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Pine Nutrition In the West Gulf Coastal Plain: A Status Report

Eugene Shoulders
and
W. H. McKee, Jr.

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PINE NUTRITION IN THE WEST GULF COASTAL PLAIN: A STATUS REPORT

Eugene Shoulders and W. H. McKee, Jr.[1]

Review of current literature establishes that forest fertilization is a proven, accepted management practice in limited areas of the South where lack of one or more mineral nutrients seriously curtails pine growth and where moderate additions of these nutrients markedly increase yields. In most of the South, however, and especially in the West Gulf Coastal Plain, general use will be deferred until amounts, kinds, and schedules of application can be reliably specified for individual soils.

Additional keywords: Fertilization, nutrient cycling, soil fertility.

In recent years, forest landowners have become keenly interested in mineral nutrition of southern pines and especially in fertilizing them to stimulate growth. Many factors have contributed: among the most important are a diminishing land base on which to grow wood and fiber to supply an expanding population, research that shows economic returns from commercial fertilization of selected stands on problem soils, and adoption by many landowners of other intensive regeneration and management practices that make fertilization a logical next step.

Many questions must be answered before commercial fertilization of southern pines can be routinely recommended. This paper considers both soil and plant aspects of the problem. It summarizes current knowledge of the chemical properties that determine the ability of soils to hold added nutrients in forms available to pines. It also evaluates results of greenhouse and field studies which indicate the kinds and amounts of nutrients required for optimum or maximum growth. In addition, it considers the impacts of climate, of physiological condition of the trees, and of genetic variation within species on response of pines to added nutrients.

The discussion is concerned chiefly with pine growth on Coastal Plain soils of Arkansas, Louisiana, Mississippi, and Texas. Much of it, however, applies equally well to other parts of the South. For those who wish a broader view, the authors strongly recommend concurrent study of "Forest fertilization research in the South: a review and analysis" (Southern Forest Environment Research Council, 1972), which may be obtained from any State agricultural experiment station in the South.

CLIMATE, SOILS, AND VEGETATION

Climate of the region varies. The growing season is longer and winter temperatures are milder near the Gulf Coast than inland. The mean frost-free period ranges from 210 days in central Arkansas to 300 days near the Coast (Southern and Southeastern Forest Experiment Stations, 1969). Average normal January temperatures vary from 45°F in the north to 55° in the south. July temperatures average 82°F thoughout the region. Annual rainfall varies from about 40 inches near the western fringe of the east Texas pineries to 60 inches in southeast Mississippi. Winter rainfall is ordinarily adequate or excessive, but growing-season rainfall is erratic. By midsummer, moisture deficits often limit growth of crops (Van Bavel, 1959). Frequency and severity of these deficits intensify from southeast to northwest.

Soils which now support or are apt to be converted to pines in the foreseeable future can be divided into three broad groups: poorly and imperfectly drained flatwoods soils, well

[1] The authors are Principal Silviculturist and Principal Research Soil Scientist in the research unit on Intensive Culture of Southern Pines, Southern Forest Experiment Station, USDA Forest Service, Alexandria, Louisiana.

drained upland Coastal Plain soils, and soils derived from loessal deposits (Lytle, 1960). Each group contains several series that vary in physical properties and in their abilities to retain added nutrients in forms available to pines. Representative important series in each group are listed in table 1. Flatwoods soils predominate near the coast. Throughout much of the area, moreover, flatwoods and upland Coastal Plain soils are intermixed, with the former occurring on the lower, leveler portions of the landscape and the latter occupying the higher, more sloping relief. Loessal soils are confined to a narrow strip on either side of the Mississippi River and may occupy the entire landscape or only the ridge tops.

Soils of the flatwoods have poorly developed profiles. Typically, they are saturated with water through part or all of the winter and become reduced during this period (McKee, 1970; McKee and Shoulders, 1970). Surface and internal drainage are poor because of low topographical position and relatively impermeable subsoils. Parent material is of recent and late Pleistocene age (Lytle, 1960). Mineralogy is mixed but kaolinitic clays predominate.[2] Vermiculites are second in importance. Montmorillonite predominates in the B-horizon of the Acadia series. In general, surface soils of the West Gulf flatwoods tend to be more silty than their counterparts farther east.

Native vegetation in the flatwoods was predominantly longleaf (*Pinus palustris* Mill.) and slash (*P. elliottii* var. *elliottii* Engelm.) pine

[2] Godfrey, C. L., Welch, C., and Coover, J. R. Texas correlations—soil type, soil fertility, soil salinity. Unpublished report, Tex. A&M Univ. 1964.

Table 1.—*Classification and drainage characteristics of some important pine growing soils of the West Gulf Coastal Plain*

Physiographic province and series	Sub-group	Family	Drainage
Flatwoods			
Caddo	Typic Glossaqualfs	Fine-silty, siliceous, thermic	Poorly
Guyton	Typic Glossaqualfs	Fine-silty, siliceous, thermic	Poorly
Wrightsville	Typic Glossaqualfs	Fine, mixed, thermic	Poorly
Acadia	Aeric Ochraqualfs	Fine, montmorillonitic, thermic	Somewhat poorly
Bude	Glossaquic Fragiudalfs	Fine-silty, mixed, thermic	Somewhat poorly
Bibb	Typic Fluvaquents	Coarse-loamy, siliceous, acid, thermic	Poorly
Iuka	Aquic Udifluvents	Coarse-loamy, siliceous, acid, thermic	Moderately well
Leaf	Typic Albaquults	Clayey, mixed, thermic	Poorly
Myatt	Typic Ochraquults	Fine-loamy, siliceous, thermic	Poorly
Rains	Typic Paleaquults	Fine-loamy, siliceous, thermic	Poorly
Beauregard	Plinthaquic Paleudults	Fine-silty, siliceous, thermic	Moderately well
Upland Coastal Plain			
Boswell	Vertic Paleudalfs	Fine, mixed, thermic	Moderately well
Susquehanna	Vertic Paleudalfs	Fine, montmorillonitic, thermic	Somewhat poorly
Kirvin	Typic Hapludults	Clayey, mixed, thermic	Well
Luverne	Typic Hapludults	Clayey, mixed, thermic	Well
Ruston	Typic Paleudults	Fine-loamy, siliceous, thermic	Well
Shubuta	Typic Paleudults	Clayey, mixed, thermic	Well
Sawyer	Aquic Paleudults	Fine-silty over clayey, siliceous, thermic	Moderately well
Lucy	Arenic Paleudults	Loamy, siliceous, thermic	Well
Stough	Fragiaquic Paleudults	Coarse-loamy, siliceous, thermic	Somewhat poorly
Bowie	Fragic Paleudults	Fine-loamy, siliceous, thermic	Moderately to well
Troup	Grossarenic Paleudults	Loamy, siliceous, thermic	Well
Eustis	Psammentic Paleudults	Sandy, siliceous, thermic	Somewhat excessively
Loessal Deposits			
Henry	Typic Fragiaqualfs	Coarse-silty, mixed, thermic	Poorly
Calhoun	Typic Glossaqualfs	Fine-silty, mixed, thermic	Somewhat poorly
Loring	Typic Fragiudalfs	Fine-silty, mixed, thermic	Moderately well
Providence	Typic Fragiudalfs	Fine-silty, mixed, thermic	Moderately well
Olivier	Aquic Fragiudalfs	Fine-silty, mixed, thermic	Moderately well
Grenada	Glossic Fragiudalfs	Fine-silty, mixed, thermic	Moderately well
Memphis	Typic Hapludalfs	Fine-silty, mixed, thermic	Well

with an understory of scrub oaks (*Quercus* spp.), southern bayberry (*Myrica cerifera* L.), and native grasses (principally *Andropogon* spp. and *Muhlenbergia expansa* [D.C.] Trin.). Loblolly pine (*P. taeda* L.) was also present in varying degrees. Slash pine is preferred in planting, except that loblolly is used in the north part of the region and on some of the less poorly drained flatwoods elsewhere.

By agronomic standards, fertility is consistently low and may vary cyclically with winter saturation and summer drying (McKee, 1970).

Soils of the upland Coastal Plain are moderately to excessively drained and their profiles are better developed than those of the flatwoods. They are derived from marine or stream alluvium of Eocene to Pleistocene age (Lytle, 1960; Carson and Kunze, 1967). Their mineralogy is mixed; however, a comprehensive regional analysis of the clay fraction is not available. Profiles from Texas indicate that the clays are predominantly kaolinitic with some vermiculite.[2] Exceptions are the soils of the Susquehanna and Boswell series, which are high in montmorillonite.

The surface soils appear to have less organic matter than those of the flatwoods, probably because better aeration promotes decomposition of organic debris. Textures range from very fine sandy loam to sand. Subsoils vary but the B horizons usually are finer textured and less permeable than the surface layers.

Native vegetation consisted of longleaf, loblolly, and shortleaf (*P. echinata* Mill.) pine, often mixed with hardwoods. Loblolly pine is the predominant species in recent plantations and managed natural stands.

Data from Louisiana on nutrients available for agronomic crops indicate that upland Coastal Plain soils are acid and low in nitrogen, phosphorus, and potassium (Brupbacher et al., 1970). The resemblance between upland and flatwoods soils in these properties does not assure that the two can be grouped in the study of pine nutrition, especially if drainage affects response to fertilizers in the West Gulf Region as it did in Florida. There, phosphorus increased pine growth more often on poorly drained than on well drained soils, even though levels of extractable nutrients were comparable (Pritchett and Llewellyn, 1966; Pritchett and Smith, 1972). Better-drained soils do not undergo waterlogging in winter. Their acidity and ability to keep available nutrients in the rooting zone may vary seasonally, however, as amounts of precipitation and degree of soil saturation influence aluminum dissociation and microbial activity (Coleman and Thomas, 1967).

Parent materials of soils derived from loess are of late Pleistocene age (Lytle, 1960). These soils occur on flat to rolling or hilly terrain and generally have moderate surface runoff and internal drainage. Some, however, have fragipans that perch water tables during wet seasons.

The mineralogy is a mixture of illite, montmorillonite, vermiculite, and kaolinite (Antie et al., 1970). The less weathered clays tend to give these soils higher permanent exchange capacities than the upland Coastal Plain or flatwoods soils and greater potentials for crops to respond to fertilizer. Nevertheless, soils derived from loess are usually infertile. They are inherently acid.

Native vegetation consisted of mixed hardwood and pine-hardwood forests. Because of their capacity to hold nutrients and their desirable physical properties, many of the soils derived from loess are now in cropland or improved pasture. The trend toward nonforest use is apt to continue, except where permanent cover is required to prevent erosion of moderate to steep slopes. The special problems in management of loessal soils on such landscapes are beyond the scope of this review. Both loblolly and slash pine are grown; slash is preferred in the southern and loblolly in the northern part of the region.

NUTRIENT-HOLDING PROPERTIES OF SOILS

Cations

Almost all important pine-growing soils of the region are characterized by low exchange capacities with weak charges that are highly pH-dependent (Coleman and Thomas, 1967). The variable, or pH-dependent, charge originates mostly from organic matter, exchangeable aluminum, and amorphous oxides. The individual and collective contributions of these components to cation retention characteristics of individual soils, and the abilities of individual soils to hold nutrient cations in forms avail-

able to pines, must be determined before fertilizer prescriptions developed for one soil can be confidently extended to another.

Some study of methods for determining cation exchange capacity (CEC) is also needed. Methods ordinarily used sometimes give values —for both imperfectly and well drained Coastal Plain soils—which are lower than the level of exchangeable bases the soils contain. What is known of the exchange properties of the various components of the complex is summarized below.

Clay minerals represent the most stable portion of the exchange complex, and the one least likely to be affected by the environment or fertilizers. As indicated above, kaolinites are probably the predominant clay minerals in most flatwoods and upland Coastal Plain soils. Kaolinite normally has a weak charge and an exchange capacity of about 10 milliequivalents per 100 grams of clay. Since clay comprises no more than 10 to 20 percent of the topsoil of many series (U.S. Soil Conservation Service, 1966), not more than one-fourth to one-third of the total exchange capacity of such topsoil may be attributed to it. The remainder is associated with organic matter, exchangeable aluminum, and amorphous oxides.

Retention and exchange of individual cations by kaolinitic clays depend on the ion species involved and the level of other cations (Wiklander, 1964). Moreover, there is a direct relationship between soil pH and the proportion of the total CEC that is occupied by bases, i.e., base saturation (Mehlich, 1942). Generally, nutrient exchange between kaolinite and plant roots is optimized by a base saturation of 40 to 50 percent (Marshall, 1964), which occurs above pH 6 (Mehlich, 1942). Since southern pines seem to prefer more acid soil, a base saturation of 30 percent may be better for them.

With base saturations from 30 to 50 percent, potassium is found in much greater amounts in the solution phase than on the exchange sites of kaolinitic systems. Consequently, only a small amount is fixed on the exchange sites to resupply the solution phase (Hipp and Thomas, 1967). Moreover, most of the potassium added in fertilizers must be taken up rapidly by plants or be lost to ground water.

The divalent cations Ca^{++} and Mg^{++} are held more tightly by the mineral fraction of the soil than are monovalent cations such as potassium (K^{+}). In consequence, smaller amounts of divalent ions are in solution and plants have to compete more with the clay for calcium and magnesium than for potassium. Availability of the calcium and magnesium over the ranges of base saturation found in this region probably can be described by the ratio law (Marshall, 1964).

The CEC of soil organic matter is quite variable but averages about 100 milliequivalents per 100 grams of material (Coleman and Thomas, 1967). The charge is highly pH-dependent, with about 40 milliequivalents per 100 grams' increase in CEC for each unit increase in pH (Wells and Davey, 1966; Khan 1969). Organic matter is normally much lower and should be expected to contribute less to the exchange capacity in well drained than in poorly drained soils. However, since organic matter of better drained soils may have more active sites per unit weight of material, the decrease in percent of organic matter does not necessarily mean a decrease in its total acid activity in the soil (Ponomareva and Plotnikova, 1957).

Organic matter tends to hold monovalent cations less strongly and multivalent cations more strongly than do clay minerals (Coleman and Thomas, 1967). Moreover, because organic matter complexes with multivalent metallic ions, different ion species do not replace each other on organic exchanges in readily predictable patterns (Evans, 1968; Naylor and Overstreet, 1969; Marshall, 1964). At low pH, multivalent cations may prevent potassium from occupying organic exchange sites (McLean and Owen, 1969).

The exchange capacity due to exchangeable aluminum and other amorphous material is also weak; however, dissociation of amorphous material is less influenced by pH than is dissociation of organic matter, and the affinity of exposed sites to individual cations is different (Coleman and Thomas, 1967). The force by which cations are bound to exchange sites of amorphous material depends on the ionic strength of the site and the cation as well as the valence of the ion (Helling et al., 1964). In this respect, amorphous oxides and exchangeable aluminum behave more like clay

minerals than like organic matter (Marshall, 1964). Their variable charge is reported to arise from the dissociation of hydrogen from hydroxy groups (De Villiers and Jackson, 1967).

At low pH's, amorphous materials have two other distinctive properties that may be important in fertilization of forest soils of the region: (1) amorphous oxides act as salt exchangers, holding both cations and anions on the exchange sites (Thomas, 1960); and (2) exchangeable aluminum complexes ammonia (Hunsaker and Pratt, 1970).

The contribution of amorphous material to the total charge may vary somewhat between flatwoods and upland Coastal Plain soils. On flatwoods soils, waterlogging in winter is thought to increase pH by reducing amorphous iron compounds to the soluble ferrous form (McKee, 1970). The reaction may precipitate aluminum in an inactive form. This hypothesis is supported by the fact that aluminum phosphates decrease and iron phosphates increase under waterlogging. Levels of exchangeable macronutrients are also depressed, probably because they are replaced by reduced iron and manganese on the exchange complex. These reactions appear to be slowly reversible and hence to result in a seasonal cycling in nutrient status of flatwoods soils. The effects of waterlogging need definitive study.

The effective CEC of a soil may be considerably less than the sum of charges on individual components of the complex. This masking of charge has been attributed to formation of amorphous-organic matter complexes (Marshall, 1964) and of iron oxide coating on clay micelles (Roth, 1969). In Roth's research removal of iron oxide coatings increased the non-pH-dependent charge of clay by 10 to 60 percent. A reaction of this type may accompany reduction of poorly drained flatwoods soils; however, the reoxidation of iron should reestablish the amorphous coatings. Some evidence has been accumulated that coatings are influencing the effective CEC of flatwoods soils.[3]

Moisture may also influence the acid reactions of weakly charged, amorphous oxides on upland soils (Westfall, 1968). Drying tends to cause greater dissociation of aluminum hydroxide and to decrease pH. As a result, pH on many soils of the region may be 0.5 to 1.0 lower in fall than in winter.

Higher levels of exchangeable bases are also found in these soils in late summer. Factors contributing to the increase are incompletely understood, but among them are a faster release of cations from organic debris in summer than in winter, and the exposure of additional exchange sites through dissociation of amorphous hydroxides. No information could be found relating seasonal patterns of soil acid properties to pine nutrition.

Phosphorus

In addition to occupying exchange sites on soil colloids, calcium, iron, and aluminum react with phosphorus to form a variety of compounds, each of which reacts differently to changes in pH (Huffman, 1962). The reactions profoundly influence retention and distribution of applied phosphorus in the rooting zone and its availability to plants.

Fox and Kamprath (1971) found, for example, that soluble monocalcium phosphate fertilizer leached rapidly through an acid organic soil devoid of aluminum oxides and exchangeable aluminum. Addition of exchangeable aluminum almost completely immobilized phosphorus, because it reacted with the aluminum to form relatively insoluble compounds. White and Pritchett (1970) reported that phosphorus moved rapidly through the profile of poorly drained sandy soils in Florida. In a more detailed study of several Florida soils, Humphreys and Pritchett (1971) found that retention of superphosphate fertilizer was related to phosphorus sorption and buffering capacities. Seven to eleven years after application, the added phosphorus had disappeared from the surface 8 inches of soils apparently lacking in these attributes. Most of it remained in this layer of soils having detectable capacities to sorb or buffer solution phosphorus. The predominant fraction in which soil phosphorus occurred was observed to shift from aluminum to iron as sorption and buffering capacities increased.

Almost nothing is known of the movement of phosphorus in pine soils of the West Gulf.

[3] Personal communication with Drs. M. S. Bhangoo and D. J. Albritton, Univ. of Arkansas at Pine Bluff, Ark.

Before closed stands can be fertilized with confidence, research is needed to learn which soils will retain added phosphorus at the surface, out of reach of feeder roots, and which soils will not unduly restrict movement of phosphorus into the root feeding zone. On soils where downward movement is seriously curtailed, ways must be found to place phosphorus where it can be utilized efficiently by pines, without injuring roots unduly, reducing growth, or promoting root disease.

Huffman (1962) stated that the rate of dissociation of aluminum and iron phosphates increases with pH over the range 3 to 11, whereas the rate of calcium phosphate dissociation declines over the same range. His phase diagram indicates that more phosphorus will be in solution and available to plants at pH 5.5 to 6.0 than at higher or lower pH's. This interpretation assumes that the phosphorus reactions are not limited by the amount of aluminum, calcium, or iron present—i.e., that there are sufficient quantities of all elements to establish stable equilibrium between the various compounds.

The amount of soil phosphorus in the aluminum, calcium, and iron fractions can be estimated (Chang and Jackson, 1957), and the phosphorus fractions were used successfully to show the availability of this nutrient to corn and soybeans on a variety of soils in Mississippi (Singh, 1970). The aluminum fraction accounted for most of the phosphorus uptake on acid soils and the calcium fraction for most on alkaline soils. Similar definitive research has not been done for southern pines, but McKee's (1973) data strongly suggest that slash pine seedlings derive most of their phosphorus from the calcium and aluminum fractions.

The approach of estimating phosphorus availability by identifying phosphorus compounds and determining their solubility products has not been universally accepted. Lewis and Quirk (1967) believed an intensity factor is also required; they expressed the factor as the ratio of phosphorus in solution to total mineral phosphorus in the soil. White and Haydock (1967) found that the intensity factor of a variety of Australian soils could be characterized by $NaHCO_3$ extraction of phosphorus with pH buffered to 8.5. The method worked well on all but the very acid soils.

On phosphorus-deficient soils in New Zealand, Ballard (1971) found good agreement between site productivity for *P. radiata* D. Don and the amount of soil phosphorus that was extracted with $NaHCO_3$—a method described by Olsen et al. (1954). Since the relationship was improved by considering the percentage of fine sand in the surface 4 inches, Ballard concluded that the Olsen test did not completely reflect availability over the range of soils he studied.

Alban (1972) found closer correlation between red pine (*P. resinosa* Ait.) site index in Minnesota and soil phosphorus if extraction was with H_2O, 0.002 *N* H_2SO_4, or 0.01 *N* HCl than if stronger reagents were used. He included in the stronger reagents 0.5 *N* $NaHCO_3$ (Olsen et al., 1954), 0.025 *N* HCl + 0.03 *N* NH_4F (Bray and Kurtz, 1945; Method 1), 0.10 *N* HCl + 0.03*N* NH_4F (Bray and Kurtz, 1945; Method 2), 0.04 *N* HCl + 0.025 H_2SO_4 (Nelson et al., 1953), and 0.4 *N* HCl.

In the South, the State of Florida has recommended extraction with acid ammonium acetate to estimate the amount of soil phosphorus available to pines (Pritchett and Llewellyn, 1966), while Virginia and North Carolina have used Nelson et al.'s (1953) mixture of sulfuric and hydrochloric acids for routine extractions.

It is uncertain if any of these approaches will be completely satisfactory in the West Gulf Coastal Plain. Selection of extraction solutions requires knowledge of local mineralogy, the phosphorus carrier, and the correlation between amounts of nutrient extracted and plant growth. Only recently has research been undertaken to compile such information for pines on West Gulf Region soils.

The cyclic reduction and oxidation that accompanies waterlogging and drying of flatwoods soils alters soil pH and causes large shifts in the proportions of phosphorus in the aluminum and iron fractions. When these soils are kept well aerated, added phosphorus seems to be divided among fractions in the same proportions as native phosphorus (McKee, 1970). The reactions increase the difficulty of devising methods for estimating levels of phosphorus available to pines growing on particular soils.

Nitrogen

Retention of nitrogen in forest soils is so intimately associated with nutrient cycling that separate consideration is impractical. It should be noted here, however, that ammonium nitrogen behaves very much like other monovalent cations in exchange reactions and that nitrate nitrogen quickly leaches from the profile if it is not taken up by soil microorganisms or by higher plants (Nommik and Popovic, 1971).

NUTRIENT CYCLING IN EVEN-AGED SOUTHERN PINE STANDS

Mineral nutrition, and especially nitrogen nutrition, of southern pines is closely tied to the cycling of elements in the ecosystem. A thorough understanding of this dynamic process is prerequisite to any research in commercial fertilization.

Knowledge of the nitrogen cycle in even-aged stands of southern pines is fragmentary. Information is available, however, to depict the range of nitrogen contents in the aboveground portions of managed stands to about age 30.

Smith (1965) observed that a 5-year-old loblolly pine plantation on a bottom-land site in Mississippi contained 64 pounds of nitrogen per acre in boles, branches, and foliage. This was an increase of 30 pounds over the amount present 1 year earlier. Comparable data for another plantation showed that 10-year-old trees had accumulated 140 pounds of nitrogen per acre aboveground. White and Pritchett (1970) found varying amounts in the biomass of a 5-year-old plantation of loblolly and slash pines in Florida; the quantity depended on depth to the water table and fertilizer treatment. Under the most favorable water regime, unfertilized loblolly contained 96 pounds per acre of nitrogen in the aboveground portions. Slash pines under the same conditions contained 168 pounds in their entire biomass (including roots). Fertilization with 350 pounds per acre of diammonium phosphate (18-46-0) increased nitrogen content by 27 percent for loblolly and 47 percent for slash pine. Working on Piedmont soils with a site index of 85 feet, Ralston and Prince (1965) estimated that about 175 pounds per acre of nitrogen was held aboveground by a 30-year-old loblolly pine stand containing 100 square feet of basal area per acre.

With allowance for a variety of soils and age classes, wide geographic distribution of the stands, and species differences in uptake of nutrients, these several estimates of nitrogen content of the aboveground biomass agree reasonably well.

Amount of nitrogen annually returned to the soil has been variously estimated. Smith (1965) thought that about 60 pounds per acre were recycled in a 4-year-old loblolly stand. Switzer et al. (1968) reported an annual return through litter fall of 27 pounds per acre for a 20-year-old loblolly pine plantation on an abandoned field in central Mississippi. At this age, uptake by the aerial portion of the trees was exceeding return to the soil by only 7 pounds per acre annually, and the quantity of cycling within the system was about 9 times that being immobilized. Maximum rates of uptake appeared to occur during the first 10 years of the stands' life.

In an earlier paper, Switzer et al. (1966) reported that loblolly pine stands during their first 30 years accumulated nitrogen aboveground at a mean annual rate of 6.3 pounds per acre on good sites and 5.0 pounds on poor sites. Annual accumulation during the next 30 years averaged 1.4 and 1.5 pounds per acre. Thus, about ¾ of the total was accumulated during the first 30 years.

The model developed by Switzer et al. (1968) showed that soils under 20-year-old loblolly pine ecosystems on good sites contained about 1,700 pounds of total nitrogen per acre but were supplying only about 34 pounds annually to the trees. The reason for this poor recovery rate may be that most of the soil nitrogen is immobile, or nearly so. Jorgensen (1967) found that less than 10 percent of the total nitrogen in three North Carolina Piedmont soils was in readily available forms (i.e., NO_3^- and exchangeable NH_4^+). The remainder was tied up in various organic compounds; over 50 percent of the total was in amino acids and 22 percent was in amino sugars.

The rate at which organic nitrogen is mineralized or made available to pines in other forms has not been reported for forest soils of the West Gulf, nor has the rate of addition of nitrogen to the soil through rain and nitrogen-

fixing organisms. The impact of other nutrients and tillage on nitrogen cycling also has been inadequately researched.

Abundance of nutrients in the tree biomass (aboveground or total) of southern pine stands appears to be in the order N > Ca ≤ K > Mg > P. Switzer et al. (1968) reported that loblolly pine stands under 30 years of age contained more potassium than calcium in their aboveground biomass but that the trend reversed with time because of greater immobilization of calcium in woody parts. White and Pritchett's (1970) data, however, show a greater accumulation of calcium than potassium in aboveground parts of a 5-year-old loblolly plantation in Florida. Potassium is highly mobile, and much of it appears to be redistributed within plants from older tissues to active meristems (Black, 1968; Switzer and Nelson, 1972).

Estimates of nutrients other than nitrogen in the stands described above are as follows:

Species, age in years, and treatment	Source	Ca	K	Mg	P
		(Pounds per acre)			
Loblolly pine					
Age 5					
Unfertilized	White and Pritchett (1970)	42	31	15	12
Fertilized	White and Pritchett (1970)	53	39	19	14
Age 20					
Unfertilized	Switzer and Nelson (1972)	80	87	21	17
Age 30					
Unfertilized	Ralston and Prince (1965)	104	105	—	16
Unfertilized	Switzer et al. (1968)	113	118	36	20
Slash pine					
Age 5					
Unfertilized	White and Pritchett (1970)	71	53	28	23
Fertilized	White and Pritchett (1970)	98	73	40	34

Loblolly data are for aboveground biomass only, whereas slash data are for both roots and aerial organs.

According to Switzer and Nelson (1972), most nutrients accumulate in the L, F, or H layers of the forest floor during the first 20 years of a loblolly stand's life. Their synthesis showed that the forest floor then contained 71 pounds of calcium, 14 of potassium, 14 of magnesium, and 8 pounds of phosphorus per acre. About 55 percent more nitrogen than calcium had accumulated.

The portion of each nutrient's total fund (in aboveground parts) that was cycled during the 20th year was estimated by Switzer and Nelson (1972) as follows: potassium, 28 percent; nitrogen, 23 percent; phosphorus, 19 percent; magnesium, 15 percent; and calcium, 7 percent. The greater proportional release of potassium than of other nutrients is in agreement with Curlin's (1970) observation that fresh litter surrenders its residual potassium in a relatively short time—probably because potassium is not immobilized in organic compounds in cells or cell walls. The relative ease with which potassium is leached from the litter makes it more liable than other metallic ions to removal in ground water.

Cycling may be influenced to some extent by cultural practicies such as site preparation, which alters competition and drainage, or by controlled burning of forest litter. Burning ensures early return of metallic ions to the soil, but it releases most of the nitrogen in the litter to the atmosphere. The loss of nitrogen may not be as serious as once supposed. Jorgensen and Wells (1971) found that annual controlled burning markedly enhanced the ability of Bladen and Bayboro soils from South Carolina to fix atmospheric nitrogen in the laboratory. Moreover, soils on annually burned plots contained 1,273 to 1,483 pounds per acre of additional nitrogen after 10 years in the 0-4 inch layer while unburned plots contained 778 to 868 pounds less. These authors thought burning improved the environment for nitrogen-fixing microorganisms by releasing inorganic nutrients and by promoting more favorable soil moisture and surface temperature regimes through reduction of litter and minor vegetation.

A better knowledge of nutrient cycling is essential to the study of fertilization, but data from unfertilized stands will not reliably indicate the quantity of individual elements in the various segments of the cycle. Therefore, this information should be collected from ongoing fertility studies.

FERTILIZATION

Considerable literature has accumulated on growth and quality responses of southern pines to applications of one or more nutrient elements since Paul and Marts (1931) found that commercial fertilizers increased growth of 100+ year-old longleaf pines and influenced the quality of the wood. Many of the publications contain insufficient information on the nutrient status of the soil before the fertilizers were applied. Moreover, many of the trials were with single elements or with fixed combi-

nations of elements and consequently are of little value in determining the total nutrient requirements of the particular species on the site where the test was made. Often the researchers did not attempt to determine what happened to the added nutrients, whether the treatments actually increased nutrient uptake by the pines, or if fertilization stimulated competing vegetation at the expense of the pines. They were satisfied to fertilize the ecosystem and measure the response of the commercial crop. Such practices led to the mistaken notion among many practicing foresters that southern pines are insensitive to level of soil fertility and do not respond to commercial fertilization.

Despite shortcomings, studies of these pioneers proved that commercial fertilizers, if applied on the right soil and at the right time, will produce economically attractive returns. As a result, fertilizers—especially phosphorus— have been applied commercially to southern pine stands in limited areas where a definite need for them has been demonstrated. Emphasis in research has also shifted from determining if southern pines respond to nutrient additions. Rather, investigations now tend to deal with the amounts and kinds of fertilizers required for optimum or maximum pine growth on particular soils, and with the changes in stand volume, quality, and geometry that accrue from various levels and combinations of soil nutrients.

Nitrogen

Nitrogen nutrition of southern pines is more complex than is the nutrition of other major elements. Nitrogen is essential to the breakdown of organic matter, and large quantities may be immobilized for considerable periods in this activity. Also, pine growth responses to nitrogen are often dependent on the addition of one or more other nutrients. A further complication is that nitrogen assimilation may be more closely coupled with carbohydrate reserves in the plant than is the assimilation of other elements. Finally, nitrogen may be supplied in several forms.

A number of authors have reported increases in basal area or diameter growth of southern pines from a single application of 20 to 300 pounds of nitrogen per acre (Jackson and Cloud, 1958; Zahner, 1959; Walker and Youngberg, 1962; Youngberg et al., 1963; Moehring, 1966; Farmer et al., 1970). Responses were usually greatest in the first year; they seldom continued beyond the third growing season, but the advantage gained initially persisted through the final measurement. Pegg (1966) found that bole form of loblolly pine was improved by nitrogen fertilization. None of these authors reported measurable increases in height. The amount of nitrogen required to obtain the responses was not adequately tested. Zahner (1959), however, observed no additional gain in growth from increasing the application rate to 300 from 100 pounds per acre.

Volumes were not reported by these authors. The differences in diameter and basal area growth reported by Zahner (1959) and Farmer et al. (1970) suggest that cubic-foot increment was speeded by 20 to 30 percent during the 5 years following treatment.

In contrast to the responses reported above, Pritchett and Robertson (1960) and Maftoun and Pritchett (1970) found that 300 to 800 pounds per acre of nitrogen applied to pots or to seedlings at planting was in some degree toxic to slash pine on Leon and Lakeland soils in Florida. They thought the soils were inadequately buffered to permit the addition of these quantities in a single application. In Louisiana, Linnartz (1961) found that nitrogen alone depressed 3-year growth of loblolly pine on flatwoods and upland Coastal Plain soils unless phosphorus was also supplied or had been added earlier when the sites were under cultivation. His results suggested an imbalance between elements as the cause of the negative response to nitrogen. He applied the fertilizers when the trees were planted.

In Florida, Pritchett and Smith (1972) also found that nitrogen alone had little effect on growth of slash pine in the first 3 years after planting. Application of 80 pounds per acre of nitrogen (as ammonium nitrate) increased response to phosphorus fertilization on wet but not on better drained sites. The fertilizer was broadcast in bands along the rows 1 to 2 months after the trees were planted.

None of the studies adequately determined the magnitude of response that can be expected from nitrogen fertilization when other nutrients are at optimum levels, as the most comprehensive of them tested only a limited number of fertilizer combinations.

Because young pines are not able to compete advantageously with other vegetation for added nitrogen, a number of investigators suggest that fertilization should be deferred until the stand has a closed canopy (Bengtson, 1971; Maki, 1960; Malac, 1968; Farmer et al., 1970). But there is no unanimity as to when in the life of a closed stand nitrogen should be supplied. Switzer et al. (1968) thought it should be added when the trees are increasing their biomass of limbs and foliage at the fastest rate, or between 7 and 20 years for loblolly pine. Applications during this period would coincide better with maximum needs of the stand than ones made earlier or later. Other authors (Malac, 1968; Stoltenberg and Phares, 1968) have suggested applying nitrogen a few years before final harvest, so as to minimize carrying charges on the investment. This approach, too, appears to have merit in light of the short time that an application increases growth.

Stocking level becomes important in fertilization of closed stands. Curlin (1963) reported that basal area growth of individual shortleaf pines in stands thinned and fertilized with nitrogen was up to 300 percent greater than in untreated stands. Nitrogen alone increased growth up to 40 percent in unthinned stands. Curlin concluded that stand density at time of application must be low enough to allow growth to proceed unhindered. However, Weetman (1968) found that thinning did not affect the response of black spruce, *Picea mariana* (Mill.) B.S.P. In 12- to 14-year-old slash pine plantations, Malac (1968) found that stocking levels between 300 and 900 trees per acre had no significant effect on response of individual trees to nitrogen. Volume growth per acre was promoted most in the denser stands, because they contained more trees. Malac concluded that fertilization might be most profitable if stocking was between 200 and 500 stems per acre. Undoubtedly, he was thinking in terms of stands at or near the same age as those he studied. The conflicting results of the various authors suggest that much remains to be learned on the relationship between stand density and response to nitrogen fertilization.

Most knowledge of southern pine responses to combination of elements has been gained from greenhouse or nursery studies. The findings provide valuable leads but must be verified in field experiments.

From pot experiments on sandy soils of west Florida, Brendemuehl (1968) concluded that slash, sand (*P. clausa* (Chapm.) Vasey), and longleaf pines grow best if the N/P ratio in added nutrients is about 1. Nitrogen alone had little effect. McKee (1973) found that optimum N/P ratio for slash pine in pots of Caddo silt loam from the flatwoods of Louisiana increased as more nitrogen was supplied. He concluded that a ratio on the order of 2 to 1 was desirable when nitrogen was supplied at a rate of 225 pounds per acre.

Nitrogen has a number of effects on phosphorus uptake. The most striking in agronomic crops is increased growth of roots, which brings the plant into contact with a greater quantity of nutrients (Grunes, 1959). Nitrogen also improves nutrient uptake by increasing the metabolic activity of roots and consequently the root exchange capacity and excretion of organic acids that solubilize phosphorus (Grunes, 1959). Inorganic nitrogen may also mobilize phosphorus in the soils to some extent. Beaton et al. showed that ammonia tends to solubilize phosphorus in forest humus.[4]

Nitrogen has interacted with potassium in some experiments. Benzian and Freeman (1967) found that concurrent application of nitrogen and potassium increased nutrient content and reduced frost-susceptibility of western coniferous seedlings in nursery and transplant beds in England. Brendemuehl (1968) reported that longleaf seedlings in pots of Lakeland sand topsoil grew best when supplied with a complete fertilizer equivalent to 150 pounds of N, 300 pounds of P, and 75 pounds of K per acre.

At least in the first rotation under intensive soil management, it may be more practical to release the nitrogen in the soil organic matter than to supply commercial fertilizers. Woodwell (1958) suggested this approach for pond pine (*P. serotina* Michx.) growing on pocosin soils in North Carolina. He thought activity of aerobic bacteria, with resulting release of organic nitrogen, could be increased by draining the site, reducing soil acidity, and correcting deficiencies of other nutrients. The

[4] Beaton, J. D., Harapiak, J. T., Speer, R. C., and Gardiner, R. T. **Release of plant nutrients from forest soil humus treated with nitrogen and sulphur fertilizers.** Agron. Abs., Annu. Meet. Am. Soc. Agron., p. 103. 1969.

approach deserves evaluation not only in the pocosins but also on the poorly drained flatwoods soils, which are characterized by a high C/N ratio (20 to 1) and approximately 3 to 4 percent organic matter in the 0- to 4-inch layer (U.S. Soil Conservation Service, 1966).

One of the most bothersome aspects of pine nutrition is the apparent low recovery of applied nitrogen. McKee and Sommers (1971) found that 3-year-old slash pine seedlings on Beauregard silt loam recovered only about 25 percent of the nitrogen from a single application of 150 or 300 pounds per acre. Baker (1971) reported that pines and herbaceous vegetation in a 3- to 4-year-old loblolly pine plantation recovered up to 14 percent from a single application and 24 percent from two applications several months apart. An additional 8 percent was found in pine roots and soil. Levels of recovery in both studies agree roughly with Waring's (1969) estimate of 25 percent recovery by 5½ year-old *Pinus radiata* in Australia. Nothing was found in the literature on nitrogen recovery of older stands.

Agronomic crops usually recover 2/3 to 3/4 of ^{15}N in carefully controlled experiments (see Allison, 1966; and Terman and Brown, 1968). Similar definitive studies have not been made with southern pines.

Part of the low recovery ratio in field experiments may result from the high C/N ratios of organic matter in forest soils. This condition leads to severe competition from soil microorganisms for added nitrogen. On soils containing 3 to 4 percent organic matter, 1,000 to 1,500 pounds of nitrogen per acre would be required to lower C/N ratios to a stable base of about 10 to 1. Research is needed to determine the fate of applied nitrogen and to establish if, indeed, important amounts are tied up in the breakdown of soil organic matter.

Finally, nitrogen may be supplied in several forms. Pines are able to utilize both ammonium and nitrate forms (Addoms, 1937); Overrein, 1967; Carrodus, 1969; McFee and Stone, 1968). The choice of a carrier should therefore depend in part on soil factors. The nitrate ion is more mobile and more readily accessible to roots in acid soils, whereas the ammonium ion is more mobile in alkaline soils (Russell, 1961; Black, 1968). Some authorities—for example, Steinbrenner (1968) and Watkins and Strand [5]—advocate urea as a carrier because of its high nitrogen content (45 percent). Urea hydrolyzes rapidly, yielding gaseous ammonia, if soils contain sufficient organic matter to support a high indigenous microbial population (Chin and Kroontje, 1962; Roberge and Knowles, 1968). Loss through volatilization is reported to be as high as 50 percent in forest humus (Overrein, 1970). However, when Volk (1970) added urea to a Florida soil on which forest litter had been removed by burning, not more than 2 percent evolved as ammonia gas during the first 7 days after application.

Slow-release carriers, such as soluble metal salts, urea formaldehyde, and coated diammonium phosphate, have been used to reduce leaching (Strand and Austin, 1966; Walters et al., 1966; Austin and Strand, 1960; Brown and Volk, 1966). Results were variable and depended on environmental factors peculiar to each study. Hydroamides or weakly dissociated nitrogen salts have been suggested as carriers (Wright, 1959), but no reports of their use in forestry were found.

Research on carriers for West Gulf Coastal Plain soils should be deferred until more is learned of the pines' needs for and response to nitrogen under field conditions.

Phosphorus

Pines respond to applications of phosphorus on a wide range of soils in temperate climates throughout the world (Gentle and Humphreys, 1967; Wiley et al., 1970; Pritchett, 1963). The main complicating factors in the study of pine response are solubility of phosphorus compounds in the soil and placement of the fertilizer. The two are related, and both affect the amount of added phosphorus that is actually available to plant roots.

Solubility of phosphorus compounds was discussed earlier in this paper.

Brendemuehl (1970) thought proper placement was the overriding consideration on Southern Coastal Plain soils. He suggested incorporation into the soil in conjunction with preplanting site preparation. Fertilization by

[5] Watkins, S. H., and Strand, R. F. **Volatilization loss of ammonia N from urea applied to forest soils and forest floor materials.** Agron. Abs., Annu. Meet. Am. Soc. Agron., p. 164. 1970.

this procedure has often stimulated southern pine growth (e.g., Brendemuehl, 1970; Pritchett and Swinford, 1961; Linnartz, 1961). It has not always been clear, however, how much of the increase accrued from fertilization and how much from site preparation. Surface applications did not stimulate growth of older loblolly pine stands in Arkansas (Zahner, 1959) or of newly planted slash pine in about half of Pritchett and Smith's (1972) trials on better drained soils in the Southeast; these results are consistent with the idea that incorporation is desirable. Conversely, surface applications have usually stimulated slash pine growth on imperfectly and poorly drained phosphorus-deficient soils (Pritchett and Llewellyn, 1966; Pritchett and Smith, 1972; Wells and Crutchfield, 1969).

The level of soil phosphorus required for pine growth is not known. Requirements are influenced by soil characteristics and environmental factors, and there is no universally satisfactory method of measuring availability. Moreover, species vary in their requirements. A number of authors suggest that a general range of 100 to 200 p/m of total mineral phosphorus is optimum for southern pines growing on highly weathered soils (Pritchett, 1968; Richards, 1958; Raupach, 1967). Richards (1958) reported optimum levels of 210 and 150 p/m of total soil phosphorus for loblolly and slash pine, respectively, in Australia. Baur (1959) was quoted by Pritchett and Llewellyn (1966) as proposing 70 p/m of total phosphorus as the critical level for a slash pine plantation in New South Wales, Australia. On sandy flatwoods soils in Florida, Pritchett and Llewellyn (1966) found that slash pine responded to 17 to 35 pounds per acre of phosphorus added as superphosphate when the level of ammonium-acetate-extractable phosphorus in the unfertilized soil ranged from 0.5 to 2.7 p/m. Total phosphorus in these soils ranged from 19 to 74 p/m. Thus, average content of the furrow slice of heavily fertilized plots was 36 to 91 p/m, which is considerably lower than that prescribed by either Richards or Baur for Australia.

Pines on well to excessively drained soils in Pritchett and Llewellyn's (1966) tests did not respond unless nitrogen was also added. The difference in response between flatwoods and better drained soils could not be explained by initial phosphorus levels in the soil. It appears, therefore, that higher levels are required on imperfectly than on well drained soils. Conversion of aluminum to iron phosphate occurs when soil is waterlogged for significant periods of time (McKee, 1970); in addition, trees in poorly aerated soils may be less able to take up the phosphorus that is available.

Foliar analyses are another means of diagnosing phosphorus deficiencies. Pritchett (1968) considered 0.09 to 0.10 percent to be the critical level in needles of 5- to 8-year-old slash pine in Florida, but cautioned that age of tree, age of foliage, position of foliage in the crown, and certain growth-limiting factors would influence the percentages. To minimize the effects of these factors, most researchers follow the procedure of Wells and Metz (1963) and analyze needles from the first flush of the current season's growth collected from the south side of the upper one-third of the crown. Critical concentrations in loblolly pine needles appear to be slightly higher than those in slash needles, or 0.10 to 0.12 percent (Miller, 1966). No close relationships have been established between phosphorus concentrations in foliage and optimum or maximum growth of pines.

A carrier that is relatively insoluble and will equilibrate very slowly may be advantageous in soils low in exchangeable aluminum or other constituents that restrict movement of phosphorus through the profile or have a high capacity to form iron phosphates. Rock phosphate has been found to be a good nutrient source under these conditions (Pritchett, 1963; Richards, 1958; Bilan, 1966; Barnes and Ralston, 1953; Humphreys and Pritchett, 1971). Its availability to pines increases with the citric acid solubility of the material.[6]

Use of rock phosphate in the West Gulf Coastal Plain will probably depend more on relative total costs than on its reactions in the soil, as few soils of the region appear to require a carrier with the unique properties it possesses. For the present, at least, research in this region should concentrate on learning how phosphorus behaves in the soil and how it should be applied for pines to use it efficiently;

[6] Bengtson, G. W., Sample, E. C., and Lehr, J. R. Factors related to performance of various rock phosphates used as sources of P for Pinus elliottii seedlings. Agron. Abs., Annu. Meet. Am. Soc. Agron., p. 123. 1969.

comparisons between carriers are of secondary importance.

Almost no research has been done to determine how often phosphorus must be applied to maintain optimum or maximum growth. Some researchers believe that enough can be added when the stand is established to satisfy needs for an entire rotation. Current data indicate that responses persist for 5 years or longer on poorly drained soils (Pritchett and Llewellyn, 1966); in 7 to 11 years, superphosphate, but not rock phosphate, had moved to depths greater than 8 inches (Humphreys and Pritchett, 1971). Tests are needed to provide similar information for other soils and to learn if growth is further enhanced or initial response is prolonged by additional applications as the stand develops. It is also necessary to determine how established stands respond to initial applications of phosphorus either alone or in combination with other elements.

Potassium, Calcium, and Magnesium

Only under rather unusual circumstances has fertilization with the major macro-cations, potassium, calcium, and magnesium, markedly increased growth of pines.

The most spectacular responses to potassium fertilizers have been on highly leached outwash sands of the Northeast (Kawana et al., 1969; Heiberg et al., 1964; Fornes et al., 1970; Heiberg and White, 1951; Madgwick et al., 1970). These soils have extremely low exchange capacities and very little native potassium.

In a 7-year-old loblolly pine plantation on Piedmont soils in South Carolina, Wells (1970) obtained no response to applications of 120 and 240 pounds per acre of potassium with or without the addition of 200 pounds per acre of nitrogen. Moreover, in trials by Pritchett and Smith (1972) potassium applied with nitrogen and phosphorus did not increase three-year growth of slash pine significantly more than did the two companion nutrients alone. The reason for this lack of response may be that potassium is one of the most mobile of ions in plants (Bukovac and Wittwer, 1957) and hence that current needs of active meristems may be largely supplied through redistribution within the plant (Switzer and Nelson, 1972).

Deficiencies in closed stands apparently can be diagnosed easily by foliar analysis (Walker, 1955; Madgwick, 1964). No clear evidence has been discovered, however, of potassium deficiencies in stands of southern pines.

Measurements of the biomass of pine stands (Ralston and Prince, 1965; White and Pritchett, 1970) indicate that calcium nutrition may become critical during the rotation if the initial amount in the soil is not more than 400 to 600 pounds per acre. Calcium and magnesium deficiencies, however, are less common than potassium deficiencies, and none have been reported for pines in the West Gulf region.

La Bastide and van Goor (1970) found that low levels of calcium and magnesium were limiting growth of slash pine on many soils in Brazil. They reported minimum requirements of about 1.5 milliequivalents per 100 grams of soil for calcium and magnesium combined (or 600 pounds per acre of calcium, if their estimate was based on depth of a furrow slice). A number of soils sampled in the Coastal Plain fall below this level (U.S. Soil Conservation Service, 1966).

In Germany, liming has doubled or tripled the growth of Scotch pine (*P. sylvestris* L.) and spruce (*Picea abies* (L.) Karst.) (Stoeckeler and Walker, 1963). It should be noted, however, that these results are for true spodsols that are very acid, are low in bases, and have thick organic surface horizons that tie up large amounts of nutrients. Moreover, establishment of perennial lupines was necessary for maximum response to lime. Much of the apparent response to calcium may actually be a response to other nutrient ions whose cycling is accelerated by liming (Mayer-Krapoll, 1956).

Calcium deficiencies are reported to retard growth of the terminal bud, reduce the size of stem tips and leaf cross sections, and decrease primary tissues in the stems of loblolly pines grown in solutions (Davis, 1949). Voigt et al. (1958) stated that calcium and magnesium deficiencies of seedlings in the field result in an intense yellowing of the outer portions of the needles. Sucoff (1961, 1962) noted similar deficiency symptoms on loblolly and Virginia (*P. virginiana* Mill.) pine in sand culture. Needle color has been suggested as a means of diagnosing such deficiencies (Lyle, 1969).

A number of papers indicate that lime is toxic to pine (Gilmore and Boggess, 1963; Bengtson, 1968). High levels of calcium and

pH have been reported to cause chlorosis (Wilson, 1959; Shoulders and Czabator, 1965).

Lyle and Adams (1971) observed that the cation balance may be critical for root growth of loblolly pine seedlings in water culture and greenhouse pot studies. They concluded that liming may be necessary for root development in young loblolly pine plantations fertilized with high-analysis, low-calcium fertilizers.

Application of lime has several implications for plantation management other than calcium nutrition. Its use to enhance organic matter breakdown and phosphorus availability has been discussed in other sections. Lime may be needed to reduce levels of toxic elements such as manganese and aluminum (Black, 1968) and to adjust base saturation of the exchange complex. Solubility of aluminum and manganese are strongly influenced by pH. How important these factors are to pine nutrition remains to be determined. Experience with agronomic and horticultural crops (Jackson, 1967) indicates that they should be explored.

Certainly, research is needed on cation nutrition of southern pines on flatwoods and upland Coastal Plain soils. These investigations, at least for the present, should seek to determine growth responses to addition of calcium and potassium after phosphorus and nitrogen have been adjusted to near optimum levels.

Minor Elements

The minor mineral elements have only recently gained the attention of forest researchers in the South. Current literature records no universal response of any species of southern pine to additions of any or all of the minor elements at planting or later. In a series of uniform fertilizer tests in the Southeast, all other essential elements stimulated early growth of slash pines on 3 to 28 sites that had also received nitrogen, phosphorus, and potassium and depressed it on 4 other sites (Pritchett and Smith, 1972). Van Lear and Smith (1972) studied minor mineral nutrition on three Southeast Coastal Plain soils in more detail. On Leon fine sand, supplementary copper was required before potted slash pines responded to nitrogen and phosphorus fertilization. Macronutrients supplemented with copper, manganese, and zinc produced greatest growth on Lakeland sand. On Bladen fine sandy loam, micronutrient supplements were unnecessary for maximum growth response to additions of 100 p/m of nitrogen and 400 p/m of phosphorus.

Van Lear and Smith's (1972) investigation supports Stone's (1968) observation that deficiencies of several minor elements may be induced by heavy liming or phosphorus fertilization. Nursery seedlings threatened by imbalances of lime and phosphorus have been salvaged by applying iron chelate (Shoulders and Czabator, 1965).

Soil organic matter is an important reservoir for chelated or nonionic forms of minor elements (Wallace, 1962). Its ability to act as a chelating agent is dependent on the type of organic compound present, valence of the ion chelated, bonding energy of the metal, ionic strength of the system, and soil pH. Complexing agents may have a direct physiological influence on plant growth as well (Schnitzer, 1969). In general, the strength of the organic-metal complex increases with valence and molecular weight. For example, fulvic acid forms a more stable complex with ferric iron than with calcium by a factor of 1×10^4 (Schnitzer and Hansen, 1970). Increasing hydrogen ion activity (i.e., lowering pH) improves the stability of metal-organic complexes, and many soil chelates break down if acidity approaches neutrality (Wallace, 1962; White, 1970).

In general, humic acids in soil all react similarly with metals, but their activity coefficients differ. Coefficients of individual acids may be important in cyclically submerged soils because of changes in pH associated with reduction and reoxidation.

Research in minor mineral nutrition of pines on flatwoods and upland Coastal Plain soils of the West Gulf should be undertaken only as a need for it is demonstrated through unusual or erratic responses to major elements.

OTHER CONSIDERATIONS

In their response to mineral nutrients, trees are influenced by their physiological condition and genetic makeup, and also by various environmental conditions. Such effects must be considered in planning and interpreting research. A brief summary of these relationships is therefore included.

Some physiological processes and conditions of southern pine have seasonal patterns, or vary with age of the tissue. For example, as needles of loblolly pine increase in age, their nitrogen, phosphorus, and potassium contents tend to decrease, while their calcium and magnesium contents increase. Moreover, about one-half of the nitrogen, phosphorus, and potassium is translocated to other organs immediately before abscission. Calcium and magnesium remain in the needles (Wells and Metz, 1963; Miller, 1966). The most reliable indexes of nutrient deficiencies in loblolly pine can be obtained by sampling the current year's needles for phosphorus in August or September and for cations in December through March; needles should be sampled for nitrogen in June through September of their second growing season (Wells and Metz, 1963). Considerable research is needed to develop completely satisfactory methods for appraising nutrient status of southern pines through needle analyses.

Organic constituents of trees also vary seasonally. Hepting (1945) found that carbohydrate reserves in shortleaf pine were low in late summer and highest in midwinter. Data for slash pine in Louisiana indicate a similar trend. Carbohydrate levels there were high in late fall and early spring and low in late summer (McKee and Sommers, 1971); these plants were not sampled at other seasons. In red pine, reducing sugars in needles and soluble proteins in needles and bark were high in winter and low in summer (Pomeroy et al., 1970).

The seasonal change in carbohydrates may influence timing of nitrogen application, since ammonium nitrogen cannot accumulate in plants (Webster, 1959) and therefore must be held in some organic compound. Carrodus (1969) indicated that available carbohydrates largely control the utilization of inorganic nitrogen. Conversely, timing of nitrogen fertilization has influenced the distribution of the total photosynthate among plant organs (Priestley, 1972). In a Louisiana study, however, application of nitrogen in late October and in early April produced similar responses in growth and nutrient uptake of 3-year-old slash pines on Beauregard silt loam soil (McKee and Sommers, 1971). In this study, the seedlings recovered only 25 percent of the applied nitrogen. Relationships between season of application and carbohydrate levels of roots will merit further study when ways have been found to improve nitrogen utilization of southern pines.

Because individual components of the environment are difficult to isolate in the field, growth chambers are often used to study the independent effects of light intensity and temperature on current rates of nutrient uptake by pines. In one such study, uptake and transport of radioactive phosphorus to needles of 1-year-old slash pines decreased with increasing day/night temperatures over the range 59/50 to 95/86 degrees Fahrenheit and with decreasing light intensity over the range 2,500 to 1,200 foot candles (McKee, 1972). The rate of phosphorus uptake was partly explained by levels of ethanol-soluble carbohydrates in the roots.

Additional research is needed to clarify the effects of light and temperature on ion flux into and through seedlings and older trees, as well as their effects on carbohydrate reserves and the relationships between carbohydrates and ion flux. The complexities in such investigations are illustrated by the work of Barnes and Berry (1969). They found that carbohydrate contents of white pine (*P. strobus* L.) seedlings in growth chambers were less affected by light intensity than by temperature, but that sugar content of tissue from field-growing seedlings was higher on sunny than on cloudy days. Research into environmental effects on physiology will require careful design, because individual trees may respond differently from stands.

That density and structure of the stand affect response to nitrogen fertilizers was noted earlier. These factors also appear to be important with other elements. Ryker and Pfister (1967) found that 40-year-old white pine did not react to a mixed N-P-K fertilizer until the stand was thinned.

Root environment affects mineral nutrition by influencing distribution of roots in the soil as well as the plant's ability to take up nutrients. Lorio et al. (1972) found that microrelief altered the distribution of roots of a 40-year-old loblolly pine stand on an imperfectly drained flatwoods site in central Louisiana. Roots of all sizes were abundant to greater depths on mounds than on surrounding flat

areas. The change in rooting patterns was explained in part by differences in water regimes and soil texture between mounds and flats. Schultz (1969) showed that slash pine seedlings in pots took up less nutrients and grew slower under waterlogged conditions than when well aerated. Burton (1971) found that growth and nutrient uptake of loblolly pine seedlings decreased with the length of time that the soil surface was submerged. Other authors have also observed that levels of nutrients in pine foliage are depressed by poor aeration of roots (Miller, 1966; Wells and Metz, 1963).

Symbiotic relationships between pines and mycorrhizae-forming fungi influence, and are influenced by, physiological condition of the trees and their uptake of mineral nutrients. A few aspects that are particularly important to pine nutrition are considered here. The degree of fungus infection on pine roots is related to levels of ethanol-soluble carbohydrates (Hacskaylo, 1959; Björkman, 1970). A close relationship has been found between mycorrhizal infection and phosphorus uptake (Ritter and Lyr, 1965; Mejstrik, 1970; Henderson and Stone, 1970; Shoulders, 1972). Moreover, Kramer's (1951) discovery that uptake of phosphorus by mycorrhizae requires metabolic energy further demonstrates that the carbohydrates supplied by the host are of mutual benefit to both symbionts.

Balance of nitrogen, phosphorus, and potassium influences development of mycorrhizae. Nutrient imbalances as well as heavy fertilization that promotes luxuriant growth depresses the number of these organs on roots (Hacskaylo, 1959; Lister et al., 1968).

Soil microbial activity and soil chemistry are affected by pine root exudates including carbohydrates, organic acids, amino acids, and vitamins (Smith, 1969). Effects of these exudates on nutrient uptake are not known.

Application of fertilizer can also affect the physiological processes and the way in which a plantation will respond to climate. Keller (1968) reported, for example, that fertilization tends to increase rate of photosynthesis but that unbalanced amounts depress CO_2 uptake. Etter (1969) reported that high levels of nitrate nitrogen in nutrient solutions reduced drought-resistance of lodgepole pine (*P. contorta* Dougl.) seedlings growing in an artificial soil. The loss of resistance was related to a lessening of carbohydrates in leaves and roots. Pharis and Kramer (1964) found that too much and too little nitrogen in culture solutions depressed survival of loblolly pine seedlings during drought; high nitrogen levels were toxic, while intermediate levels improved drought-resistance. Parker (1969) noted that addition of potassium and phosphorus tended to improve drought hardiness in a number of woody plants.

Schmehl (1967) thought that nitrogen levels influenced "hardness" of herbaceous plants by changing growth patterns and competition for food reserves. Moderate additions increased the leaf area and total carbohydrate fixation, but excessive applications stimulated top growth at the expense of root reserves.

Complex responses of stands to fertilizer are difficult to anticipate, but careful observations should be made especially when the trees are under environmental stresses such as those imposed by drought or waterlogging.

Foster (1968) indicated that fertilizers may modify the severity of damage from forest pests. Froelich et al. (1966) found that high incidence of *Fomes annosus* infection was associated with low organic matter, high pH, a sandy texture, and a sparse grass understory. The impacts on insect and disease susceptibility of stands may, in the long run, be a major factor in adoption or rejection of a particular fertilization practice.

Almost invariably, fertilization at planting stimulates a profuse growth of grasses and other herbaceous plants. Few researchers have faced squarely the impact of competition from these plants for nutrients and growing space. Derr (1957) showed that fertilization increased early growth of planted longleaf pine only if competition was adequately controlled. Box et al. (1966) reported that a fertilized 3-year-old loblolly plantation had benefited markedly from three mowings annually, but the combined effects of mowing and fertilizing could not be separated from those of mowing alone. Probably mowing enhanced the response of the pines to the fertilizer. Baker (1973) found that slash pine in a 5-year-old plantation on Lakeland sand in Florida had benefited about as much from fertilization as from complete control of competition. Each treatment in-

creased height growth about 45 percent. In combination, they resulted in a 70-percent increase.

Many authorities, including Schultz (1969), Pritchett and Goddard (1967), Walker and Hatcher (1965), and Zobel and Roberds,[7] believe that southern pines of different genetic backgrounds vary widely in their response to fertilizers. Experience with agronomic crops indicates that this aspect of pine nutrition deserves immediate and thorough investigation. In fact, spectacular gains from fertilization may depend as much on developing strains of southern pines that are unusually responsive as on solving other problems in pine nutrition.

CONCLUSIONS

Emphasis in pine nutrition research in the West Gulf Coastal Plain should be placed on determining how growth is related to various levels and combinations of mineral nutrients, especially nitrogen and phosphorus, and on learning the reasons for these relationships. Such information will give individual landowners a quantitative basis for deciding which practices are feasible for them to adopt. The basic knowledge gained through this approach will be useful in planning new studies with unusually responsive strains.

The research must consider both the soils' abilities to hold nutrients in available forms and the pines' abilities to respond to fertilizers through increased production of merchantable fiber. If results of individual fertilizer trials are to be extrapolated from one soil to another, data are needed on the nature and the components of the exchange complex of individual soils, on the reactions which added phosphorus undergoes in them, and on the cycling of nitrogen through them.

The cycling of nutrient elements by the stand throughout the rotation must be understood if mineral supplements are to be balanced with the nutrient-supplying power of the ecosystem.

Fertilizer trials must determine nutrient levels and balances which optimize growth at different stages of stand development. Ways must be found to increase the efficiency of pines in recovering added nutrients, especially nitrogen, and to ensure that competing vegetation does not utilize added nutrients to the detriment of pines. Soils that immobilize phosphorus fertilizers at the surface must be identified, and techniques developed whereby phosphorus may be supplied to established stands of pine growing on them. Conventional methods of incorporating fertilizers into the soil inflict undue injury on roots of older trees.

Deficiencies of micronutrients may limit pine growth on some soils of the region, especially if macronutrients are at optimum or luxury levels. For the present, at least, research in this area should be limited to situations where fertilization with macronutrients has produced increased or erratic responses.

On many soils in the West Gulf, spectacular gains will not be obtained until geneticists develop strains that are unusually responsive to fertilization. Experience with agronomic crops indicates that this aspect of pine nutrition deserves immediate and thorough investigation.

[7] Zobel, B., and Roberds, J. H. **Differential genetic response to fertilizers within tree species.** Paper presented at First North American Forest Biology Workshop, August 5-7, 1970. Mich. State Univ., East Lansing. 1970.

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Review of current literature establishes that forest fertilization is a proven, accepted management practice in limited areas of the South where lack of one or more mineral nutrients seriously curtails pine growth and where moderate additions of these nutrients markedly increase yields. In most of the South, however, and especially in the West Gulf Coastal Plain, general use will be deferred until amounts, kinds, and schedules of application can be reliably specified for individual soils.

Additional keywords: Fertilization, nutrient cycling, soil fertility.