted from [103]).

Competition for soil nutrients by both crop and understory species was the most important factor limiting potential productivity of loblolly and slash pine growing on a somewhat poorly drained flatwoods soil in north-central Florida [77, 103]. Continuous elimination of either nutrient deficiencies or interspecific competition increased stand volume production 5-fold after four growing seasons. The combined (additive) effects of both cultural treatments increased stand volume production more than 10-fold (Fig. 14.6).

Results from these and others tests suggest that current productivity levels for many southern pine sites fall far below their potential and that opportunities to increase productivity through fertilization and weed control are much greater than was traditionally believed. However, there can be ecological drawbacks to channeling all energy flow into just pine growth. Such factors as ecosystem diversity and stability, along with wildlife habitat requirements (see Chapters 21 and 22, this volume), should be given equal consideration in the development of long-term management plans for forested lands.

14.6.2 Genetic Tree Improvement

Reports are inconsistent concerning fertilizer x genotype interactions on tree growth. In part, this may be attributed to the philosophy of tree breeding programs, which select for broadly adapted genotypes that grow well across a wide range of site types [108]. In one of the few field trials comparing response to fertilization of different progenies (first-generation slash pine) at conventional spacings, fertilization was found to have little effect on tree volume, specific gravity, or incidence of fusiform rust [90], although the performance of a few progenies varied considerably across fertilizer treatments. Similar results with loblolly pine progenies were reported by Goddard et al. [41]. Twenty-two loblolly pine families grew better with fertilization, but family x fertilizer interactions were usually nonsignificant except on wet, P-deficient sites. Under such conditions, proper choice of genotypes can significantly affect wood production ([40]; see also chapter 11, this volume).

14.6.3 Prescribed Burning

Interactions between fertilization and prescribed burning have not been well researched. Theoretically, if N fertilizers are applied immediately before prescribed fire, much of the added N could be volatilized. Similarly, much of the urea applied to an alkaline ash layer following burning could be volatilized. In one trial with slash pine, prescribed burning either 6 months before or after fertilization had little impact on growth response. It remains uncertain, however, whether burning closer to the time of fertilization would affect response ([70]; see also chapter 12, this volume).

14.7 Other Considerations in Fertilization

The wise and effective use of fertilizers in forestry requires that practitioners appreciate possible interactions and environmental impacts resulting from fertilizer additions to the ecosystem. Much attention has been focused on susceptibility of fertilized trees to damage from pests, impact of fertilization on wood quality, and concern over environmental stresses (particularly water quality).

14.7.1 Pest Relations

Host-parasite interactions with plant nutrition have been the subject of considerable research in both agriculture and forestry over the past 50 years. Fertilization has been implicated in both increasing and decreasing the incidence of forest diseases, damage from insects and animals, and human influence (see also chapter 20, this volume). No general rule prevails regarding the relationship of fertilization to pest incidence or resistance. Each pest, and interactions between or among pests, must be evaluated individually in light of host genotype, soil environment, and specific nutrient being applied.

Numerous reports have shown that the incidence of fusiform rust, caused by *Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme*, increases with increasing soil fertility and more intensive forest-management practices such as fertilization [17, 27, 38, 47, 68, 82]. Logically, any practice that increases growth in the early years provides more young tissue for fusiform rust infection. Burton et al. [19] reported that both weeding alone and the combination of weeding and bedding in an area highly susceptible to fusiform rust significantly increased infection rates relative to the noncultivated controls (85 vs. 54% of trees infected). However, fertilization and irrigation, used alone or in combination, had no significant effect on rust infection when applied after weeding and bedding.

Whether genotypic variation predisposes trees to disease susceptibility continues to be an important research issue in the South. Greenhouse and field studies designed to examine the effects of fertilization on incidence of fusiform rust in resistant and susceptible families have produced dissimilar results [40, 82, 91]. In one study, resistant slash pine seedlings were not significantly affected by varying rates of fertilization, but high amounts of P and K increased rust incidence in the susceptible trees [46]. In another study, fertilization increased rust incidence of both resistant and susceptible families of loblolly and slash pine [91]. These differences reflect the difficulty of experimentally partitioning the nutritional and genetic effects of disease resistance. When these sources of variation are better understood, tree breeding programs should become more efficient in promoting disease resistance.

Accumulating experimental evidence suggests that interactions exist among pitch canker [*Fusarium subglutinans* (Wollenw. & Reinking) Nelson, Tossoun & Marasas comb. nov.] incidence, soil fertility, and host nutrition [15]. Increasing incidence and severity of pitch canker in slash pine stands have been associated with increasing soil fertility, especially following heavy fertilizer applications of N or N plus P [21, 32, 80]. In east-central Florida, heavy annual applications (224 kg/ha each) of N, P, and K fertilizers were associated with increased pitch canker incidence after 6 years [117]. The relationships involved are unclear. Heavy fertilization may make plant tissues more succulent (facilitating fungus entry), may increase production of free amino acids (improving trophic conditions for the invading fungus), or may reduce the level of plant metabolites inhibiting pathogen development [45]. Conversely, small amounts of added N (40 kg/ha) did not significantly increase pitch canker infection on a variety of soil types in west-central Florida [5]. Maintaining balanced tree nutrition and avoiding excessive and repetitive fertilization should reduce the risks of damage.

Relationships between soil-site conditions and southern pine bark beetle [*Dendroctonus frontalis* Zimmermann (Coleoptera: Scolytidae)] infestations have been reported in the South [10, 59]. Wet and waterlogged sites generally support heavier bark beetle infestations than well-drained sites [9]. Yet surprisingly few studies have examined the interactions between fertilization and susceptibility of stands to bark beetle attacks [43, 81]. Moore and Layman [72] reported that fertilization did not significantly increase the resistance of 9- to 11-year-old loblolly pines to attacks by the southern pine bark beetle or black turpentine beetle [*Dendroctonus terebrans* (Oliver)]. They hypothesized that spring fertilization may confer on trees greater resistance to bark beetle attack because they would have sufficient time to take up nutrients before beetle activity peaked during the summer. This and other hypotheses still require further testing, however.

Cultural treatments (such as fertilization) that induce rapid growth of young pines have increased the incidence of attacks by pitch moth *[Dioryctria amatella* (Hu1st)] larvae on some sites [49, 57, 58]. Trees weakened or girdled by pitch moth larvae may be killed directly or may break off later during high winds as a direct result of moth attack [58]. Pitch moth attacks may also serve as suitable infection courts for the pitch canker fungus, thereby increasing the severity of impact from this insect [pers. commun., 16]. Management strategies that utilize insect- and disease-resistant families, together with appropriate cultural treatments minimizing the potential risks of such losses, have been promoted for susceptible sites [19, 93].

14.7.2 Wood Quality

The impact of fertilization on wood quality varies depending upon stand age, response magnitude, and position along the stem. Many wood properties such as the proportion of latewood to earlywood, fiber (tracheid) length, density, and amount of juvenile corewood can be influenced by fertilization. These same properties are also under genetic control, and can be affected by other silvicultural treatments and site conditions (including climate) that influence growing space, transpiration, and water availability.

Specific gravity has been found to increase [90, 94], decrease [8], or remain unchanged [50] following fertilization. Wood density can be reduced from either a smaller proportion of latewood or, conversely, an absolute increase in earlywood formation [13]. However, this does not normally represent a major management concern because increased volume production resulting from fertilization will usually more than compensate for any reductions in density.

Experimental evidence suggests that fertilization has little effect on pulp yield or fiber strength [42], or on lignin content and the amount of extractives [94]. In some cases, fertilization has reportedly increased wood uniformity, a favorable attribute for pulp and paper manufacturing; uniformity improves when cell walls of earlywood fibers thicken while those of latewood fibers thin [39].

Among the more contemporary and problematic issues being raised is whether fertilization and other early stand-establishment practices promoting rapid growth cause a larger proportion of juvenile corewood to be formed. This may cause difficulties in utilization. However, the influence of genetics, cultural practices, and the environment on juvenile corewood properties will require additional research. Indeed, the influences of fertilization and other silvicultural practices on wood properties are probably inconsequential compared to problems associated with harvesting younger trees (which contain proportionately more juvenile corewood than do older trees). Nevertheless, to paraphrase Bevege [13], we may need to rethink some of our silvicultural strategies so that, in our enthusiasm for achieving early maximum growth rates, we do not lose sight of our ultimate objective - to grow trees of suitable wood quality at optimum cost.

14.7.3 Environmental Issues

The rapid development of intensive forest-management practices in the South has prompted concern over forest soil degradation and associated impacts on water quantity and quality. Numerous investigations have been conducted to quantify environmental impacts resulting from site preparation, varying levels of harvest intensity, and applications of forest insecticides and herbicides [28, 74-76, 89, 101]. Water yield, stormflow, and some water-quality parameters (pH; suspended sediment; levels of K and Ca) have increased as a result of harvesting and regeneration operations. These effects are generally small, transient, and manageable, and appear to be proportional to the degree of site disturbance [102]. Management practices that minimize disturbance and include protective stream-management zones are recommended to reduce nonpoint sources of pollution [88].

Few reports are available in the South regarding the impacts of forest fertilization on water quality, though this topic has received considerable attention elsewhere [60, 92]. Most studies indicate that nutrient losses associated with operationally applied N and P fertilizers are minimal, and that water quality is not adversely affected [71]. Stream nutrient concentrations may briefly increase following fertilization, resulting from direct and inadvertent application of fertilizers to stream channels or from surface runoff, erosion, and leaching.

Present-day P fertilization in the South should not threaten surface water quality. Only small amounts of added P should be lost from surface runoff and erosion, given the topography, plant cover, soil types, and land-use patterns characterizing the region. In addition, because P is readily immobilized as Fe and Al compounds in most acid forest soils, leaching losses to ground water should be minor. Exceptions to this rule may occur on acid, organic soils low in overall nutrient availability, and on acid, quartzitic sands low in Fe and Al [86]. Under such conditions, application of phosphatic fertilizers of low solubility, such as RP, would represent a better fertilizer source than the more soluble, acidulated superphosphates.

The potential for losing added fertilizer N is greater than that for losing P. Highly soluble anions such as NO_3^- are not readily absorbed or precipitated in soil. Consequently, if not utilized by plants or microorganisms, they are easily leached by water moving through the soil profile. Mobile anions, produced from nitrification (conversion of NH_4-N to NO_3-N) and other biological activity (e.g., bicarbonate production from respiration), may also enhance cation leaching. Mead and Pritchett [67] reported that, after two growing seasons, total recovery of labeled N in an 11-year-old slash pine ecosystem was 50% of that applied; most N was lost during the first few months after fertilization,

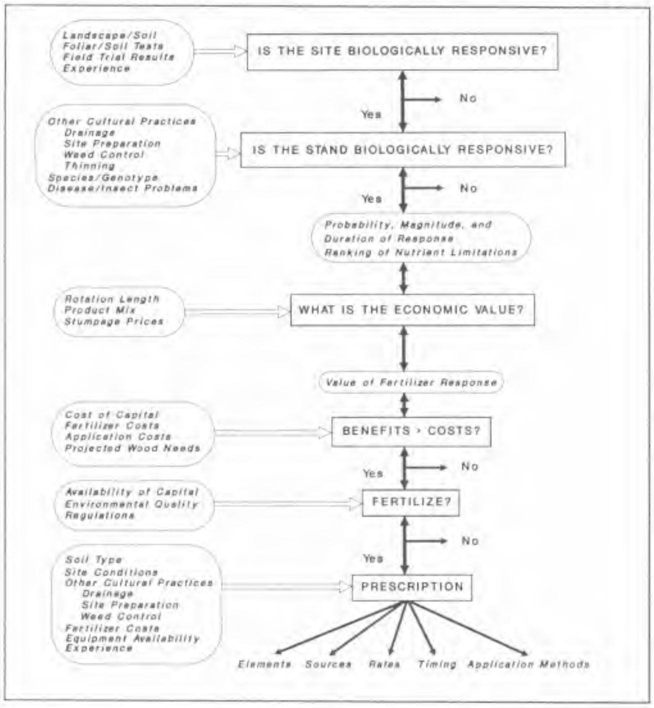

Figure 14.7. Schematic to help forest managers decide when and how to fertilize young southern pine stands.

probably through leaching and volatilization. Cations such as NH_4^+ are adsorbed by clay and organic fractions in the soil and do not leach as readily as anions from the root zone. However, nitrification will eventually foster leaching, though this transformation is slow in most acid forest soils.

Research in Sweden [1041 has shown that fertilization with ammonium nitrate produced higher concentrations of NO_3^- in ground water than equal amounts of N applied as urea. Therefore, urea may be preferable to ammonium nitrate for reducing potential pollution from N fertilization. Clearly, continued investigations are needed to quantify the fate and effects of fertilizers and other chemicals added to forest ecosystems to ensure their continued safe and effective use.

14.8 Conclusions

This chapter has described general principles of forest nutrition and the practice of fertilization as a silvicultural treatment for young southern pine stands. Large gains have been made during the last two decades in both diagnosing nutrient deficiencies and predicting response to fertilization. The development of cost-efficient, biologically sound fertilizer prescriptions requires integration of numerous site, stand, and economic considerations (Fig. 14.7). As with any silvicultural treatment, specific conditions may cause results to deviate from those reported in this chapter. Therefore, forest managers should use the relationships and recommendations presented here as general guides.

Forest fertilization programs will become more efficient as technological advances further improve the accuracy of diagnosing nutritional problems and the reliability of predicting stand responses to fertilization. Regardless of technology, achieving success in managing the nutrition of southern pine stands will require not only skill and careful attention to detail by foresters, but also appreciation of other important silvicultural interactions with fertilization.

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