ESTIMATING SOIL NITROGEN SUPPLY AND FERTILIZER NEEDS FOR SHORT-ROTATION WOODY CROPS

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Abstract

Short-rotation woody crops are becoming important supplies of hardwood fiber, but little is known about the early nutritional needs of these systems, especially on different site types. The study objectives were, on two young (ages 3-6) sweetgum plantations with contrasting soil types, to 1) determine the plant growth and foliar nutrition response to repeated nitrogen (N) fertilizer applications, 2) determine soil N supply, plant N demand, foliar N resorption, and soil and fertilizer uptake efficiencies, and 3) test a simple N supply model. In order to expand the findings to the range of sweetgum site types, the study objectives were also to 4) evaluate rapid methods for determining N mineralization potential, 5) characterize the soils of 14 sweetgum site types in the Atlantic coastal plain, and 6) review current N fertilizer prescriptions in forestry and recommend strategies for improvement. Two young sweetgum (*Liquidambar styraciflua* L.) plantations on a converted agricultural field and a pine cutover site in South Carolina were fertilized biannually with three rates of N fertilizer (0, 56, 112 kg N ha^{-1}). Fertilization doubled foliar biomass and leaf area on the cutover pine site in the years fertilizer was applied, and stem biomass increased 60%. Critical values, the N concentration required for 90% of optimum growth, is approximately 1.75%. Foliar N uptake increased at both sites when fertilizer was applied. Modeled annual soil N supply was within 20% of that measured on the two plantations even though monthly N supply was not accurately estimated. Potential N mineralization was accurately estimated with a 3-day incubation of rewetted soils that were previously dried, but not by hot salt extraction or anaerobic incubation. Across a spectrum of 14 sweetgum sites, the agricultural fields had lower mineralizable nitrogen (126 kg ha^{-1}) than the cutover sites (363 kg ha^{-1}). Current N fertilizer prescriptions are not sufficient for repeated fertilizer applications to fast-growing hardwood plantations, but simple models of soil N supply and an N-balance approach may improve prescriptions.

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CHAPTER I. INTRODUCTION

RATIONALE

Short-rotation woody crops (SRWC) are increasingly being used to meet the demand for fine paper pulp (Steinbeck, 1999) and, in some areas, biomass energy production (Wright and Berg, 1997). Historically, foresters in the southern United States have been blessed with a relatively large land base for fiber production. Increasing fiber demand could be met by expanding existing land bases or by applying relatively simple management changes. Currently, land areas available for forestry are decreasing, and simple management changes have already been incorporated. In order to continue to meet demand, management intensity must increase. Increases in management intensity are prohibitively costly, though, if they fail to improve fiber supply. Furthermore, local, regional, and global environmental issues and policies, e.g., local water quality ordinances, the American Forest and Paper Association's (AF&PA) Sustainable Forestry Initiative^{SM}, and the United Nations Kyoto Protocol all are requiring or causing land managers to maintain a high level of environmental stewardship. Therefore, it is imperative to base intensive-silviculture decisions on the best biological information possible.

Tuskan (1998) defines SRWC as forest management systems that use "appropriate site selection and preparation . . . , in combination with the use of improved clonal planting stock, extensive weed control . . . , fertilization as required based on the use of plant-based fertilizer prescriptions for micro- and macro-nutrients, pest control . . . , and efficient harvesting and post-harvest processing." According to Tuskan (1998), the greatest unresolved issues in SRWC silviculture are those related to tree nutrition and fertilizer prescriptions.

Specifically, research is needed to identify site-specific controls on native soil fertility, especially with regard to nitrogen (N), and the possible plant and soil responses to N fertilization. Most N fertilizer prescriptions use plant indicators, such as visual symptoms or foliar N concentrations (Ballard, 1979; Dickmann and Stuart, 1983) to assess whether tree N demand (biomass increment X N concentration in biomass) is being met by natural soil nutrient supply (quantity of available N per unit area per unit time). This approach can work to fulfill short-term goals of ameliorating nutrient deficiencies, but growth reductions may occur before deficiencies are observed and ameliorated. A more proactive method of N nutrition management is to manage N from a supply perspective, in which fertilization is used to supplement native soil N supply in order to continually meet plant demand. Because both approaches have strengths and weaknesses, the best tree nutrition program combines positive aspects of both approaches (Geypens and Vandendriessche, 1996).

Because intensively managed hardwood trees require substantially more N than traditional pine plantations for optimal growth, the prescriptions and approaches used for pine plantations are insufficient for maintaining SRWC growth. Fertilizer recommendations for SRWC need to be based on an overall understanding of the nutritional needs of specific species and the N supplying capacity of specific soils. In order to maintain sufficient N for optimal growth, we must first be able to quantify native soil N supply and species-specific N demands under varying soil and climate conditions.

For decades, ecological, agronomic, and forest science researchers have promoted biological process models as tools that can integrate our scientific understanding of ecophysiology, hydrology, and soil nutrient dynamics and provide insights for intensive forest management. Unfortunately, the record shows that foresters and SRWC managers have rarely adopted process models due to their complexity, need for highly detailed data, and lack of meaningful outputs. On the other hand, applied silvicultural researchers have continued to fertilize SRWC stands with little regard for individual site conditions in order to test limited objectives on tree response. Between these two groups of researchers are the foresters and SRWC managers who have the responsibility of maintaining optimal growth while keeping economic and environmental costs to a minimum. SRWC managers need more scientifically based information than that gleaned from limited fertilizer response studies, but they do not need complex models that require research scientists to collect the necessary data and operate.

One scientific and biologically based approach to determining N fertilizer recommendations is a balance-sheet approach modified from agronomy. The amount of N fertilizer (N_f) required by an annual crop depends on the dry matter yield (Y_{dry}), the N concentration in the biomass (N_y), and the amount of N that the soil will supply during the growing season (N_s) (Stanford, 1973) (Equation I-1):

$$N_f = \left(Y_{dry} N_y\right) - e_s N_s \tag{I-1}$$

The crop will not recover all fertilizer N (N_f) or soil N (N_s); N uptake efficiency from soil (e_s) and fertilizer (e_f) will be less than 100%. Therefore, N uptake efficiency will influence the quantity of N needed to achieve a certain yield (Equation I-2):

$$N_f = \frac{\left(Y_{dry} N_y\right) - e_s N_s}{e_f} \tag{I-2}$$

For annual agronomic crops this representation is sufficient. In forest systems, especially with deciduous tree species, this approach is not complete. The nutrient balance concept was developed for agronomic systems in which N_y can readily be determined for the entire plant or for certain plant components of interest. In SRWC systems, the concentration and growth of the foliage and fine roots represent the greatest contribution to yearly plant N demand. Furthermore, a portion of mobile nutrients, e.g., N, P, K, are resorbed by the perennial plant organs prior to leaf senescence. Nitrogen resorption can be expressed as a modification to Equation I-2, where e_y is the N resorption efficiency, or the proportion of N recovered before leaf-fall (Equation I-3):

$$N_f = \frac{\left(Y_{dry} N_y\right) - e_s N_s - e_y N_y}{e_f} \tag{I-3}$$

The most difficult component of this equation to estimate is N_s, soil N supply and the efficiency factors. Due to its dynamic nature, N_s cannot be easily estimated from laboratory soil analyses. Complex process models are available for simulating N dynamics, but generally require very detailed site-specific information that SRWC managers cannot easily obtain. On the other hand, a relatively simple soil N supply model may be useful if it does not require large amounts of input data.

OBJECTIVES

The overall goal of this research was to determine the N fertilizer required to supplement soil N supply to meet potential plant demand in sweetgum (*Liquidambar styraciflua*) plantations in the Atlantic coastal plain of the United States through these objectives:

1. Determine the plant growth and foliar nutrition response to repeated N fertilizer applications in two young sweetgum plantations with contrasting soil types;

2. Determine soil N supply, plant N demand, foliar N resorption, and soil and fertilizer uptake efficiencies in two young sweetgum plantations with contrasting soil types;

3. Develop and evaluate a N mineralization potential-based soil N supply model in two young sweetgum plantations with contrasting soil types;

4. Evaluate rapid methods for determining N mineralization potential across the spectrum of soils conducive to intensive sweetgum management in the Atlantic coastal plain; and

5. Characterize the soils and their silvicultural implications for the spectrum of sites conducive to intensive sweetgum management in the Southeast.

This dissertation is organized in individual chapters designed to meet each of these objectives. The second and third chapters present a brief review of the pertinent literature and the general study location and design. The fourth chapter, which is the first chapter to present data, examines plant growth and nutrition in response to fertilizer applications. The fifth chapter uses N fertilizer rate trials to calculate the foliage N content, resorption, and uptake. It also uses measured soil N supply to calculate foliage N uptake efficiency and, ultimately, suggest N fertilizer rates for young sweetgum plantations. The sixth chapter uses measured soil properties and a relatively simple process model to estimate the cumulative N supply on two contrasting sites. The seventh chapter describes rapid laboratory methods for estimating the most important parameter in Chapter VI. The eighth chapter describes soil properties found across the range of sweetgum plantations in the Atlantic coastal plain and provides interpretations for site-specific management. Finally, the ninth chapter provides a summary that specifically addresses the 5 main research objectives.

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CHAPTER II. LITERATURE REVIEW

INTRODUCTION

Light, temperature, carbon dioxide (CO_2), water, and mineral nutrients are the primary determinants of forest productivity. When biotic potential is not limited by climate, mineral nutrients are growth-limiting if they are not available in adequate supply. Nutrient management is thus a main interest of SRWC research, and the focus of this study. Management intensity in SRWC is similar to that of agronomic crops, where soil fertility is considered a priori instead of after the fact as a corrective procedure. Nutrient supply must be considered equally important as water supply for economically and environmentally optimal yields.

Mineral nutrients can be classified into two groups based on their biogeochemistry (Deevey 1970). In the first, the nutrient element occurs in a biologically mediated volatile form during part of the cycle; nitrogen (N) and sulfur (S) are two examples. All other mineral nutrient elements have nonvolatile cycles. Plant supply of nutrients of the second group, those with nonvolatile cycles, is generally easier to regulate because nutrient elements of this group originate from soil minerals and their supply is governed by the physical chemistry of acid-base and solubility reactions. If any nutrient in this group becomes plant-growth limiting, it is usually economically feasible to supplement the demand requirement via fertilization. These nutrients, such as phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) are relatively inexpensive, easy to apply in solid form, and have soil reaction chemistries that buffer their availability through time. Sulfur is generally not limiting in forest systems, especially in areas receiving elevated levels of SO_4^{2-} in rainfall due to acid rain. Nitrogen stands alone as the nutrient element whose cycling and plant supply is almost entirely biologically-mediated and thus difficult to manage.

Nitrogen is not a constituent of most mineral soil parent materials. Its primary source is soil organic matter (SOM) where SOM is in equilibrium with a vegetation system. Nitrogen availability to plants is regulated by SOM decomposition, a complex combination of biological processes. Ideally, the soil system would supply the exact amount needed by the crop. To do this, the nutrient flux from the labile pool to the soil solution would need to increase at the same rate as plant nutrient uptake increases to maintain optimum growth (Ingestad et al., 1981). A review of the literature shows that native soil N supply is rarely sufficient for optimum growth, as evidenced by large growth responses to fertilization.

SHORT-ROTATION HARDWOOD RESPONSE TO N FERTILIZER

Research on hardwood SRWC fertilization in the South has provided only a few conclusions but has generated many questions. In most studies, N fertilization has resulted in growth responses unless the stand was constrained by an excessive moisture deficit (Johnson and Todd, 1988), or was very young (Blackmon, 1977). These studies illustrated what had already been shown for loblolly pine, but Buckner and Maki (1977) showed that sweetgum and yellow poplar are even more responsive to N fertilization than loblolly pine. However, the response of hardwoods to fertilizer is not well understood, especially on different sites.

A few studies have linked N fertilization response to soil or previous management type (Torreano and Frederick 1988; Wittwer, 1980; Wittwer, 1978; Blackmon, 1977), illustrating that the soil N supply can control the tree response to added N. For example, Wittwer (1980) applied N fertilizer each year to sycamore on a bottomland site and on a terrace, and found a 45% increase in growth on the bottomland site and a 205% increase on the terrace site at age 5. Torreano and Frederick (1988) and Blackmon (1977) showed that hardwoods may respond quite differently on pine cutover sites than on abandoned agricultural sites. These studies again support the site-specific nature of soil N supply, plant growth, and N fertilizer need.

Several studies dealt with fertilizer interactions with other cultural treatments. Wood et al. (1977) found no interaction between fertilizer and spacing of planted trees. Hansen et al. (1988) found a significant interaction between fertilizer and weed control in the early ages of a plantation. When weeds were not controlled in the first 5 years, the hybrid poplar stand responded to N, but once the stand reached crown closure, N was not needed, as crown shading reduced weed competition. Nelson and Switzer (1992, 1990) found that the relative N response was different between seed sources for sweetgum. Lockaby et al. (1997) found a significant species X fertilization X irrigation interaction. Sycamore responded to both fertilization and irrigation, but sweetgum responded only to fertilization. These empirical studies have added new information about the system that show the need for a comprehensive approach that takes all plant growth factors into account.

Hardwoods have not responded significantly to P fertilization or N X P combinations (Guo et al., 1998; Nelson and Switzer, 1990; Wittwer, 1980; Wittwer 1978), but Nelson et al. (1995a) posited that, following N fertilization, P may have been limiting. Guo et al. (1998) did find a significant N X P interaction 8 years after fertilization, suggesting that P had become limiting without P fertilization due to increased growth from N fertilization. Although none of these studies reported a soil test for P, they were all planted to lands formerly in agriculture and were likely not P deficient. Phosphorus limitations on cutover forested lands, however, could occur, but foliar and soil tests can show the level of available P and the need for fertilizer. Because the P is held much more strongly than N in the soil, P fertilizer is highly retained and should not have to be reapplied often in these systems.

Few studies have reported fertilizer uptake efficiency, and none have examined root uptake. Wittwer (1980) found that aboveground recovery of N fertilizer was only 11-14 %, but Nelson et al. (1995b) reported 26-76 % efficiency. They showed that uptake efficiency increased as the stand age increased, which supported the findings of van Miegroet et al. (1994).

Most recently, studies have focused on determining fertilization effects on specific plant responses other than height or volume growth. Since approximately 50% of aboveground plant N uptake is met by the resorption of foliar N into perennial plant organs prior to senescence (Chapin and Van Cleve, 1989), factors which affect the resorption efficiency of SRWC may dramatically change fertilizer needs. The influence of nutrient availability on resorption is unclear across broad scales of species and sites, as well as in sweetgum plantations. Nelson et al. (1995a) reported resorption efficiencies of 50-74% and ascribed differences to environmental conditions, i.e., moisture availability, but not N fertilization. Kuers and Steinbeck (1998a) found similar efficiencies of 43-62%, but also reported significant increases in resorption in the fertilized treatment.

FUNDAMENTALS OF TREE NUTRITION

Nitrogen is not retained well in the soil, especially when applied in fertilizer. In hardwood and conifer plantations, N fertilizer is applied at planting and at mid-rotation, which correspond to the easiest time to fertilize and the time when fertilization has the greatest response, respectively. General fertilizer rates set by practical experience are sufficient for this frequency of fertilization (Allen, 1987).   Unfortunately, single large applications do not increase the long-term availability of N (Johnson et al., 1980), and generally less than 30% of applied N is captured by the stand (Baker et al., 1974; Wittwer et al., 1980). Thus, N fertilization generally elicits ephemeral, rather than permanent, stand growth responses (Figure II-1) (Ballard, 1984). Because N fertilization has little effect on total site N but growth responses can be great, Miller (1981) argued that foresters do not fertilize sites; they fertilize trees.

Many of the major advances in tree nutrition have come from the work pioneered in Sweden in the 1960’s and 1970’s. Since foliar N concentrations generally change through time in response to one-time fertilizer applications, interpreting growth response to nutrition is difficult (Tamm, 1968). Therefore, Tamm and coworkers (Tamm, 1968; Tamm et al., 1974a; 1974b) started some of the first experiments to test if a constant, optimal internal nutrient concentration could be maintained through repeated fertilizer applications. In one representative study, Tamm (1968) applied four rates of N fertilizer annually to a Norway spruce stand. In response to fertilization, nutrient contents remained constant through time for each treatment, but that the absolute concentration was greatest in the highest N treatment (Tamm, 1985).

Furthermore, each application (about 40 kg ha^{-1} yr^{-1} depending on year) had little individual effect on growth, but cumulatively, growth increased almost 500% with N and P fertilization (Tamm, 1985).

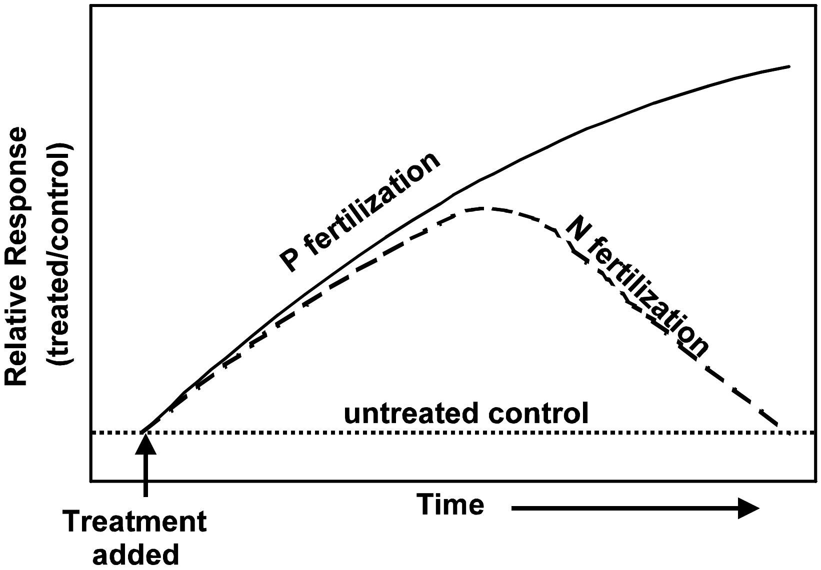

Figure II-1. Generalized comparison of nutrient amendments that elicit relatively permanent (P) versus ephemeral (N) responses in stand growth. After Ballard (1984).

Ingestad (1988) proposed that N fertilization rates during the period of exponential growth should be adjusted with the goal of supplementing soil N supply, or the natural N flux density (kg ha^{-1} yr^{-1}) just enough to meet plant demand and maintain constant plant N concentrations. This would entail progressively increasing fertilization rates until such time as the soil N flux density increased, which would theoretically be caused by increased soil organic matter quality. However, to achieve this type of nutritional control would require daily applications that would vary within the season and among seasons. Although this approach has been tested in willow (Salix) “fiber-farms” (Christersson, 1986) with good success, this fertilization intensity will not likely be feasible on the soil and site types available in the southeastern United States.

Forest scientists have tested the multiple application approach at a more operational level in loblolly pine and yellow poplar (Johnson and Todd, 1988) and sycamore (van Miegroet et al., 1994) in the southern U.S. Johnson and Todd (1988) applied 100 kg N ha^{-1} yr^{-1} in single or quarterly applications to determine if tree growth and fertilizer N recovery would increase with increasing frequency of N fertilization. They found that optimal growth and N recovery occurred with single annual applications, and nitrification and nitrate leaching was enhanced to a greater extent by quarterly applications. Although they cautioned that fertilizer might need to be applied more frequently than quarterly to achieve N supply / demand synchrony in the field (as suggested by the Ingestad (1988) fertilization model), their data show that annual fertilization may be optimal for field conditions when fertilizer and irrigation (fertigation) are not available. Higher soil NO_3^- levels and potential NO_3^- leaching have been reported by several authors as a consequence of smaller, more frequent N doses that benefit nitrifiers (Raison et al., 1987).

Van Miegroet et al. (1994) followed up on Johnson and Todd's (1994) work by incorporating Ingestad's (1988) major tenet, i.e, progressively increasing fertilizer rates. They applied 450 kg N ha^{-1} over three years to a newly planted, short-rotation sycamore (*Platanus occidentalis*) plantation, but they spread the 450 kg ha^{-1} out in four ways: treament 1 was a single application of 450 kg ha^{-1} in yr 1, treatment 2 was three annual applications of 150 kg ha^{-1}, treatment 3 was three applications of 50 kg ha^{-1} in each of the three yrs, and treatment 4 was a progressively increasing annual rate (50, 150, 250 kg ha^{-1} in years 1, 2, and 3, respectively). Although all four treatments caused growth responses at some age, only treatment 4, the progressively increasing N rate, showed a significant growth response over the control at age 3. Furthermore, treatment 4 had, after 3 yr, about 34 g biomass g^{-1} applied N (cumulative), while the other three treatments had only about 16 g biomass g^{-1} N. These findings show that adjusting an annual fertilization rate to correspond with the growth rate provides the best stand growth, and, presumably, N uptake efficiency. The authors proposed that the 250 kg ha^{-1} applied at age 3 was excessive, and that efficiency would have been even higher with a lower rate. However, without knowledge of the native N flux density and uptake rates, improving the efficiency would be difficult.

While many questions remain regarding optimal fertilization schemes, the results of Johnson and Todd (1988) and van Miegroet et al. (1994) support three concepts for N fertilization management in short-rotation woody crops: 1) where daily fertigation (fertilization in irrigation water) is not feasible, N applications more frequent than annual are not beneficial to tree growth, increase N leaching, and reduce fertilizer uptake efficiency compared to one annual application, 2) increasing fertilizer rates in concert with stand growth maximizes growth and N use efficiency, and 3) fertilization at planting or in the very early stages of stand development may be unwarranted without continued fertilization through the exponential growth phase.

These studies on SRWC nutrition illustrate that N is limiting in virtually all situations and fertilization is needed for optimum production. Several authors have reported on the responsiveness of hardwoods, the effect of fertilization on ecophysiological processes, and on fertilizer timing, but none have specifically tested fertilizer rates.

SOIL NITROGEN SUPPLY

Soil N supply is a generalized term that encompasses many processes that control the availability of mineral N to plant roots. At the center of soil N supply is the biologic conversion of organic N, contained in soil humus, microbial biomass, and plant roots, to inorganic N in the mineralization process. Much of the site and soil specificity of soil N supply is due to the soil organic material composition and the soil environment. Soil organic material derived from different vegetation types or even species will have different physico-chemical compositions that affect the microbial transformation of the N contained in various amine groups to mineral forms. Variations in the soil environment, which are related to site, soil, and vegetation characteristics as well as the general climate for the area, affect the biochemical processes in the microbial population and control the rate of mineralization. Although research has shown how mineralization is altered by these influences, researchers must characterize new sites and soils to determine how mineralization may be affected by SRWC system management.

Soil N supply can be thought of in terms of Quantity, Capacity, and Intensity (Figure II-2). “Quantity” is the total amount of potentially mineralizable N. Some of the organic N in soils cannot be mineralized by the microbial population to an extent beneficial to plants. The rate that this potentially mineralizable N is converted to mineral forms is “Capacity”, which is related to a wide variety of biotic and abiotic factors. Finally, the actual amount of mineral N contained in the soil at any point in time is nutrient “Intensity”. This conceptualization provides a basis for understanding the soil N cycle, and it provides a framework for organizing research approaches and findings.

Quantity

The quantity of potentially mineralizable N is usually about 10% of the total soil N, but the exact amount varies due to SOM chemistry and soil properties. The chemistry of soil organic matter is extremely complex and seemingly random (Schulten and Schnitzer, 1998). Some of the chemical forms, e.g., lignin-based humic components, cannot readily be used by the microbial population and are considered recalcitrant to mineralization. These recalcitrant chemical forms that stabilize SOM are the basis for much of soil aggregation (Sollins, 1996) and are directly related to the ambient vegetation. Lignin in plant tissues is relatively recalcitrant and forms the building block for even more stable humus forms (Paul and Clark, 1996). The microbial community characteristics also affect the recalcitrance of various compounds.

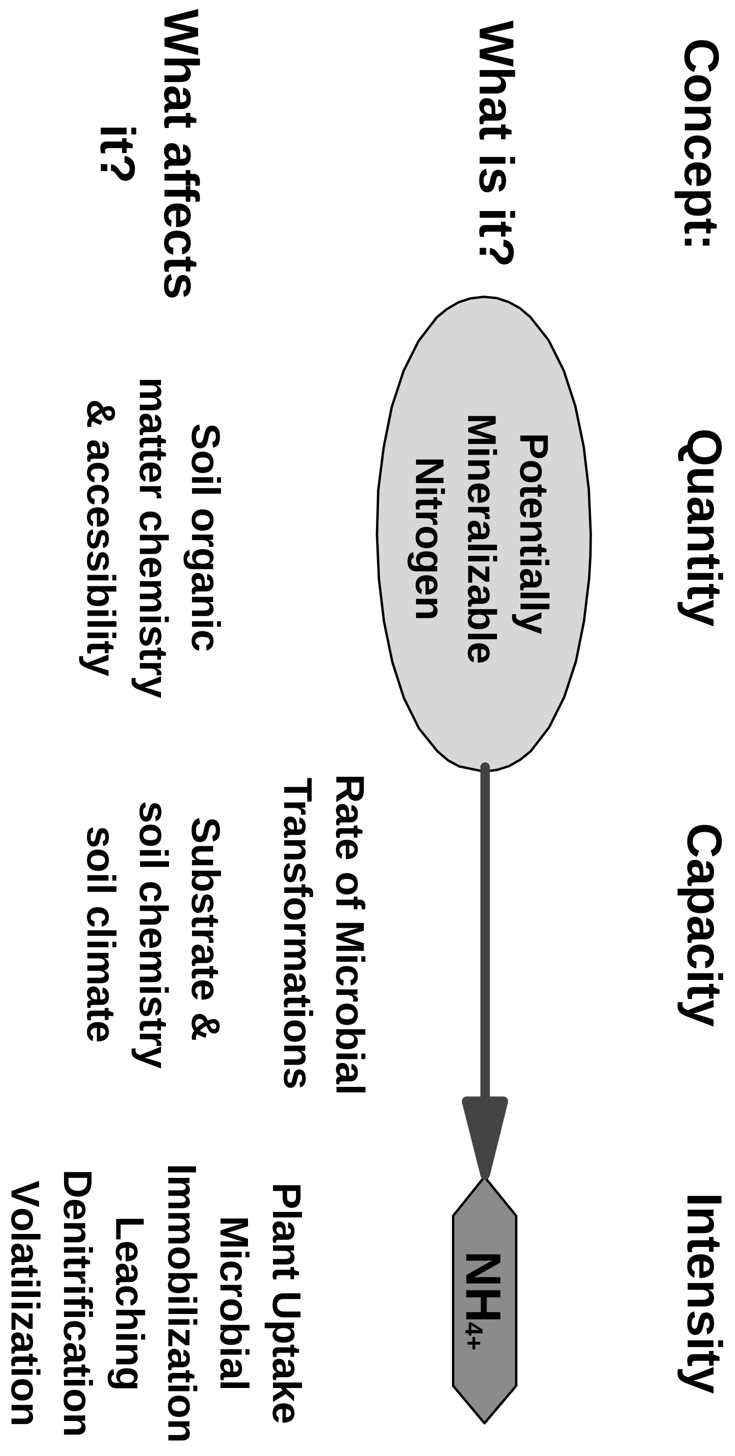

Figure II-2. Simple conceptual model of the soil nitrogen supply process illustrating the Quantity, Capacity, and Intensity relationship.

Bacteria, fungi, and actinomycetes, the three main components of the microbial community, all have different abilities to decompose recalcitrant materials. Variations in the relative amounts of these microbes affect the relative proportion of mineralizable N to total soil organic N. Soil chemical and physical properties affect the microbial population makeup, and in turn, the quantity of mineralizable N. Soil physical properties, such as clay content, macro and micro structure, and aggregate stability, also influence the ability of the microbial population to physically access the soil organic matter. In sandy, non-aggregated soils, virtually all of the SOM is physically available for microbial decomposition, but in clayey, well aggregated soils, some of the SOM may not be accessible for microbial utilization due to chemical and physical bonds between organic matter and clay particles (Hassink, 1992). Soil, site, and vegetation management activities can affect many of these factors, including, but not limited to, the vegetation system, soil chemical properties, and microbial accessibility of the SOM.

SRWC systems are currently being targeted in the Southeast on two contrasting site types characterized by past land use. First, many of the original SRWC plantations, as well as many current plantings, are on marginal agricultural lands (McAlpine et al., 1966; Steinbeck, 1999). These sites range from alluvial sites along the Mississippi River to clayey Gulf coastal plain flatwoods sites to sandy uplands in the Atlantic coastal plain. The other site type is on cutover forest land previously in loblolly pine (*Pinus taeda* L.) management. Although these two site types vary tremendously across the regional spectrum, some inherent differences between lands previously used for agriculture (old agricultural fields) and those in forest management (cutovers) are quite important for determining the “Quantity” and “Capacity” components of soil N supply.

Old agricultural fields tend to have lower quantities of SOM compared to cutovers due to decreased inputs from the vegetation and faster decomposition rates. Old agricultural fields also tend to have quite different chemical and physical properties due to differences in the soils used for agriculture versus forest management and quite different management practices. Tillage and drainage, which have been a part of agricultural management since these sites were first cleared, and fertilization and liming, which have occurred intensively on most sites for the last 40-50 years, have changed these sites from those with relatively low-input and low-output forestry uses. Old agricultural fields tend to have higher pH values due to liming and the removal of acid-producing forest litter, and higher levels of P and cations, again through fertilization. However, cutovers tend to have much higher quantities of SOM, more aggregated soils, and less inherent fertility (Richter et al., 2000). These site-specific differences illustrate the need for understanding the processes that control the quantity of potentially-mineralizable N.

Capacity

The Capacity factor, or the rate at which organic N becomes plant-available, is related to both abiotic and biotic factors and can be estimated as the rate of nitrogen mineralization. Mineralization, however, is coupled with immobilization by the microbial community, which is a function of the substrate quality. Most studies of N mineralization are concerned only with the resulting product of mineralization and immobilization, plant-available N, but an understanding of the subprocesses and their kinetics is necessary to understand the impacts of management practices on soil N supply.

Substrate quality is a nebulous term used to describe an observed process for which science has relatively untested mechanistic theories. The microbial community substrate is the soil organic matter, which in forest plantations includes the litter, living root exudates, and dead roots. Soil organic matter quality can be defined as the relative level of microbial activity that it can support. “Active”, or “high” quality soil organic matter is readily used by soil microorganisms for energy. Several studies propose that the C:N ratio (or N:C ratio) is the best measure of soil quality, but Janssen (1996) proposes that C:N is the dominant factor controlling decomposition when the chemistry of the substrate is otherwise similar. The ratio of labile (easily decomposed, i.e., sugars, proteins) to recalcitrant (difficult to decompose, i.e., lignin, polyphenolics, etc.) C components of organic materials can also be used to describe the decomposability of substrates (Jansson and Noij, 1996), and Janssen (1996) attempted to group soil organic matter into classes of decomposability and then model the C:N ratio control of decomposition rates. This approach appears to have merit in recognizing that certain C compounds, primarily lignin and polyphenolics (Constantinides and Fownes, 1994; Palm and Sanchez, 1991; Melillo et al., 1982), may exert more control over decomposition than C:N ratio. Janssen (1996) applied a “resistance index” to the data of Tian et al. (1992a, b) based on lignin and polyphenolic concentration and found that the proportion of substrate N mineralized could be well predicted using this resistance index and the substrate C:N ratio.

Immobilization within a growing microbial community can represent a very significant process controlling the intensity of available N (Jansson, 1958), and in many situations where labile C is readily available, immobilization may exceed mineralization, resulting in a net decrease in available N. Most plant residues have C:N ratios of 60-80:1 (Paul and Clark, 1996) while the microbial biomass has a C:N ratio of 4-12:1, depending on the relative abundance of bacteria and fungi, with a C:N ratio of 10:1. The addition of plant residues, e.g., litterfall and root turnover in SRWC systems, allows the microbial biomass to increase in size, but this increase becomes N limited. The growing population must then acquire mineral N from the soil until its N needs are met by the substrate, which generally occurs near a substrate C:N ratio of 30:1 (Tate, 1995). Most soils have C:N ratios between 10:1 and 30:1 (Post et al., 1985). In forested ecosystems with large fluxes of labile organic C from decomposing litter and fine roots, the C:N ratio of microsites may be much higher, resulting in greater rates of immobilization than would be expected based on average C:N ratio..

The kinetics (capacity) of mineralization-immobilization-turnover and thus net N mineralization are largely controlled by abiotic soil properties such as temperature, moisture, aeration, and chemistry. Soil temperature’s importance in regulating soil N mineralization has been observed for many years, but because of the complexity of the microbial processes, variable organic substrates, and other abiotic factors, a definitive quantitative description of soil N mineralization rate at varying temperatures has not been found. Most early attempts used a modified Arrhenius equation (Atkins, 1998) or a Q_{10} function to simulate the direct effects of temperature on the microbial processes. These approaches are thermodynamic in nature rather than biological. They work well under some circumstances since the biologic conversion of organic N to inorganic N has many enzymatic and chemical kinetic processes that do follow rather simple thermodynamics, but in other cases, other abiotic factors may interact with temperature to render these models inaccurate. More recent studies have attempted to link N mineralization rates to more biologically meaningful expressions of temperature, such as heat units (Honeycutt et al., 1988) and S-curve (De Neve et al., 1996) approaches. These approaches have not gained wide acceptance in the scientific community, however.

The classic studies of the effect of temperature on mineralization rate were published in the early 1970's, although much work had been done before, e.g., Cook (1952), Frederick (1956), Sabey et al. (1959). Campbell and Biederbeck (1972) and Stanford et al. (1973) both applied the Q_{10} function (Equation II-1) (van't Hoff, 1898):

$$k(T) = Q_{10}^{\frac{T-T_{ref}}{10}} \tag{II-1}$$

where k(T) is the rate constant, Q_{10} is the ratio of constant rates measured at temperatures differing by 10 °C, T is the actual temperature, and T_{ref} is the optimum temperature.

Both studies found Q_{10} values near 2, which is the generally accepted value for enzymatic-catalysed reactions. Stanford et al. (1973) also applied the Arrhenius equation, from which the Q_{10} function was derived, to describe the reaction rate response to temperature. The Arrhenius equation (Equation II-2) relates the temperature dependence of a chemical reaction rate to the reaction activation energy and a steric factor that accounts for the specific configuration the molecules must be in to react (Atkins, 1997):

$$k(T) = Ae^{-Ea/RT} \tag{II-2}$$

where k(T) is the rate of N mineralization, A is a steric factor, E_a is the activation energy, T is temperature (in Kelvin), and R is the gas constant.

A simplified form of Equation II-2 for studying complex reactions where A and E_a are not known and must be estimated empirically is (Equation II-3):

$$k(T) = Ae^{-B/T} \qquad \text{II-3}$$

where A is a constant and B is the temperature sensitivity of the reaction.

Stanford et al. (1973) fit this equation to the data generated earlier (Stanford and Smith 1972). They found, first, that the approach did not work well for temperatures less than 15 ^{o}C, and second, that the temperature dependence of N mineralization was relatively constant for several soils and corresponded to Q_{10} values of 2. Based on this finding, they postulated that soil N mineralization in field conditions could be estimated by modifying the first order reaction rate for ambient temperature conditions. This work, along with Stanford and Epstein's (1974) study of the relationship of N mineralization rate to soil moisture paved the way for simulations of N mineralization under field conditions.

Other researchers have examined several variations to this central theme associated with the temperature dependence of N mineralization. Stanford et al. (1975) studied the effect of fluctuating temperatures on N mineralization as opposed to stable temperatures and found no difference in N mineralization with fluctuating temperatures compared to with stable temperatures. This was contrary to the previous work by Campbell and Biederbeck (1972) who found that when temperatures declined from the optimum, the nitrification rate did not decline as much as would be expected, while when the temperature rose from a suboptimal to optimal, the rate did not increase as quickly as expected. Stanford et al. (1975) hypothesized that ammonification in their study was not affected as much due to the wider range of soil organisms involved as opposed to nitrification in the Campbell and Biederbeck (1972) study. Myers (1975) examined the role of general soil climate on the temperature sensitivity of N mineralization, and found that the optimum temperature for nitrification, which had previously been shown to be 35 ^{o}C for temperate regions, was higher in the tropics due to a different assemblage of decomposers, as proposed by Mahendrappa et al. (1966). Ammonification, however, did not appear to be related to climatic region, as the generally accepted optimum is near 50-70 ^{o}C (Harmsen and Kolenbrander, 1965). Cassman and Munns (1980) examined the influence of temperature, moisture, and sample depth on mineralization rates and found that unlike Stanford et al.'s (1973) assertion that decomposition rates were relatively similar for all soils and the temperature effect was also soil-independent, mineralization rates varied with depth and the temperature effect was not independent of moisture. Sierra (1997) similarly concluded that the Arrhenius/Q_{10} approach was sufficient for assessing the direct influence of temperature on N mineralization, but was not adequate for explaining the combined effects of temperature and aeration, and proposed that knowledge of the soil bulk density and aggregate stability might be useful in modifying the Arrhenius temperature effect. MacDonald et al. (1995) showed that not only is k temperature dependent, but the measurement of N_o, or the quantity factor, may also be temperature dependent.

Recently, other researchers have attempted to use different expressions to simulate the temperature dependence of N mineralization given the inadequacy of the Arrhenius approach in certain circumstances. Honeycutt et al. (1988) attempted to use heat units, or degree days, to predict N mineralization. This approach worked well in determining the onset of net N mineralization (as opposed to net N immobilization) under field conditions during a growing season, but consistently moist conditions would be needed for accurate future predictions (Doel et al., 1990). De Neve et al. (1996) evaluated an S curve equation (Equation II-4) of the form:

$$k(T) = k_{opt} e^{-(\kappa(1-\frac{T}{T_{opt}})^2)} \qquad \text{II-4}$$

where k(T) is the rate constant as a function of temperature, k_{opt} the maximum rate constant, T_{opt} the optimum temperature (in ^{o}C), and κ a rate parameter reflecting the temperature sensitivity of k.

The authors chose this form because the Arrhenius approach has no biological significance as related to soil biomass (the optimum temperature implied by the Arrhenius equation is ∞), the fitting is poor for low temperatures (Addiscott, 1983; Stanford et al., 1973), and since absolute temperature is used, the values of the A and B parameters are difficult to interpret. While De Neve et al. (1996) did not compare this approach to the Arrhenius equation, they did find that the κ value, which is an indicator of the sensitivity of mineralization to temperature, varied with substrate. Reichstein et al. (2000) evaluated a quadratic function proposed by Ratkowsky et al. (1982) that implies an increasing Q_{10} with decreasing temperature, but found that a standard Q_{10} approach worked better. Although these approaches may have biological merit, they have not been shown to be more effective than the Arrhenius or Q_{10} approaches in estimating N mineralization rates at different temperatures.

Similarly to soil temperature, the soil moisture dependence of N mineralization has also been studied in depth. Stanford and Epstein (1974) provide one of the more generally accepted models of the moisture dependence of N mineralization. They found that mineralization is optimum for most soils at approximately field capacity (-0.03 MPa) and decreases approximately linearly between field capacity and the permanent wilting point (-1.5 MPa). While this relationship has been liberally applied to all soil types, they also found that mineralization in soils with high C:N ratios shows a distinctly non-linear response and may be related to an increase in N immobilization at near-optimum moisture contents. Their work generally agreed with previous work that showed a proportional decrease in N mineralization between field capacity and permanent wilting point (Miller and Johnson,1964; Reichman et al., 1966). Both of these studies and Robinson (1957) found little N mineralization at potentials less than -1.5 MPa. The specific contribution of Stanford and Epstein's study was to provide a general form of an equation relating N mineralization to soil moisture. They found that by expressing the mineralized N and moisture content as the percent of the maximum and optimum, respectively, they could satisfactorily fit a linear equation between soil moisture and N mineralization. Thus, if the maximum N mineralization is known from an incubation study and the optimum water content is estimated to be field capacity, then N mineralization at various water contents can be estimated. Most modeling efforts have used this approach because, in general, it has worked well. For some soils, it has not worked well, and researchers have tried other approaches.

Myers et al. (1982) found that mineralization was significant to -4.0 MPa, and was related more to available water (water held between -0.03 MPa and -4.0 MPa) than to a proportion of the optimum. Extending the relationship to -4.0 MPa helped explain N mineralization on dry, sandy sites, which were not present in Stanford and Epstein's study. Other researchers have also found that the limit to mineralization is much lower than -1.5 MPa (Sierra 1997; Bramley and White, 1990; Frazer et al., 1990). Myers et al. (1982) also found a curvilinear response at high water potentials in some soils. Six of nine soils that followed a curvilinear response had characteristics conducive to increased immobilization, as Stanford and Epstein (1974) found, but three did not. These three did have high colloid contents, though, and Myers et al. (1982) suggest that knowledge of a soil's CEC may be a useful indicator of the potential for curvilinearity. They proposed a model (Equation II-5) that is based on the ratio of water content to the potential available water and accounts for the curvilinearity found in some soils:

$$Y = bX + (1-b)X^2 \qquad \text{II-5}$$

where Y is net N mineralization expressed as a proportion of the maximum,

$$X = \frac{(w - w_o)}{(w_{\max} - w_o)}$$

where w= soil water content, w_o= water content at -4.0 MPa and w_{max}= water content at -0.03 MPa, and b=a coefficient of curvature.

While this model may provide a better method for empirically estimating the effect of moisture on N mineralization, no studies have been conducted to determine b from soil properties.

Several studies have been conducted to determine the relative effects of moisture cycles as compared to constant moisture conditions. Some authors have found that fluctuations in moisture content have a greater influence in determining mineralization rates than the equivalent average moisture content would be expected to (Gonçalves and Carlyle, 1994; Cabrera,1993; Campbell et al., 1974). Soil drying causes some microbes to die, which provides an easily decomposable substrate for the remaining microbes following rewetting. Both Cabrera (1993) and Gonçalves and Carlyle (1994) have attempted to model this N flush due to rewetting of dried soils. Cabrera (1993) used a modified first-order equation to explain the kinetics of laboratory incubations of dried and rewetted soils. His model, however, is an adaptation of Stanford and Smith's (1972) model and not a method for estimating N mineralized under field conditions. Gonçalves and Carlyle (1994) used a logistic model (Equation II-6) to simulate the effects of moisture on N mineralization for forest soils:

$$N_{\min} = \frac{1}{[a + b^{(M-c)}] + d} \tag{II-6}$$

where N_{min}= quantity of N mineralized, M is the gravimetric soil moisture content, d is the asymptotic minimum quantity of N mineralized, c is a constant which defines the point of inflection of the logistic curve, b is a slope parameter and a=1/(asymptotic maximum N_{min}-d).

However, as with Myers (1982) model, the fitting parameters must be determined for new soils, as they were not able to show a relationship applicable for all soils. Gonçalves and Carlyle (1994) tested their approach with data from Hopmans et al. (1980), but these two studies only provide a limited sample of soil types. Since neither Cabrera's (1993) or Gonçalves and Carlyle's (1994) modeling attempts used a mechanistic approach based on process-level knowledge, their results are only applicable to the range of soils studied.

Edaphic factors not directly related to climate also may affect N mineralization. Soil pH has been studied for its role in regulating N mineralization and nitrification, but no consensus has been reached. Reviews by Adams and Martin (1984) and Jenkinson (1988) state that N mineralization is generally insensitive to pH. Morrill and Dawson (1967) studied ammonification and nitrification in 116 U.S. soils and found four patterns of pH response: (1) NH_4^+ oxidized rapidly to NO_2^- which accumulated for extended periods of time before being oxidized to NO_3^- (pH 6.93-7.85); (2) NH_4^+ and NO_2^- oxidized rapidly to NO_3^- (pH 5.01-6.38); (3) NH_4^+ oxidized slowly to NO_3^- without NO_2^- appearing ($pH \leq 5.39$); and (4) accumulation of NH_4^+ with very little oxidation to NO_2^- and NO_3^- ($pH \leq 5.39$). They related the differences in nitrification patterns to changes in numbers of nitrifying bacteria (Nitrosomonas and Nitrobacter spp.). However, Biederbeck et al. (1995) found long term N fertilization, which induced a pH gradient (lower pH with increasing fertilization), had no effect on fungi and bacteria.

Dancer et al. (1973) studied the influence of both pH and previous N treatments on mineralization and nitrification and found that on high N fertilization plots, those with lower pH values resulted in higher rates of N mineralization and nitrification. Fu et al. (1987) found greater N immobilization at low pH when residues are added. Oades et al. (1988), however, reviewed the mechanisms controlling SOM decomposition and postulated that the initial lag of decomposition normally found in neutral or alkaline soils is not retarded by Ca^{2+} and organo-clay complex stabilizing mechanisms in acid soils. During the initial decomposition of high C:N substrates, net N immobilization generally occurs. If, as Oades et al. (1988) postulate, the initial phase of substrate decomposition is not retarded and this initial phase of decomposition is characterized by net N immobilization, then adding high C:N residues to acid soils, i.e., sweetgum litterfall on southeastern Ultisols, may increase net N immobilization. Since most of the rigorous process-level soil N dynamics models were developed for agricultural soils, few if any forest researchers take this possibly important mechanism into account. However, Weier and Gilliam (1986) found no relationship between pH and N mineralization in histosols with poor substrate quality, and Donnelly et al. (1990) found no relationship between pH and litter cellulose or lignin decomposition in a forest soil. Although this mechanism has not been fully explored, it may be a possibly important regulator of net N mineralization in acid soils, especially when short-term (weekly or monthly) N supply dynamics may be more important for rapidly growing trees compared to yearly or rotation-length N dynamics (Ingestad, 1988).

Because N mineralization is controlled by active heterotrophic microorganisms, any mechanism that restricts this active microbial population from accessing an N-containing substrate will lower the capacity to mineralize N. These mechanisms that restrict microbial access to substrates are generally labeled “protection” mechanisms. Physical protection mechanisms, which sequester N pools within micro- or macro-aggregates or through encrustation with clay minerals, have been shown to be quite effective in reducing the amount of N accessed by microbes (Tisdall and Oades, 1982; Gupta and Germida, 1988; Hassink, 1992). Biological protection also occurs. If N is immobilized within living but non-active biomass or within components of the active biomass that have slow mineralization rates, i.e., fungal hyphae, then the N is not accessible for rapid mineralization. Kristensen et al. (2000) studied agricultural soils subjected to either no-till or annual moldboard plowing since 1976, and found that non-tilled soils contained about twice as much total N as the plowed soils. The authors sieved both soils to disrupt any physical protection mechanisms, and found that the disruption of soil aggregates caused a 250 % increase in mineral N release from no-tilled soils but only a 29% increase in mineral N release from conventionally-tilled soils. These findings have important potential consequences for SRWC grown on converted agricultural fields or cutover pine plantations.

SRWC plantations grown on agricultural lands will likely increase soil aggregation and the level of N protection will increase accordingly over time. However, on sites planted on cutover forested sites, the initial site preparation will generally cause a decrease in N protection and subsequent increased mineralization over time. Becuase the intensity and frequency of soil disturbance is lower in SRWC management than in agronomic management, converted agricultural soils will likely see a reduction in the ratio of potentially mineralizable N to actually mineralizable N. The frequency of soil disturbance in SRWC management will be increased compared to the previous pine plantation management. This increased frequency of disturbance may increase the potentially mineralizable N : total N ratio.

Intensity

The intensity of N, or the amount of mineral N available for plant uptake at any point in time, is governed by many processes. Inputs come from the decomposition of nitrogenous substrates, as described previously, deposition from the atmosphere, and biological fixation. Available N as NH_4^+ has several potential fates, as does the product of one of those fates, NO_3^-. The transformations and reactions that affect the fate of mineral N control the outputs of soil N.

Wet and dry deposition consist of N that has become airborne by wind erosion (which can be considered a transfer of N from one system to another rather than a true N accession) and true N accession through atmospheric phenomena, such as lightning (Wetselaar, 1981). In polluted areas of the U.S., N deposition approaches 8 kg ha^{-1} yr^{-1}, but deposition in the Southeast and Atlantic coastal plain is low (0-4 kg ha^{-1} yr^{-1}) (NADP, 2001). Lovett and Lindberg (1993) found that N deposition reaching the forest floor was 60% of the total received, while 40% was absorbed by the forest canopy, or immobilized within the microbial biomass present on foliar surfaces.

Symbiotic N_2 fixation occurs when N_2-fixing bacteria invade a host plant to gain an easily accessible C source and protection from aerated soil environments. Biological N fixation occurs through the use of nitrogenase, an enzyme that splits dinitrogen (N_2) but does not function in the presence of oxygen. The host plant benefits from the increased availability of N, enabling it to compete well in N-deficient systems. Plants commonly found in southeastern forests associated with symbiotic N fixation are waxmyrtle (*Myrica cerifera* L.) and *Sesbania* spp. Permar and Fisher (1983) measured symbiotic N fixation rates of up to 10 kg N ha^{-1} yr^{-1} in slash pine plantations with a large component of wax myrtle in the understory. The nature of SRWC systems results in a relatively clean forest stand with little understory and few volunteer trees or shrubs of non-crop species origin, so symbiotic N fixation will not likely be a factor in SRWC sweetgum N management.

Non-symbiotic N_2 fixation occurs in autotrophic, free-living bacteria, mainly cyanobacteria (blue-green algae) and diazotrophs. Few rates of non-symbiotic N fixation have been published, and those that have been are very low. Permar and Fisher (1983) estimated approximately 1.9 kg N ha^{-1} yr^{-1} was fixed in free-living bacteria, and Jorgensen and Wells (1971) found rates of up to 0.95 kg N ha^{-1} yr^{-1} in a burned, poorly drained loblolly pine stand. Very poorly drained sites may have somewhat greater rates of N fixation (Jorgensen and Wells, 1971), but still will not likely be larger than the uncertainties involved with measurement and can be considered negligible in most sweetgum sites.

After the first stage of the heterotrophic microorganism-mediated conversion of organic N substrates to the mineral form of NH_4^+, several processes can occur (Paul and Clark 1989):

1. It can be taken up by plants,
2. It can be utilized for microbial growth (immobilization),
3. It can be held on the cation exchange complex and released by replacement with other cations,
4. It can become fixed within the interlayer of 2:1 clay minerals,
5. It can react with organic matter to form quinone-NH_2 complexes, which stabilizes the organic matter from further decomposition,
6. If present in an unadsorbed state, it can be volatilized to NH_3, and
7. It can be used as an energy source by autotrophic microorganisms and converted to NO_3^-.

Evaluating each of these fates quantitatively is nearly impossible to accomplish on a practical scale. However, quantifying fates 1 and 2 are the most important for determining fertilizer rates due to their relative importance. In soils dominated by 2:1 clay minerals, fixation of NH_4^+ within clay lattices can be significant (Havlin et al., 1999). Volatilization of native NH_4^+ is low, and is further impeded by low pH values, common to most forested systems. The adsorption of NH_4^+ to exchange sites and resulting diffusion to soil solution for plant growth, though, can control the kinetics of soil N supply within small time scales, and may be related to the level of substrate decomposition (Seneviratne et al., 1994) . The conversion of NH_4^+ to NO_3^-

does not directly negatively affect plant uptake. In fact, since NO_3^- is only held appreciably on anion exchange sites in special circumstances (Eick et al., 1999), and is therefore more mobile within the soil profile, NO_3^- is commonly taken up more readily by plants, but this preference is plant- and soil- specific. Indirectly, however, nitrification can decrease the level of available N in the soil by enabling other loss mechanisms not associated with NH_4^+ to occur. These loss mechanisms are leaching and denitrification. Nitrate leaching is controlled directly by hydrology and indirectly by biological factors that promote NO_3^- production from NH_4^+. Thus, nitrate leaching can be examined through the factors that affect nitrification (capacity factors) or that affect the hydrologic cycle.

Denitrification, or the conversion of NO_3^- to gaseous forms, can be a major process in some soils and drastically affect the net soil supply for plant uptake. Davidson et al. (1990) reviewed the controls and conditions in which denitrification in forested systems may proceed, but except for the influence of water filled porosity, few attempts have been made to model these processes. Davidson et al. (1990) illustrated the conditions needed for denitrification (Figure II-3).

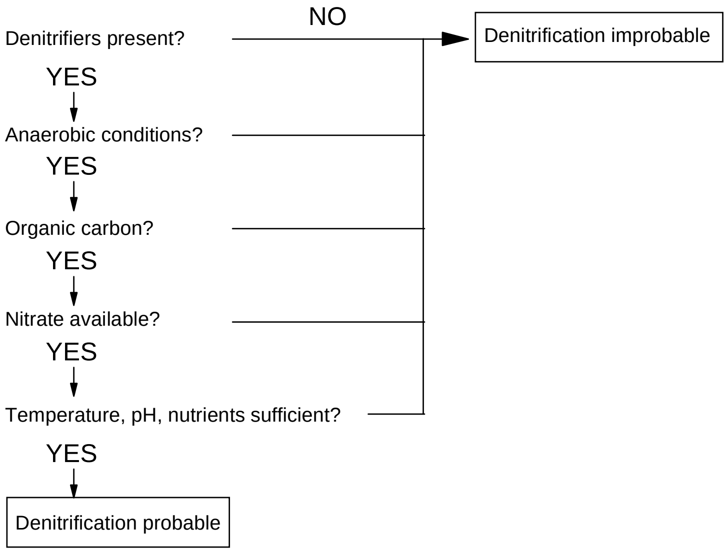

Figure II-3. Regulation of denitrification at the scale of an individual bacterium or a soil microsite (after Davidson et al., 1990).

Litter Decomposition and Nutrient Release

Nitrogen mineralized from the SOM represents, in young plantations with little forest floor development, the majority of N supply. However, because SOM quantity and quality is a function of the vegetation, edaphic factors, and climate, a thorough understanding of forest floor development, decomposition, and nutrient release is needed. Understanding litter decomposition and nutrient release are especially important in short-rotation woody crops, because in most cases, SRWC are being planted on lands that formerly supported forests (pine plantations) or agricultural crops. As a SRWC rotation progresses, biogeochemical cycling of C and mineral nutrients from the trees to the soil will determine the quantity and quality of the SOM later in the current rotation and in future rotations. This is supported by McClaugherty et al. (1985), who found that soil N mineralization was linearly related to native litter decomposition rates in five forest types, but decomposition rates of transplanted sugar maple (Acer saccharum) were not affected by soil N mineralization rates. Thus, early in the conversion of agricultural fields or pine plantations to intensively managed hardwood plantations, litter decomposition will not likely be affected by soil N mineralization. As the forest floor develops and influences SOM quality, soil N mineralization will become a function of litter decomposition rates.

Litter decomposition is controlled by many of the same factors that control N "capacity" in the mineral soil. Forest floor climate, fauna and flora, and litter chemical nature all influence decomposition rates and nutrient transfer. In general, climatic influences on litter decomposition are similar to those for soil N dynamics (Moore, 1986). Microbial activity in the forest floor increases exponentially with increasing temperature (Edwards, 1975), and follows a Q10=2 (Singh and Gupta, 1977). Water affects forest floor decomposition similarly to SOM decomposition, but because intact litter on the surface undergoes more rapid drying than the mineral soil, dry conditions may limit surface litter decomposition more than fragmented litter and humus (Waring and Schlesinger, 1985).

More importantly for SRWC is the influence of litter quality on decomposition rates and N dynamics. Litter quality is primarily a function of its initial carbonaceous and nutrient components. High quality litter, like high quality SOM, is characterized by a rapid decomposition and nutrient mineralization rate. In general, high quality leaf litter has relatively high N and P concentrations and relatively low acid-insoluble carbon compounds, such as lignin and polyphenolics.

Decay rates during the initial stages of decomposition are relatively high, and are correlated with the loss of soluble C and substances rich in soluble C, such as sugars (Melillo et al. 1989). Further litter decomposition is controlled by acid-soluble and acid-insoluble substances, e.g., lignin. Melillo et al. (1989) and Aber et al. (1990) propose that litter decomposition from intact leaves to SOM occurs in a two-phase sequence. In first phase, which represents about 80 % of mass loss, decay occurs exponentially. Nitrogen concentrations, however, increase linearly with decreasing percent mass loss due to N immobilization within the decomposer biomass. Melillo et al. (1989) show that litter quality, as related to C fractions, is similar across many sites at the end of the first phase of decomposition, but N concentrations vary widely as a function of initial litter N concentration. Constantinides and Fownes (1994) similarly found that for 12 tropical species with very different chemical compositions, short-term N release (16 wk) was better related to initial N concentration than to any other index. Litter with initial N concentrations above 2 % had net release of N after 16 wk, while litter with initial N concentrations of less than 2 % had not released N by 16 wk. Although litter decomposition rates are largely a function of C fractions, N dynamics within a given species are related to initial litter N concentration, which will be a function of soil N supply and fertilizer N applied in intensively managed plantations.

Once an intensively managed stand has progressed beyond the establishment phase, N release from litter may represent a significant source or sink of N. Nelson et al. (1995b) found that 9 to 13 yr old sweetgum plantations had about 4000 kg ha^{-1} of foliage biomass with a N concentration of 0.70 %, for a total N return to the forest floor of 28 kg ha^{-1}. Although no data are available for sweetgum litter decomposition, Aber et al. (1990) showed that the change in N concentration was linearly related to the percent mass loss for several hardwood species. They also found that decomposition progressed relatively rapidly for 3 to 4 yr, at which point about 20% of the initial mass remained. Following Aber et al.'s (1990) model, about 8 kg N ha^{-1} would be released over a 3 to 4 year period in mid-rotation sweetgum stands. The remaining 20 kg ha^{-1} would be slowly incorporated into the soil organic matter. Furthermore, their model also predicted that the litter would be a net sink of up to 10 kg ha^{-1} N until about 70 % of the litter was decomposed, at which point the litter would be a net source of N. This example, however, is for only a single year's cohort of litter. Because each year, up to 4 separate litter cohorts may be decomposing, net N release from litter decomposition is highly complex. Little information is available for litter decomposition processes in short-rotation woody crops in the Atlantic coastal region. Research needs to quantify the amount and timing of litter N release for accurate estimates of N supply to these plantations.

Because the myriad of processes involved in determining litter and soil organic matter Quantity, Capacity, and Intensity interact and are interdependent, researchers cannot predict soil N supply for a given site without a mathematical representation of each process. Furthermore, process-based models are the only tool available to test our current understanding of the effects of climate, hydrology, and soil N supply on physiological processes and growth in trees at specific sites.

SIMULATION MODELS FOR SRWC MANAGEMENT

Short-rotation woody crops (SRWC) are an increasingly important component of industrial forestry operations in the United States and worldwide. SRWC forestry represents the most intensive form of silviculture, by which trees are cultured similarly to agricultural crops. SRWC operations seek to realize the full genetic potential of the plant species cultivated for maximum biomass or fiber production, but in pursuit of this maximum productivity, much more intensive management is required than traditional forest plantation management (Fox, 2000) .

This intensity makes the use of conventional decision-making tools less useful due to the increased complexity of the system. Faced with this problem, scientists have been proposing the development and use of process-based models to integrate our understanding of ecophysiology, hydrology, and soil nutrient dynamics (Johnsen et al. 2002). Because SRWC have similarities to intensive agriculture and forestry, models from either discipline may be useful to help guide fertilizer prescriptions.

Agricultural and forest simulation models vary widely in their scope, inputs required, and outputs produced. A number of papers have defined and described models and modeling approaches. Addiscott and Wagenet (1985) define models as *functional* or *mechanistic,* and *deterministic* or *stochastic*. Functional models tend to be relatively simple approximations of the processes involved and are usually based on capacity parameters. Functional forest models are those generally described as empirical. Mechanistic models attempt to describe each process with state-of-the-art information. Deterministic models assume that a given set of inputs will always result in the same set of outputs whereas stochastic models introduce random variability in the process. Kimmins et al. (1990) described three approaches to modeling: the *empirical predictive* approach, the *mechanistic* approach, and hybrids of the two. Kimmins et al.'s *empirical predictive* approach is a generalized form of Addiscott and Wagenet's *functional* description. Others have separated models even more generally into empirical and process models, or statistically-based versus biologically-based (Mohren and Burkhart, 1994).

Models that are simply representations of systems have three main purposes in natural resource management. Models for natural resource management are used for predicting future events under the same conditions as past observations, for examining our current understanding of the relationships between system components, or for estimating the future response of a system component to a change in another component. Modelers in agriculture and forestry have long debated which of the three main uses is “best”, but this debate reflects personal biases and a misunderstanding of the goals of modeling. Models can be conceptual and qualitative, or abstract and mathematical. Neither extreme is less useful; the usefulness of a model depends solely on the objectives of the modeler.

In production agriculture or forestry, quantitative models have been used for many end-uses, and as such, have had many approaches. Two main approaches have been identified repeatedly: process-based models or empirical models. Process based models attempt to describe and define mathematically the relationships between system components, e.g., influence of radiation on net primary productivity. Empirical models strive to provide a robust description of past observations from other, more limited observations, e.g., wood yield based on stand and site type. Several reviews have discussed the relative merits of these two approaches, but as Korzukhin et al. (1996) propose, few models are completely empirical or process-based, but lie on a continuum from empirical to process-based. Furthermore, the issue of empiricism vs. mechanism becomes unclear as model resolution changes. One description of a system may appear empirical in nature when viewed from a perspective with higher resolution, but may appear quite mechanistic when viewed from a lower resolution perspective (Sharpe, 1990). An example is the classical model for soil nitrogen mineralization (Equation II-7) proposed by Stanford and Smith (1972):

$$N_s = N_o\left(1 - e^{-kT}\right) \qquad \text{II-7}$$

where N_s is net N mineralization, N_o is potential N mineralization, k is the decomposition rate, and T is time.

When viewed from a biochemical perspective, this equation simply represents an empirical model of the overall observations. It provides no insight into the specific biochemical processes involved, and the parameters have no specific biological meaning. Thus, it fails to meet two of the requirements for a mechanistic model. However, from the perspective of plant-available N, the model parameters are based on the physical and biological properties of the overall biochemical system, and the model represents one of the several processes involved with the soil N cycle. When coupled with similar models of other N cycle processes, i.e., N_2 fixation, nitrification, leaching, denitrification, etc., this model becomes part of an overall mechanistic N cycle model. This example shows that the level of mechanism and empiricism is directly proportional to our current level of understanding.

Conversely, pure empirical models are rare as well. In forestry, growth and yield models are based on a statistical description of observed data. However, a purely empirical model of a system over time would necessarily have only one input: time. Since virtually all empirical models use other inputs, such as site quality in the case of growth and yield models, these models do provide some level of mechanism. In this case, the model does not describe the mechanism by which site quality influences growth, but it recognizes the importance of the process.

Empirical models, or those based mostly on the statistical description of previous observations, can be accurate and robust predictors of yield under circumstances similar to the ones the for which the model was developed. They are accurate, in that they closely fit observed data, but have few outputs and are specific to certain conditions. They are not general descriptors of forest growth, where generality is defined as the applicability of a concept to a range of conditions (Sharpe, 1990).

Process models also tend to always be in development, which makes using them in forest management difficult when the model’s outputs change as more information becomes available (Sands, 1998). Because models with a more empirical nature are more accurate and are consistent over time and process models are able to respond more to changes in management options, the agriculture and forestry communities have used the two model approaches differently.

Simulation modeling may be especially beneficial in predicting crop growth, water relations, nutrient availability, and subsequent fertilizer requirements under various management scenarios. Since detailed parameter values are easier to measure in annual crops and agriculture has an even greater array of cultural practices to manage than forestry, process models have been developed for agronomy to explore many management scenarios. Process-based models have been less attractive to forest managers due to the long time needed to measure model parameters and test the model. Forest managers also require robust and accurate growth and yield predictions, which has further added to the reluctance of foresters to adapt process-based modeling for operational management purposes (Mohren and Burkhart, 1994). However, because empirical nutrient management schemes fail to account for complex, site-specific nutrient dynamics, they may not be economically optimal or environmentally benign.

Process-based models are better suited to this need for site-specific information than empirical models, and with proper validation may provide the needed accuracy. Combinations of process-based and empirical approaches may be the best first approximation to an overall SRWC model by using the adaptability of process-based models and the accuracy of empirical models to achieve a working model more rapidly than by attempting to develop a completely process-based model.

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CHAPTER III. STUDY APPROACH AND SITE DESCRIPTIONS

PROJECT OVERVIEW

This research addressed the N fertilization needs of short-rotation woody crops in general and sweetgum (*Liquidambar styraciflua* L.) plantation management in the Atlantic coastal plain of the U.S., in particular. Soil N supply was modeled as a function of potential N mineralization and adjusted for field conditions in two young sweetgum plantations on a well-drained, converted agricultural field, and on a poorly drained, cutover pine plantation. Plant N demand was determined on these two sites from plant and litter sampling, and fertilization needs was determined with a balance-sheet approach to approximate the most efficient nutrient flux density for sweetgum growth. Soil characteristics influencing sweetgum management and nutrition were measured on 12 additional sites that represent the spectrum of sites suitable for sweetgum management. This approach used the strengths of all three forms of forest research, i.e., modeling, field experiments and process studies, to comprehensively study and address the problem of N nutrition in SRWC (Figure III-1).

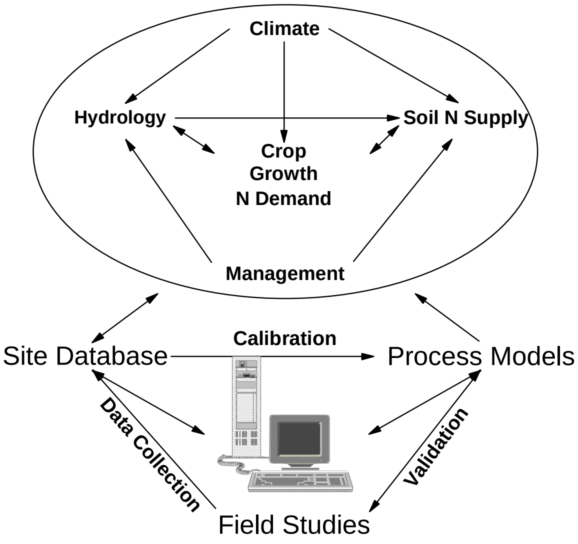

Figure III-1. Linkages between process studies, field experimentation, and modeling concepts for designing research on forest productivity (after Foster et al., 1997)

STUDY SITE DESCRIPTIONS

Characterization Sites

The International Paper site types are located in the lower and middle coastal plain of southeast Virginia and northeast North Carolina and the middle coastal plain of South Carolina (Table III-1). The northern sites have a recent site history of loblolly pine plantation management while those in South Carolina have been in dryland agriculture for years to decades. The combination of climate and site history differences provides the basis for a main comparison International Paper would like to explore. Four sites were selected to represent the two main soil catenas found in both areas. Two additional sites, one in each area, represented the floodplain land common to the northern area and clay flats common to the southern area. The MeadWestvaco site types are located in southern and southeastern South Carolina. Five of the six MeadWestvaco site types are converted loblolly pine plantations and the other is converted agricultural land. The site types represent gradients in surface and subsoil texture and soil fertility.

Experimental Validation Sites

The model development and testing was done within existing fertilization trials owned and managed by MeadWestvaco and International Paper Corporations. Species and management objectives were similar in both trials, but differences in site and soil type and past management history exist between the two plantations. These contrasts allowed qualitative extrapolation to other sites and evaluation of model effectiveness to predict fertilizer needs.

Table III-1. Site names and locations used to characterize the range of SRWC sites in the Southeast. The first seven sites are International Paper sites, while the second seven are MeadWestvaco sites.

Site (Abbr)	County	Soil Series	Taxonomy	Land use	Drainage Class
Block 818 (NOH)	Northampton, NC	Wagram	Arenic Kandiudult	Ag field	Well
Burch Fiber Farm (BFF)	Bamberg, SC	Norfolk	Typic Kandiudult	Ag field	Well
Trice RW46 (TR)	Sumter, SC	Norfolk	Typic Kandiudult	Ag field	Well
Scarborough 10 (SC10)	Richland, SC	Goldsboro	Aquic Paleudult	Ag field	Moderately well
Block 73 (SOH)	Southampton, VA	Goldsboro	Aquic Paleudult	Pine	Moderately well
Featherbed (FEB)	Colleton, SC	Yauhannah	Aquic Hapludult	Pine	Moderately well
Scarborough 2 (SC2)	Richland, SC	Lynchburg	Aeric Paleaquult	Ag field	Somewhat poorly
Beech Hill (BEH)	Dorchester, SC	Yemassee	Aeric Endoaquult	Pine	Somewhat poorly
North Cherokee (NC)	Colleton, SC	Argent	Typic Endoqualf	Pine	Poorly
Trice 8 (TR8)	Sumter, SC	Coxville	Typic Paleaquult	Ag field	Poorly
Block 221S	Isle of Wight, VA	Myatt	Typic Endoaquult	Pine	Poorly
Dick West (DIW)	Dorchester, SC	Mouzon	Typic Albaqualf	Pine	Very poorly
Powell Bay (POB)	Berkeley, SC	Byars	Umbric Paleaquult	Pine	Very poorly
Jacksonboro (JAB)	Colleton, SC	Meggett	Typic Albaqualf	Pine	Very poorly

The MeadWestvaco study site (hereafter referred to as “North Cherokee”) is located in Colleton County, South Carolina (32^o 8' N 80^o 7' W) (Figure III-2) on the lower Atlantic coastal plain, which is characterized by gentle to rolling topography consisting of a series of marine terraces paralleling the Atlantic Coast. The region is dissected by many broad valleys containing wide meandering streams which terminate in estuaries along the coast. The drainage systems are often poorly defined and restricted, resulting in slow water movement through this region to the Atlantic Ocean. Soils in this region developed from nearly level beds of unconsolidated sands, clays, and soft limestone (Runge, 1977). The climate in this part of South Carolina is characterized by long, hot summers and short, relatively mild winters. The annual growing season averages 212 days with an average last spring frost of April 3 and an average first fall frost of November 2. Summer temperatures (June, July, and August) average 26 ^{o}C with daily high temperatures of 32.3 ^{o}C and nightly low temperatures of 19.7 ^{o}C. Winter temperatures (December, January, and February) average 9.3 ^{o}C with daily high temperatures of 16.3 ^{o}C and daily low temperatures of 2.2 ^{o}C. Mean annual precipitation is 132.5 cm. Rainfall during the summer months averages 50.0 cm while winter precipitation is 26.7 cm (Soil Conservation Service, 1993).

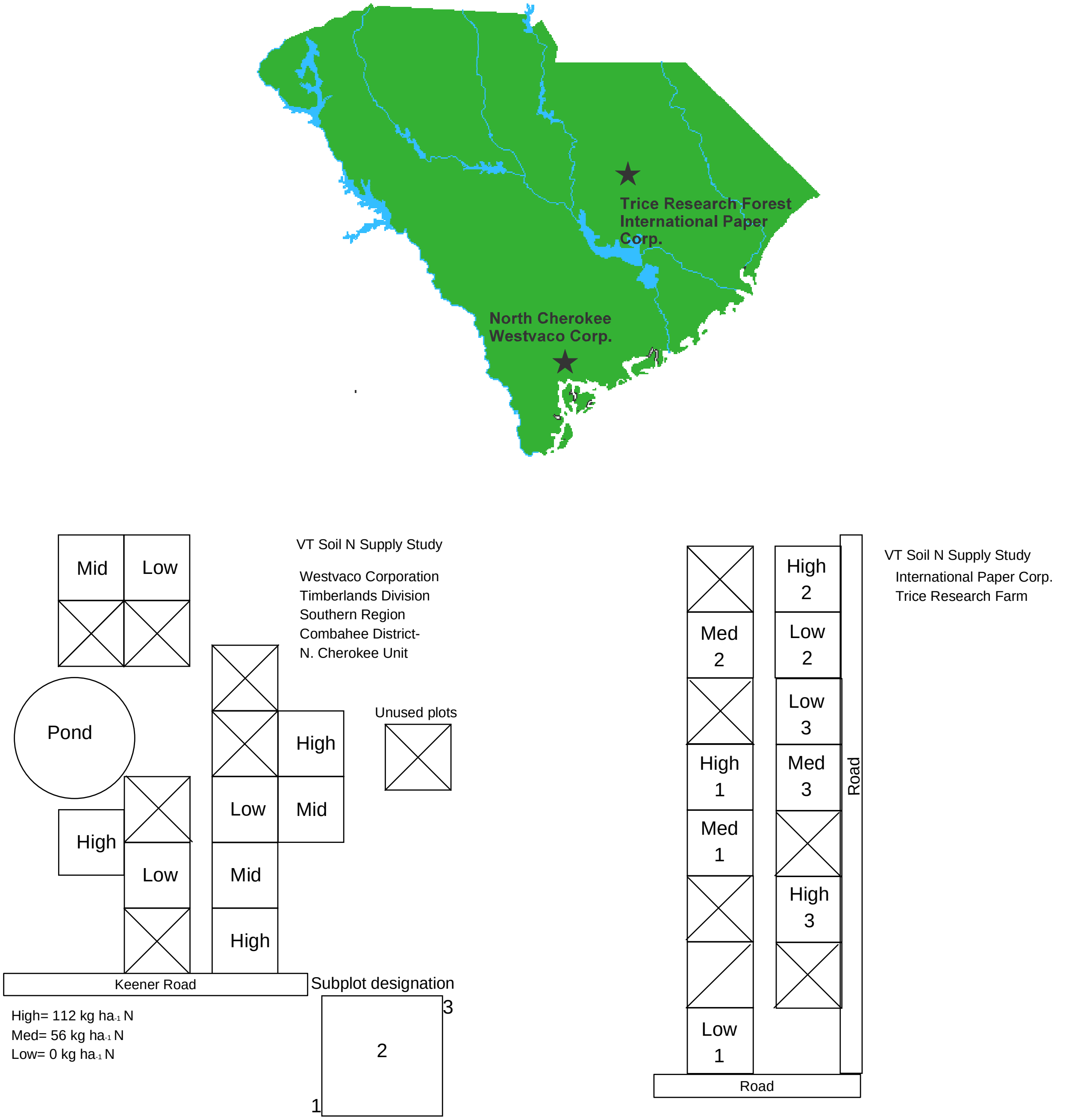

Figure III-2. Experimental sites in South Carolina. The experimental treatment plots were 0.2 ha.

The International Paper (IP) study site (hereafter referred to as “Trice”) was located in Sumter County, South Carolina (33º 58' N 80º 12' W) (Figure III-2) on the middle Atlantic coastal plain, which is generally more dissected and has more relief than the lower coastal plain. Poorly and very poorly drained soils are less common, but basin wetlands called Carolina bays are prevalent (Stanturf and Schoenholtz, 1998). The climate in this part of South Carolina is characterized by long, hot summers and short, relatively mild winters. The annual growing season averages 209 days with an average last spring frost of March 27 and an average first fall frost of October 22. Summer temperatures (June, July, and August) average 26.7 ºC with daily high temperatures of 33.0 ºC and nightly low temperatures of 20.4 ºC. Winter temperatures (December, January, and February) average 9.3 ºC with daily high temperatures of 15.7ºC and daily low temperatures of 2.8 ºC. Mean annual precipitation is 113.0 cm with rainfall fairly well distributed throughout the year. Rainfall during the summer months averages 38.4 cm while winter precipitation is 23.9 cm (Soil Conservation Service, 1974).

Experimental Design

The North Cherokee site was established in February and March of 1995. It is a Completely Randomized Design (CRD) with 3 replications of 3 treatments. Nine 0.2-ha sweetgum plantations were established following harvest of loblolly pine and site preparation, which consisted of bedding, fertilization and non-crop vegetation control. All plantations received 280 kg ha^{-1} diammonium phosphate (DAP) in November 1994. Non-crop vegetation control consisted of pre-emergent herbicide applications in February and March of 1995, 1996, and 1997. Herbicides were also applied by directed spray in 1995 and 1996 during the growing season. Beginning in 1996 and every other year thereafter, N has been added at the following rates:

Treatment

1 (Control, Low) 0 kg ha^{-1} NH_4NO_3, 0 kg ha^{-1} N
2 (Medium) 168 kg ha^{-1} NH_4NO_3, 56 kg ha^{-1} N
3 (High) 336 kg ha^{-1} NH_4NO_3, 112 kg ha^{-1} N

The Trice site is a Randomized Block Design with three blocks consisting of 3 treatments each. Blocking criteria consisted of depth to Bt horizon and presence of redoximorphic features. Nine 0.2-ha sweetgum plantations were established in 1996. The sites had been regularly managed for dryland crops (corn, soybeans, etc.) for more than 20 years, and soybeans (*Glycine max.* (L.) Merr) were the primary crop for the 5 years previous to woody crop plantation conversion. Following the final soybean harvest, the sites were converted to an operational sweetgum plantation in spring 1995, which failed. In 1995 the site was bedded with agricultural bedding machines that produced a bed approximately 0.3 m wide and 0.1 m tall. All plots were treated with an initial fertilizer program of 280 kg ha^{-1} diammonium phosphate (DAP) in November 1995 and 101 kg ha^{-1} urea in August 1996. Three N fertilizer (NH_4 NO_3) treatments corresponding to the same levels as at the North Cherokee site were initiated spring 1997 and will be continued every 2 years thereafter.

The soil on the North Cherokee site is a somewhat poorly to poorly drained Argent series (Typic Endoaqualf) developed from marine deposits in the lower Atlantic coastal plain. The site undergoes wide fluctuations in soil water content, from saturated soils with standing water in the bed furrows in the late fall until spring to dry soil during the growing season. The soil on the Trice site is a well-drained Norfolk series (Typic Kandiudult), developed from marine deposits in the middle Atlantic coastal plain.

Three subsampling points were installed within each of the 0.2 ha plantations from which all soils measurements were taken. The linear model and analysis of variance (Table III-2) for each site (for plant and soil experimental analyses) was: $y_{ij}=\mu+\tau_i+\varepsilon_{ij}$

Where:

y_{ij} represents the response of the ith treatment and jth experimental unit

μ represents the mean response

τ_i represents the treatment response

ε_{ij} represents the experimental error

Table III-2. Basic Analysis of Variance (ANOVA) for Trice and North Cherokee

Source	Trice df (RCBD)	North Cherokee df (CRD)
Blocks (b)	(b-1) = 2	
Treatments (t)	(t-1) = 2	(t-1) = 2
Experimental error	(b-1)(t-1) =4	t(r-1) =6
Total	bt-1 = 8	tr-1 = 8

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CHAPTER IV. GROWTH AND NUTRITION OF FERTILIZED YOUNG SWEETGUM PLANTATIONS ON DIFFERENT SITE TYPES

ABSTRACT

Short-rotation intensive tree culture is being investigated in the southern US as a method of producing needed hardwood fiber, but little is known about the early productivity and nutritional needs of these systems, especially on different site types. We studied the growth and foliar nutrition response of two sweetgum (*Liquidamber styraciflua* L.) plantations on a converted agricultural field and a pine cutover site to biannual applications of three nitrogen (N) fertilizer rates: 0, 56, and 112 kg N ha^{-1}. The trees did not respond to treatment at any age on the agricultural field site, but the fertilized trees on the cutover site had about 60% greater biomass at ages 5 and 6. Fertilization doubled foliar biomass and leaf area on the cutover site in the years fertilizer was applied. Stem biomass was directly related to foliar biomass, but the relationship was age-specific at both sites. Stem biomass was also related to the foliar N concentration. Critical values of N were about 1.75 % N. Foliage phosphorus, potassium, calcium, and magnesium contents were diluted by the N fertilization-induced growth responses at both sites. Fertilization of young intensive-culture sweetgum plantations is necessary for optimum foliar N concentrations and foliar and stem biomass production, but is site-specific.

INTRODUCTION

Hardwood plantations will be needed as a source of fiber in the US and across the world, but their success depends heavily on management intensity (Ford, 2000). Hardwood fiber is required in certain pulping mixtures, especially those used for producing high-quality writing and packaging papers. Until recently, hardwood fiber has generally been available from natural stands, but the availability and reliability of this source is becoming more and more uncertain. As an alternative to fiber production from naturally regenerated hardwood stands, the feasibility of producing hardwood fiber in short-rotation, intensively-cultured plantations at an operational level is being explored throughout the U.S. Relative to most plantation systems, short-rotation hardwood plantations require more intensive site selection and preparation, herbaceous and woody competition control, and nutrient management for plantation success. Nutrient management is especially important in managing hardwood plantations because they generally require more nutrients per unit biomass than conifers, but we have only cursory knowledge of the nutritional control on growth of most hardwood species.

Marginal agricultural fields have been used as growing sites for most hardwood plantations throughout the southern US (Groninger et al., 2000). Compared to forest sites, agricultural fields tend to have higher soil pH due to liming and the removal of acid-producing forest litter, and they have higher levels of phosphorus and nutrient cations due to repeated fertilization (Richter et al., 2000b). Herbaceous weed communities dominate these sites due to past cultivation and weed control, and equipment access and soil trafficability is excellent due to the nature of the past land use. However, harvested forest sites, or cutovers, are generally less eroded and tend to have much higher quantities of soil organic matter (Richter et al., 2000a). Except for erosion and the loss of organic matter, the characteristics of marginal agricultural fields are ideal for intensively-managed hardwood plantations. Unfortunately, marginal agricultural lands are not always affordable or available in geographical proximity to fiber processing facilities, in which other lands may be needed for hardwood plantations.

The demand and value of hardwood fiber coupled with the relative paucity of affordable agricultural lands in some areas has increased the area of cutover conifer lands planted to hardwood plantations. Cutover conifer lands, in comparison to agricultural fields, have not been repeatedly fertilized and have not had annual weed control. Therefore, base cations and phosphorus may be marginal to inadequate for short-rotation woody crop plantations, and both woody and herbaceous competition may be high and need to be controlled. However, cutover forest land generally has higher soil organic matter and is less eroded. Within these two land use groupings, wide differences in soil types and properties cloud our understanding of site-specific plantation responses to various fertilization treatments.

Foliage nutrient concentrations are used operationally to indicate nutrient status in plantations (Fisher and Binkley, 2000). Nutrient concentrations of a standardized foliar sample are commonly used to diagnose nutrient status in slash (*Pinus Elliott* Engelm.) and loblolly (*P. taeda* L.) pines in the southeastern U.S. (Comerford et al., 1983; Wells and Allen, 1986) and a variety of conifers in western North America (Miller and Fight, 1979; Carter, 1992; Brockley, 1996) with a critical level approach (Dow and Roberts, 1982), which is based on the well-established yield and nutrient sufficiency relationship. Although foliar nutrient concentrations have been reported for some hardwood species in natural stands and plantations, critical levels have not been established for most hardwoods.

Furthermore, low nutrient concentrations in a diagnostic foliage sample do not necessarily indicate a nutrient deficiency, nor do high concentrations necessarily indicate sufficiency (Timmer and Stone, 1978). Increases in foliage nutrient concentrations without a concomitant increase in foliage biomass and nutrient content may be due to luxury consumption, and increases in foliage biomass and nutrient content with a decrease in foliage nutrient concentration indicate nutrient dilution. Trees may also appear to have “sufficient” foliage nutrient concentrations when foliage production is limited by available soil nutrients and foliage nutrient concentrations thus do not decrease (Farnum et al., 1983).

Rapid early growth is essential in short-rotation woody crop plantations, and nutrients may limit growth prior to crown closure, the objectives of our study were to determine stem and foliar biomass responses of young sweetgum plantations to repeated N fertilization on an old agricultural field and a cutover pine site, and to measure tree response as a function of foliage nutrition.

MATERIALS AND METHODS

Site Descriptions

Two sites of contrasting soil type and land use history were selected for this study. One was a well-drained agricultural field, while the other was a poorly-drained harvested loblolly pine plantation site, hereafter referred to as the “ag field” and “cutover” sites, respectively.

The ag field study site was located on International Paper’s Trice Research Forest in Sumter County, South Carolina (33° 58' N 80° 12' W) on the middle Atlantic coastal plain. The soil is a well-drained Norfolk sandy loam (loamy, kaolinitic, thermic Typic Kandiudult). Nine 0.2-ha treatment plots with 0.04-ha measurement plots were established in February 1996 with 280 1-0 bare-root sweetgum seedlings (~1400 ha^{-1}). The sites had been regularly managed for dry land crops, e.g., corn (*Zea mays* L) and soybeans (*Glycine max.* (L.) Merr), for more than 20 years, and soybean, a N_2 fixing legume, was the primary crop for the 5 years previous to plantation establishment. All plots were treated with an initial fertilizer application of 280 kg ha^{-1} diammonium phosphate (DAP), which supplied 50 kg N ha^{-1} and 56 kg P ha^{-1} in November 1995 and 100 kg ha^{-1} urea, which supplied 46 kg N ha^{-1}, in August 1996. Non-crop vegetation was restricted to herbaceous vegetation, mostly broomsedge (*Andropogon virginicus* L.), due to the agricultural legacy and early-rotation chemical weed control. The site was also mowed intermittently throughout the 5 years to reduce the herbaceous competition for water and nutrients.

The cutover pine site was on MeadWestvaco Corporation land, located in Colleton County, South Carolina (32° 8' N 80° 7' W) on the lower Atlantic coastal plain, and was established in February 1995. The soil is a somewhat poorly to poorly drained Argent sandy loam (clayey, mixed, active, Typic Endoaqualfs) developed from marine deposits. The site undergoes wide fluctuations in soil water contents, from saturated soils with standing water in the dormant season to dry soils during the growing season. The heavy clay subsoil restricts water percolation through the solum, and the low elevational gradient (<2%) restricts lateral flow. These mechanisms induce short-term saturation after heavy rain events throughout the growing season. Nine 0.2-ha treatment plots with 0.04-ha measurement plots were established with 280 1-0 bare-root sweetgum seedlings (~1400 ha^{-1}) of the same genetic source as the ag field site following loblolly pine harvest and site preparation. Site preparation consisted of bedding, fertilization and non-crop vegetation control. All plots received 50 kg N ha^{-1} and 56 kg P ha^{-1} as DAP in March 1995. The plots also received 3.9 Mg ha^{-1} dolomitic lime in March 1995. The lime application raised pH at 0-20 cm from approximately 4.75 to 5.5. Non-crop vegetation control consisted of pre-emergent herbicide applications in February and March of 1995, 1996, and 1997. Herbicides were also applied by directed spray in 1995 and 1996 during the growing season. Although this aggressive chemical weed control program was used for the first three years, woody and herbaceous plants were present when competition control measures ceased. Compared to most young cutover pine plantations, this site was relatively clean with respect to non-crop vegetation, but not compared to the ag field site.

Experimental design

At each site, three biannual N fertilizer rates were initiated at age 2 and replicated three times. Every two years, i.e., ages 2, 4, 6, ammonium nitrate (NH_4NO_3) was applied at the following rates: 0 kg ha^{-1} (Control), 168 kg ha^{-1}, and 336 kg ha^{-1}, which provided 0, 56, and 112 kg ha^{-1} N, respectively. At the cutover site, 56 kg P ha^{-1} was added as triple superphospate at age 6 because fertilization with N alone at age 4 induced P deficiencies (Donald Kaczmarek, personal communication). The error control design at the cutover site was a Completely Randomized Design, while the design at the ag field site was a Randomized Complete Block Design (Steele and Torrie, 1980), where the blocking factor was the depth to redoximorphic features. The wide separation of the sites in space, the different establishment years (1996 at the ag field site and 1995 at the cutover site), and slightly different cultural management approaches between the two sites precluded a quantitative comparison of the two sites. The similarity in fertilizer application rates and data collection procedures, however, allowed qualitative comparisons of site-to-site differences in plant responses.

Treatment effects within a site and age class were determined using analysis of variance at $\alpha=0.10$. If the model was significant, Duncan's Multiple Range test was used to separate the means (SAS Institute, 2000). Linear regression analysis was used to test for a relationship between tree growth responses and foliage nutrient concentration and content. A vector analysis was performed following procedures by Weetman (1989) to elucidate the relative response of foliar biomass, nutrient concentration, and content. Vectors were computer-generated using SigmaPlot software (SPSS, Chicago, IL).

Soil characterization

Soil samples were collected from each treatment plot in 1999 and 2000. Nine 2-cm diameter subsamples were collected per treatment plot in April and November of each year from two soil depths: 0-20 cm (A horizon) and 20-40 cm (E horizon). The subsamples were air-dried, sieved to pass a 2-mm sieve and bulked by treatment plot, depth, and year. The samples were then analyzed for total carbon (C), N, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and pH. Carbon and N were determined with a vario MAX CNS analyzer (Elementar, Hanau, Germany). Available phosphorus was determined by extracting the soils with Mehlich I extractant (Mehlich, 1953) and analyzing the extract via Inductively Coupled Plasma – Atomic Emission Spectroscopy (ICP) (SpectroFlame Modula Tabletop ICP, Spectro Analytical Instruments, Fitchburg, MA). Exchangeable K, Ca, and Mg were determined by ammonium acetate (pH 7) extractant (Thomas, 1982) and analyzed via ICP. Soil pH was determined for the samples in a 1:2 soil:water mixture with a combination pH probe.

Diagnostic foliage sampling

In September 1998, 1999, and 2000, which corresponded to ages 3, 4, and 5 at the ag field site and ages 4, 5, and 6 at the cutover site, respectively, a diagnostic foliage sample was taken from the southern portion of the canopy from five trees in each treatment plot. The diagnostic sample consisted of 6 fully developed leaves from the upper crown position on the South side of each of the 5 trees.

Whole-Crown Foliage Sampling

Three foliage samples were taken from the southern portion of the canopy from five trees in each treatment plot for the whole-crown sample. The samples consisted of 6 leaves of all stages of development from single branches, and were collected within the upper, middle, and lower crown positions (Kuers and Steinbeck, 1998).

Foliage analyses

The diagnostic and whole-crown foliage samples were chilled on-site, transported to the laboratory in a cooler, and processed within 24 hr. Leaf area was determined on the fresh whole-crown samples with a leaf area meter (Delta-T Devices, Cambridge, UK). Specific leaf area (SLA) was determined using the area and mass of each sample, and leaf area index (LAI) was determined by multiplying the SLA by the foliage mass for each crown position. The SLA was not determined for the ag field samples in 2000, so the SLA values from 1999 were used in calculating LAI.

The leaves were oven-dried at 65 ^{o}C to a constant weight and ground to pass a 40 mesh screen. We determined the foliage mass for each crown position by multiplying the total litterfall, measured from 5 randomly located litter traps (approximately 1 m^2 per trap) per plot by the relative weighting factors of Kuers and Steinbeck (1998), who showed that fertilization increases young sweetgum foliage mass disproportionately among crown positions. Foliar N concentrations were determined on each sample with a N analyzer (LECO FP-528, St. Joseph, MI). Nutrient cation (P, K, Ca, and Mg) concentrations were determined by dry ashing 0.03 g of tissue at 420 °C for 4 hr, digesting the ash with 2 mL conc. HCl, diluting the digest with 20 mL of 5% HNO_3 and 2.5% HCl, and measuring the concentrations via ICP (Perkin Elmer Optima 3000, Wellesley, MA). Total foliage nutrient content on an area basis was determined for the whole-crown samples by multiplying the whole-crown foliage nutrient concentration by the foliage mass for each crown position.

Tree growth

Total height was measured with a height pole and diameter at breast height (dbh) was measured using a diameter tape. Stem biomass (outside bark) was determined on each tree using a biomass equation developed by Reams et al. (1982); it was summed by treatment plot for area-based estimates of stem biomass.

RESULTS AND DISCUSSION

Soil characterization

The cutover site surface horizons had about 5 times the soil C and 3.5 times the soil N concentrations of the ag field (Table IV-1). The organic substrate quality, as measured by C:N ratio of these two sites was also quite different due to the recent vegetation. The other soil nutrients were also directly related to past land use history. Mehlic I extractable P was about 5 times greater throughout the surface soil at the ag field site than at the cutover site due to past P fertilization, since P fertilization at tree establishment was similar. However, exchangeable K, Ca, and Mg were 228, 28, and 900% greater, respectively, in the A horizon at the cutover site compared to the ag field site, due to inherent differences in soil properties and historic crop removals. Although the cutover site was expected to have lower soil pH than the ag field, the cutover site's soil pH was similar to the ag field's because the cutover site was limed at establishment.

Table IV-1. Soil chemical characteristics at 0-20 cm (A horizon) and 20-40 cm (E horizon) in two young sweetgum plantations in South Carolina.

Site	C	N	C:N	P	K	Ca	Mg	pH
	-----%-----			---------------mg kg^{-1}---------------				
Ag field A	0.52	0.03	15.2	29.3	112.0	47.5	15.7	5.0
Ag field E	0.31	0.02	14.6	20.3	176.0	54.2	17.2	5.1
Cutover A	3.23	0.11	29.6	9.1	342.0	54.7	134.0	5.2
Cutover E	0.99	0.05	21.6	2.7	79.5	54.3	81.3	5.2

Growth responses

Stem growth responses to fertilization varied by site (Table IV-2). The trees on the ag field site did not respond to N fertilizer applications by age 5, the last year measured (Figure IV-1). Since the stand biomass had not yet shown any fertilizer response , the trees on the ag field site will not likely respond in the next year or two. The trees at the cutover site did not respond to fertilization until age 5, even though they had received fertilizer at ages 2 and 4. At age 5, the fertilized trees were about 12% taller, 23% greater in diameter, and had 58% more stem biomass than the unfertilized control treatment. These growth responses were maintained at age 6, but were not increased by the fertilizer application in the spring of that year. Apparently, the tree growth responses lag one year behind fertilizer applications at the cutover site. In general, when foliage N concentrations increase due to increased soil N availability, photosynthetic efficiency is increased due to the ability to produce chlorophyll (Kramer and Kozlowski, 1979). This increase in photosynthetic efficiency then allows greater leaf area production, which, in turn, allows total photosynthesis (and stem growth) to increase.

Table IV-2. Growth responses of two young sweetgum plantations to nitrogen fertilizer applications in South Carolina. Treatment means within a site and column followed by the same letter are not significantly different at α=0.10.

	Height				**Diameter**				**Stand Biomass**			
	---------------m---------------				---------------cm---------------				------------Mg ha^{-1} ------------			
Ag field	**Age 3**	**4**[1]	**5**	**6**	**Age 3**	**4**	**5**	**6**	**Age 3**	**4**	**5**	**6**
Control	3.53a	5.01a	5.87a	--	4.42a	5.84a	6.56a	--	1.96a	4.55a	6.57a	--
56 kg ha^{-1}	3.57a	4.95a	5.96a	--	4.18a	5.54a	6.55a	--	1.80a	4.18a	6.85a	--
112 kg ha^{-1}	3.63a	5.05a	5.99a	--	4.39a	5.92a	6.78a	--	1.93a	4.63a	7.08a	--
Cutover	**Age 3**	**4**	**5**	**6**	**Age 3**	**4**	**5**	**6**	**Age 3**	**4**	**5**	**6**
Control	--	4.54a	5.50b	6.31b	--	5.34a	5.71b	6.99b	--	3.84a	5.13b	8.40b
56 kg ha^{-1}	--	4.84a	6.04ab	6.98a	--	6.46a	6.85a	8.63a	--	5.52a	7.80a	13.56a
112 kg ha^{-1}	--	4.84a	6.28a	7.02a	--	6.49a	7.23a	8.50a	--	5.78a	8.80a	13.66a

[1] Shaded columns indicate the years fertilizer was applied to the 56 and 112 kg treatment plots.

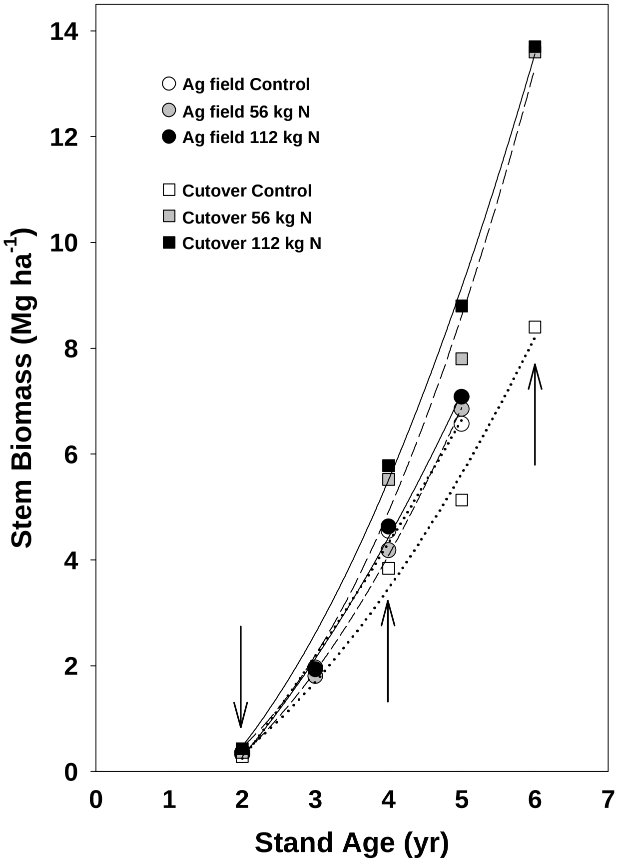

Figure IV-1. Stem biomass response to fertilizer through time at two young sweetgum plantations in South Carolina. Arrows indicate when fertilizer was applied.

In general, trees at the old agricultural field, regardless of treatment, were larger than unfertilized trees on the cutover site, but were smaller than the fertilized trees on the cutover site. Tree heights were similar between the sites regardless of treatment, but the fertilized trees at the cutover site had 9% greater diameters and had 21% more total stem biomass than the ag field trees. Although fertilization increased tree heights at the cutover site, diameter was the more responsive variable. The biomass responses were a direct result of the diameter responses, because plantation density was very similar at both sites.

Tree growth on both sites was excellent for sweetgum plantations because of the intensive-culture. These plantations were managed as short-rotation woody crop systems, which entailed rigorous site selection, mechanical and chemical site preparation, three years of complete weed control, and improved genetic stock. While several studies have reported planted sweetgum growth data, few have studied growth on sites managed this intensively. Williams and Gresham (2000, 2002) reported age 4 and 5 total biomass (bole, branch, and leaf) estimates of three treatments; control, irrigated, and fertigated, in a study designed to determine maximum sweetgum biomass growth, i.e., fiber farming. They found 7.5, 15, and 31 Mg ha^{-1} for the three treatments, respectively, at age 4, and 10.4, 22.5, and 49.9 Mg ha^{-1} for the three treatments at age 5. Using their total biomass equation, the estimated total biomass in this study ranged from 7.3 Mg ha^{-1} to 10.6 Mg ha^{-1} at age 4 and 9.5 to 16.1 Mg ha^{-1} at age 5, respectively. Overall, biomass production on the two sites in the current study was similar or greater than the control treatment of Williams and Gresham’s (2000, 2002) studies. The irrigation and fertigation (fertilizer applied in irrigation water) treatments in their study caused a much greater growth response than found in our study, which was designed to determine N fertilizer response without supplemental water.

Because the expected rotation length of these plantations is short, i.e, twenty years or less, the time required to reach a given biomass production may be a more meaningful measure of plantation success than relative biomass response. The fertilized trees at the cutover site were, in effect, one full year advanced in biomass growth compared to the unfertilized trees, i.e., the biomass of the fertilized trees on the cutover site at age 5 was greater than the biomass of the unfertilized trees at age 6. The biomass trajectories (Figure IV-1) indicate that the fertilized trees at the cutover site may be 2 to 3 years advanced in biomass growth at age 6. Assuming that the current relative response is maintained, fertilization will allow the trees on the cutover site to reach a targeted biomass level 3 years or more in advance of the unfertilized trees.

Nitrogen rate had little effect on biomass growth. Neither the 56 nor the 112 kg N ha^{-1} fertilization rate improved growth at the ag field site, and the 56 kg N treatment performed almost as well as the 112 kg N treatment at the cutover site, and appears to be sufficient for early growth (Table IV-2). These fertilization rates were, however, applied at very frequent intervals, i.e., biannually. It is likely that optimum fertilization rates will vary with changes in the frequency of application and more biologically and economically efficient fertilization regimes may be possible. As these stands reach crown closure, their N demand will likely increase, and 112 kg N biannually may be needed to sustain optimum growth.

Fertilization responses were dependent upon the stage of plantation development. The fertilized trees did not respond at either site until age 5. Although some residual fertilizer may have remained from the initial urea fertilization at the ag field site and the fertilization treatment at age 2 on both sites, it is more likely that this fertilization was unwarranted at either site, and fertilization may not be necessary at the ag field site until age 6 or beyond. This study was part of a larger study at the ag field site that also included a mid-rotation treatment, in which N fertilizer will be applied when the 112 kg N treatment has a growth response of 30% or more. For the ag site, this treatment will likely achieve the best N supply-demand synchrony.

Foliage responses

Foliage biomass and leaf area responses to fertilization were similar to biomass growth responses at both sites (Table IV-3). Foliage biomass was similar among all treatments within all three ages at the ag field site, except for the 56 kg treatment at age 5, which had 81% greater foliage biomass than the Control. The lack of a response on the 112 kg treatment was perplexing, and was probably due to an unknown measurement error. At the cutover site, foliage biomass on the 112 kg treatment plots was twice that of the control plots at ages 4 and 6, years in which fertilizer was applied. The age 4 responses were not maintained at age 5, when no fertilizer was applied to any plots. Thus, the foliage biomass responses (Table IV-3) occurred in the year in which fertilizer was applied, while stem growth responses (Table IV-2) occurred in the following year.

Table IV-3. Foliage biomass and leaf area responses of two young sweetgum plantations to nitrogen fertilizer applications in South Carolina.

	Foliage Biomass kg ha^{-1}				**Leaf Area Index**			
Ag field	**Age 3**	**4**[1]	**5**	**6**	**Age 3**	**4**	**5**	**6**
Control	476a[2]	2260a	1540b	--	0.324a	1.63a	1.12a	--
56 kg ha^{-1}	475a	2470a	2780a	--	0.301a	1.76a	1.97a	--
112 kg ha^{-1}	586a	3100a	2220ab	--	0.414a	2.32a	1.67a	--
Cutover	**Age 3**	**4**	**5**	**6**	**Age 3**	**4**	**5**	**6**
Control	--	1340b	2110a	1750b	--	1.43b	3.61a	1.65b
56 kg ha^{-1}	--	1950ab	2640a	2670ab	--	2.22ab	4.24a	2.40ab
112 kg ha^{-1}	--	2820a	3220a	3480a	--	2.94a	5.96a	3.00a

[1] Shaded columns indicate the years fertilizer was applied to the 56 and 112 kg N treatment plots

[2] Treatment means within a site and column followed by the same letter are not significantly different at $\alpha=0.10$.

In order to relate foliage biomass production to stand biomass growth, we used linear regression to test the relationship between stem biomass and foliage biomass (Figure IV-2) across both sites and ages. Because the relationship appeared to be site and age-specific, we performed separate regressions on each site and used categorical variables to test the age-specific relationship within each site. First, the regression was performed using the full model; all intercept and slope adjustment terms were included as well as foliage biomass, the main

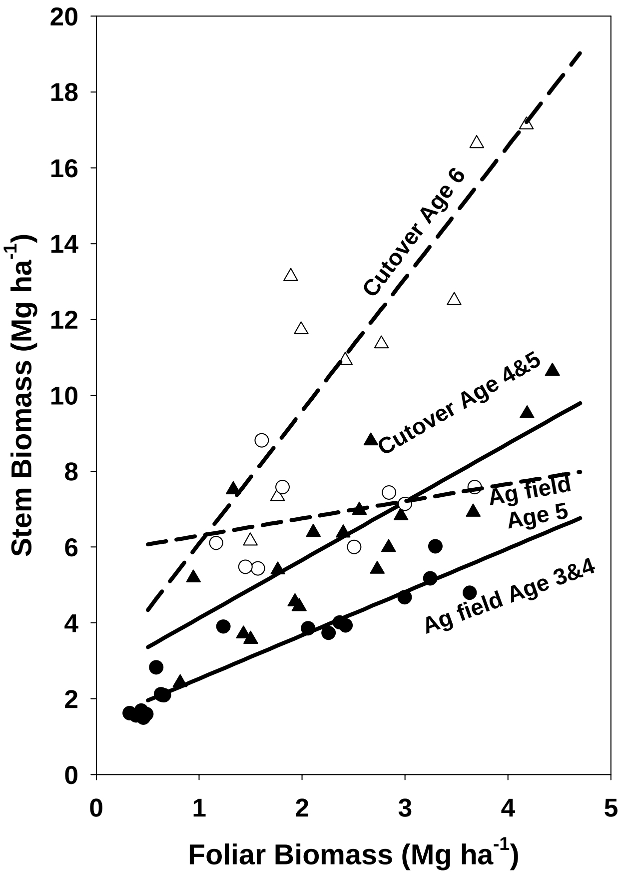

Figure IV-2. Stand biomass in relation to foliar biomass for two young sweetgum plantations in South Carolina. The overall regression lines for the ag field site and the cutover pine site were both significant ($p<0.0001$) and had R^2 values of 0.90 and 0.84, respectively.

regressor. The regression was retested using the slope and intercept terms that were significant in the full model analysis. If either the slope or the intercept terms for an age were significant, both were included in the second iteration. Finally, the models were retested with those parameters found to be significant in the second iteration. For the ag field site, the slope (b1) and intercept (bo) parameters were not different between ages 3 and 4, while both parameters were different for age 5 (Table IV-4). In other words, the relationship between foliage and stem biomass was significantly different at age 5 than the relationship at ages 3 and 4. Overall, the model for the ag field site was significant ($p<0.0001$) and explained 90% of the variation. At the cutover site, the age-specific intercept parameters were not significant, but the slope of the age 6 regression line was greater than the slope of the ages 4 and 5 regression line (Table IV-4). Overall, the model for the cutover site was significant ($p<0.0001$) and explained 84% of the variation.

Table IV-4. Analysis of variance and parameter estimates for stem biomass and foliar biomass for two young sweetgum plantations in South Carolina.

Agricultural field					
Source	**df**	**Sum of Squares**	**Mean Square**	**F value**	**Pr>F**
Model	3	113688575	37896192	67.30	<.0001
Error	23	12950694	563074		
Total	26	126639269			
Variable (Age)	**df**	**Parameter Estimate**	**Standard Error**	**t value**	**Pr>|t|**
Intercept (3,4)	1	1387	295.9	4.69	0.0001
Slope (3,4)	1	1.14	0.1517	7.53	<0.0001
Intercept adj[1]. (5)	1	4458	779.75	5.72	<0.0001
Slope adj. (5)	1	-0.688	0.34529	-1.99	0.0581
Cutover pine stand					
Source	**df**	**Sum of Squares**	**Mean Square**	**F value**	**Pr>F**
Model	2	319626906	159813453	63.48	<.0001
Error	24	60424244	2517677		
Total	26	380051149			
Variable (age)	**Df**	**Parameter Estimate**	**Standard Error**	**t value**	**Pr>|t|**
Intercept (4,5,6)	1	2595	823	3.15	0.0043
Slope (4,5)	1	1.53	0.331	4.62	0.0001
Slope adj. (6)	1	1.96	0.241	8.15	<.0001

[1] The slope and intercept adjustment term is added to its base value to achieve separate models for the age groupings

This analysis indicates two patterns. First, except for the ag site at age 5, stem biomass is highly related to foliage biomass, as expected. Although specific leaf area varied somewhat among sites and ages, foliage biomass was linearly related to leaf area ($p<0.0001$, $R^2=0.61$), which is directly related to photosynthetic capacity and growth potential. Secondly, because the canopy closed in the fertilized plots at the cutover site at age 6, the greater stem:leaf biomass response at age 6 implies that the fertilization treatments not only increased leaf biomass and area, but also increased growth efficiency, defined as the stem biomass growth per unit leaf biomass. The response of the ag field site at age 5 showed a reduced growth efficiency compared to ages 3 and 4. About 30 to 50 % of the foliage on the ag site at age 4 senesced early due to a drought in July and August, and then re-flushed following September rains. Growth efficiency at age 5 was probably reduced by decreased photosynthate as a result of the extra foliage production at age 4.

Foliage nutrition

Regression analysis was used to determine if a relationship existed between the diagnostic foliage N concentrations and tree biomass. If so, we hypothesized that a first approximation foliage N critical level could be established. Because the foliage N concentrations and tree biomass were both highly site-dependent, the biomass data were first standardized, by site, to the mean biomass across both sites for ages 4 and 5 (SAS, 2000). Because data were not available from both sites at ages 3 and 6, the non-standardized original data were used for those two ages. The square-root quadratic model (Stem Biomass = foliar N % + foliar $N^{0.5}$) (Colwell, 1994) was then fit to the data from each age class.

A significant relationship ($p<0.06$, $R^2=0.31$) was found for the standardized data at age 4 (Figure IV-3). No significant relationship was found for the ag field data at age 3 ($p<0.14$, $R^2=0.48$) or for the standardized data at age 5 ($p<0.33$, $R^2=.14$). The cutover data at age 6 ($p<0.12$, $R^2=0.50$), while not significant at $\alpha=0.1$, had the best fit of any of the ages and followed a similar relationship to the age 4 data.

Foliage critical levels, defined as the concentration sufficient for 90% of maximum growth, were determined for the age 4 and age 6 data (Figure IV-3) using these regression analyses. The least squares regression lines were solved algebraically for the biomass maxima, which were multiplied by 0.90 to determine the 90% maximum biomass level. The nutrient concentrations were then determined arithmetically from the 90% maximum biomass levels and the least squares regression lines. The critical levels at age 4 and 6 were 1.45 and 1.90 % N, respectively, for an average critical level of 1.68 % N. At age 4, the stem biomass to foliage N concentration relationship was not as steep as at age 6, possibly due to the inclusion of the relatively high foliage N ag field plots which had relatively low biomass due to water limitations and the lack of trees with very high N concentrations at age 6. The foliage N concentration associated with 90 % of maximum biomass at age 4 (1.45 % N) was much lower than the level associated with 100 % of maximum biomass (1.76 % N).

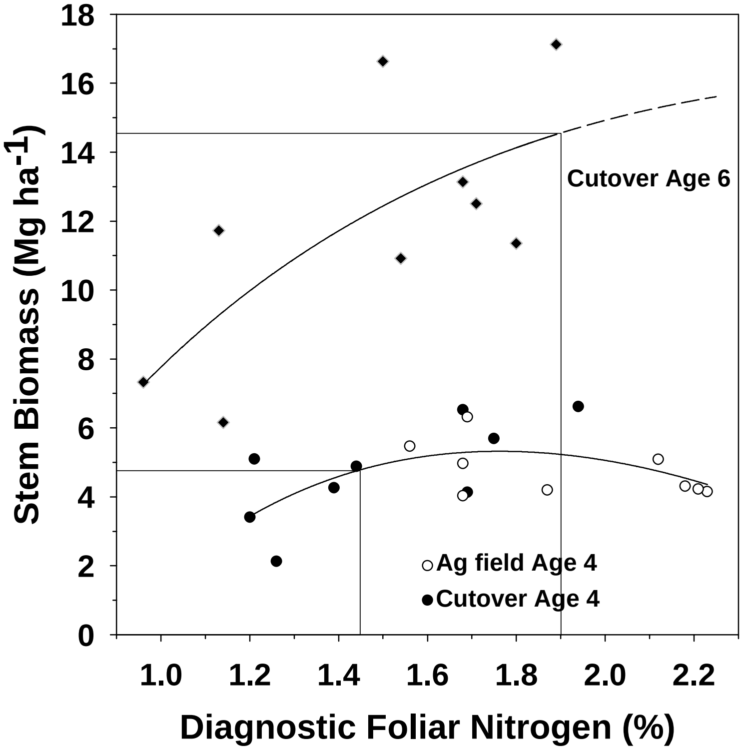

Figure IV-3. Sweetgum stand biomass as a function of diagnostic foliar N concentration at an old agricultural field and a pine cutover.

Therefore, we suggest using the level associated with maximum biomass at age 4 and 90 % biomass at age 6, which results in an average critical level of about 1.8 % N for young, intensively managed sweetgum plantations. While this value was obtained from a limited sample size, it represents the first published value for N critical levels in young intensive-culture sweetgum plantations. Given the relationship between stem biomass growth and foliage N concentration in a diagnostic foliage sample, we examined the treatment effect on foliage N concentrations. Foliage N concentrations were not affected by N fertilization on the ag field site (Table IV-5). The foliage N concentrations decreased by about 0.2 % N per year as the trees matured, but there were no differences among treatments in any year. Except for the unfertilized trees at age 5, the ag field trees all had foliage N concentrations in excess of 1.75 %, indicating that, in general, N was sufficient even for the unfertilized trees and fertilization was not necessary. At the cutover site, the foliage N concentrations were higher in the fertilized plots at ages 4 and 6, which were the years in which N was applied. No differences existed at age 5, when no N was applied. At age 4, the foliage N concentration of the trees in the 56 kg treatment was about 23 % greater than the control, and the foliage concentration of the trees treated with 112 kg was about 19 % greater than the 56 kg treatment. At age 6, the foliage concentrations of the 56 kg and 112 kg were about the same as at age 4, and showed the same response. At age 5, when no N was applied, the foliage concentrations of the 56 and 112 kg treated trees were about 10 % lower than the average of the same treatments across ages 4 and 6. In general, the foliage N concentrations of the unfertilized trees and the trees treated with 56 kg N were below the critical level, indicating that the trees were likely N deficient.

Table IV-5. Diagnostic foliage nutrient concentrations for two N-fertilized sweetgum sites. Treatment means within a site and column followed by the same letter are not significantly different at P<0.10.

	Diagnostic Foliage Nutrient Concentration			
		---------------%---------------		
		Nitrogen		
Ag field	**Age 3**	**4**[1]	**5**	**6**
Control	2.00a	1.75a	1.37a	--
56 kg ha^{-1}	2.10a	2.03a	1.85a	--
112 kg ha^{-1}	2.16a	1.96a	1.73a	--
Cutover				
Control	--	1.22c	1.33a	1.08c
56 kg ha^{-1}	--	1.50b	1.39a	1.57b
112 kg ha^{-1}	--	1.79a	1.58a	1.80a
		Phosphorus		
Ag field	**Age 3**	**4**	**5**	**6**
Control	0.24a	0.26a	0.24a	--
56 kg ha^{-1}	0.29a	0.23a	0.22a	--
112 kg ha^{-1}	0.24a	0.19a	0.16b	--
Cutover				
Control	--	0.14a	0.18a	0.22a
56 kg ha^{-1}	--	0.12a	0.18a	0.24ab
112 kg ha^{-1}	--	0.13a	0.14a	0.14b
		Potassium		
Ag field	**Age 3**	**4**	**5**	**6**
Control	0.87a	1.1a	1.4a	--
56 kg ha^{-1}	0.86a	0.85a	0.87b	--
112 kg ha^{-1}	0.83a	0.93a	0.96b	--
Cutover				
Control	--	0.51a	0.47a	0.49a
56 kg ha^{-1}	--	0.44a	0.50a	0.47ab
112 kg ha^{-1}	--	0.45a	0.46a	0.41b
		Calcium		
Ag field	**Age 3**	**4**	**5**	**6**
Control	0.78a	0.61a	0.79a	--
56 kg ha^{-1}	0.84a	0.62a	0.70a	--
112 kg ha^{-1}	0.78a	0.56a	0.69a	--
Cutover				
Control	--	0.65a	0.60a	0.77a
56 kg ha^{-1}	--	0.56b	0.61a	0.75a
112 kg ha^{-1}	--	0.55b	0.56a	0.71a
		Magnesium		
Ag field	**Age 3**	**4**	**5**	**6**
Control	0.23a	0.16a	0.23a	--
56 kg ha^{-1}	0.25a	0.17a	0.21a	--
112 kg ha^{-1}	0.25a	0.16a	0.20a	--
Cutover				
Control	--	0.32a	0.33a	0.34a
56 kg ha^{-1}	--	0.32a	0.33a	0.33a
112 kg ha^{-1}	--	0.31a	0.31a	0.37a

[1] Shaded columns indicate the years fertilizer was applied to the 56 and 112 kg N treatment plots.

Foliage P concentrations did not vary with respect to treatment or age at the agricultural field site, except for the 112 kg treatment at age 5, which was about 33 % lower than the other two treatments (Table IV-5). The P concentrations at the cutover site were not different among treatments at age 4 or age 5. Because this study was primarily designed to study the stand N dynamics without P limitations, approximately 56 kg P ha^{-1} was applied to all plots as triple superphosphate on the cutover site at age 6 when N was applied to the two N fertilizer treatments. The P concentrations at age 6 were greater than at age 5 for the Control and 56 kg treatments, but the concentration of the 112 kg N treatment did not change, resulting in a lower P concentration compared to the other treatments.

The P concentrations were consistently higher at the ag field site than at the cutover site. The average P concentration of the ag field site was 75 and 20% greater than the average concentration at the cutover site at ages 4 and 5, respectively, and was expected given the much higher level of Mehlich I extractable soil P at the ag field site.

Foliage K concentrations did not vary at the agricultural site among treatments at ages 3 or 4 (Table IV-5). At age 5, the trees treated with N had lower K concentrations than the Control, but the concentration of the Control treatment was exceptionally high compared to ages 3 and 4. Foliage K concentrations at the cutover site were not different among treatments at ages 4 or 5, but the concentration of the 112 kg treatment at age 6 was 16 % lower than the Control due to dilution. The average foliage K concentration at the ag field site was twice that of the cutover site at ages 4 and 5, even though soil K at the ag site was almost half that of the cutover site. This indicates that at the ag field site, K is being taken up at much greater rates than needed.

Applications of N fertilizer had little effect on Ca and Mg concentrations. Foliage Ca concentrations tended to be higher with high soil test Ca values. The average foliage Ca concentrations were almost identical between the two sites at age 4, but were 56 % greater at the ag field at age 5. However, the average Ca concentration at the cutover site rose from 0.59 at ages 4 and 5 to 0.74 at age 6.

Whole-crown foliage nutrition

Vector analyses were performed with the total crown nutrient concentrations, contents, and associated foliage biomass to interpret relative responses among sites, tree ages, and fertilization rates. The nutrient concentration, content, and foliage biomass of each N fertilizer treatment was set relative to the control, and expressed as a percent (Weetman, 1989). Interpretations of this analysis are used to illustrate qualitative responses to all three variables and their interactions. One assumption of this approach is that the third axis, in this case foliage biomass, is correlated with the desired tree response variable, e.g., stand biomass. Stem biomass was highly correlated to foliage biomass at both sites and at all ages (Figure IV-2).

At both sites and at all ages, except for the 56 kg treatment at the ag field site at age 5, the vectors were positive, i.e., when N was added, N concentration, content, and foliage biomass all increased, which indicates that the Control plots were deficient with respect to N (Figure IV-4 A, B). The magnitude of the responses, shown by the length and horizontal angular deviation of the vector lines, varied widely due to site and age. At the ag field site, foliage concentrations of the 112 kg treated trees were 8 and 20% greater than the Control trees at ages 3 and 5, respectively, but were otherwise similar among treatments (Figure IV-4 A). Foliage biomass of the 56 kg treatment was 81% greater than the control at age 5, but was otherwise similar among treatments. Foliage N content in the trees treated with 112 kg at age 4 was 73% higher than the Control trees, but was otherwise similar among treatments (Figure IV-4B). At the cutover site, sweetgum responded to all fertilizer treatments, but the magnitudes varied due to age. The trees of the 112 kg treatment had about 110 and 99 % greater foliage biomass than the Control treatment at ages 4 and 6, respectively, which were ages in which N was applied. The greater foliage biomass of the 112 kg treatment trees was associated with 35 and 62 % greater foliage N concentrations and 193 and 223 % greater contents at ages 4 and 6, respectively. Foliage biomass did not respond to 56 kg N, but N concentrations were 22 and 25 % greater in the treated trees than in the Control trees at ages 4 and 6, respectively.

In general, N applications greatly increased N concentrations, contents and foliage biomass, showing that sweetgum was N deficient at this early age. The greatest foliage responses occurred in the same years that N was applied. In years in which no N was applied to any plot, the foliage N concentrations were similar to years in which N was applied, but foliage biomass and N contents were much less. These results suggest that 1) sweetgum was clearly N deficient on the cutover site at this early age, 2) foliage N response is very short-lived and the applied N is not increasing the available soil N, and 3) the stands were not able to produce as much leaf biomass during years when no N was applied compared to years in which is was applied due to N limitations.

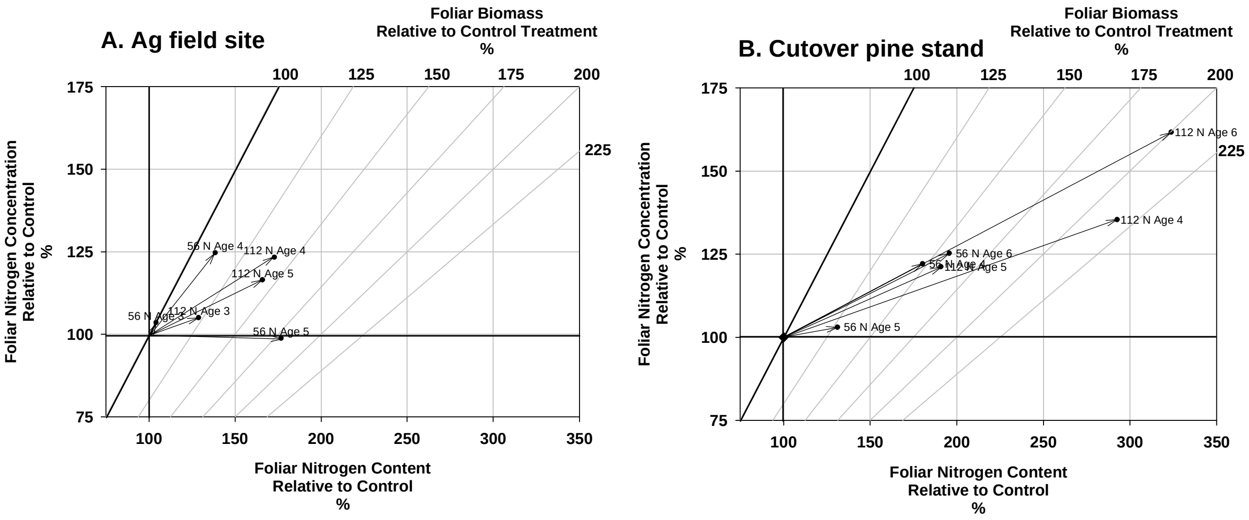

Figure IV-4. Vector analyses of the foliage N dynamics of two young sweetgum plantations in South Carolina in response to N fertilization.

Phosphorus response to the N fertilizer applications varied with site and age (Figure IV-5 A,B). Foliage P concentrations of the fertilized trees at the ag field site were generally lower than the unfertilized trees, but foliage P contents and biomass were greater in the fertilized trees than in the unfertilized trees, indicating that foliage P was diluted due to the greater amount of biomass induced by the N treatments. At the cutover site, all P shifts but the 56 kg treatment at age 6 were toward lower P concentrations with higher P contents and biomass, indicating that foliage P was diluted by the N fertilizer applications.

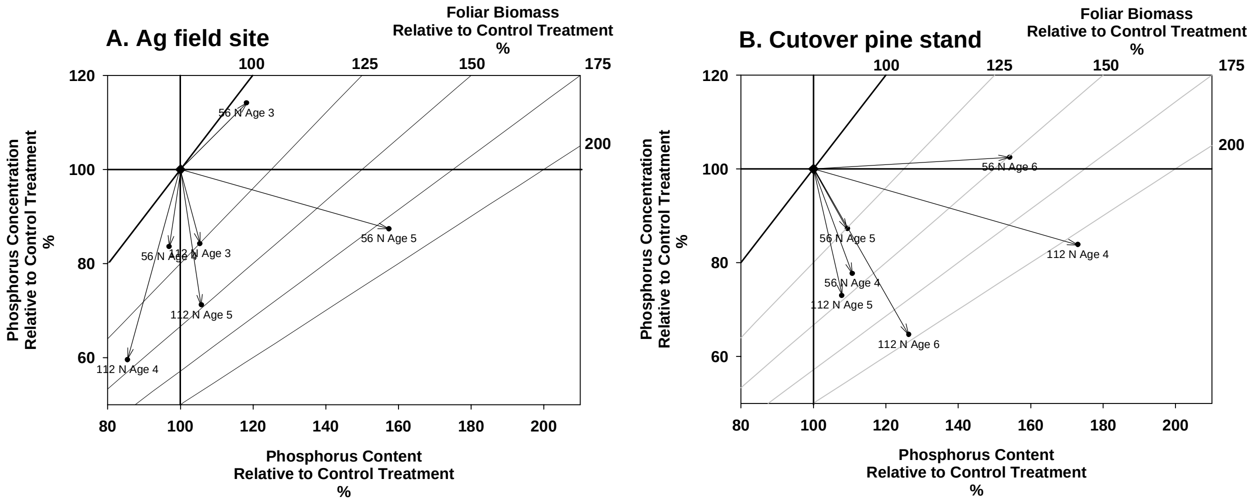

Figure IV-5. Vector analyses of the foliage P dynamics of two young sweetgum plantations in South Carolina in response to N fertilization.

Potassium response at the ag field site ranged from dilution to antagonism, with no apparent consistency (Figure IV-6 A,B). The 56 kg treatment at ages 3 and 4 and the 112 kg treatment at age 5 caused a slight antagonism to K, but the 56 kg treatment at age 5 and the 112 kg treatment at ages 3 and 4 all indicated dilution rather than antagonism. Although the K concentrations of the trees treated with 56 kg N on the ag field site were 17 % lower than those of the Control trees, there were no content differences. Because the foliage K concentrations of the ag field site trees were almost twice that of the cutover site trees, the high dilution and slight antagonism to K seen at the ag field site indicates that much of the K uptake in the unfertilized trees was luxury consumption. At the cutover site, K response to N additions varied from slightly synergistic for the 56 kg treatment at ages 5 and 6 to moderately diluted for the other treatment-age combinations, indicating that little to no luxury consumption occurred.

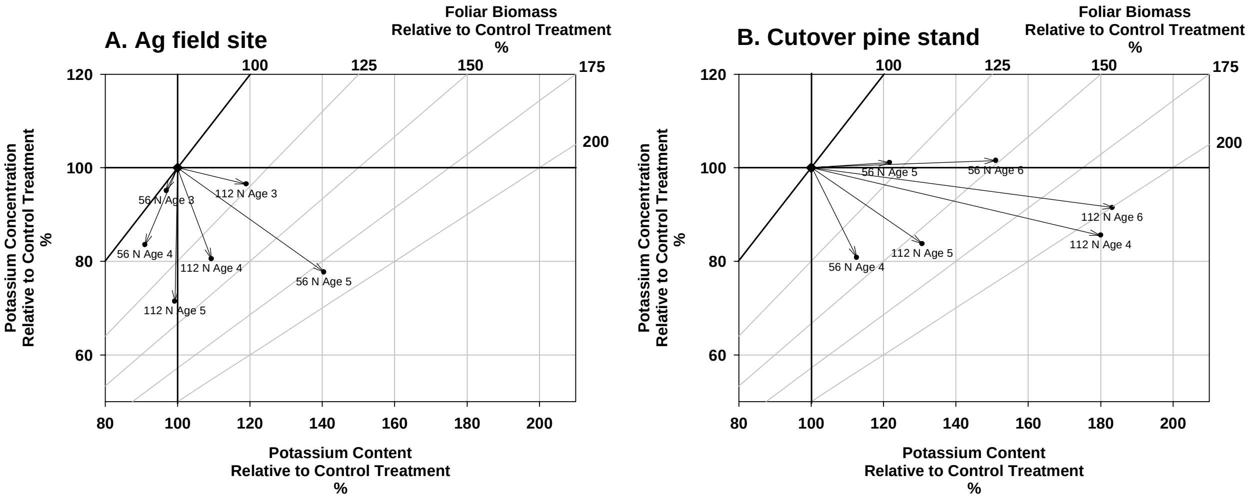

Figure IV-6. Vector analyses of the foliage K dynamics of two young sweetgum plantations in South Carolina in response to N fertilization.

The growth and nutrient responses observed at the two sites were contrary to our initial expectations. We initially hypothesized that the ag field site would be much more responsive to added N due to its 3-fold lower total soil N content. Instead, the ag field site was not as responsive to N fertilization as the cutover site with respect to biomass production or foliage nutrition. The lack of response to N at the ag field site is probably due to greater N mineralization, also unexpected, and the presence of another, untested deficiency: water. The ag field site, in comparison to the poorly-drained cutover site, is well-drained and receives, on average, approximately 8 cm less rainfall from May through September (SERCC, 2002).

The low levels of available soil P at the cutover site may be insufficient for future growth responses to added N. The additional P application at age 6 on the cutover site was probably necessary for a full response to the added N, and it is likely that both N and P should be added together when soil P levels are low to ensure a full response to added N. Because P fertilizer largely remains in the soil, the P fertilization at age 6 may have remedied future P deficiencies, but further P fertilization may be necessary if P uptake had not yet reached a maximum by age 6. We had no evidence to suggest that K, Ca, or Mg dilutions are restricting potential growth. The lack of antagonisms or low diagnostic concentrations of other nutrients suggests that the trees at both sites are not limited by Ca or Mg. Whether an N-induced deficiency of P or K will occur at either site is uncertain, but soil and foliage P and K status should be monitored using more than one approach along with N in these fast-growing stands.

CONCLUSIONS

Characterizing the soil chemistry and monitoring the nutrition of young sweetgum stands is necessary to avoid over-fertilization on unresponsive sites and to avoid losing potential growth responses to nutrient deficiencies. One rationale for using marginal ag fields for hardwood plantations is the higher relative fertility of these sites with respect to P, K, Mg, and Ca, and the relatively higher requirements of hardwoods for these nutrients compared to pines. In this study, the ag field was actually less fertile than the cutover for total N, exchangeable K, Ca, and Mg. This suggests that the assumption of ag fields as the more fertile site type is in error, because the Norfolk soil is a widespread soil type. Height, diameter, stem biomass, foliage biomass, leaf area, and foliage N concentrations and content all increased in response to N fertilization treatments at the cutover site due to inadequate soil N supply, while only foliage biomass and foliage N concentrations and contents responded at the ag field site. The lack of response at the ag field site can also be seen in the foliage N concentrations. Foliage N concentrations were below 1.8 %, our proposed critical level, only at the cutover site. Foliage P, K, Ca, and Mg concentrations were generally diluted when N fertilization caused growth responses. Although we did not observe a P or K deficiency, they may occur on some sites when biomass growth rates (and nutrient uptake) reach their maximum levels.

This study showed that early, repeated N fertilization of short-rotation sweetgum plantations can greatly increase foliage and stem biomass production, but the responses are site-specific. Although sites with greater organic matter are generally assumed to have more available N and exhibit less response to N fertilizer, we showed this assumption is false. Soil N availability is governed by a host of factors, of which total soil N is only one.

While early fertilization can increase the effective age of a plantation with respect to stem biomass accumulation by 1-3 years prior to crown closure, fertilization is probably not needed until age 4 or 5 on sites similar to our cutover site, and is probably not needed until crown closure on sites similar to our ag field site if sustained competition control is maintained. Furthermore, the 112 kg N treatment was necessary to increase the foliage N concentrations to 1.8 % at the cutover site, but with biannual fertilization frequencies, stem biomass growth was not improved by the higher N rate at either site, and was not needed for optimum early growth.

Based on these limited data, our recommendations for fertilizing young sweetgum plantations are:

1) N fertilization is not needed in sweetgum plantations that are managed with sustained competition control until age 4 or beyond.
2) If diagnostic foliage N concentrations are below 1.8 % N, four, five, or six year-old plantations will respond to N applications of 56 kg N ha^{-1} or greater.
3) Phosphorus should be applied at 56 kg ha^{-1} to all cutover pine plantations at tree establishment and again at canopy closure unless the site has a history of repeated P fertilization.
4) A greater understanding of soil nutrient supplying capacities with particular focus on N dynamics is needed.

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CHAPTER V. NITROGEN SUPPLY AND DEMAND IN SHORT-ROTATION SWEETGUM PLANTATIONS

ABSTRACT

Intensive management is crucial for optimizing hardwood plantation success, and nitrogen (N) nutrition management is one of the most important practices in intensive management. Because management of short-rotation woody crop plantations is a hybrid between row-crop agriculture and plantation forestry, we tested the usefulness of an agronomic budget modified for deciduous perennial trees for estimating N fertilizer recommendations. We studied the foliage N demand, resorption, and uptake response of two sweetgum (*Liquidambar styraciflua* L.) plantations on a converted agricultural field and a pine cutover site to biannual applications of three nitrogen (N) fertilizer rates: 0, 56, and 112 kg N ha^{-1}. We also estimated soil N supply, N uptake efficiency, and fertilizer N uptake efficiency. Fertilization increased foliage demand (defined as total foliage N content), resorption, and uptake at both sites, but to a greater degree on the cutover site, which had lower soil N supply. Resorption efficiency did not increase with fertilization, but resorption proficiency, the N concentration of senesced leaves, was reduced (N concentrations higher) at the drier ag field site and in the fertilized trees. Foliage N uptake increased at both sites when fertilizer was applied; foliage N uptake was 20 and 28% of fertilizer N applied at the ag field and cutover sites, respectively. Uptake was similar for all trees at both sites when fertilizer was not applied. Less than 15% of fertilizer N remained in the soil in the year following fertilization. We recommend fertilizing young sweetgum plantations 1 kg N ha^{-1} for each 40 kg ha^{-1} of foliage biomass, beginning at age 4, assuming they have 45-65 kg of soil N supply.

INTRODUCTION

Nitrogen (N) fertilizer applications to forest systems are generally limited to the correction of diagnosed tree deficiencies, and then only in intensively managed plantation systems. Plantation forest systems have been structured around relatively nutrient efficient species, e.g. *Pinus* spp., that achieve acceptable production with relatively little input (Bowen and Nambiar, 1984). These plantations become N-limited during or shortly after canopy closure, and a combination of thinning and fertilization is generally sufficient to synchronize N supply with plant N demand. Short-rotation woody crop (SRWC) systems are the most intensively-managed forest system, and are usually grown in 5 to 20 year cycles for rapid production of wood that is used for pulp or fuel. The tree species used in SRWC are generally deciduous hardwoods that are less N efficient compared to pines due to greater N concentrations required by the trees and a complete renewal of foliage each year. The greater N demand by these intensively-managed hardwoods creates an asynchrony between soil N supply and tree N demand well before canopy closure. Repeated applications of fertilizer are needed to minimize N deficiencies (van Miegroet et al., 1994), but we do not know the optimal N fertilizer rate and timing that will maximize plantation productivity and minimize N export from the system, especially on a species- and site-specific basis.

Because SRWC systems are analogous to cropping systems, an agronomic model may be useful for determining fertilizer recommendations. The N fertilizer (N_f) required by an annual crop depends on the dry matter yield (Y_{dry}), the N concentration in the biomass (N_y), and the soil N supply during the growing season (N_s) (Stanford, 1973; Neeteson et al., 1990) (Equation V-1):

$$N_f = (Y_{dry} N_y) - e_s N_s \tag{V-1}$$

The crop will not recover all the fertilizer N (N_f) or soil N (N_s); N uptake efficiency from soil (e_s) and fertilizer (e_f) will be less than 100%. These uptake efficiencies will influence the quantity of N needed to achieve a certain yield and can be represented as a modification of Equation V-1 (Equation V-2):

$$N_f = \frac{(Y_{dry} N_y) - e_s N_s}{e_f} \tag{V-2}$$

Trees can internally transfer N, known as resorption (Killingbeck 1986), from the foliage prior to senescing. Nitrogen resorption can be expressed as a modification of Equation V-2, where e_y is the N resorption efficiency, or the proportion of N recovered before leaf-fall the previous year, and e_yN_y is the total amount recovered the previous year. The N fertilizer required is then a function of the plant N demand adjusted for soil supply and its efficiency of uptake, resorption efficiency, and the efficiency of fertilizer use (Equation V-3).

$$N_f = \frac{(Y_{dry} N_y) - e_s N_s - e_y N_y}{e_f} \tag{V-3}$$

In perennial tree crop systems, a complete N demand budget would entail measurements of the biomass and N concentration of all the various plant components (i), e.g., foliage $(Y_{dry\,foliar} N_{y\,foliar})$, branches $(Y_{dry\,branch} N_{y\,branch})$, bole $(Y_{dry\,bole} N_{y\,bole})$, and roots $(Y_{dry\,roots} N_{y\,roots})$ (Equation V-.4).

$$\sum_{1}^{i} Y_{dry_i} N_{y_i} \tag{V-4}$$

Foliage N represents approximately 75 % of the total tree N in young deciduous trees, and only the foliage and fine root components undergo annual turnover and re-growth. Thus, foliage N demand is most useful for diagnostic and prescriptive purposes, especially since foliage is relatively easily measured compared to fine roots. Similarly, a complete N supply budget would include measurements of all sources of N supply and potential N losses (i); deposition (atmospheric and overland flow), throughfall, stemflow, litter N release, and soil supply

Atmospheric deposition, throughfall, and stemflow are generally consistent across small to medium scales of space and time. Intensively-managed hardwood plantations are in a phase of rapid forest floor change and receive little N from litter release from ages 3-6. If the previous land use was agriculture, the forest floor is aggrading since no forest floor existed prior to plantation establishment, and not enough litter has fallen to be significant. If the previous land use was a natural or planted forest, the forest floor will mostly be decomposed within a few years in warm, humid climates. Therefore, estimating N inputs from litter release in young SRWC across site types and stand ages is difficult and not needed for diagnostic and prescriptive purposes. Net N mineralization remains the most significant and estimable natural source of N, and may be measured directly (Eno, 1960) or estimated with models (Molina and Smith, 1988).

With respect to plant uptake, soil N supply can be defined as the positive net N mineralization. Negative values of net N mineralization, which represent net N immobilization, are irrelevant to estimating plant-available N because microbial communities do not extract N from the plant, they can only remove N from available pools. Accordingly, the objective of our study was to determine the N fertilizer needed for two sweetgum (*Liquidambar styraciflua* L.) plantations in the southeastern U.S. by determining the foliage component of Y_{dry} and N_y, the soil N supply ($N_{s)}$, e_s, e_y, and $e_{f,}$ and solving Equation V-3. This was done on two contrasting soils to determine the usefulness of this approach for diagnosing N needs and prescribing N fertilizer.

MATERIALS AND METHODS

Site Descriptions

Two sites of contrasting soil type and land use history were selected to study the effect of site and soil type on soil N supply, plant N demand, and fertilizer need. One was a well-drained agricultural field, while the other was a poorly-drained harvested loblolly pine (*Pinus taeda* L.) plantation site, hereafter referred to as the “ag field” and “cutover” sites, respectively. Compared to forest sites, agricultural fields in general tend to have higher soil pH due to liming and the removal of acid-producing forest litter, and they have higher levels of phosphorus and nutrient cations due to repeated fertilization. Herbaceous weed communities dominate ag fields due to past cultivation and weed control, and equipment access and soil trafficability is excellent due to the nature of the past land use. Harvested forest sites, or cutovers, are generally less eroded and tend to have higher quantities of soil organic matter and nitrogen (Richter et al., 2000). However, they have not been repeatedly fertilized and have not had annual weed control, so soil nutrients and weeds must be managed. Within these two land use groupings, wide differences in soil types and herbaceous and competing woody vegetation cloud our understanding of site-specific plantation responses to various fertilization treatments. These two sites were selected to represent the range of site types currently considered for operational plantations by forest industry in the southeastern U.S.

The ag field study site was located on International Paper's Trice Research Forest in Sumter County, South Carolina (33° 58' N 80° 12' W) on the middle Atlantic coastal plain. The soil is a well-drained Norfolk sandy loam (loamy, kaolinitic, thermic Typic Kandiudult). Nine 0.2-ha treatment plots with 0.04-ha measurement plots were established in February 1996 with 280 1-0 bare-root sweetgum seedlings (3 m X 2.4 m spacing, ~1400 ha^{-1}). The sites had been regularly managed for dry land crops, e.g., corn (*Zea mays* L) and soybeans (*Glycine max.* (L.) Merr), for more than 20 years, and soybeans, a N_2 fixing legume, were the primary crop for the 5 years previous to plantation establishment. All plots were treated with an initial fertilizer application of 280 kg ha^{-1} diammonium phosphate (DAP), which supplied 50 kg N ha^{-1} and 56 kg P ha^{-1} in November 1995 and 100 kg ha^{-1} urea, which supplied 46 kg N ha^{-1}, in August 1996. Non-crop vegetation was restricted to herbaceous vegetation, mostly broomsedge (*Andropogon virginicus* L.), due to the agricultural legacy and early-rotation chemical weed control. The site was also mowed intermittently throughout the 5 years to reduce the herbaceous competition for water and nutrients.

The cutover pine site was on MeadWestvaco Corporation land, located in Colleton County, South Carolina (32° 8' N 80° 7' W) on the lower Atlantic coastal plain, and was established in February 1995. The soil is a somewhat poorly to poorly drained Argent sandy loam (clayey, mixed, active, Typic Endoaqualfs) developed from marine deposits. The site undergoes wide fluctuations in soil water contents, from saturated soils with standing water in the dormant season to dry soils during the growing season. The heavy clay subsoil restricts water percolation through the solum, and the low elevational gradient (<2%) restricts lateral flow. These mechanisms induce short-term saturation after heavy rain events throughout the growing season. Nine 0.2-ha treatment plots with 0.04-ha measurement plots were established with 280 1-0 bare-root sweetgum seedlings (3 m X 2.4 m spacing, ~1400 ha^{-1}) of the same genetic source as the ag field site following loblolly pine harvest and site preparation, which consisted of bedding, fertilization and non-crop vegetation control. All plots received 50 kg N ha^{-1} and 56 kg P ha^{-1} as DAP and 3.9 Mg ha^{-1} dolomitic lime in March 1995. The lime application raised pH from approximately 4.75 to 5.5. Non-crop vegetation control consisted of pre-emergent herbicide applications in February and March of 1995, 1996, and 1997. Herbicides were also applied by directed spray in 1995 and 1996 during the growing season. Although this aggressive chemical weed control program was used for the first three years, woody and herbaceous plants were present when competition control measures ceased. Compared to most young cutover pine plantations, this site was relatively clean with respect to non-crop vegetation, but not compared to the ag field site.

Experimental Design

At each site, three biannual N fertilizer rates were initiated at age 2 and replicated three times. Every two years, i.e., ages 2, 4, 6, ammonium nitrate (NH_4NO_3) was applied at the following rates: 0 kg ha^{-1} (Control), 168 kg ha^{-1}, and 336 kg ha^{-1}, which provided 0, 56, and 112 kg ha^{-1} N, respectively. At the cutover site, 56 kg P ha^{-1} was added as triple superphospate at age 6 because fertilization with N alone at age 4 induced P deficiencies. The error control design at the cutover site was a Completely Randomized Design, while the design at the ag field site was a Randomized Complete Block Design (Steel and Torrie, 1980), where the blocking factor was the depth to redoximorphic features. The wide separation of the sites in space, the different establishment years (1996 at the ag field site and 1995 at the cutover site), and slightly different cultural management approaches between the two sites precluded a quantitative comparison of the two sites. The similarity in fertilizer application rates and data collection procedures, however, allows qualitative comparisons of site-to-site differences in plant responses.

Treatment effects within a site and age class were determined using analysis of variance at α=0.10. If the model was significant, Duncan’s Multiple Range test was used to separate the means (SAS Institute, 2000).

Soil Characterization

Soil samples were collected from each treatment plot in 1999 and 2000. Nine 2-cm diameter subsamples were collected per treatment plot in April and November of each year from the 0-20 cm depth. The subsamples were air-dried, sieved to pass a 2-mm sieve and bulked by treatment plot and year. The samples were then analyzed for total carbon (C), N, phosphorus (P), and pH. Carbon and N were determined with a vario MAX CNS analyzer (Elementar, Hanau, Germany). Available phosphorus was determined by extracting the soils with Mehlich I extractant (Mehlich, 1953) and analyzing the extract via Inductively Coupled Plasma – Atomic Emission Spectroscopy (ICP) (SpectroFlame Modula Tabletop ICP, Spectro Analytical Instruments, Fitchburg, MA). Soil pH was determined for the samples in a 1:2 soil:water mixture with a combination pH probe. Bulk density (Blake and Hartge, 1986) was determined on five 5-cm diameter by 5-cm tall cores at each site by oven drying at 105 ^{o}C to a constant weight.

Foliage Sampling

In September 1998, 1999, and 2000, which corresponded to ages 3-5 at the Ag field site and ages 4-6 at the Cutover site, respectively, three foliage samples were taken of the canopy from five trees in each treatment plot. The samples were comprised of 6 leaves of all stages of development from single branches and were collected within the upper, middle, and lower crown positions on the south side of each tree (Kuers and Steinbeck, 1998). The samples were chilled on-site, transported to the laboratory in a cooler, and processed within 24 hr. The leaves were oven-dried at 65 ^{o}C to a constant weight. We determined the foliage mass for each crown position by multiplying the total litterfall, measured from 5 randomly located litter traps (approximately 1 m^2 per trap) per plot by the relative weighting factors of Kuers and Steinbeck

(1998), who showed that fertilization increases young sweetgum foliage mass disproportionately among crown positions. Foliage N was determined on each sample with a N analyzer (LECO FP-528, St. Joseph, MI). Total foliage nutrient content on an area basis was determined by multiplying the foliage N concentration by the foliage mass for each crown position. Litter N concentrations and contents were determined similarly.

***In situ* nitrogen production**

Annual soil N supply was estimated for 1999 and 2000, which corresponded to ages 4 and 5 at the ag field and ages 5 and 6 at the cutover site. Our original design called for measuring N mineralization for two growing seasons. Therefore, net N mineralization was measured from April 1999 to September 2000 with the buried bag method (Eno, 1960). To provide an estimate of soil N supply for the 2 calendar years, data from January to March 2000 was used to complete the annual production rate estimate for 1999, and data from October to December 1999 was used to complete the annual production rate estimate for 2000. Because the data used to complete the annual estimates occurred during the fall and winter months, they represented only about 20% of the total estimate for both years and sites. Furthermore, analysis of variance on the supplemental dormant period data revealed no treatment differences.

Two soil samples (bags) were collected for each sampling date for the buried bag procedure. One was incubated *in situ* and the other returned to the laboratory for analysis. For each experimental unit, three subsamples were taken of the top 15 cm, each consisting of three composited 1.5 cm soil core samples. Each soil sample was air-dried, sieved to pass a 2 mm sieve, and the NH_4^+ and NO_3^- -N extracted with 2 M KCl in a 10:1 solution:soil ratio. The NH_4^+ and NO_3^- concentration in each extract was determined via automatic colorimetric spectrophotometry on a TRAACS 2000 Autoanalyzer (Bran & Luebbe Corporation, Oak Park, IL). Nitrogen supply was calculated as the difference between the N intensity in the soils incubated for approximately 30 d and the samples taken at the time of incubation. If negative values occurred, which represent immobilization or denitrification, the soil N supply was set to 0 for that sample.

RESULTS

The soils on the two sites were quite different (Table V-1). Compared to the ag field, the cutover site had 6 times the concentration of organic matter and almost 2.5 times the total soil nitrogen. The C:N ratio, a measure of substrate quality, was only 15:1 at the ag field site but twice that at the cutover site.

Table V-1. Soil properties of the top 0.2 m at two sweetgum plantations in South Carolina.

Site	**Organic Matter** %	**Total N** kg ha^{-1}	**C:N**	**Bulk Density** g cm^{-3}
Ag field	0.88	834	15.2	1.39
Cutover	5.49	1958	29.6	0.89

Foliage biomass $\left(Y_{\text{dry foliar}}\right)$ was the same across fertilization treatments at the ag site at ages 3 and 4 and averaged 512 and 2610 kg ha^{-1}, respectively (Table V-2). The biomass was similar across all treatments at age 3, suggesting that the fertilizer applied at age 2 had no significant carry-over effect. At age 4, when fertilizer was again applied, the treatments had no effect on foliage biomass. At age 5, a year after the fertilization at age 4, foliage biomass at the ag site ranged from 1540 to 2780 kg ha^{-1}, and was 80% greater on the 56 kg N ha^{-1} treatment plots than the control plots. The foliage biomass on the 112 kg N ha^{-1} was the same as that on the 56 kg ha^{-1} treatment plots. Foliage biomass was about 20% greater at age 4 than at age 5 due to a late flush that occurred following a drought-induced leaf fall. In August 1999 (age 4 at the ag field), about 30-50% of the foliage senesced. Most of this foliage was replaced by late September following several rainfall events, causing the age 4 values to be greater than expected.

On the cutover site, foliage biomass at age 4 ranged from 1340 kg ha^{-1} on the control plots to 2820 kg ha^{-1} on the 112 kg N ha^{-1} treatment plots, a 110 % increase. At age 5, when no fertilizer was applied, foliage biomass averaged 2657 kg ha^{-1}, and was not different among treatments. At age 6, when fertilizer was again applied, the foliage biomass was 1750 kg ha^{-1} on the control plots and almost twice that on the 112 kg N ha^{-1} treatment plots.

Whole-crown (comprised of leaves from all crown positions) foliage N concentrations $\left(N_{y\,\mathrm{foliar}}\right)$ ranged from 1.19 to 1.76 at the ag field site (Table V-2). At the ag field site, the foliage N concentration of the trees treated with 112 kg N ha^{-1} was 5, and 17 % greater than the unfertilized trees at ages 3, and 5, respectively. At the cutover site, the foliage N concentrations of the unfertilized trees were 1.14, 1.16, and 1.08 at ages 4, 5, and 6. At age 4, when fertilizer was applied, the application of 56 and 112 kg N ha^{-1} increased the foliage N concentration by 22 and 35 % over the control trees, respectively. At age 5, when no fertilizer was applied, the foliage N concentration of the 112 kg ha^{-1} treatment was 22 % greater than the control, but the 56 kg N ha^{-1} treatment was not different from the control. At age 6, when fertilizer was again applied, the 56 and 112 kg N ha^{-1} treatment plots had 25 and 62 % higher foliage N concentrations than the control, respectively.

Table V-2. Foliage biomass, N concentration and demand, litter N concentration and content, and resorption across three levels of N fertilization in two sweetgum plantations of different site history and soil type. Shaded data represent years in which fertilizer was applied. Means within a row and site followed by the same letter are not different at P<0.10.

		N Fertilizer Treatment					
		Ag field			**Cutover pine site**		
		0	**56**	**112**	**0**	**56**	**112**
	Age	**kg N ha^{-1}**			**kg N ha^{-1}**		
Foliage Biomass kg ha^{-1}	3	476a	475a	586a	--	--	--
	4	2260a	2470a	3100a	1340b	1950ab	2820a
	5	1540b	2780a	2220ab	2110a	2640a	3220a
	6	--	--	--	1750b	2670ab	3480a
Foliage N Concentration (%)	**3**	1.68b	1.74ab	1.76a	--	--	--
	4	1.37a	1.69a	1.71a	1.14c	1.39b	1.54a
	5	1.21b	1.19b	1.41a	1.16b	1.20b	1.41a
	6	--	--	--	1.08c	1.35b	1.75a
Foliage N Demand kg ha^{-1}	**3**	8.0a	8.3a	10.3a	--	--	--
	4	30.3b	42.0ab	52.4a	15.0b	27.1ab	44.0a
	5	18.7a	33.0a	31.0a	24.4b	32.1b	46.6a
	6	--	--	--	18.8b	36.7b	60.8a
Litter N Concentration (%)	**3**	1.00a	0.97a	0.97a	--	--	--
	4	1.04b	0.98c	1.22a	0.63b	0.73ab	0.76a
	5	0.85a	0.81a	0.77a	0.66a	0.74a	0.78a
	6	--	--	--	0.72b	0.93a	1.02a
Litter N Content kg ha^{-1}	**3**	4.7a	4.6a	5.7a	--	--	--
	4	23.5a	24.2a	37.7a	8.6b	14.6ab	21.7a
	5	13.1a	22.4a	16.9a	13.8a	18.7a	25.7a
	6	--	--	--	12.6b	25.0a	35.2a
Resorbed N kg ha^{-1}	**3**	3.2a	3.6a	4.6a	--	--	--
	4	6.8a	17.8a	14.7a	6.4b	12.5ab	22.3a
	5	5.6a	10.7a	14.1a	10.7a	13.4a	20.9a
	6	--	--	--	6.2b	11.8b	25.6a
Resorption Efficiency %	**3**	0.41a	0.44a	0.45a	--	--	--
	4	0.24a	0.43a	0.26a	0.44a	0.47a	0.51a
	5	0.30b	0.32b	0.45a	0.43a	0.38a	0.44a
	6	--	--	--	0.33a	0.31a	0.42a

Foliage N demand $\left(Y_{dry\ foliar} N_{y\ foliar}\right)$ was 7.95, 30.3, and 18.7 kg ha^{-1} on the control plots at ages 3, 4, and 5, respectively, at the ag field site (Table V-2). At ages 3 and 5, when no fertilizer was applied, the foliage N demand did not respond to fertilizer treatment at p=0.10, although the 112 kg N ha^{-1} treatment had 66% more foliage N than the control at age 5. At age 4, the application of 112 kg N ha^{-1} increased the total foliage N 73% over the control. At the cutover site, the unfertilized trees had 15.0, 24.4, and 18.8 kg ha^{-1} N at ages 4, 5, and 6, respectively. The trees treated with 112 kg N ha^{-1} had 193, 91, and 223 % greater foliage N at ages 4, 5, and 6, respectively, while the 56 kg N ha^{-1} treatment was consistently higher than the control, but these differences were not statistically significant at the 10% level.

Litter N concentrations were used to determine the amount of N resorption and the resorption proficiency (Killingbeck, 1996). Litter concentrations ranged from 0.77 to 1.22 % at the ag field site. At ages 3 and 5, the litter concentrations were unaffected by fertilizer treatment (Table V-2). At age 4, the N concentration of the litter from the trees treated with 112 kg N ha^{-1} was 17% greater than the unfertilized trees, but because the litter was not kept separated by replicate plot at age 4, statistics were not performed on these data. At the cutover site, the litter concentrations ranged from 0.63 to 1.02 %. At ages 4 and 6, when fertilizer was applied, the trees that received 112 kg N ha^{-1} had 21 and 42 % higher litter N concentrations than the unfertilized trees. At age 5, when no fertilizer was applied, the litter N concentrations were similar among all treatments.

The midsummer foliage N content that was not returned in the leaf litter was considered to be resorbed (Equation V-6)

$$\text{Resorbed N} = \left(Y_{dry\ foliar}\right) \times \left(N_{y\ foliar} - N_{y\ littter}\right) \qquad \text{(V-6)}$$

About 4, 13, and 10 kg N ha^{-1} was resorbed at ages 3, 4, and 5, respectively, at the ag field site, and was not significantly affected by fertilization at any age, although the amount returned at age

4 varied from 6.8 to 17.8 kg N ha^{-1}. At the cutover site, the unfertilized trees resorbed 6.4, 10.7, and 6.2 kg N ha^{-1} at ages 4, 5, and 6, respectively. The trees fertilized with 112 kg N ha^{-1} resorbed 248% and 313 % more N at ages 4, and 6, respectively. At age 5, the trees of the 112 kg N ha^{-1} treatment resorbed 95% more N, but the difference was not significant at p=0.10. The efficiency of N resorption, calculated as the proportion of total foliage N resorbed, ranged from 24 to 45% at the ag field site and 31 to 51% at the cutover site. At the cutover site, fertilization did not affect N resorption rates. At the ag field site, N resorption in the 112 kg N ha^{-1} treatment was significantly greater than the control or 56 kg N ha^{-1} treatment at age 5, but did not differ among rates at ages 3 or 4.

Mineralized N in the top 0.20 m of the unamended treatment plots, or soil N supply (N_s), was about 69 kg ha^{-1} at the ag field site and about 47 kg ha^{-1} at the cutover site (Table V-3). On the ag field at age 4 and the cutover at age 6, soil N supply was about 37% greater in the plots fertilized with 112 kg N ha^{-1} than the other plots. Soil N supply was similar across treatments at age 5, when no fertilizer was added at either site.

Foliage N uptake was calculated as the foliage N content of the current year less the N resorbed the previous year (Equation V-7):

$$\text{Foliar N uptake} = \left(Y_{\text{dry foliar}} N_{\text{y foliar}}\right)_{T1} - \left(\left(Y_{\text{dry foliar}}\right) \times \left(N_{\text{y foliar}} - N_{\text{y littter}}\right)\right)_{T0} \qquad \text{(V-7)}$$

N uptake at the ag field site ranged from 27.1 to 47.9 kg ha^{-1} at age 4 and 11.9 to 16.3 at age 5 (Table V-3). Foliage N uptake of the 56 and 112 kg N ha^{-1} treatment plots was 11.2 and 20.8 kg ha^{-1} greater, respectively, than the unfertilized treatment plots at age 4. The fertilizer treatments at age 4 had no residual effect on uptake at age 5. The uptake at age 4 was greater than at age 5 due to the drought-induced re-flush and generally higher foliage N concentrations. At the cutover site, foliage N uptake ranged from 18.0 to 24.3 kg N ha^{-1} at age 5 and 8.1 to 39.8 kg N ha^{-1} at age 6. Uptake did not differ among treatments at age 5, when no fertilizer was applied. At age 6, uptake was 15.3 and 31.7 kg ha^{-1} greater for the 56 and 112 kg N ha^{-1} treatment plots compared to the control plots.

Table V-3. Soil N supply, foliage N uptake, and foliage uptake efficiency for two sweetgum plantations with different land use histories and soil type. Shaded data represent years in which fertilizer was applied. Means within a row and site followed by the same letter are not different at α=0.10.

		N Fertilizer Treatment					
			Ag field			**Cutover**	
	Age	**0**	**56**	**112**	**0**	**56**	**112**
			kg N ha^{-1}			**kg N ha^{-1}**	
Soil N Supply ($kg\ ha^{-1}$)	**4**	67.3	69.5	92.4	--	--	--
	5	70.1	59.6	66.6	47.5	47.7	46.0
	6	--	--	--	47.2	48.3	66.7
Foliage N Uptake ($kg\ ha^{-1}$)	**4**	27.1b	38.3ab	47.9a	--	--	--
	5	11.9a	15.2a	16.3a	18.0a	19.6a	24.3a
	6	--	--	--	8.10c	23.4b	39.8a
Foliage N Uptake Efficiency (%)[1]	**4**	43a	31ab	24b	--	--	--
	5	18a	27a	28a	38a	39a	51a
	6	--	--	--	17a	22a	23a
Fertilizer Uptake Efficiency (%)[2]	**4**	--	20a	19a	--	--	--
	6	--	--	--	--	27a	28a

[1] Foliage N Uptake Efficiency was calculated as the total N supply (soil+fertilizer) divided by foliage N uptake for each treatment plot.

[2] Fertilizer Uptake Efficiency was calculated as the fertilizer N applied divided by the foliage N uptake for the fertilized plots less the foliage N uptake for the unfertilized plots.

Foliage N uptake efficiency (Equation V-8) was calculated as the total N supply (soil+fertilizer) divided by foliage N uptake (Equ. 7).

$$\text{Foliar N uptake efficiency} = \frac{\text{Foliar N uptake (Equation V - 7)}}{N_f + N_s} \qquad \text{(V-8)}$$

Soil N uptake efficiency (e_s) is the foliage N uptake efficiency for the unfertilized plots. At the ag field site, foliage uptake of the unfertilized trees at age 4 was 43% of the total N supply (Table V-3). Foliage uptake of the trees fertilized with 56 and 112 kg N ha^{-1} at age 4 was 31 and 24%, respectively, of total N supply. At age 5, when no fertilizer was applied, the foliage N uptake efficiency of the fertilized trees, regardless of treatment, was about 28%, while the foliage N uptake efficiency of the unfertilized trees was only 18%. However, this difference was not significant at p=0.10.

At the cutover site, foliage N uptake efficiencies ranged from 17 to 51 % of the total N supply. At age 6, unlike the ag field site, fertilization had no effect on foliage N uptake efficiency. In fact, the trees fertilized with 112 kg N ha^{-1} had the highest foliage N uptake efficiency (23%) at age 6. At age 5, which was a non-fertilized year, the fertilized trees were not significantly more efficient than the unfertilized trees.

The fertilizer uptake efficiency (e_f) was estimated as the proportion of fertilizer applied that could be attributed to increased canopy N uptake (Equation 9). It does not account for uptake by aboveground perennial plant components, roots, or competing vegetation.

$$\text{Fertilizer uptake efficiency} = \frac{\text{Nf}}{\text{Foliar N uptake}_{\text{fertilized plots}} - \text{Foliar N uptake}_{\text{unfertilized plots}}} \qquad (9)$$

For example, at the ag field site at age 4, the foliage uptake of the trees fertilized with 56 kg N ha^{-1} was 38.3 kg ha^{-1}, while uptake of the unfertilized trees was 27.1 kg ha^{-1}, which indicates that about 11.2 kg of foliage uptake was met by the 56 kg N ha^{-1} applied, or 20%. The fertilizer uptake efficiencies calculated for the two sites varied little. At the ag field site, fertilizer uptake was 11.2 and 20.8 kg ha^{-1} for the 56 and 112 kg N ha^{-1} treatments, respectively, which was about 20% of the fertilizer applied for both treatments. At the cutover site, the fertilizer uptake was 15.3 and 31.7 kg ha^{-1} for the 56 and 112 kg N ha^{-1} treatments, respectively, which was about 28% of the fertilizer applied for both treatments. The similarity in fertilizer efficiency among treatments within each site and across sites was remarkable given the number of inputs to the calculation and the differences between the two sites.

DISCUSSION

Several studies have shown that shortly after stand establishment, soil N supply is elevated due to high soil temperature and water availability caused by the absence of site cover and evapotranspiration as well as soil perturbations inherent in site preparation operations (*assart* effect) (Tamm, 1974). Near canopy closure, however, tree N demand reaches a maximum. The increase in canopy cover and evapotranspiration with stand age reduces soil temperature and moisture. Reduced soil temperature and moisture, along with changes in soil microbial populations and activity, cause soil N supply to decrease. The increase in tree N demand and the decrease in soil N supply explain the general timing of the asynchrony between soil supply and tree demand in tree plantations. Because soil N supply is quite variable across soils and sites and tree N demand is influenced by a host of factors other than N availability, plantations reach N deficiency at different times and to different degrees. In general, the greatest asynchrony occurs at or near canopy closure, and in operational plantations a single application of N fertilizer at or near that time is usually all that is done to correct the asynchrony. Even in the most intensive operational plantations, fertilization generally only occurs in response to a N deficiency diagnosed by, for example, foliage N concentrations.

In young, short-rotation woody crop plantations, however, foliage demand (through higher foliage N concentrations) is greater and creates an asynchrony between supply and demand at an earlier age. A conservative fertilizer approach promotes fertilization only in response to a diagnosed deficiency (Dickmann and Stuart, 1983). However, N demand constrained by low supply, i.e, N deficiency, is difficult to diagnose and detect in SRWC plantations due to a lack of well-developed indicators for each species or clone. Potential yield losses arising from undiagnosed N deficiencies, e.g., “hidden hunger” (Dow and Roberts, 1982), can be high (Heilman and Fu-Guang, 1993). In this study, N demand (foliage N content) ranged from 8 to 61 kg ha^{-1} from age 3 to 6. Applying 112 kg ha^{-1} of fertilizer N more than doubled demand (133%) at age 4 across both sites. At age 6, the trees on the cutover site fertilized with 112 kg N ha^{-1} had over 3 times the demand as the unfertilized trees. At age 5, when neither site received fertilizer, the demand remained 80% greater in the trees fertilized with 112 kg N ha^{-1} compared to the unfertilized trees. Obviously, the potential demand of these young plantations was greater than the amount they were able to take up from the soil and from resorption. Only the fertilized trees at the cutover site at age 6 reached crown closure, indicating that N supply was limiting plant demand up to 2 years in advance of crown closure.

Foliage demand is met in tree plantations from three sources: soil N (which includes forest floor, fine root, and soil organic matter turnover), fertilizer N, and internal N stores arising from resorption of N from senescing leaves. In most forest systems, about 50% of foliage N is resorbed prior to leaf fall (Aerts and Chapin, 2000). However, since the foliage biomass in young, pre-canopy closure plantations is rapidly aggrading, the amount resorbed in one year will generally be less than 50% of the demand in the following year. Only when foliage demand reaches a semi-steady state will 50% of the annual demand be met by resorption.

The range of resorption efficiencies, defined as the proportion of green leaf nutrient content resorbed prior to leaf fall in the current year, observed in this study (24-51%) is low for sweetgum plantations. Nelson et al. (1995) found that 9-yr-old sweetgum resorbed about 50% of foliage N, while Kuers and Steinbeck (1998) found that 43-62% of foliage N was resorbed by 4-yr-old sweetgum. In this study, the average resorption efficiency for the ag field at age 3 and the cutover at ages 4 and 5 was 44%, which, although still low, is more similar to the findings of Nelson et al. (1995) and Kuers and Steinbeck (1998). The lowest resorption efficiencies, which occurred at the ag field at ages 4 and 5 and the cutover at age 6, were caused by higher litter N concentrations in those years.

Resorption proficiency is the terminal content in senesced leaves (Killingbeck 1996), and is measured as the nutrient concentration in the senesced leaves, i.e., litterfall. Killingbeck postulated that a biochemical limit exists to the degree nutrients can be resorbed prior to leaf fall for a given species, and comparisons using fresh litter concentrations may yield more insight on the factors influencing resorption than resorption efficiency. The ag field site had 25% higher litter N concentrations than the cutover site (0.96% N to 0.77% N) across all treatments and ages, suggesting that site conditions were limiting N resorption to a greater extent at the ag field site than at the cutover site. del Arco et al. (1991) showed that resorption is positively related to water availability, and the ag field site, in comparison to the poorly-drained cutover site, is well-drained and receives, on average, approximately 8 cm less rainfall from May through September (SERCC, 2002). Thus, the lack of available water may have hindered resorption at the ag field site.

The relationship between plant nutrient status and resorption efficiency has been debated for some time. The classic theory holds that plants growing on nutrient-poor sites have greater resorption efficiency than those growing on nutrient-rich sites (Chapin, 1980). However, this theory has been questioned by Chapin (1980) and Aerts (1996), who showed that the evidence from the literature does not support the theory. In this study, except for the trees on the 112 kg N ha^{-1} treatment plots at the ag field at age 5, which were 50% more efficient than the unfertilized trees, fertilization had no effect on N resorption efficiency at either site at any age. These findings are in general agreement with Nelson et al. (1995), who found no influence of fertilization on resorption efficiencies in sweetgum, but in contrast to Kuers and Steinbeck (1998), who found that fertilization increased resorption efficiency. Because N fertilization generally increases foliage N concentrations, the lack of a fertilization effect on resorption efficiency means that resorption proficiency must be less (litter N concentrations higher) when fertilized. In fact, this pattern can be seen at age 4 on the ag field and ages 4 and 6 on the cutover site. Foliage N concentrations were greater when fertilized, but resorption efficiency was not increased because resorption proficiency was reduced.

Plant N demand in excess of internal N stores from the previous year's resorption must be met by root uptake of soil or fertilizer N. Uptake clearly responded to fertilizer application at both sites when applied. Foliage N uptake was 77 and 391% greater on the ag field and cutover sites, respectively, in the trees fertilized with 112 kg N ha^{-1} than the unfertilized trees. On the ag field at age 4, the foliage N demand was almost exclusively (91%) met by uptake, since resorption at age 3 was minimal. On the cutover site, about 43% of the demand at age 6 was met by resorption, and the remaining 57% met by uptake. These results indicate that resorption was not an effective N source until age 4, and even then uptake was limited by soil N supply and its uptake efficiency.

Differences in plant uptake between sites occur due to differences in either soil N availability or uptake efficiency. The ag field site had about 40% more soil N supply than the cutover site, which was somewhat unexpected given the nature of the two soils. The cutover site has twice the soil organic matter (SOM) as the ag field site, but the cutover SOM has a higher C:N ratio than the ag field SOM and is probably more recalcitrant due to the difference in plant origin (loblolly pine vs. soybeans) between the two sites (Table V-1). Nitrogen immobilization within the microbial biomass can represent a very significant process controlling the intensity of available N (Jansson, 1958), and in many situations where labile C is readily available and the C:N ratio is above about 30:1 (Tate, 1995), immobilization may exceed mineralization, causing net N supply to be zero. Because the cutover site had an average C:N ratio of 30:1, a greater proportion of the gross N mineralization was probably immobilized by the microbial biomass than at the cutover site. At both sites, soil N supply was about 22 kg more on the plots fertilized with 112 kg N than the unfertilized plots in the year fertilizer was applied, i.e., 1999 at the ag field and 2000 at the cutover site. The effect was not apparent in the years fertilizer was not applied. These results indicate that the application of fertilizer increased net N mineralization, probably by reducing immobilization. This effect, called “priming” (Jenkinson et al., 1985, Kuzyakov et al., 2000), is important, since it effectively increased the fertilization rate from 112 kg N ha^{-1} to about 135 kg N ha^{-1} at both sites. Because our objective was not to study “priming” effects, these results are not definitive, and further work needs to be done in these soils and plantations to determine if native soil N supply is affected by fertilizer applications, especially repeated applications (Whynot and Weetman, 1991; Binkley and Reid, 1985). Johnson et al.

(1980) showed that soil C is an important regulator of urea-N dynamics and microbial immobilization, so differences in soil C, such as those between the ag field and cutover sites in this study, may cause the “priming” response to vary across site types.

The soil uptake efficiency (e_s) was taken as the foliage N uptake efficiency for the unfertilized plots. Uptake efficiency is a function of both plant root architecture and function and soil characteristics. The rooting habits were not studied at either site, but studies have shown that in both natural systems and plantations, proportional biomass allocation to roots is greater on dry, infertile sites compared to moist, fertile ones (Keyes and Grier, 1981). The soil uptake efficiency was surprisingly similar between the two sites. The ag field, in comparison to the cutover site, was dry. Both sites could be considered fertile. This would suggest that the ag field site might have a lower shoot:root ratio compared to the cutover site.

Soil and site characteristics that influence uptake efficiency are those that control the fate of soil N, such as hydrology and other plant competition. Losses of N occur when NO_3^- is removed in runoff, leached, or denitrified. Runoff and erosional losses were minimal on both sites since neither site had slope gradients greater than 2 percent and both had little bare soil (Dissmeyer and Foster, 1980). Leaching, however, was probably much different on the two sites. The cutover site was poorly drained, while the ag field was well-drained. Therefore, the potential for nitrate leaching was probably much higher at the ag field site. The ag field site is similar in soil and site characteristics to a study on intensively-managed loblolly pine and sweetgum on a converted peanut (*Arachis hypogaea* L.), which is a N-fixing legume, farm (Williams and Gresham, 2000), in which significant nitrate leaching was observed in both fertilized and unfertilized treatments after 4 years of tree growth.

Denitrification potential was greater at the cutover site, since it remained saturated longer after rainfall events and had relatively high levels of soil carbon that act as an energy source for denitrifying microorganisms (Davidson and Swank, 1987). Competition from herbaceous and woody plants was greater on the cutover site. Since soil N uptake efficiency was, on average, only 28% of annual soil N supply, these plant and soil factors were important in determining the uptake efficiency. However, given the similarity in soil uptake efficiency between the two sites, the difference in these factors between the two sites was either small, or, more likely, many of the differences counteracted each other. The ag field probably lost more available N via leaching, but the cutover probably lost more through denitrification or weed competition.

Soil N uptake efficiency, though, is generally different than fertilizer N uptake since soil N is made available through the season in relatively small doses, whereas fertilizer N is applied in one large dose. By assuming that the fertilized trees absorbed the same amount of N from the soil as the unfertilized trees and that any additional uptake was met by fertilizer N, we were able to estimate the proportion of fertilizer that was absorbed in the year fertilizer was applied. This estimate does not take into account fertilizer-induced changes in overall N uptake efficiency, e.g., through differential fine root growth patterns. Sweetgum fine root growth is plastic in response to N-rich microsites (Ludovici and Morris 1996; Mou et al. 1995), so roots may respond to localized increases in soil N rapidly after fertilization and improve fertilizer N uptake efficiency. However, if N-rich microsites homogenize once the fertilizer N diffuses throughout the soil profile, then the roots may not have an ideal architecture for capturing N arising from mineralization, thus reducing the soil N uptake efficiency. It also does not account for increased soil N availability due to fertilization, i.e., priming, which was evident at both sites in the 112 kg treatment. Even so, estimating fertilizer uptake separate from soil N in this manner gives us a general idea of the relationship between fertilizer N, soil N, and foliage N uptake in sweetgum plantations. From a practical standpoint, it does not matter if tree N uptake is met from actual fertilizer N, soil N made available by fertilizer “priming”, or N captured through altered rooting patterns.

Fertilizer uptake efficiency was similar and unexpectedly consistent within and across sites. It is also remarkable that the average fertilizer uptake efficiency (24%) was quite similar to soil uptake efficiency (28%). The discrepancy between the cutover site and ag field site was probably related to fertilizer timing. Fertilization at the ag field at age 4 did not occur until early

August due to operational constraints, while fertilization at the cutover site at ages 4 and 6 occurred in March. Fertilizer uptake efficiency would likely have been even less at the ag field site, but the year fertilization occurred was also the year that about 70% of the foliage fell in July and re-flushed in September due to summer-long droughts. The re-flushing probably was responsible for most of the fertilizer uptake.

One factor not specifically addressed with our proposed fertilizer estimate model is fertilizer carry-over to the following year. About 50% of fertilizer N remains on-site after fertilization in operational forest stands (Johnson 1992); about half in tree biomass and half in the soil, regardless of N input rate. In these intensively-managed plantations, the potential for loss is much greater due to the repeated inputs and reduced weed nutrient uptake and storage. Studies have shown that smaller, more frequent doses of fertilizer increase nitrification and leaching losses (Johnson and Todd, 1988; Tschaplinski et al. 1991). In our study, we expected to see an improvement in overall uptake efficiency in the fertilized trees during the unfertilized year, which would reflect fertilizer carry-over. At age 5, when no fertilizer was applied, foliage N uptake was about 4.4 and 6.3 kg greater in the trees that were fertilized at age 4 with 112 kg N ha^{-1} than in the unfertilized trees on the ag field and cutover sites, respectively. If soil N uptake efficiency was 28% (the overall average), about 16 and 23 kg of fertilizer N were available at the ag field and cutover sites, respectively, at age 5. The fertilizer N remaining at age 5 from the 56 kg N ha^{-1} treatment at age 4 was about 12 and 6 kg at the ag field and cutover sites, respectively. Overall, these data suggest that only about 15% of the fertilizer N remained available in the year following application.

From these results, the fertilizer needed for young sweetgum plantations was estimated by solving equation 3 for N_f given a level of Y_{dry}. Since Y_{dry}, N_y, e_s, e_f, and e_y varied between sites, among treatments, and across years, we estimated parameters for each site given our results. We estimated that the whole-crown foliage N concentration (N_y) would be 1.70%, since this is approximately the highest concentration reached at both sites (Table V-1). The uptake efficiency of mineralized soil N (e_s), was taken as the foliage uptake efficiency on the unfertilized plots, which averaged 30 and 28% at the ag field and cutover sites, respectively. Soil N supply was estimated as the average supply on the unfertilized plots at each site, and set at 68.7 kg ha^{-1} for the ag field site and 47.4 kg N ha^{-1} for the cutover site. Because we calculated uptake as the foliage N content less the resorption from the previous year, we calculated the resorption efficiency for equation 3 as the proportion of the current year's foliage N that was met by the previous year's resorption. Since resorption at age 3 at the ag field was much lower than at other ages, we used only age 4, 5, and 6 data. At the ag field site, about 46% of the age 5 foliage N was met by the resorption at age 4. At the cutover site, about 40% of the foliage N at ages 5 and 6 was met by resorption at ages 4 and 5. The fertilizer uptake efficiency was estimated as the average efficiency at each site, which was 20% at the ag field and 28% at the cutover site.

Using these parameters, the final equations for the two sites are

Ag field site:
$$N_f = \frac{(Y_{dry} \times 0.0175) - (0.30 \times 68.7) - (0.38 \times Y_{dry} \times 0.0175)}{0.20}$$

Cutover site:
$$N_f = \frac{(Y_{dry} \times 0.0175) - (0.28 \times 47.4) - (0.39 \times Y_{dry} \times 0.0175)}{0.28}$$

Because the foliage N concentrations are not independent of fertilizer rate, we estimated that about 60 and 110 kg N ha^{-1} was necessary to reach a foliage N concentration of 1.75% at the ag field and cutover sites, respectively. Solving these equations for an estimated foliage biomass of 3500 kg results in fertilizer N recommendations of 87 and 86 kg N ha^{-1} yr^{-1} for the ag field and cutover sites, respectively, which translates into a fertilizer recommendation of 1 kg N ha^{-1} per 40 kg of foliage biomass. While our recommendations for these two sites are similar, each arose from quite different circumstances. The ag field site had 40% more soil N supply than the cutover site, but had a 20% fertilizer uptake efficiency compared to the 28% of the cutover site. While this approach appears to work well for these two sites, more detailed investigations of soil N supply and N uptake efficiency (both soil and fertilizer N) are needed to extend this approach to varied site types.

With a minimum estimated soil N supply of 45 kg N ha^{-1}, and a soil uptake efficiency of 28%, foliage N demand will probably not respond until the potential uptake is greater than 13 kg N ha^{-1}, which, in our study, did not occur until age 4, and we suggest caution in fertilizing stands before age 4. Using general estimates based on these results from ages 3 to 6, we projected foliage biomass and recommended fertilizer rates for young, intensively-managed sweetgum plantations based on optimum foliage N biomass (Figure V-1). Although this approach resulted in a calculated fertilizer rate of 15 kg N ha^{-1} at age 3, this low amount is not practical and is not recommended. These recommendations do not address tree growth explicitly, but Scott et al. (2002), Kuers and Steinbeck (1998), and Nelson et al. (1995) all showed that tree growth is well-correlated with foliage biomass production and nutrition. Linking fertilizer rates to plant uptake by increasing the fertilizer rate as the stand matures has been shown by several researchers (van Miegroet et al., 1994; Ingestad, 1988; Landsberg, 1986) to improve N fertilizer use efficiency, defined as total biomass growth per unit N applied.

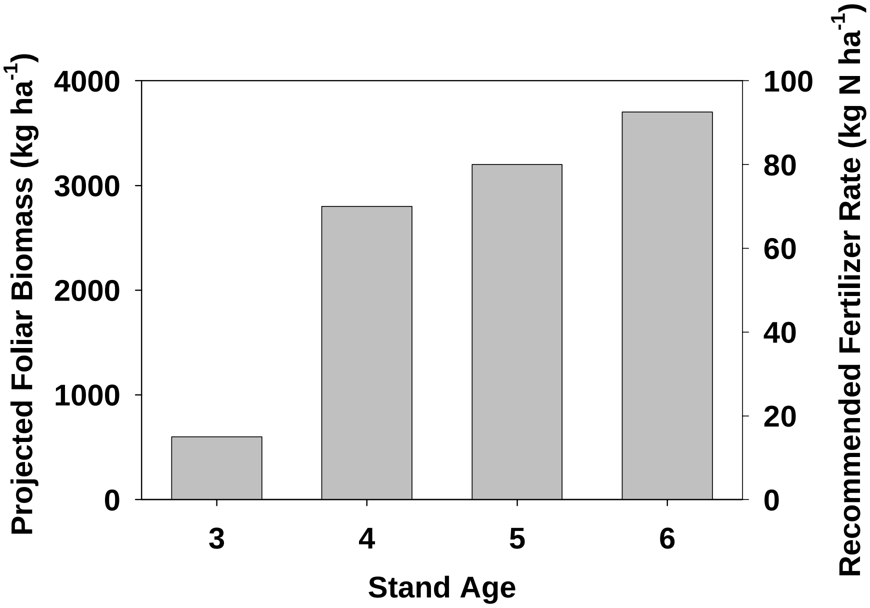

Figure V-1. Projected foliage biomass and recommended fertilizer rates for young sweetgum plantations.

The discrepancies among these predicted optimum rates and the actual results at age 4 on the ag field and age 6 on the cutover site are due to year-specific conditions. At age 4 on the ag field site, soil uptake efficiency was 43%, compared to the average of 30.5% across ages 4 and 5. The actual N available from resorption was also very low, since the foliage biomass and N demand at age 3 was low. At the cutover site at age 6, soil uptake efficiency was 17% compared to the average of 27.5% across ages 5 and 6. Given the limited ranges of N rates and fertilization frequencies tested, our general fertilizer recommendation for sweetgum plantations is 90 kg N ha^{-1} yr^{-1} beginning at age 4 until canopy closure, which should occur between ages 5 and 7 on fertilized sites. Fertilization before age 4 (this study was fertilized at planting and at age 2) is unnecessary. Instead of fertilizing at stand establishment and age 2, these two fertilization events could be moved to ages 5 and 7 to avoid over-fertilization early in the rotation, when potential loss would be high.

CONCLUSIONS

Forest management, especially for wood fiber, is intensifying in order to meet an increasing demand. Efficient fertilization is key to maintaining high productivity while avoiding deleterious environmental and economic effects. Using an agronomic approach, modified for perennial plants, we were able to budget soil N supply and foliage demand, determine uptake efficiency of soil and fertilizer N, and prescribe N fertilizer rates for young sweetgum plantations in the southeastern U.S. We found that foliage N demand responded to fertilizer applications as early as age 4, when the foliage biomass was greater than 1000 kg ha^{-1}. The increase in foliage N demand was met by both increases in total resorption and by increased uptake. Foliage N resorption efficiency was not changed by fertilization, but resorption proficiency was reduced. About 28% of the N supplied from soil N mineralization was taken up, and about 25% of fertilizer N applied was taken up by the foliage. Our recommendations for repeated fertilization of young sweetgum using this budget approach, support the concept and findings of Ingestad (1988), and suggest fertilizing at a rate of 1 kg N for each 40 kg of expected foliage biomass after age 4. Further work needs to be done to (1) quantify the influence of water availability on foliage dynamics and growth in young sweetgum and other important SRWC species, (2) better understand the site controls on soil N supply, and (3) characterize and quantify root production and nutrient uptake on different soils and under different levels of water and nutrient availability.

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CHAPTER VI. ESTIMATING SOIL NITROGEN SUPPLY FOR INTENSIVE HARDWOOD MANAGEMENT

ABSTRACT

Intensive hardwood forest management requires relatively high rates of nitrogen (N) fertilization to maintain maximum growth. Budgetary approaches to determining the need for N fertilization are relatively simple and can be applied on a site-specific basis, but we lack a reliable method of estimating soil N supply on various sites. Therefore, we tested a simple process model of soil N supply based on a first-order production function modified for soil climate on two highly-contrasting sweetgum plantation soils through two growing seasons and one dormant season. Annual N production, which was calculated as the sum of the average summer and winter production, was 26.8 and 24.7 mg kg^{-1} on an Argent soil that previously supported a loblolly pine forest and a Norfolk soil that was a converted agricultural field, respectively. The modeled production for the two soils was 26.7 and 19.7 mg kg^{-1}, respectively. The influence of soil water content on N supply was not accurately estimated on a monthly basis and should be refined for field conditions, especially in soils conducive to N immobilization. Overall, the model described cumulative N supply on two highly contrasting soil and site types, and should be investigated further for improving N fertilizer estimates in short-rotation intensive culture forestry.

INTRODUCTION

Synchronizing available nitrogen (N) to tree uptake through fertilization, weed control, and organic matter conservation is one primary goal of intensive forest management, but is difficult to achieve across a variety of soils. In low-input forest plantation systems, N fertilizer is commonly applied at planting and possibly at mid-rotation if visual deficiencies or measured foliage N levels indicate a N deficiency. In high-input, short-rotation woody crop plantations, however, N fertilization is required at high rates or in more frequent applications to maintain maximum production. Unlike the goal of N management on low-input plantations, which is to alleviate obvious N deficiencies and maximize the fertilization response, the goal of N management in short-rotation woody crops needs to be a synchronization of soil N supply and plant N demand through the rotation. Empirical growth and yield models coupled with measurements or estimates of plant N concentrations can help predict N demand through time. Fertilizer prescriptions can then be made based on a balance-sheet approach that accounts for soil N supply, plant N demand, and N uptake efficiency (modified from Stanford 1973) (Equation VI-1).

$$N_f = \frac{(Y_{dry} N_y) - e_s N_s - e_y N_y}{e_f} \qquad \text{(VI-1)}$$

where: N_f = N fertilizer need
Y_{dry} = Biomass
N_y = N concentration in biomass
N_s = Soil N supply
$e_{s,f,y}$ = Uptake efficiencies from soil, fertilizer, and resorption, respectively

The most difficult part of balance-sheet approaches is estimating soil N supply. Static soil N indices, such as total N (Bremner and Mulvaney, 1982) or anaerobic N incubations (Powers, 1980), may be correlated to growth across large gradients in productivity, but static indices cannot account for site and treatment-induced changes in the capacity parameters (soil climate) of soil N supply (Burger and Pritchett, 1984). Actual measurements of soil N supply are costly, time consuming, and difficult to achieve reliably. Several process models exist for estimating soil N supply, but generally require many theoretical parameters that cannot be directly measured or estimated. For example, two leading agricultural soil N models, NCSOIL (Molina et al., 1983) and CERES-N (Godwin and Jones 1991), require the estimation of three pools of organic matter that cannot be directly measured. In contrast, what plantation managers need to predict site-specific N supply is a simple model that is based on site characteristics and established relationships.

Soil N supply is largely governed across soil regions by the quantity of organic substrate and, within a given region, by the nature of the substrate, soil chemistry, and soil climate conditions. Within the southeastern U.S., short-rotation hardwood plantations are being managed on two distinct land types that have different substrates and soil climate conditions. Converted agricultural fields are common for short-rotation hardwood plantations across the U.S. and southern Canada due to their relatively high levels of base cation and phosphorus fertility, ease of operability, and lack of competing vegetation. However, in some areas of the southeastern U.S., marginal agricultural lands are not available near fiber processing plants. In these areas, the pulp and paper industry has concentrated their short-rotation plantations on high-quality “pine” sites that were recently managed as conifer plantations.

With respect to soil N supply, agricultural fields tend to have lower quantities of organic substrate compared to cutover forest sites due to site and cultural factors. Soils suitable for agriculture are inherently different than those suited for forests, and agricultural fields have less soil organic matter as a result of cultivation. Within each land-use type, soil climate characteristics control the rate of N supply. We hypothesized that soil N supply could be estimated by adjusting a static measure of substrate quantity with monthly estimates of soil climate conditions.

Accordingly, the objective of this study was to test a kinetic model using independently measured soil characteristics to estimate annual soil N supply in short-rotation hardwood plantations. We specifically wanted to test a model that could be applied to a wide range of sites using only simple, relatively easily measured parameters without on-site calibration. The model was based on measurable site characteristics and established process-level relationships and tested on two sites that represent contrasting points on the spectrum of site types currently used for intensively managed hardwood plantations in the Southeast.

MATERIALS AND METHODS

Site Descriptions

Two sites of contrasting soil type and land use history were selected to study the effect of site and soil type on soil N supply. One was a well-drained agricultural field, while the other was a poorly drained harvested loblolly pine (*Pinus taeda* L.) plantation site, hereafter referred to as the “ag field” and “cutover” sites, respectively. These two sites were selected to represent opposite ends of the spectrum of site types currently used for short-rotation hardwood plantations in the southeastern U.S.

The ag field study site was located on International Paper’s Trice Research Forest in Sumter County, South Carolina (33º 58' N 80º 12' W) on the middle Atlantic coastal plain. The soil is a well-drained Norfolk sandy loam (loamy, kaolinitic, thermic Typic Kandiudult). Nine 0.2-ha treatment plots with 0.04-ha measurement plots were established in February 1996 with 280 1-0 bare-root sweetgum seedlings (3 m X 2.4 m spacing, ~1400 ha^{-1}). The site had been regularly managed for dry land crops, e.g., corn (*Zea mays* L) and soybeans (*Glycine max.* (L.) Merr), for more than 20 years, and soybeans, a N_2 fixing legume, were the primary crop for the 5 years previous to plantation establishment. All plots were treated with an initial fertilizer application of 280 kg ha^{-1} diammonium phosphate (DAP), which supplied 50 kg N ha^{-1} and 56 kg P ha^{-1} in November 1995 and 100 kg ha^{-1} urea, which supplied 46 kg N ha^{-1}, in August 1996. Non-crop vegetation was restricted to herbaceous vegetation, mostly broomsedge (*Andropogon virginicus* L.), due to the agricultural legacy and early-rotation chemical weed control.

The cutover pine site was on MeadWestvaco Corporation land, located in Colleton County, South Carolina (32º 8' N 80º 7' W) on the lower Atlantic coastal plain, and was established in February 1995. The soil is a somewhat poorly to poorly drained Argent sandy loam (clayey, mixed, active, Typic Endoaqualfs) developed from marine deposits. The site undergoes wide fluctuations in soil water contents, from saturated soils with standing water in the dormant season to dry soils during the growing season. The heavy clay subsoil restricts water percolation through the solum, and the low elevational gradient (<2%) restricts lateral flow. These mechanisms induce short-term saturation after heavy rain events throughout the growing season. Nine 0.2-ha treatment plots with 0.04-ha measurement plots were established with 280 1-0 bare-root sweetgum seedlings (3 m X 2.4 m spacing, ~1400 ha^{-1}) following loblolly pine harvest and site preparation, which consisted of bedding, fertilization and non-crop vegetation control. All plots received 50 kg N ha^{-1} and 56 kg P ha^{-1} as DAP and 3.9 Mg ha^{-1} dolomitic lime in March 1995. The lime application raised pH from approximately 4.75 to 5.5. Non-crop vegetation control consisted of pre-emergent herbicide applications in February and March of 1995, 1996, and 1997. Herbicides were also applied by directed spray in 1995 and 1996 during the growing season. Although this aggressive chemical weed control program was used for the first three years, woody and herbaceous plants were present when competition control measures ceased. Compared to most young cutover pine plantations, this site was relatively clean with respect to non-crop vegetation, but not compared to the ag field site.

At each site, three biannual N fertilizer rates were initiated at age 2 and replicated three times. Every two years, i.e., ages 2, 4, 6, ammonium nitrate (NH_4NO_3) was applied at the following rates: 0 kg ha^{-1} (Control), 168 kg ha^{-1}, and 336 kg ha^{-1}, which provided 0, 56, and 112 kg ha^{-1} N, respectively.

This study is part of a larger study on fertilizer rate and short-rotation hardwood nutrition, so the model was tested on each experimental unit of the two sites. We did not use the experimental plots to test treatment effects in this study; we used the treatment plots to mimic the range of natural and culturally induced variation in soil climate conditions and N supply across a given soil type.

Soil Characterization

Soil samples were collected from each treatment plot in 1999 and 2000. Nine 2-cm diameter subsamples were collected per treatment plot in April and November of each year from the 0-20 cm depth. The subsamples were air-dried, sieved to pass a 2-mm sieve and bulked by treatment plot and year. The samples were then analyzed for total carbon (C), N, phosphorus (P), and pH. Carbon and N were determined with a vario MAX CNS analyzer (Elementar, Hanau, Germany). Available phosphorus was determined by extracting the soils with Mehlich I extractant (Mehlich, 1953) and analyzing the extract via Inductively Coupled Plasma – Atomic Emission Spectroscopy (ICP) (SpectroFlame Modula Tabletop ICP, Spectro Analytical Instruments, Fitchburg, MA). Soil pH was determined for the samples in a 1:2 soil:water mixture with a combination pH probe (McLean 1982).

Model Description

The model was created based on the soil nitrogen mineralization potential concept and decomposition rate (Equation VI-2) (Stanford and Smith, 1972; Campbell et al., 1973).

$$N_T = N_0 \times \left(1 - e^{-kT}\right) \tag{VI-2}$$

where N_T = Cumulative N production in mg N kg^{-1} soil at time T

N_0 = Mineralizable N at time T = 0

k = N mineralization rate at optimum (35 ^{o}C and -0.03 MPa)

T = time

This approach estimates the N supply for a given time under optimal environmental conditions. Because soil temperature, water content, and other abiotic factors in the field are seldom optimal, we modified k for soil temperature with a Q_{10} function (Equation VI-3) (Stanford et al. 1973).

$$F_t = \left(2.0^{\frac{t_1 - t_0}{10}} \right)^{-1} \tag{VI-3}$$

where F_t = a proportional temperature factor

t_1 = high temperature (°C) (temperature at which k was determined)

t_0 = low temperature (°C) (measured soil temperature)

We used the relationship of Stanford and Epstein (1974) to estimate the effect of soil water on soil N supply. They found that mineralization is optimum for most soils at approximately field capacity (-0.03 MPa) and decreases proportionally from the optimum (Equation VI-4). Although they did not specify a function to account for F_t when water content was greater than field capacity, their data suggest that k is reduced by water contents above field capacity as well. We inverted the proportional equation (Equation VI-4) to account for water contents greater than field capacity.

$$\begin{gathered} F_\Theta = \frac{\Theta}{\Theta_{opt}}, \Theta < \Theta_{opt} \\ F_\Theta = \frac{\Theta_{opt}}{\Theta}, \Theta > \Theta_{opt} \end{gathered} \tag{VI-4}$$

where F_Θ= a proportional water factor

Θ= soil water content (v/v)

Θ_{opt}= soil water content (v/v) at -0.03 MPa

We incorporated the influence of temperature and water content on predicted soil N supply by multiplying the rate (k) in equation 2 by the two climate adjustment factors (Equation VI-5) (Campbell et al. 1988).

$$N_T = N_0 \times \left(1 - e^{-k(F_T \times F_\Theta)T}\right) \qquad \text{(VI-5)}$$

We calculated the cumulative N supply for each time period in an iterative manner with Equation VI-5 (Campbell et al. 1988). For the first time period, we calculated N_T using the initial N_0, k, F_t, and F_Θ. For each successive time period, we reduced N_0 by the cumulative N_T at that time. After one year from the start of measurements, we assumed N_0 had returned to its initial value.

Aerobic Incubation (N_0)

Potential N mineralization (N_0) was determined on fresh soil samples taken between January and March, 1998, following laboratory techniques of Burger and Pritchett (1984). Approximately 40 g of 2-mm sieved soil was mixed thoroughly with 150 g silica sand and placed in 5 cm diameter by 15 cm long PVC tubes and sealed with one-hole rubber stoppers. A separate 10-g subsample was dried at 105 ^{o}C to determine moisture content. The samples were leached every 2 wk with 250 mL of 0.01 M $CaCl_2$, followed by 100 mL of a minus-N Hoagland solution. After the solution was allowed to leach through the samples gravimetrically, a vacuum was applied to drain the samples to approximately field capacity (-0.03 MPa). The collected leachates were analyzed for NH_4 and NO_3^--N with a TRAACS 2000 colorimetric autoanalyzer (Bran&Luebbe Corp., Oak Park, IL). A first-order model for N_0 (Equation VI-1) was fit to the cumulative N production using PROC NLIN in SAS (SAS, 1996).

Soil climate monitoring

Soil temperature and water content were monitored at each site. Soil temperature was measured hourly at 20 cm at one location on each site with a buried sensor coupled to a datalogger (Onset Corporation, Bourne, MA). An initial analysis of individual plot temperature measurements showed no significant difference in soil temperature among plots, so the same hourly temperature was used for all plots within each site. The mean soil temperature for each sampling period (approximately 30 d) was then determined and used in the model.

Soil water content was monitored via Time Domain Reflectometry. Three sets of 20 cm rods were permanently installed on each measurement plot and measured monthly (TRASE, SoilMoisture Equipment Corp., Goleta CA). Water content at -0.03 mPa, i.e., field capacity, was determined on five 5-cm diameter by 5-cm length intact cores with a pressure plate (Klute 1986). Gravimetric water content was determined on loose soil samples at -1.5 mPa (wilting point, θ_{wp}) with a pressure membrane and converted to θ_v by multiplying by the soil bulk density (ρ_b), which was determined by drying the intact cores at 105 ^oC for 48 hrs.

***In situ* nitrogen production**

Soil N supply was measured from April 1999 through September 2000, which corresponded to approximately two growing seasons (April-September 1999 and 2000) and one dormant season (October 1999-March 2000). We measured soil N supply with the buried bag method (Eno, 1960). Three measurement points (subsamples) were taken for each treatment plot. Two soil samples (bags) were collected for each sampling date at each measurement point (six bags per treatment plot per sampling date). One was incubated *in situ* at 20 cm and covered with soil and the other returned to the laboratory for analysis. For each bag, three 1-cm push tube samples were taken of the soil to a 20 cm depth. At the bedded cutover site, all samples were taken from within the beds. Each soil sample was air-dried, sieved to pass a 2 mm sieve, and the NH_4^+ and NO_3^- -N extracted with 2 M KCl in a 10:1 solution:soil ratio. The NH_4^+ and NO_3^- concentrations in each extract were determined via automatic colorimetric spectrophotometry on a TRAACS 2000 Autoanalyzer (Bran & Luebbe Corporation, Oak Park, IL). Nitrogen supply was calculated as the difference between the N intensity in the soils incubated for approximately

30 d and the samples taken at the time of incubation. If negative values occurred, which represent immobilization or denitrification, the soil N supply was set to 0 for that sample.

RESULTS

Soil characteristics

Chemical and physical properties of the two soils studied were very different. The soil C and N concentrations of the Argent soil, which was on the cutover pine plantation, were 6 and 3.2 times, respectively, those of the Norfolk soil, which was on the converted agricultural field (Table VI-1). The C:N ratio of the Argent soil (29.6) was almost twice that of the Norfolk (15.2). Available phosphorus was more than 3 times greater in the Norfolk soil (29 mg kg^{-1}) compared to the Argent soil (9 mg kg^{-1}). Soil pH was surprisingly low in the Norfolk soil (5.01), and was lower than the pH of the Argent soil (5.20).

Both soils classify as sandy loam textures and have similar concentrations of clay, but they have very different physical characteristics due to the difference in sand and silt concentrations (Table VI-1) and soil aggregation (data not shown). Bulk density of the Norfolk site (1.39 Mg m^{-3}) was 50% greater than the Argent soil (0.89 Mg m^{-3}). The water content of the Argent soil at field capacity and wilting point, measured at -0.03 and -1.5 mPa, was 0.29 and 0.065 cm^3 cm^{-3}, respectively. The water contents of the Norfolk soil at field capacity (0.12 cm^3 cm^{-3}) and wilting point (0.02 cm^3 cm^{-3}) were less than half that of the Argent soil. The available water of the surface 20 cm of the Argent soil (4.5 cm) was also more than twice that for the Norfolk soil (2 cm).

Table VI-1. Chemical, physical, and hydrologic characteristics of two for two contrasting soils currently managed for short-rotation hardwood plantations in South Carolina.

Property		**Ag field**	**Cutover**
Series		Norfolk	Argent
Location		Middle C.P.	Lower C.P.
Site type		sandy upland	flatwoods
Drainage		well	poor
Depth to water		>2 m	1.5 m (winter) >2 m (summer)
Carbon	%	0.52b	3.23a
Nitrogen	%	0.04b	0.11a
C:N		15.2b	29.6a
Phosphorus	mg kg^{-1}	29.3a	9.1b
pH		5.02b	5.22a
Sand	%	84	61
Silt	%	0	19
Clay	%	16	20
D_b	Mg m^{-3}	1.39	0.89
θ_{fc}	$cm^3\ cm^{-3}$	12	29
θ_{wp}	$cm^3\ cm^{-3}$	2	6.5
Avail. Water	cm	2	4.5

Cumulative N mineralization from the laboratory aerobic incubation procedure was fit to first-order N production curves (Figure VI-1). The Argent soil had 50% more mineralizable N (46.9 mg kg^{-1}) than the Norfolk soil (30.7 mg kg^{-1}), and it mineralized at a slightly greater rate. About 6 and 11% of the total N was mineralizable in the Argent and Norfolk soils, respectively.

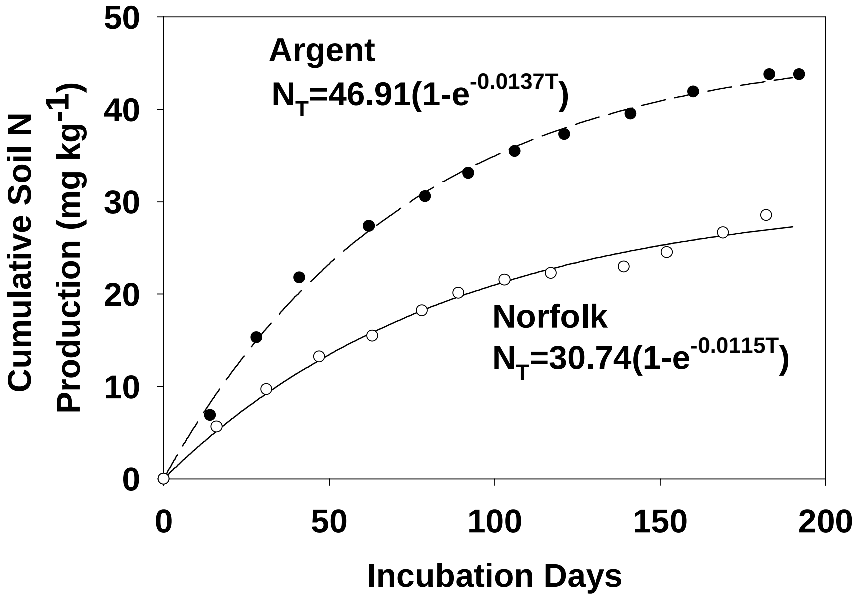

Figure VI-1. Cumulative N mineralization in a 24-week laboratory incubation and associated first-order production functions for two contrasting soils currently managed for short-rotation hardwood plantations in South Carolina.

In situ soil climate

Soil temperature followed a classical seasonal distribution at both sites throughout the study period (Figure VI-2). Temperatures reached maxima of 28 and 26 °C in mid-August of 1999 and 2000, respectively, and minima in mid-February of about 7 °C. Summer temperatures were indistinguishable, but the Argent soil had slightly higher temperatures in the winter. Soil water contents varied widely seasonally and between the two sites (Figure VI-3). The water content of the Argent soil ranged from 0.07 to 0.18 $cm^3\ cm^{-3}$ in the growing season (April to September) and 0.20 to 0.33 $cm^3\ cm^{-3}$ in the dormant months. The Norfolk soil showed less seasonality in θ_v; the range in the summer was 0.05 to 0.17 $cm^3\ cm^{-3}$ while only 0.07 to 0.14 $cm^3\ cm^{-3}$ in the dormant season. Because the θ_{fc} for the Argent and Norfolk soils were 0.29 and 0.12 $cm^3\ cm^{-3}$, respectively, both soils were near field capacity for much of the dormant season.

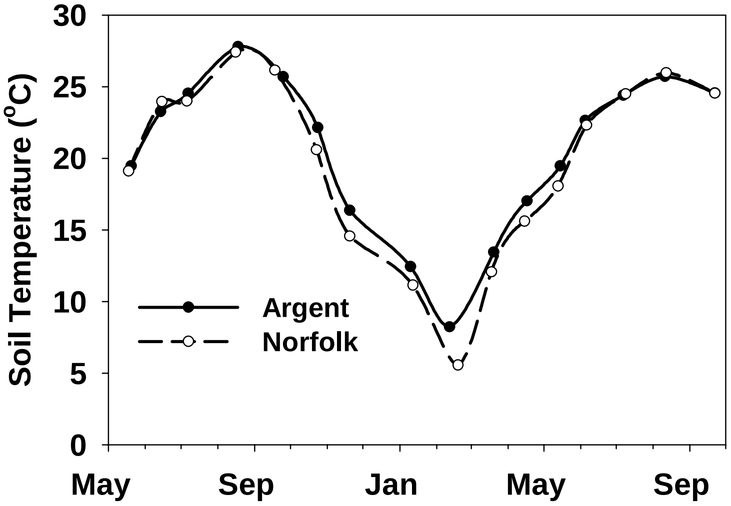

Figure VI-2. Soil temperature from May, 1999 to October, 2000 in two contrasting short-rotation hardwood plantation soils in South Carolina.

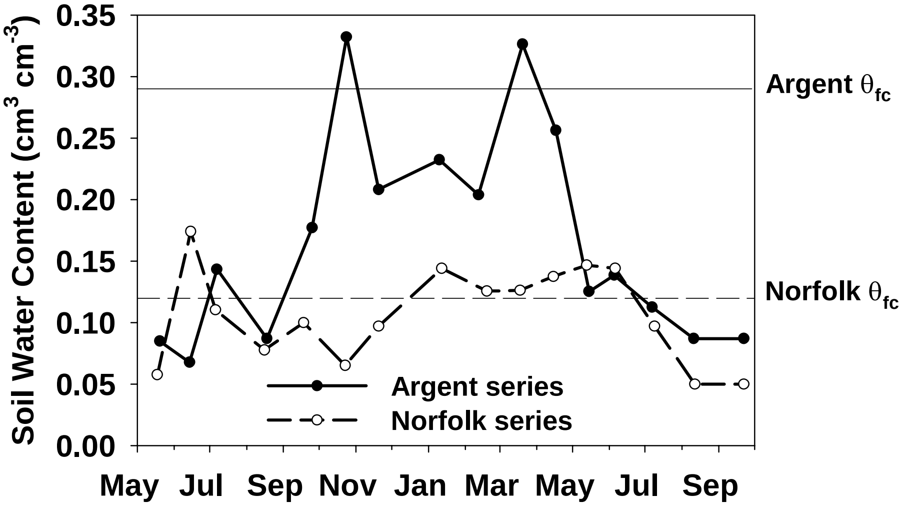

Figure VI-3. Volumetric soil water content from May, 1999 to October, 2000 in two contrasting short-rotation hardwood plantation soils in South Carolina. Lines indicate field capacity for the Argent and Norfolk soils.

Soil N Supply

We examined the data as two separate growing seasons and one dormant season to attempt to derive an average annual N supply and to help determine the time periods the model fit the data well and those times that the model did not perform well. Across the entire study period, monthly soil N production ranged from 0 to almost 10 mg kg^{-1} in the Argent soil, but only 0 to 6 mg kg^{-1} in the Norfolk soil (Figure VI-4 A,B). In the Argent soil during the first growing season (April-October), about 60% of the 16.4 mg kg^{-1} was produced in a single time period (August-September). The remaining 6 mg kg^{-1} was distributed from April to August. No N was produced in September following the large amount produced in August. In the Norfolk soil during the first growing season, monthly production was low (less than 3 mg kg^{-1}) until August. About 75% of the seasonal production in the Norfolk soil (11.7 mg kg^{-1}) occurred in the August-October period. Across this first season, the Argent soil produced about 40% more N than the Norfolk soil.

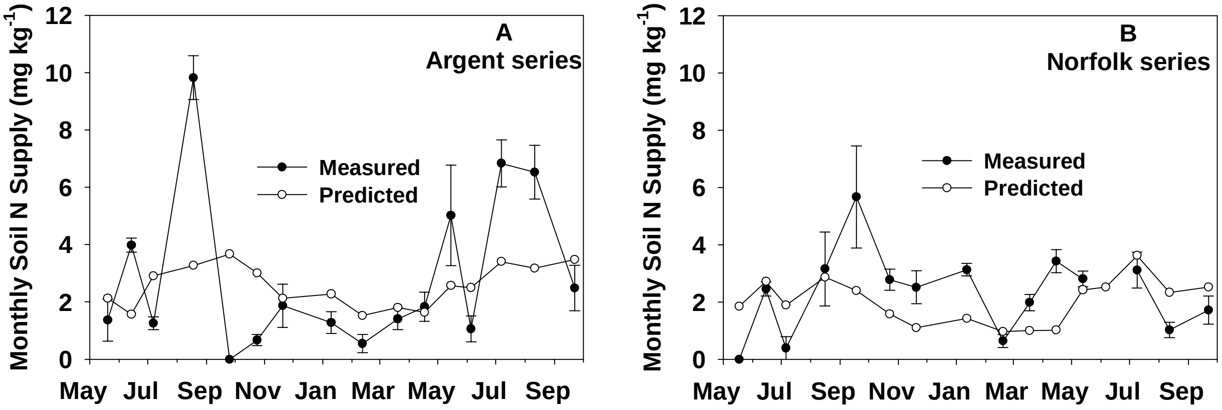

Figure VI-4. Measured and predicted monthly soil N production through time in two contrasting short-rotation hardwood plantation soils in South Carolina. Error bars indicate one standard error.

During the dormant season (winter), the Argent soil produced only 7.6 mg kg^{-1}, and it was evenly distributed across the season. Production was also evenly distributed across the season in the Norfolk soil, but a total of 14.5 mg kg^{-1} was produced, which was about 90% more than in the Argent soil.

In the second growing season, the Argent soil did not have the large single spike of production as in the first growing season, but about 60% of the 21.9 mg kg^{-1} production was produced in the June-August time period. The Norfolk soil produced only 8.7 mg kg^{-1} in the second growing season, which was only 40% as much N as the Argent soil. The production was evenly distributed across the time period.

On average, the Argent soil produced about 90% more N (19.2 mg kg^{-1}) through the growing season as the Norfolk soil (10.2) (Table IV-2). However, the Norfolk soil (14.5 mg kg^{-1}) produced about 90% more N through the winter than the Argent soil (7.6 mg kg^{-1}). Annual production was calculated as the sum of the average summer production and the winter production, and was 26.8 mg kg^{-1} for the Argent soil and 24.7 mg kg^{-1} for the Norfolk soil. With bulk densities of 0.89 and 1.39 Mg m^{-3}, these concentrations corresponded to annual supplies of 48 and 69 kg N ha^{-1}, respectively.

Table VI-2. Measured and predicted soil N production for two growing seasons and one dormant season for two short-rotation hardwood plantations in South Carolina.

Season	**Argent Measured**	**Predicted**	**Relative Error**	**Norfolk Measured**	**Predicted**	**Relative Error**
	----------mg kg^{-1}----------		%	----------mg kg^{-1}----------		%
Summer 1999	16.4a[1]	13.6	-17	11.7b	11.8	1
Winter 1999-2000	7.6b	12.4	63	14.5a	7.1	-51
Summer 2000	20.9a	15.1	-31	8.7b	13.5	55
Summer mean	18.7	14.4	-23	10.2	12.6	24
Annual estimate	26.8	26.7	0	24.7	19.7	-20

[1] Site means within a measurement period (Summer 1999, Winter 1999-2000, or Summer 2000) followed with the same letter were not different at α=0.10.

Model Performance

The model did not predict individual monthly soil N supply well at either site (Figure VI-4 A,B), but it predicted cumulative soil N supply reasonably well for the Argent soil in both summers and the Norfolk soil during one summer (Figure VI-5 A,B) . The model did not perform well on either site during the winter. The model under-predicted soil N supply in the Argent soil during the 1999 and 2000 summers by 2.8 and 6.8 mg kg^{-1}, respectively, which corresponded to 17 and 31% relative errors calculated as ((predicted-measured)/measured) (Table IV-2). The model over-predicted N supply by 4.8 mg kg^{-1} (63%) during the 1999-2000 winter. Measured and predicted soil N supply were equal (26.8 and 26.7 mg kg^{-1}, respectively) on an annual basis (0% error). In the Norfolk soil, the model over-predicted N supply during the 1999 and 2000 summers by 0.1 and 4.8 mg kg^{-1} (1 and 55% error), respectively, and under-predicted winter N supply by 7.4 mg kg^{-1} (51%). Annually, the model under-predicted soil N supply by 5.0 mg kg^{-1}, or 20% for the Norfolk soil.

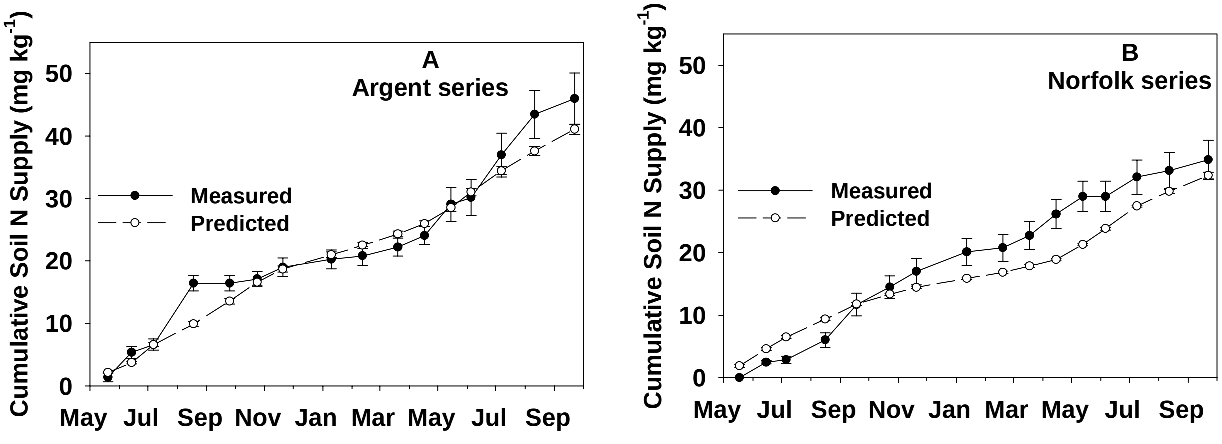

Figure VI-5. Measured and predicted cumulative soil N production through time in two contrasting short-rotation hardwood plantation soils in South Carolina. Error bars indicate one standard error.

Because we modeled soil N supply with simple functions for soil water and temperature, we investigated the specific influences of each on measured N production in the field environments. On both soils, N production was clearly influenced by factors other than temperature (Figure VI-6 A,B). The upper boundary of the data in Fig. 6 A,B follow the Q10 function, but the data representing low soil N production at high temperatures clearly indicates that production was limited by factors other than soil temperature.

Soil N production in relation to soil water content is shown in Figure VI-7 A,B. Although soil water contents were only measured at the same time that soil N supply was sampled, i.e., monthly, we measured soil N supply in polyethylene bags, which kept soil water content constant for the incubation period. Production was greatest in the Argent soil at about 0.10 cm^3 cm^{-3}, which was much closer to the wilting point (0.065 cm^3 cm^{-3}) than to field capacity (0.29 cm^3 cm^{-3}). Production appeared to be negatively related to soil water content from about 0.10 cm^3 cm^{-3} to 0.29 cm^3 cm^{-3} as opposed to positively related, which was expected. Production in the Norfolk soil was greatest about 0.08 cm^3 cm^{-3}, which was close to field capacity (0.12 cm^3 cm^{-3}). Production decreased from its maximum at 0.08 cm^3 cm^{-3} water content approximately linearly with either decreasing or increasing water content.

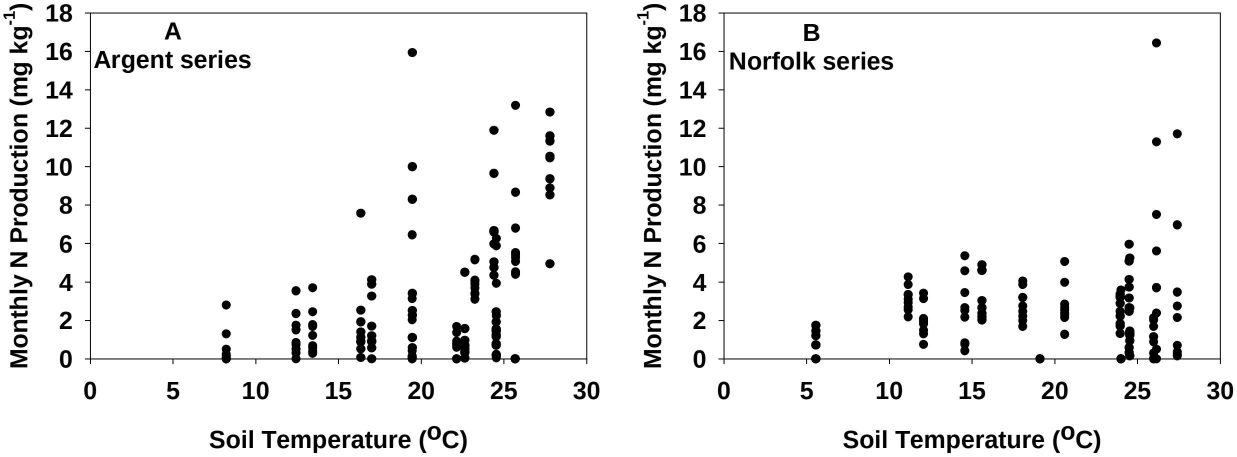

Figure VI-6. Soil N production in relation to soil temperature in two contrasting short-rotation hardwood plantation soils in South Carolina.

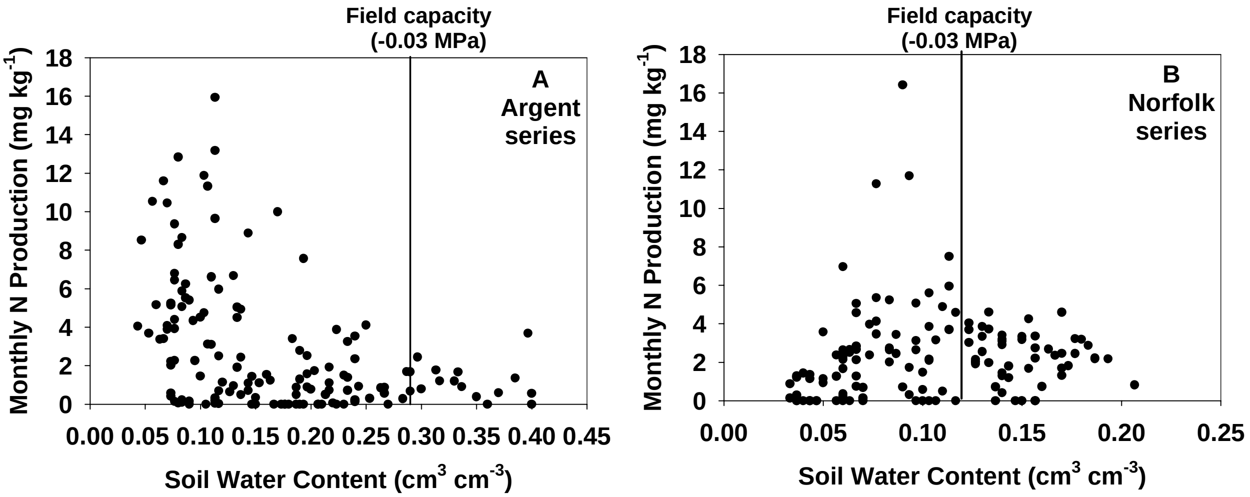

Figure VI-7. Soil N production in relation to soil water content in two contrasting short-rotation hardwood plantation soils in South Carolina. Water content was measured at the beginning of the buried-bag incubation period.

DISCUSSION

Soil characteristics

The differences in soil characteristics between the two soils were the result of edaphic, vegetative, and cultural influences. Soil chemical differences were largely related to recent land management. Because the Norfolk soil had presumably been limed previously for row-crop agriculture while the Argent soil had not been limed prior to this study, we expected soil pH to be much lower in the Argent soil than in the Norfolk soil. The Argent soil was limed at study establishment in order to raise pH from 4.75 to a target of 5.5, but we had expected the Norfolk soil to be near or above 5.5. Apparently, either the pH 5.0 Norfolk soil had not been limed often or the leaching environment and coarse texture had reduced the effectiveness of past lime applications. Soil P, on the other hand, was directly related to edaphic and cultural practices. Both soils were probably inherently low in P prior to cultivation or forest management, but repeated fertilization of the Norfolk soil resulted in the 3-fold greater available P.

Land management also had effects on the physical properties of the soils. The difference in bulk density was caused by the lack of soil structure at the Norfolk soil and the recent bedding treatment of the Argent soil. Repeated tillage, combined with the sandy texture in the Norfolk soil, caused the surface soil structure to be weak and granular (data not shown). The low bulk density of the Argent soil is somewhat misleading; many soil voids were large (> 1 cm) due to the bedding site preparation, and many fine and medium roots were present in the surface soil. Over time, the large voids will collapse and the bulk density will equilibrate at or above 1.0 Mg m^{-3}.

Mineralizable N on these two sites was related to the amount and origin of the soil organic matter. Prior to European settlement, the Argent soil probably supported a dense wetland forest, while the Norfolk soil probably supported an upland mixed pine-hardwood forest. Decomposition rates were likely less in the Argent soil than in the Norfolk soil due to saturated conditions. Greater organic production and lower decomposition rates created an organic-matter rich Argent soil, while the sandy, well drained Norfolk soil probably had only a moderate amount of organic matter. Recent management magnified the difference in organic matter return to the soil through loblolly pine plantation management and row-crop agriculture. Although some organic matter was removed with loblolly pine management, the annual harvest on the Norfolk soil limited the organic return to the soil. The Argent soil organic matter originated from high-lignin, high-wax content, low N content vegetation (loblolly pine), while the organic matter of the Norfolk soil originated most recently from low-lignin, high-N vegetation (soybeans). The two soils, therefore, had very different pools from which N supply occurred.

Soil N Supply and Model Performance

Measured soil N supply was more variable than predicted on a monthly basis (Figure VI-4 A,B), but cumulative N supply was well predicted (Figure VI-5 A,B). Because the model only accounted for the pool of mineralizable N and soil climate, it was not able to account for the monthly variation in soil N supply caused by the myriad of microbial and chemical transformations. However, the model worked well cumulatively because the measured periods of high production countered periods of low production.

The basis for using a Q_{10} function to simulate the effect of soil temperature on N supply is well supported by the literature, although some newer approaches have been developed. Campbell and Biederbeck (1972) and Stanford et al. (1973) both applied the Q_{10} function to mineralization as defined by a first-order decomposition rate (Stanford and Smith 1972). Both studies found Q_{10} values near 2, which is the generally accepted value for enzymatic-catalysed reactions. Stanford et al. (1973) also applied the Arrhenius equation, from which the Q_{10} function was derived, to describe the reaction rate response to temperature. The Arrhenius equation relates the temperature dependence of a chemical reaction rate to the reaction activation energy and a steric factor that accounts for the specific configuration the molecules must be in to react. Stanford et al. (1973) fit this equation to the data of Stanford and Smith (1972). They found that although the approach did not work well for temperatures less than 15 ^{o}C, the temperature dependence of N mineralization was relatively constant for several soils and could be estimated as Q_{10}=2. Based on this finding, they postulated that soil N mineralization in field conditions could be estimated by modifying the first order reaction rate for ambient temperature conditions using a simple Q_{10}=2 relationship.

Researchers have used different expressions to simulate the temperature dependence of N mineralization. Honeycutt et al. (1988) used heat units, or degree days, to predict N mineralization. This approach worked well in determining the onset of net N mineralization (as opposed to net N immobilization) under field conditions during a growing season, but consistently moist conditions would be needed for accurate future predictions (Doel et al., 1990). Reichstein et al. (2000) evaluated a quadratic function proposed by Ratkowsky et al. (1982) that implies an increasing Q_{10} with decreasing temperature, but found that a standard Q_{10} approach worked better. Therefore, while other approaches may work better for certain situations, the Q_{10} approach is the simplest and easiest relationship to apply across a range of soil types, and our data did not indicate that some other relationship would be better.

The response of soil N production to soil water content for both soils was different from what one might expect from lab-derived relationships. The data visually suggest a negative relationship between N production and water content above about 0.10 $cm^3\ cm^{-3}$ on both sites (Figure VI-7 A,B), which is near the field capacity of the Norfolk soil (0.12 $cm^3\ cm^{-3}$), but is only about a third of the field capacity of the Argent soil (0.29 $cm^3\ cm^{-3}$). Data representing low N production at high water contents could have been the result of low temperatures. Low temperatures did occur often with high water contents, since the water content of both soils was near or above field capacity for much of the winter (Figure VI-3). However, this does not explain why production was low in some summer months when temperature and water content were high or why the Argent soil had its maximum production at only 0.10 $cm^3\ cm^{-3}$ water content instead of at field capacity. Other influences, such as the level of soluble carbon and the immobilization potential, may have played a significant role in the N production.

Immobilization was probably much less on the Norfolk soil. The absolute level of soil C was low (0.52%), and the relative level of N in relation to C was high (C:N=15.2). This implies that the soil microbial community was constrained largely by its energy source, and not by N. On the Argent soil, however, soil C was quite high (3.22 %), and the proportion of N was low (C:N=29.6). These factors would make the Argent soil much more prone to immobilization than the Norfolk soil, and could explain why the Argent soil had low production at supposedly “optimum” water contents.

Skopp et al. (1995) postulated that microbial processes are controlled by water content through its impact on O_2 and substrate diffusion. Their model provided a theoretical basis for the observation that maximum microbial activity occurs at approximately 60% of water holding capacity (Greaves and Carter, 1920) or total porosity (Linn and Doran, 1984). The model hypothesizes that at low water contents, substrate (soluble organic matter) diffusion is limited, while at high water contents, O_2 diffusion is limited. Soil characteristics that influence substrate and O_2 diffusion could modify this relationship. Substrate diffusion is controlled by the amount of substance available and fluid resistance. Since the Argent soil had a high concentration of C and a comparatively low concentration of N, C diffusion may have occurred at fluid resistance (water content) levels lower than the water content needed for soluble N to diffuse. Fluxes of high C:N ratio substrates in the Argent soil may have occurred when water contents were high, and induced immobilization.

Others have found similar results. Stanford and Epstein (1974) found that mineralization in soils with wide C:N ratio substrates shows a distinctly non-linear response at high water contents and may be related to an increase in N immobilization at near-optimum moisture contents. Myers et al. (1982) also found a curvilinear response at high water potentials in some soils. Six of nine soils that followed a curvilinear response had characteristics conducive to increased immobilization, as Stanford and Epstein (1974) found, but three did not. Myers et al. (1982) proposed a model that is based on the ratio of water content to the potentially available water and accounts for the curvilinearity found in some soils (Equations VI-6,VI-7):

$$Y = bX + (1-b)X^2 \tag{VI-6}$$

where Y is net N mineralization expressed as a proportion of the maximum, and X is

$$X = \frac{(w - w_o)}{(w_{\max} - w_o)} \tag{VI-7}$$

where w is the measured θ_v, w_o is the θ_v at -4.0 MPa, w_{max} is the θ_v at -0.3 MPa, and b is a curvature coefficient.

While this model may provide a better method for empirically estimating the effect of soil water content on N mineralization, no studies have been conducted to determine b from independent soil properties; b must be observed empirically.

While our study did not specifically address this process, our data lend observational evidence to suggest that immobilization may have increased when soil water contents were high. In order to effectively simulate annual N supply rates across converted agricultural fields and cutover forests, this relationship must be elucidated and defined based on measurable site characteristics, such as C:N ratio. Even so, our results show promise for using this relatively simple process model to estimate soil N supply.

The use of the potentially mineralizable N concept to define the pool of N available for decomposition and the maximum rate of decomposition has merit. Furthermore, adjusting this potential rate for the major soil environmental factors was sufficient to estimate annual soil N supply within 20% on two highly contrasting forest soils. Because the monthly soil N supply was not accurately estimated on either site, this model would have less usefulness for plantations fertilized several times throughout a growing season in irrigation water (fertigation). Several more detailed process models exist that simulate multiple substrate pools, microbial community dynamics, and N transformations, but each requires many inputs unattainable by forest managers. In general, these models must also be calibrated (predicted outputs compared with measured production) to fit various parameters for individual soils. Our approach, which has been used successfully by Campbell et al. (1988) for Canadian wheat fields but heretofore has not been attempted for forest soils, needs only soil-specific values for mineralizable N, the water content at field capacity, and soil climate. The procedure used to estimate mineralizable N is cumbersome, but may be estimated from rapid laboratory methods (Gianello and Bremner 1986, Scott et al. 2003). The water content at field capacity can be estimated from soil survey data, soil texture and bulk density or direct measurement. Soil climate remains as the most intensive measurement requirement. Our results indicated that, even though our water content adjustment factor may not account for immobilization at high soil water contents, soil N supply can be reasonably estimated with our model. Furthermore, simplified soil water balance models should be developed to describe the general pattern of soil water content and be based on readily available historical climate data and soil information.

However, the use of this soil N supply model to refine N fertilizer estimates requires the elimination of other limiting factors. Managers must ensure that other nutrients are not limiting, or this budget approach will not be useful. Finally, further research needs to elucidate the fertilizer and native soil N uptake efficiencies for different site types and species. These efficiencies must account for N leaching, denitrification, fixation, etc.

CONCLUSIONS

High rates or frequent doses of N fertilizer are commonly needed to maintain high growth rates in intensive hardwood plantations. The amount of fertilizer needed will be a function of plant demand and soil supply, but we have no good estimates of soil N supply across the range of soil types needed. In order to estimate soil N supply across sites, we attempted to model soil N production with a simple process model developed from established theories and measurable site properties that would not require calibration. Overall, the model was adequate for predicting cumulative soil N production on two highly contrasting soil types. Annual measured soil N production was about 27 mg kg^{-1} on the cutover pine plantation's Argent soil and about 25 mg kg^{-1} on the converted agricultural field's Norfolk soil. Predicted estimates for the Argent and Norfolk soils were 27 and 20 mg kg^{-1}, respectively. Since the aerobic incubation alone estimated that the Argent soil would have 50% more soil N production than the Norfolk soil, this model adequately described the cumulative effects of soil climate and mineralization rate on soil N supply. Our data suggest that the relationship between water content and N production needs to be better refined on soils conducive to immobilization. Further work needs to be done to quantify the influence of water availability on soil N mineralization and immobilization and develop simple approaches to estimating soil water content on various soil types

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CHAPTER VII. RAPID INDICES OF POTENTIAL NITROGEN MINERALIZATION FOR INTENSIVELY MANAGED HARDWOOD PLANTATIONS

ABSTRACT

Hardwood response to N fertilizer is highly site-specific. Methods for estimating soil N supply and, in turn, fertilizer rates, are needed. Models exist that may be able to estimate soil N supply through time, but they require an estimate of each soil's potentially mineralizable N, which is usually much less than half the total soil N. Because the procedure to measure mineralizable N is time consuming and costly, we tested three rapid methods for estimating it on six converted agricultural fields and seven cutover pine sites currently in intensively managed sweetgum plantations on the eastern coastal plain of the U.S. Two procedures (anaerobic incubation and hot KCl extract) were not useful for estimating mineralizable N in either ag field soils or cutover pine soils. The third index, a 3-day incubation of rewetted soils previously dried, was linearly correlated to mineralizable N ($p<0.0001$, $R^2=0.88$). This method, which heretofore had not been tested in forest soils, worked best for the cutover soils ($p<0.0051$, $R^2=0.89$) and less so for the ag field soils ($p<0.0977$, $R^2=0.45$). However, none of the procedures estimated potentially mineralizable N better, across all sites, than total N ($p<0.0001$, $R^2=0.93$). Total N was not effective, however, in estimating mineralizable N within the ag field sites ($p<0.1903$, $R^2=0.31$). Because the drying-rewetting flush index worked well on both site types, because it has the ability to estimate soil microbial biomass, and because it can be performed at little cost and with standard lab equipment, this method can help refine fertilizer estimates for intensively managed hardwood plantations.

INTRODUCTION

Nitrogen (N) fertilizer applications to forest systems are generally limited to the correction of diagnosed tree deficiencies, and then only in intensively managed plantation systems. Plantation forest systems have been structured around relatively nutrient efficient species, e.g. *Pinus* spp., that achieve acceptable production with relatively little input (Bowen and Nambiar, 1984). These plantations become N-limited during or shortly after canopy closure, and a combination of thinning and fertilization is generally sufficient to synchronize N supply with plant N demand. Short-rotation woody crop (SRWC) systems are the most intensively-managed forests, and are usually grown in 5- to 20- year cycles for rapid production of wood that is used for pulp or fuel. The tree species used in SRWC in the Southeast are generally deciduous hardwoods that are less N efficient due to greater N concentrations required by the trees and a complete renewal of foliage each year. The greater N demand by these intensively managed hardwoods creates an asynchrony between soil N supply and tree N demand well before canopy closure. Repeated applications of fertilizer are needed to minimize N deficiencies (van Miegroet et al., 1994), but we do not know the optimal N fertilizer rate and timing that will maximize plantation productivity and minimize N export from the system, especially on a species- and site-specific basis.

Nitrogen fertilizer recommendations can be determined using an agronomic budget model (Stanford, 1973) modified for deciduous, perennial plants and estimates of foliage biomass and soil N supply (Equation VII-1).

$$N_f = \frac{\left(Y_{dry} N_y\right) - e_s N_s - e_y N_y}{e_f} \qquad \text{(VII-1)}$$

where: N_f = N fertilizer need

Y_{dry} = Biomass

N_y = N concentration in biomass

N_s = Soil N supply

$e_{s,f,y}$ = Uptake efficiencies from soil, fertilizer, and resorption, respectively

The most difficult measurement is that of soil N supply. Soil N supply, or the quantity of mineral N available for plant uptake through time, is highly dynamic and represents only a very small fraction of total soil N. Soil N is mostly contained within soil organic matter, but chemical and physical constraints to microbial decomposition limit the potentially mineralizable N to 5-40% of total soil N (Stanford and Smith, 1972). Within this pool of potentially mineralizable N, the rate at which it becomes available is controlled largely by soil climate.

Campbell et al. (1988) showed that the rate at which soil N becomes available could be estimated with a measure of potentially mineralizable N (N_0) (Stanford and Smith, 1972) and soil climate. Unfortunately, the standard measure of N_0 involves a minimum 24-wk laboratory incubation and field moist soil. Shorter incubation times generally only measure the contribution of microbial biomass and soluble N sources, whereas longer incubations are thought to be indicative of the whole active fraction. Field moist soil is needed to avoid disturbing or modifying the microbial biomass. For these reasons, several rapid methods of estimating potential soil N supply have been studied (Keeney, 1980; Binkley and Hart, 1989). Most of the indices were originally developed for agricultural soils, but several have been tested in forest soils as well.

Marginal agriculture fields have been used as growing sites for most hardwood plantations throughout the southern US (Groninger et al., 2000). Unfortunately, marginal agricultural lands are not always affordable or available in geographical proximity to fiber processing facilities, and harvested, or cutover, forest sites are needed for SRWC. Compared to harvested forest sites, ag fields tend to be more fertile with respect to nutrient cations and phosphorus and have other attributes amenable to intensive plantation management. Cutover forest sites, though, are generally less eroded and tend to have much higher quantities of soil organic matter (Richter et al., 2000). However, the organic matter in the cutover forest sites is generally more recalcitrant and has a much higher C:N ratio than ag field soils, especially when N-fixing legumes such as soybeans (*Glycine max* (L.) Merr). or peanuts (*Arachis* spp.) have been grown.

Because the SOM chemistry of ag field and cutover forest soils is different, indices that work well within each soil type may not work well when both soil types are tested simultaneously. Since both ag fields and cutovers are being converted to SRWC plantations, an index of N_0 that works well across both site types is needed.

The most common indices include short-term incubations in aerobic or anaerobic conditions and chemical extractions (Binkley and Hart, 1989). Of the incubation indices, the 7-day anaerobic incubation (Waring and Bremner, 1964; Powers, 1980) is common and has been used with success in both agricultural soils and forest soils. Because nitrification is not as dominant in some acidic forest soils as in agricultural soils, the measurement of NH_4^+-N in the anaerobic technique has appealed to forest soils scientists (Pritchett and Fisher, 1987). The hot KCl extraction (Gianello and Bremner 1986) has also been tested in several studies in both agricultural (Jalil et al. 1996, Sembiring et al., 1988) and forest soils (Hart and Binkley, 1985), although Hart and Binkley (1985) did not find it to be a useful index in pine plantations. Recently, Franzluebbers et al. (1996) showed that the CO_2 released after oven-drying and rewetting soils was closely related to N mineralization and microbial biomass, and Franzluebbers et al. (2000) showed that this flush was related to the active fraction of soil organic matter. Therefore, the objectives of this study were to determine the ability of these three indices to estimate N_0 determined by a 24-wk aerobic incubation.

MATERIALS AND METHODS

Site Descriptions

Surface soils (0-20 cm) were collected from six converted agricultural fields and six pine cutover sites in southeast Virginia and central and southern South Carolina. The sites selected for this study represent the gradient of site types currently explored by forest industry for sweetgum plantations on the southeastern Atlantic coastal plain (Donald Kaczmarek, MeadWestvaco Corporation, and Michael Kane, International Paper Corporation, personal communication). The soils on these sites vary widely due to landscape position, parent material, and prior land use. The particular soils sampled in this study were meant to represent more specific site types. Within the converted ag fields sampled, the Norfolk, Goldsboro, and Lynchburg series represented the upper, middle, and lower portions, respectively, of a catena common throughout the upper and middle coastal plain. The Coxville soil was a poorly to very poorly drained soil found in depressional areas within the Lynchburg soils. The Wagram series was a sandy alluvial soil found close to rivers in the northern region of the study area. Within the loblolly pine cutover sites sampled, the Argent, Meggett, Yauhannah, and Yemassee soils were found in proximity to each other. The Argent and Meggett soils were found on low-lying clay flats and were similar to the Coxville series in landscape position and drainage. The Yauhannah and Yemassee soils, found on slightly elevated positions, are similar to the Lynchburg and Goldsboro soils. The Byars series represented soils found in Carolina Bays, while the Myatt series was found on a broad stream terrace. Both series were selected, in part, due to their extremely acidic nature.

At each site, a bulk soil sample of the surface 20 cm was collected from five 7-cm diameter auger samples. Each sample was subdivided into two replicate samples, which were prepared differently. One of the replicate samples was kept at field moisture and room temperature until analyzed within one week, while the other was air-dried.

Soil Characterization

The dry soil samples were analyzed for total carbon (C), N, pH, and texture. Total carbon was determined via infrared analysis (LECO Total Carbon Analyzer, LECO Corp., Saint Joseph, MI). Total N was determined on a 5 g soil sample using the macro-Kjeldahl digestion method (Bremner and Mulvaney, 1982) followed by colorimetric analysis (Bran+Luebbe TRAACS 2000, Oak Park, IL). Soil pH was determined with a combination electrode in the supernatant of a 1:2 soil:water mixture (McLean, 1982). Texture was determined by the hydrometer method (Gee and Bauder, 1986).

Aerobic Incubation (N_0)

Potential N mineralization (N_0) was determined on the fresh soil samples. The samples were sieved through a 2-mm sieve at the field moisture content. Approximately 40 g of soil were mixed thoroughly with 150 g silica sand and placed in 5 cm diameter by 15 cm long PVC tubes and sealed with one-hole rubber stoppers. A separate 10-g subsample was dried at 105 ^oC to determine moisture content. The samples were leached when prepared and every 2 weeks thereafter with 250 mL of 0.01 M $CaCl_2$, followed by 100 mL of a minus-N Hoagland solution described by Burger and Pritchett (1984). After the solution was allowed to leach through the samples gravimetrically, a vacuum was applied to drain the samples to field capacity (-0.03 MPa). The leachates for the 2nd through 24th week were collected and analyzed for NH_4 and NO_3-N with a TRAACS 2000 colorimetric autoanalyzer (Bran&Luebbe Corp., Oak Park, IL). A first-order model for N_0 (Equation VII-2) was fit to the cumulative N production using PROC NLIN in SAS (SAS Institute 2000) to determine N_0.

$$N_T = N_0 \times (1 - e^{-kT}) \qquad \text{(VII-2)}$$

where N_T = Cumulative N production in mg N kg^{-1} soil at time T

N_0 = Potentially mineralizable N

K = N mineralization rate at 35 ^oC and -0.03 MPa water tension

T = time

Extractable N

Extractable NH_4^+ and NO_3^- were measured by placing 5 g soil and 50 mL of 2M KCl in a 100 mL centrifuge tube. The tubes were shaken for 30 min. and the extracts filtered through Whatman #2 filters. The concentrations of NH_4^--N and NO_3^--N were determined on a colorimetric autoanalyzer. Each sample was performed in triplicate.

Anaerobic Incubation Index (ANI)

We used the anaerobic incubation method of Keeney (1982) and Powers (1980) as one rapid index of $N_{0.}$ Five g of air-dried, sifted soil were added to 1-cm diameter by 10 cm length glass tubes, which were then filled with deionized water. The samples were then incubated at 40 ^{o}C for 7 d. After incubation, the samples were extracted with 50 mL of 2 M KCl and analyzed for NH_4^+-N using a colorimetric autoanalyzer. Each sample was performed in triplicate.

Hot KCl Extraction (HKCL)

This procedure was a modified version of Gianello and Bremner (1984). Three g of air-dried and sieved (2-mm) soil and 20 mL of 2M KCl were added to 150 mL digestion tubes. The tubes were heated at 100ºC for 4 h in a digestion block. The tubes were allowed to cool, and then the extract was filtered through Whatman #42 filter paper. Ammonium (NH_4^+) and nitrate (NO_3^-) in the extracts were determined with a colorimetric autoanalyzer. Each sample was performed in triplicate.

Drying Rewetting CO_2 Flush (CFLUSH)

We indirectly measured N_0 with a microbial activity index developed by Franzluebbers et al. (1996). Fifty g of air-dry, sifted soil were placed in a 50 mL plastic beaker and dried at 60ºC for 24 h. The samples were then wetted to 60% water-filled pore space (WFPS). We determined the total pore space by subtracting the volume of soil particles from the total soil volume in the beaker (Equation VII-3). We then determined the amount of water needed to fill 60% of these pores using the density of water (1.0 g cm^{-3}).

$$\text{Pore Space} = V_T - \frac{\text{Soil}_{\text{Mass}}}{\text{Soil}_{\rho_p}} \qquad \text{(VII-3)}$$

Where: V_T = Total volume (cm^3)

$\text{Soil}_{\text{Mass}}$= mass of soil dried at 60 °C (g)

Soil_{ρ} = particle density of soil (2.65 g cm^{-3})

The samples were then placed in a sealed glass jar (475 cm^{-3}) along with another 50mL plastic beaker containing 10 mL of 0.5 M NaOH and incubated for 72 hr at 35ºC. The CO_2 released was captured in the alkali trap and measured by titrating to a phenolphthalein endpoint with HCl. To do this, 1 mL of concentrated $BaCl_2$ solution and 5 drops of phenolphthalein were added to the NaOH and then titrated with 0.5 M HCl.

Data analysis

The influence of previous land use on N_0 and the three indices was investigated using t-tests. Linear regression was used to compare each method's accuracy and usefulness for estimating N_0. All procedures were performed in SAS (SAS Institute, 2000).

RESULTS AND DISCUSSION

The soil properties related to mineralizable N were strikingly different between the cutover pine plantations and the converted ag fields. Total soil C and N were over 3.7 times greater in the surface 20 cm of the cutover pine plantations compared to the converted agricultural sites (Table VII-1). Total N ranged from 192 to 424 and 624 to 2920 mg kg^{-1} on the ag field and cutover soils, respectively. Soil substrate quality, as measured by the C:N ratio, was not different between the two land use categories, but varied from 19.0 to 39.9 and averaged 28.1. Soil pH averaged 5.53 at the ag fields compared to 4.70 at the cutover pine sites. Soil textures ranged from fine sand to sandy clay, but most soils were loams across both site types.

Table VII-1. Soil properties of 12 sites that represent the range of operational conditions for operational sweetgum plantations in the southeastern U.S.

Site type	Soil series	Taxonomy	Total C	Total N	C:N	pH	Texture
			%	mg N kg^{-1}			
Converted agricultural fields	Norfolk 1	Typic Kandiudult	0.57	200	28.4	5.23	sandy loam
	Goldsboro	Aquic Paleudults	0.83	302	27.3	5.76	sandy clay loam
	Norfolk 2	Typic Kandiudult	0.51	192	26.8	5.21	sand
	Coxville	Typic Paleaquult	0.91	424	21.6	6.14	sandy clay
	Wagram	Arenic Kandiudult	0.84	254	32.8	4.83	loamy sand
	Lynchburg	Aeric Paleaquult	1.01	357	28.1	6.00	sandy loam
Cutover loblolly pine plantations	Argent	Typic Endoaqualf	3.09	863	35.8	5.56	sandy loam
	Meggett	Typic Albaqualf	2.45	1130	21.6	4.77	silt loam
	Yauhanna	Aquic Hapludult	2.49	624	39.9	4.57	sandy loam
	Yemassee	Aeric Endoaquult	2.73	1120	24.3	5.15	sandy loam
	Byars	Umbric Paleaquult	3.70	1540	24.1	4.53	sandy clay loam
	Myatt	Typic Endoaquult	5.60	1550	36.2	3.84	loam
	Mouzon	Typic Albaqualf	5.53	2920	18.6	4.46	clay loam
Ag fields	**MEAN**		**0.78**	**288**	**27.5**	**5.53**	
	s.d.		0.19	91.3	3.62	0.52	
Cutovers	**MEAN**		**3.66**	**1390**	**28.7**	**4.70**	
	s.d.		1.37	751	8.34	0.55	
	p-value[1]		**0**	**0.0079**	**0.751**	**0.02**	

[1] p-values were determined with a two-sample t-test, using pooled variances or Satterthwaite's method for unequal variances when necessary

Potentially mineralizable N (N_0) was about 3 times greater in the cutover sites compared to the ag sites. Within the ag field sites, N_0 averaged 38.5 mg kg-1 and only varied by 16 mg N kg^{-1} (30.7 to 46.7 mg kg^{-1}), while N_0 averaged 116 mg kg-1 and varied by 176 mg N kg^{-1} in the cutover sites (46.9 to 223 mg kg^{-1}) (Figure VII-1, Table VII-2). Our original goal was to test each index across the range of site types without regard to previous land history. The relative lack of variation in N_0 on the ag field soils reduces the importance of an accurate index on these soils; the ag soils all varied less than 20% from the mean, while the cutover soils varied as much as 92% from the mean.

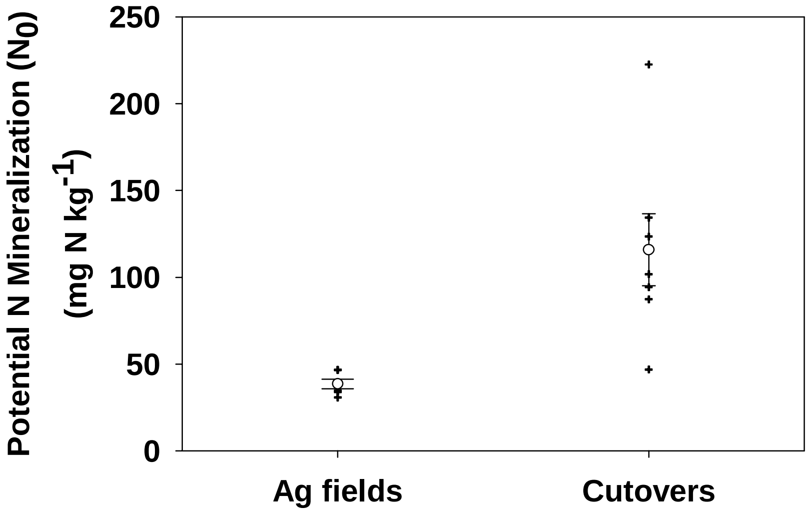

Figure VII-1. Potential N mineralization determined aerobically using first-order kinetics (N_0) on converted ag fields and pine cutovers. Open circles represent site type means, and bars represent one standard error.

We first tested total soil N to see if it could predict N_0. Binkley and Hart (1989) concluded that total N can be used to index N availability across a regional scale. On a local scale, differences in substrate quality may be more important and total N may not adequately index N_0. We hypothesized that, although soil organic matter varied widely across the site types, the difference in substrate quality between the ag fields and cutover sites would limit the usefulness of using total N as an estimate of N_0. However, total N was a good predictor of N_0; linear regression explained 93% of the variance in N_0 (Figure VII-2). Furthermore, the greatest residual was only 32 mg N kg^{-1}, and only two soils (Argent and Yauhannah) had residuals over 10 mg N kg^{-1}. The close mathematical relationship between N_0 and total N across the two site types was partly due to the relative importance of the cutover soils.

Table VII-2. Measurement and indices of potentially mineralizable N (N_0) of 12 soils across the range of operational conditions for operational sweetgum plantations in the southeastern U.S.

Site type	Soil series	N_0[1]	ANI[2]	HKCL[3]	CFLUSH[4]
		-----mg N kg^{-1}-----			mg C kg^{-1}
Converted agricultural fields	Norfolk 1	30.7	4.9	9.9	87
	Goldsboro	34.0	10.6	9.3	103
	Norfolk 2	34.6	9.3	12.5	91
	Coxville	38.7	28.8	14.9	146
	Wagram	46.6	9.6	10.5	117
	Lynchburg	46.7	18.8	12	138
Cutover loblolly pine plantations	Argent	46.9	30.5	22.3	243
	Meggett	87.4	32.4	52.7	229
	Yauhanna	94.4	19.0	26.6	197
	Yemassee	101.7	35.9	27	246
	Byars	123.5	31.4	29.5	307
	Myatt	134.3	8.3	35.2	365
	Mouzon	222.5	112.4	223	452
Ag fields	**MEAN**	**38.5**	**13.7**	**11.5**	**114**
	s.d.	6.76	8.67	2.05	24.3
Cutovers	**MEAN**	**115.8**	**38.6**	**59.5**	**291**
	s.d.	54.8	33.9	72.8	90
	p-value[5]	**0.0095**	**0.1041**	**0.1318**	**0.0016**

[1] N_0 was determined by a 24-wk incubation and first-order kinetics, where Cumulative N supply=N_0*(1-e^{-kt})

[2] ANI refers to a 7-day anaerobic incubation and extraction index of N_0

[3] HKCL refers to a Hot KCl extraction index of N0

[4] CFLUSH refers to the CO_2 released (expressed as mg C kg^{-1}) after drying at 60 ^{0}C and rewetting to 60% water filled pore space

[6] p-values were determined with a two-sample t-test to compare ag fields versus cutovers, using pooled variances or Satterthwaite’s method for unequal variances when necessary

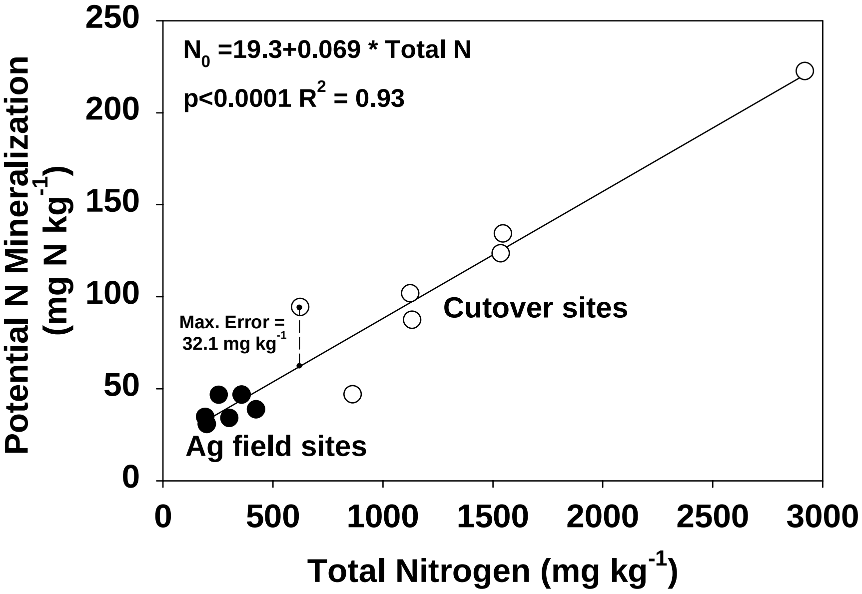

Figure VII-2. Relationship of potential N mineralization determined aerobically using first-order kinetics (N_0) and total nitrogen.

The anaerobic index (ANI), which has been used in both forested and agricultural soils as an index of N_0 was not a good indicator across the soils studied, especially for forest soils. Extracted N was, as with N_0, about 3 times greater in the cutover pine sites than in the ag fields, but the difference between land uses was not significant ($p<0.1041$) (Table VII-2). About 14 mg N kg^{-1} was extracted after anaerobically incubating the ag field soils (36% of N_0), while about 39 mg N kg^{-1} (33% of N_0) was extracted from the cutover site soils. The range of index values was 23.9 mg N kg^{-1} on the ag field sites and 104 mg N kg^{-1} on the cutovers. Although the relationship between this index and N_0 was significant ($p<0.0013$) and had an R^2 of 0.63, much of the variance was explained because of the influence of the Mouzon soil, which had the highest N_0 and ANI values (Figure VII-3A, Table VII-2). We reanalyzed the data without the Mouzon soil and found that a linear relationship was not significant ($p<0.2703$) and only explained 12% of the variation (Figure VII-3B). We had no reason to expect ANI to perform differently on the Mouzon soil compared to the other soils. Although the Mouzon soil had almost twice the total N of the next highest soil, it had over 3 times more N extracted after the anaerobic incubation than the next highest soil. Although the Mouzon soil differed from the other soils in several properties (Table VII-1), we could not detect any patterns to the lack of correlation between the ANI and $N_{0.}$

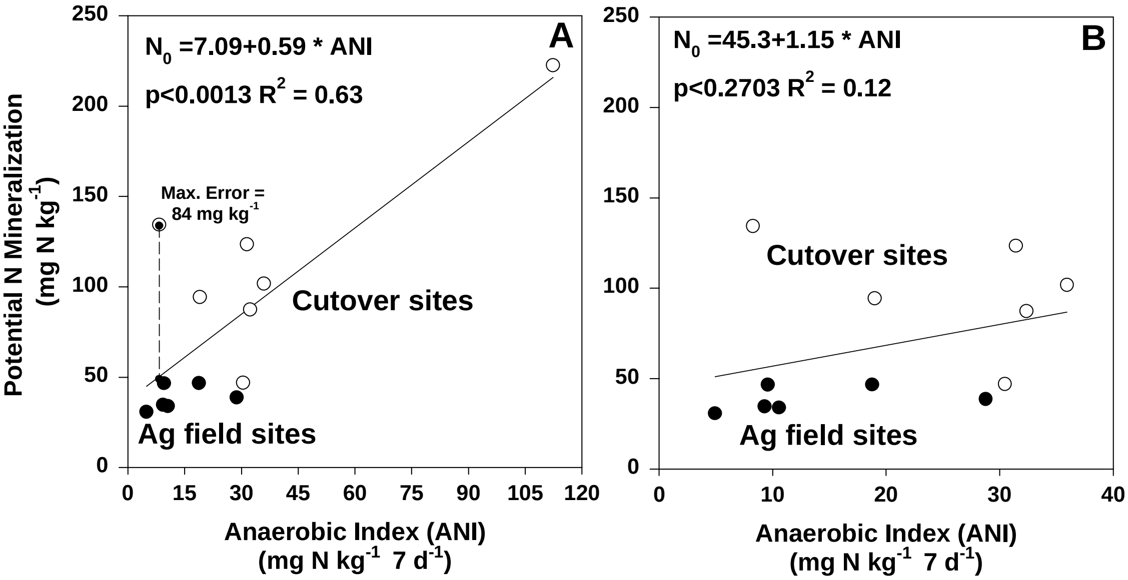

Figure VII-3. Relationship between potential N mineralization determined aerobically using first-order kinetics (N_0) and a 7-day anaerobic incubation. Figure VII-3A has all sites included; Figure VII-3B has all but the Mouzon soil included to illustrate the lack of relationship among the remaining soils.

The hot KCl extraction index (HKCL) was also a poor index of N_0. As with ANI, about 30% of N_0 was extracted in the ag field soils (11.5 mg kg^{-1}) (Table VII-2), while, unlike ANI, about 51% of N_0 (59.5 mg kg^{-1}) was extracted on the cutover sites. Again, the Mouzon soil, in which 100% of the N_0 was extracted by HKCL, altered the results considerably. About 33% of N_0 was extracted from the other cutover site soils. A linear relationship between the HKCL extract and N_0 was significant ($p<0.0002$) and had a R^2 of 0.73 (Figure VII-4A) when all soils were analyzed. When the Mouzon soil was removed from the analysis (Figure VII-4B), the cutover pine site soils exhibited non-linear trends that were not related to measured soil properties; the regression was still significant ($p<0.0056$), but its fit was not as good (R^2=0.55).

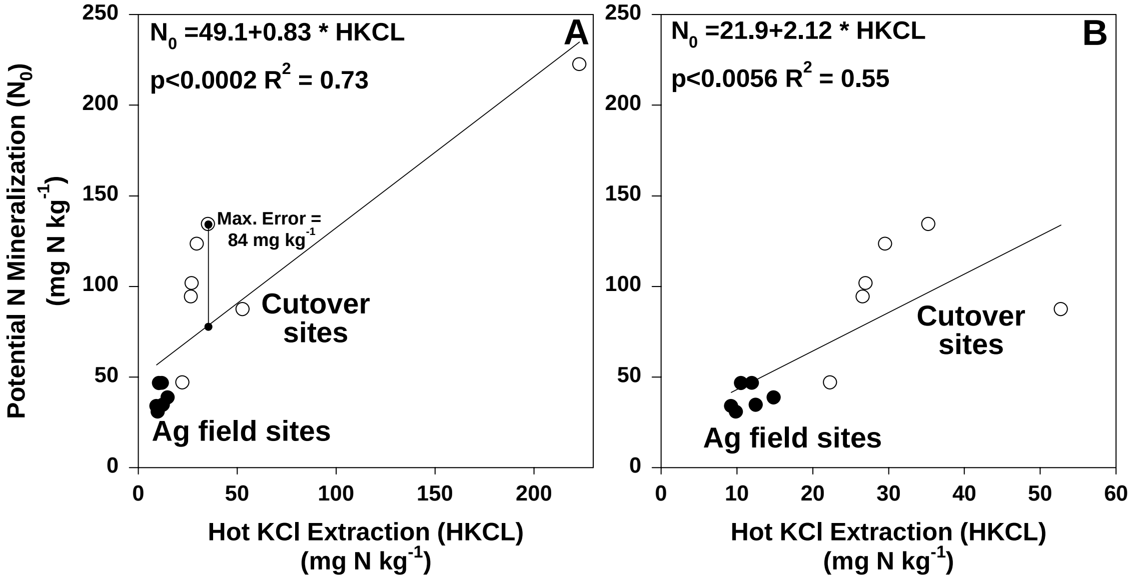

Figure VII-4. Relationship between potential N mineralization determined aerobically using first-order kinetics and a chemical extraction index.

The CO_2 flush index (CFLUSH) was a good index of $N_{0.}$ The ag field soils released 114 mg C kg^{-1}, while the cutover site soils released 291 mg C kg^{-1} in the three-day incubation. These values correspond to CO_2-C:N_0 ratios of 2.96 and 2.51, respectively. A linear relationship between N_0 and the CFLUSH index was significant ($p<0.0001$) and had a good fit ($R^2=0.88$). This method was almost as good as total N for estimating N_0. Unlike the ANI and HKCL indices, the CFLUSH index worked equally well across the entire range of sites. This index may also be used to estimate microbial biomass (Franzluebbers et al., 1996) and the active fraction of the SOM. Furthermore, this index can be performed without expensive analytical apparatus.

Across the range of site types encountered, we found that absolute substrate amount (total N) was the best predictor for N_0 based on R^2 values, and total N is routinely offered as a soil test from commercial soil laboratories. Because the CFLUSH index does require more time than total N and is not more accurate than total N across both converted ag fields and pine cutovers, our findings suggest that total N is the preferred measurement. However, within a given site type, the CFLUSH technique may be the preferred index.

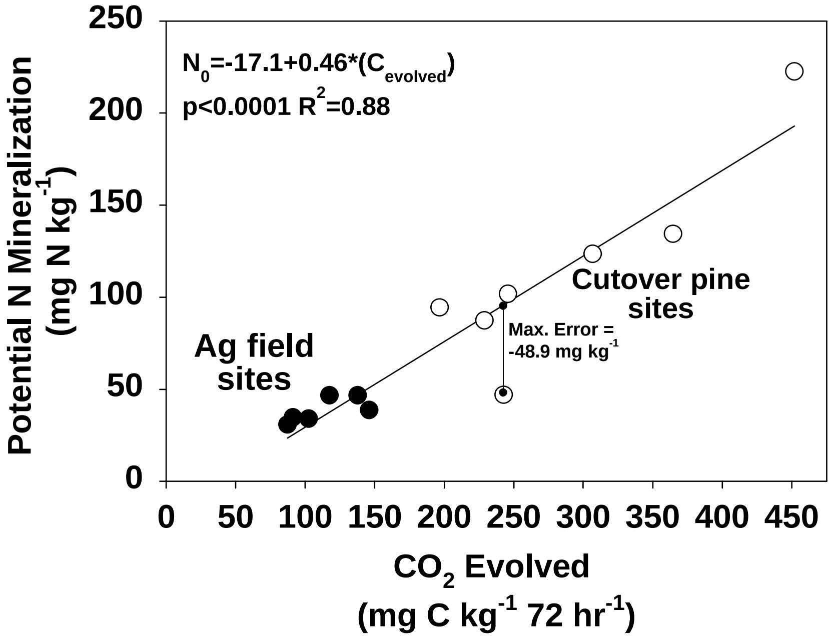

Figure VII-5. Relationship between potential N mineralization determined aerobically using first-order kinetics and a the CO_2 evolved in 72 hours after drying at 60 °C and rewetting to 60% water-filled pore space.

We performed separate regression analyses by site type for the total N and CFLUSH techniques to investigate which technique was better within a site type. Within the cutover sites, either technique appeared to be adequate. Both total N ($p<0.0018$) and CFLUSH ($p<0.0051$) were significant predictors of N_0, and both explained about 90% of the variation in N_0 (93 and 89 %, respectively). However, within the ag field sites, which had a much narrower range of N_0, total N was not linearly related to N_0 ($p<0.1903$) and explained only 31% of the variation. CFLUSH, on the other hand, was significant ($p<0.0977$) and explained almost half the variation (45%). These results indicate that CFLUSH may be a better overall indicator of N_0 for both converted ag fields and cutover pine stands.

CONCLUSIONS

Repeated fertilization of SRWC is necessary to maintain high levels of productivity, and accurate fertilizer recommendations are needed across wide ranges in soil types. Across the range of sites explored for SRWC management in the Southeast, previous land use was the most important factor in determining potentially mineralizable N. Although the substrate quality of these two site types might have been different, the total quantity of soil organic matter was the more important influence on N_0, and thus total N had the best correlation with N_0. The anaerobic incubation and chemical extraction methods were not well correlated with N_0, even when a highly influential soil was removed from the analysis. The CFLUSH index, which measured the CO_2 produced following the rewetting of an oven-dried sample, was well correlated with N_0 and was superior to total N for estimating N_0 on ag field sites. This procedure may also have merit for estimating soil microbial biomass and the active soil organic matter in both agricultural and forest soils, and should be explored further.

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CHAPTER VIII. A CHARACTERIZATION OF SOIL AND SITE FACTORS INFLUENCING THE PRODUCTIVITY AND MANAGEMENT OF INTENSIVE-CULTURE HARDWOOD PLANTATIONS ON THE ATLANTIC COASTAL PLAIN

ABSTRACT

Successful hardwood plantation management has been difficult to achieve due to the sensitivity of hardwood species to site and soil conditions and resource availability. Productive hardwood plantations require careful matching of species to site characteristics, herbaceous and woody weed control, and site-specific soil management. We studied the soil fertility, soil rooting environment, and potential nitrogen supply on 14 young, successful sweetgum plantations across the coastal plain of Virginia, North Carolina, and South Carolina. The sites were compared in two ways; previous land-use (converted ag fields versus cutover pine stands) and drainage class (well-drained, moderately-well to somewhat poorly drained, poorly to very poorly drained). In general, the converted ag fields were more fertile with respect to phosphorus and potassium and had low acidity compared to the cutover pine sites. Both converted ag fields and cutover pine sites had conditions unfavorable to root growth or gas exchange in the subsoils, but some ag fields with moderately well to somewhat poorly drained soils had excessively high bulk densities within 20 cm of the surface as a result of repeated trafficking. The surface soils of the converted ag fields had lower total soil organic matter (1.27%), total nitrogen (933 kg ha^{-1}), mineralizable nitrogen (126 kg ha^{-1}) and potential nitrogen supply rates (24 kg ha^{-1} 30 d^{-1}) than the cutover sites (5.17%, 3780 kg ha^{-1}, 363 kg ha^{-1}, 71 kg ha^{-1} 30 d^{-1}, respectively). However, individual cutover sites had much less mineralizable N and lower N supply rates than were expected, and soil organic matter was not an adequate predictor of site-specific soil N supply. This generalized soil information covered the range of site types suitable for sweetgum management in the Atlantic coastal plain. It should help forest industry and private landowners interested in intensive

hardwood plantations to recognize potential soil limitations and seek more detailed information to ensure productive hardwood plantations.

INTRODUCTION

Short-rotation woody crops and intensively cultured hardwood plantations are potentially important sources of biomass energy (Hohenstein and Wright, 1994; Cook and Beyea, 2000) and hardwood fiber. Hardwood fiber is needed from plantations in the southern and Atlantic coastal plain in areas with limited supplies of natural hardwood fiber or during wet periods when natural hardwood lands cannot be harvested. Intensively cultured hardwoods and short-rotation woody crops were initiated in the South following the 8th Southern Forest Tree Improvement Conference in 1965 (Steinbeck, 1999). Many of the early attempts at hardwood plantations resulted in low initial survival, and growth rates were similar to natural hardwood stands (Robison et al., 1998), but after three decades of research, intensively managed hardwood plantations are now viable due to improvements in weed control, site-species matching, improved seedling quality, and soil management (Ford, 2000).

Compared to conifers, hardwoods tend to be more sensitive to soil and site conditions and more water and nutrient demanding. Proper matching of species to site and soil characteristics helps ensure adequate survival and better growth rates (Kellison et al., 1979; Groninger et al., 2000), but all sites have some water or nutrient limitations. Understanding and managing species-specific water and nutrient needs and soil-specific water and nutrient supply rates remains the most difficult and least understood component of hardwood plantation management (Tuskan, 1998). Unfortunately, few opportunities exist to study long-term growth trends across soil and site types because viable plantation management is still in its relative infancy in the southern and Atlantic coastal plain. Because little data exists to empirically relate long-term growth to soil and site properties, general principles of soil productivity must be used to describe and characterize soil and site properties influencing productivity and management of short-rotation woody crops.

Based on preliminary studies, it is evident that the most important soil factors in determining hardwood plantation success are 1) soil physical condition, 2) water availability during the growing season, 3) nutrient availability, and 4) aeration (Baker and Broadfoot, 1979). Given a site's climate, these factors can be more generally grouped as the soil air/water balance and the ability to supply nutrients, especially nitrogen (N). The soil air/water balance is an important regulator of gas exchange, root growth, and water availability to trees and the soil microbial community. The soil microbial community, in turn, converts soil organic N to plant-available N. Compared to N, most required plant nutrients are relatively easy to supplement via fertilization at planting. Nitrogen, though, is difficult to manage since the majority of soil N supply arises from the microbial decomposition of soil organic matter and fertilizer N is not retained well in the soil. Site and soil properties that affect the quantity and chemistry of soil organic matter and the microclimate in which the microbial community functions are important for understanding soil-specific N supply and hardwood plantation productivity.

The objectives of this study were to 1) determine the range of site and soil types viable for plantation management of sweetgum, a commonly planted hardwood species, 2) describe the general site and soil characteristics important to plantation establishment and productivity on sites representative of the spectrum of potential site types, and 3) determine the potential nitrogen supplying capacity of each site type.

MATERIALS AND METHODS

Site Selection

In 1998, we selected fourteen sites in South Carolina, North Carolina, and Virginia that represented the range of site types currently in forest industry-managed operational or research sweetgum plantations (Table VIII-1). After identifying the major site types currently in sweetgum plantations throughout the Atlantic coastal plain, we selected individual sites based on the following criteria: 1) sites selected must be a viable sweetgum plantation, defined as two-year old or older plantations with survival and initial growth acceptable to forest industry, 2) sites must represent a site type with significant land area of importance to a variety of landowners in the Atlantic coastal plain, and 3) sites must be unfertilized or operationally fertilized more than two years prior to sampling. After selecting the sites that represented viable plantations, we observed that land-use history (converted agricultural fields versus cutover pine stands) and drainage class were important contrasts to be studied.

Table VIII-1. Location and classification of the sites and soils studied in Virginia, North Carolina, and South Carolina.

Site (Abbreviation)	County	Soil Series	Taxonomy	Land use	Drainage Class
Block 818 (NOH)	Northampton, NC	Wagram	Arenic Kandiudult	Pine	Well
Burch Fiber Farm (BFF)	Bamberg, SC	Norfolk	Typic Kandiudult	Ag field	Well
Trice RW46 (TR)	Sumter, SC	Norfolk	Typic Kandiudult	Ag field	Well
Scarborough 10 (SC10)	Richland, SC	Goldsboro	Aquic Paleudult	Ag field	Mod. well
Block 73 (SOH)	Southampton, VA	Goldsboro	Aquic Paleudult	Pine	Mod. well
Featherbed (FEB)	Colleton, SC	Yauhannah	Aquic Hapludult	Pine	Mod. well
Scarborough 2 (SC2)	Richland, SC	Lynchburg	Aeric Paleaquult	Ag field	S. poorly
Beech Hill (BEH)	Dorchester, SC	Yemassee	Aeric Endoaquult	Pine	S. poorly
North Cherokee (NC)	Colleton, SC	Argent	Typic Endoqualf	Pine	Poor
Trice 8 (TR8)	Sumter, SC	Coxville	Typic Paleaquult	Ag field	Poor
Block 221S	Isle of Wight, VA	Myatt	Typic Endoaquult	Pine	Poor
Dick West (DIW)	Dorchester, SC	Mouzon	Typic Albaqualf	Pine	Very poor
Powell Bay (POB)	Berkeley, SC	Byars	Umbric Paleaquult	Pine	Very poor
Jacksonboro (JAB)	Colleton, SC	Meggett	Typic Albaqualf	Pine	Very poor

The soils comprised two soil orders (Alfisols and Ultisols), two suborders (Udic and Aquic moisture conditions), five great groups (Kand-, Hapl-, Pale-, Alba-, Endo-) and five subgroups (Arenic, Aquic, Aeric, Typic, and Umbric) (Table VIII-1). Although we recognized that land-use history and drainage class were important site attributes, we did not select sites specifically to test the influence of these two site attributes on soil properties. However, these two attributes provided the most consistent basis for general comparison of site types. All of the soils had either been in row-crop agriculture or pine plantations prior to sweetgum plantation establishment. The soils previously used for row-crop agriculture were located in the middle coastal plain, while those previously in pine plantations were found in the lower coastal plain. Because the middle coastal plain is a geologically older landscape (Buol 1973), the ag fields were all Ultisols and many were Paleudults or Paleaquults, while the cutover pine plantations were both Alfisols and Ultisols.

The soils were also distributed across a drainage gradient that we grouped into three categories to assist interpretations. The well-drained category (WD) consisted of soils with either excessively well drained or well-drained soils. The moderate drainage category (MD) consisted of moderately well or somewhat poorly drained soils, and the poor drainage category (PD) consisted of poorly and very poorly drained soils. Although slopes never exceeded 3 percent on any of the sites, topographic position had a strong influence on drainage class. Within the middle coastal plain, four soils (Norfolk (WD), Goldsboro (MD), Lynchburg (MD), Coxville (PD)) were selected that represented a soil catena. The Norfolk soil was a well-drained ridge-top soil. The Goldsboro and Lynchburg were located at top (near the shoulder) and bottom (near the foot-slope) of a hill-slope, respectively, and the Coxville (PD) was a poorly drained depression located at the toe-slope of the hill. Within the pine cutovers, the Yauhannah and Yemassee soils (MD) were located at top and bottom of a hill-slope, respectively. The Mouzon and Meggett soils (PD) were both depressional soils in the lower coastal plain. The Argent soil (PD) selected was poorly drained, but occupied a slightly higher position on the landscape than the Mouzon or Meggett soils. The Wagram soil (WD) was a well-drained, sandy river terrace soil, and the Byars soil (PD) was representative of Carolina Bay soils. No well-drained soils were selected in the lower coastal plain.

Site Characterization and Soil Analysis

In the winter of 1998-1999, each soil and site was characterized and sampled for general site characteristics and soil chemical and physical properties. The sites were characterized for previous land use and neighboring vegetation, landscape position, and mapped soil series. On each site, a point representative of the entire site type was selected. Each soil profile was described to 1.5 m using standard techniques.

In addition to the soil horizon description, four layers of the upper meter were arbitrarily defined for sampling based on horizon, depth, and any special properties evident in approximate increments of 20, 20, 30, and 30 cm. The exact thickness depended on horizon differentiation and soil properties. Any soil horizon that was substantially different from neighboring horizons, e.g., A or Ap horizons, were not included with any other horizons in a given layer, while thick, relatively consistent horizons, e.g. deep B horizons, were split into separate layers. The overall goal of separating the soil into 4 layers was to standardize the sampling process between sites while maximizing the quality of the soil information as it relates to soil fertility, soil N supply, and soil air/water balance.

Five 5-cm diameter, 5-cm tall intact soil cores were taken from each of the four layers at the soil pit with a core sampling hammer. Prior to analysis, the intact core samples were placed in a plastic container with approximately 0.5 cm water to enable the micro-pores to fill with water through capillary action. The soil cores were analyzed for water retention at -0.005 MPa with a tension table to estimate macroporosity (Kohnke, 1968), water retention at -0.03 (field capacity) with a pressure plate extractor (Klute, 1986), and bulk density (Blake and Hartge, 1986). Gravimetric water content was determined on loose soil samples at -1.5 MPa (wilting point, θ_{wp}) with a pressure membrane and converted to θ_v by multiplying by the soil bulk density (ρ_b), which was determined by drying the cores at 105 °C for 48 hrs. Water holding capacity was determined as the difference in volumetric water held at field capacity and wilting point.

Loose soil samples were taken at five locations within 3 m of the soil pit with a bucket auger. If the site was bedded, all sample points were located on the beds. One subsample was collected with a bucket auger from each soil layer at each of 5 sample points and composited by layer for a total of 4 composite samples per site; one per each layer. The composite loose samples were split into two bags for differential preparation. For most analyses, the samples were air-dried at 25 ^{o}C and sieved (2 mm). The second sample was sieved at the field moisture content (2 mm) within 3 d after sampling, and stored at 25 ^{o}C for less than 3 d before analysis.

Soil N mineralization potential (Stanford and Smith, 1972) was determined with a 24 wk aerobic incubation (Burger and Pritchett, 1984). Approximately 40 g of 2-mm sieved soil was mixed thoroughly with 150 g silica sand and placed in 5 cm diameter by 15 cm long PVC tubes and sealed with one-hole rubber stoppers. A separate 10 g subsample was dried at 105 ^{o}C to determine moisture content. The samples were leached every 2 wk with 250 mL of 0.01 M $CaCl_2$, followed by 100 mL of minus-N Hoagland solution. After the solution was allowed to leach through the samples gravimetrically, a vacuum was applied to drain the samples to approximately field capacity (-0.03 MPa). The biweekly-collected leachates were analyzed for NH_4 and NO_3^--N with a TRAACS 2000 colorimetric autoanalyzer (Bran&Luebbe Corp., Oak Park, IL). A first-order model for N_0 (Equation VIII-1) was fit to the cumulative N production using PROC NLIN in SAS (SAS Institute, 2000).

$$N_T = N_0 \times \left(1 - e^{-kT}\right) \qquad \text{VIII-1}$$

Total soil carbon and nitrogen were analyzed to determine the quantity of substrate available for microbial processes and for an index of organic matter “quality”. Total carbon was determined via infrared analysis (LECO Total Carbon Analyzer, LECO Corp., Saint Joseph, MI). Total N was determined on a 5 g soil sample using the macro-Kjeldahl digestion method (Bremner and Mulvaney, 1982) followed by colorimetric analysis (Bran+Luebbe TRAACS 2000, Oak Park, IL). Soil pH was determined with a combination electrode in the supernatant of a 1:2 soil:water mixture (McLean, 1982). Exchangeable acidity was determined with 1 *M* KCl in a 1:50 soil to solution extract (Thomas, 1982). The exchangeable base cations calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+) were determined by extraction with 1 *M* NH_4OAc (pH 7) and analysis via inductively coupled plasma (ICP) spectroscopy (Jarrell-Ash Corp., Franklin, M.A.)(Thomas, 1982). An index of available P was determined by extraction with the Mehlich I double-acid extract (0.05 *N* HCl + 0.025 *N* H_2SO_4) in a 1:4 soil to solution extract (Mehlich,

1953) followed by ICP spectroscopy (Jarrell-Ash Corp., Franklin, M.A.). Soil texture was determined with the hydrometer method (Gee and Bauder, 1986).

Data Analysis

Because the sites were originally selected to adequately characterize the potential sweetgum plantation landbase and not to test specific site attributes, we did not attempt to develop a rigorous experimental design to test the effects of land-use type or drainage class. Furthermore, land-use type and drainage class were not mutually exclusive; no cutover sites were found on well-drained soils, and only one ag field was found on a poorly drained soil. This is not surprising, since most well drained to somewhat poorly drained soils on the Atlantic coastal plain have, at some time, been cleared for agriculture. Poorly and very poorly drained soils, however, are not as suitable for row-crop agriculture due to their excessively wet nature. Given these limitations, the data were analyzed using pooled t-tests and analysis of variance at α=0.10 for land-use type and drainage class, respectively. These statistical analyses are not necessarily indicative of true cause and effect relationships, but they helped to guide the analysis.

The four soil layers were grouped into two general soil strata for analysis. Layers designated as A or E horizons were classified as “surface” strata, while all B horizons were classified as “subsoil” strata. The weighted average for each soil property was determined by multiplying each layer by the relative volume of the surface or subsoil strata it composed. For example, if two A horizons comprised a surface strata but the first was 20 cm thick and the second was 10, the weighting factor was 0.67 for the first A horizon (20/20+10) and 0.33 for the second (10/20+10). This weighting was done to group the data into more meaningful and comparable groupings.

RESULTS

Organic Matter and Nitrogen Supply

Soil organic matter was highly influenced by land-use history and drainage class (Figure VIII-1, Table VIII-2). The concentration of organic matter in the surface horizons was over 4 times greater on cutover sites (5.17%) than on converted ag fields (1.27%). Soil organic matter averaged about 0.63% across the subsoils of both land-use types.

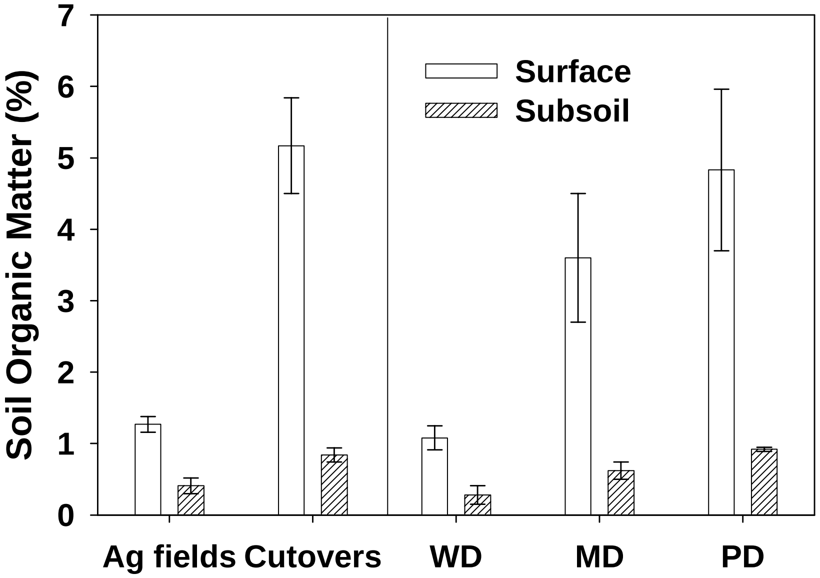

Figure VIII-1. Soil organic matter of 14 viable sweetgum plantations across land-use categories and drainage class. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils. Error bars indicate one standard error.

Table VIII-2. Selected properties of the soil organic matter of 14 surface and subsoil soils supporting viable sweetgum plantations in the Atlantic coastal plain.

Soil series-Site	**Horizon**	**SOM**	**-----N-----**		**C:N**	**-----N_0-----**		**-----N_{30}-----**		**N_0/N**
		%	mg kg^{-1}	kg ha^{-1}		mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	%
Wagram-VA818	Surface	1.41	254	480	32.7	46.6	88	10.0	19.0	18
	Subsoil	0.83	75	982	20.1	8.6	117	1.4	17.6	12
Norfolk-BFF	Surface	0.87	192	815	26.6	34.6	147	7.3	31.1	18
	Subsoil	0.77	98	1190	16.2	14.3	178	1.2	14.9	16
Norfolk-Trice	Surface	0.97	200	557	28.5	30.7	86	4.5	12.5	15
	Subsoil	1.02	107	1370	19.4	13.2	168	1.1	14.3	12
Goldsboro-SC10	Surface	1.39	302	1110	27.1	34.0	124	6.5	23.9	11
	Subsoil	0.94	105	1320	16.5	6.7	88	0.9	11.4	6
Goldsboro-SOH	Surface	6.66	1300	2260	30.2	N/A		N/A		N/A
	Subsoil[1]	1.94	143	1350	25.0	N/A		N/A		N/A
Yemassee-FEB	Surface	5.75	437	1330	37.8	63.8	193	10.3	31.2	14
	Subsoil	1.07	187	2040	16.3	12.1	134	1.6	17.4	6
Lynchburg-SC2	Surface	2.89	274	1260	32.3	39.6	183	6.9	31.8	15
	Subsoil	0.77	171	1990	12.5	12.8	150	1.3	15.0	7
Yauhannah-BEH	Surface	6.55	801	4960	22.4	87.4	541	13.5	83.4	12
	Subsoil	1.92	264	2070	20.2	28.9	218	2.6	19.5	10
Argent-NC	Surface	6.12	680	1210	53.0	46.9	84	7.9	14.1	7
	Subsoil	3.33	224	2750	26.3	40.6	505	3.2	39.7	18
Coxville-TR8	Surface	1.55	424	1380	21.5	38.7	126	8.7	28.4	9
	Subsoil	3.04	351	4980	15.7	17.8	255	3.4	49.3	5
Myatt-VA221S	Surface	7.37	1200	4800	35.9	105	417	20.3	87.4	9
	Subsoil	0.58	171	1990	20.1	16.9	199	2.2	26.3	10
Mouzon-DIW	Surface	7.27	2280	7050	18.6	188	590	47.5	151.4	8
	Subsoil	1.11	513	5570	12.6	34.9	376	4.8	49.5	7
Byars-POB	Surface	4.62	1090	4850	25.5	87.9	390	14.6	64.7	8
	Subsoil	0.96	467	5080	15.9	25.7	281	6.3	69.5	6
Meggett-JAB	Surface	3.34	835	3840	24.6	70.4	329	14.4	67.5	9
	Subsoil	0.68	215	1740	18.3	17.3	139	1.9	15.1	8

Across the drainage classes, the PD surface soils had about 4.83% organic matter, which was about 35% greater than that on the MD soils (3.60%) and over 4.5 times greater than that of the WD soils (1.08%) (Figure VIII-1). The subsoils of the PD and MD soils averaged about 0.77% organic matter, which was over twice that of the WD soils (0.28 %). The effect of landscape position on SOM is even more pronounced when viewed from within each land-use category. Within the ag fields, SOM in the surface soils averaged about 0.95% on the two WD soils and about 2.2 % on the MD soils. The one PD ag field soil measured (Coxville-TR8) was intermediate at 1.55%. Within the cutover sites, SOM was 1.4% on the one WD soil (Wagram), averaged about 6.3% on the MD soils, and about 5.6% on the PD soils. The PD soils, however, were quite site-specific. Two of the PD soils had the highest SOM of any of the sites (7.3 and 7.4%), while two had only about half that (4.6 and 3.3 %).

Total N and potentially mineralizable N followed similar trends as organic matter (Figures VIII-2, VIII-3, Table VIII-2). Total and mineralizable soil N averaged 3780 kg ha^{-1} and 363 kg ha^{-1}, respectively, in the cutover site surface soils. These quantities were four and three times the quantities of total and mineralizable N, respectively, on the ag field sites (933 and 126 kg ha^{-1}). The subsoils of the cutover sites contained about 2800 kg ha^{-1} total and 265 kg ha^{-1} mineralizable N, respectively, while the ag sites had only 1970 kg ha^{-1} total and 159 kg ha^{-1} mineralizable N, respectively. The cutover sites contained over twice the total and mineralizable N as the ag sites over the entire 1 m depth. Cutover sites had about 6610 kg ha^{-1} total N and 630 kg ha^{-1} mineralizable N, while the ag fields had 2910 kg ha^{-1} total and 285 kg ha^{-1} mineralizable N, respectively.

As with organic matter, N increased in the surface soil as the drainage class progressed from WD to PD soils (Figures VIII-2,VIII-3, Table VIII-2). The PD surface soils contained the greatest amount of total and mineralizable N (4390 and 370 kg ha^{-1}, respectively), followed by the MD surface soils (2020 kg ha^{-1} total and 225 kg ha^{-1} mineralizable) and the WD surface soils (617 kg ha^{-1} total and 107 kg ha^{-1} mineralizable).

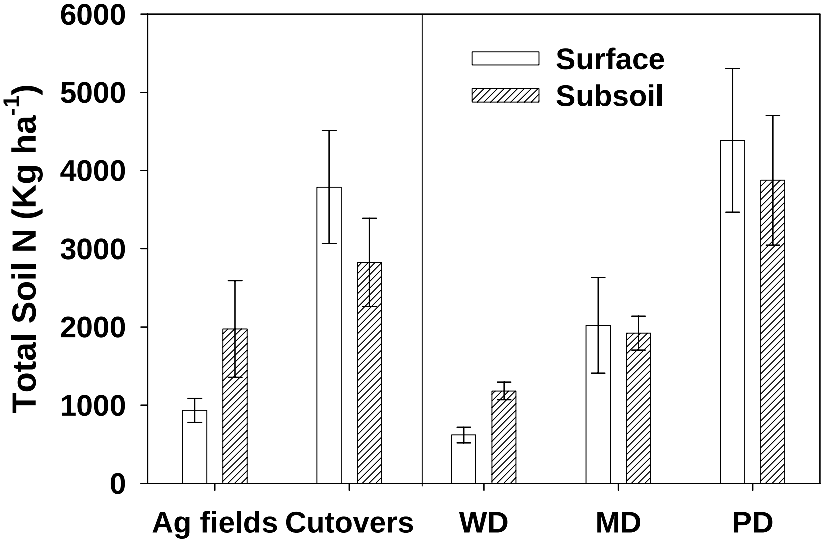

Figure VIII-2. Total soil nitrogen of 14 viable sweetgum plantations across land-use categories and drainage class. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils. Error bars indicate one standard error.

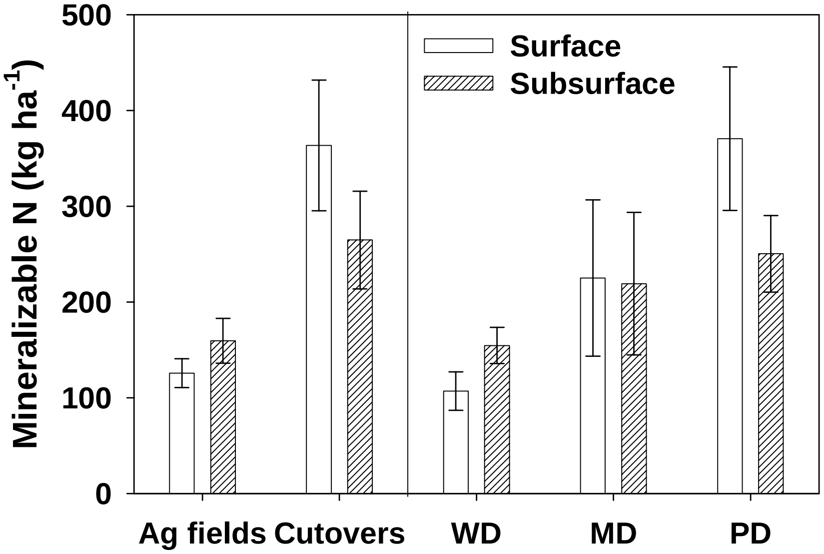

Figure VIII-3. Mineralizable nitrogen of 14 viable sweetgum plantations across land-use categories and drainage class. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils. Error bars indicate one standard error.

The quality of the organic matter as measured by the C:N ratio was remarkably similar across land-use types and drainage classes (Figure VIII-4). The cutover sites' surface soil C:N ratio (31) was similar to that of the ag field soils (28), but much more variation occurred in the cutover soils. The C:N ratio ranged from 18.6 to 53.0 in the cutover soils, but only from 21.5 to 30.2 in the ag field soils. The subsoil C:N ratios averaged 18 across both categories.

The C:N ratio of the surface soils varied widely (25.2 to 33.8) but were not different (Figure VIII-4). Similarly, the subsoil C:N was greatest on the MD soils (19.5) and lowest on the PD soils (16.5), but were not different because of large variation, especially within the MD soils.

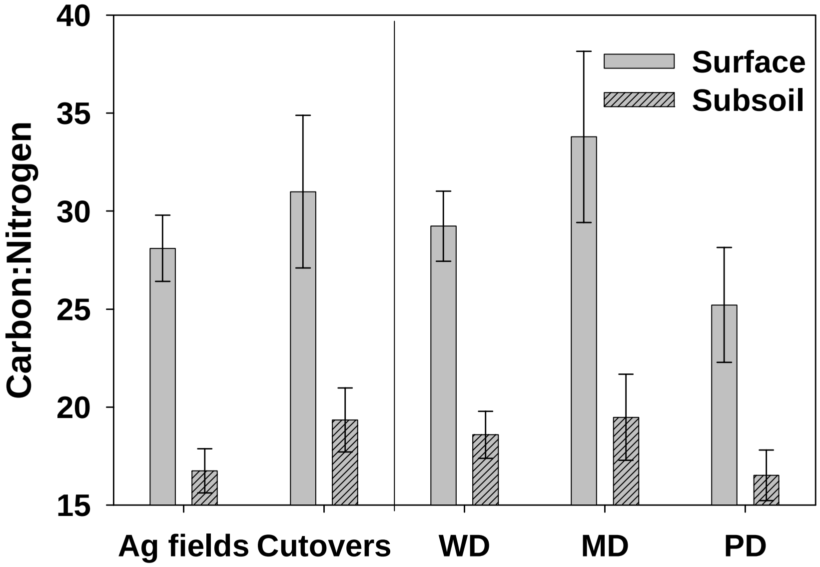

Figure VIII-4. Carbon to Nitrogen ratio of 14 viable sweetgum plantations across land-use categories and drainage class. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils. Error bars indicate one standard error.

About 10% of total N was mineralizable in the surface and subsoil of the cutover sites and the subsoil of the ag fields, while about 15% of the total N was mineralizable in the ag field surface soils (Figure VIII-5). The proportion of N that was mineralizable decreased as drainage class decreased. About 17 % of the total N of the WD surface soils, which had the coarsest soils, was mineralizable, while only 8.3 % of the total N on the PD soils was mineralizable. The MD soils averaged about 13 %.

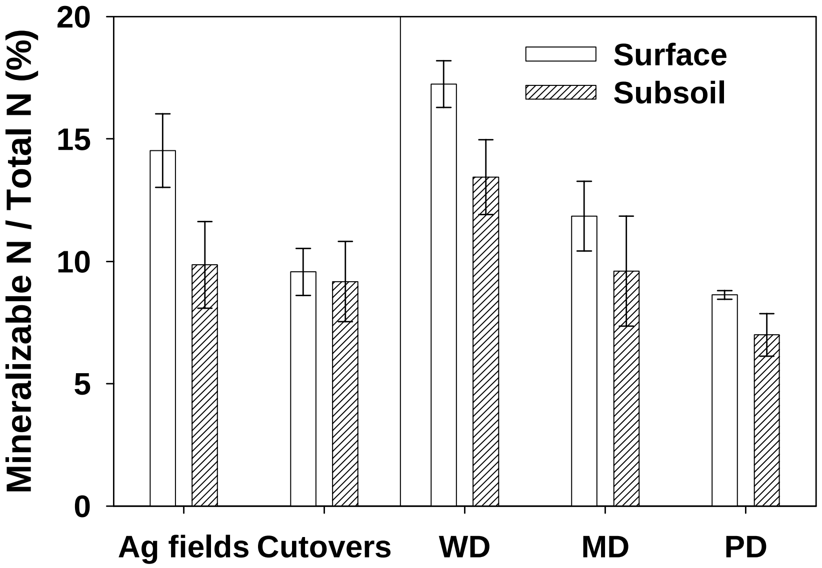

Figure VIII-5. Mineralizable N as a proportion of total N on 14 viable sweetgum plantations across land-use categories and drainage class. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils. Error bars indicate one standard error.

Because organo-clay complexes can physically protect organic matter from decomposition, we regressed the N_0:Total N ratio against clay concentration in the surface and subsoils across the drainage classes (Figure VIII-6). The proportion of total N that was mineralizable was significantly ($p<0.0038$, $R^2=0.54$) reduced by clay concentration. This pattern was not observed in the subsoils due to soils with clay concentrations greater than 30%. In the subsoils, the ratio of mineralizable to total N was not linearly related to clay concentration ($p<0.3109$), but N_0:Total N decreased as clay increased up to about 30% clay, at which point the N_0:Total N appeared to be unaffected by the % clay. We repeated the analysis on both surface and subsoils after removing soils with greater than 30% clay. When only those soils with less than 30% clay were considered, the N_0 : Total N ratio was linearly related to clay concentration for both surface soils ($p<0.0058$, $R^2=0.59$) and subsoils ($p<0.0006$, $R^2=0.83$). When grouped together, the relationship is even more significant ($p<0.0001$, $R^2=0.72$). Except for the Argent subsoil, less than 10% of the total N was mineralizable on soils with greater than 30% clay content. This suggests that organo-clay complexes are, in fact, physically protecting organic matter from decomposition.

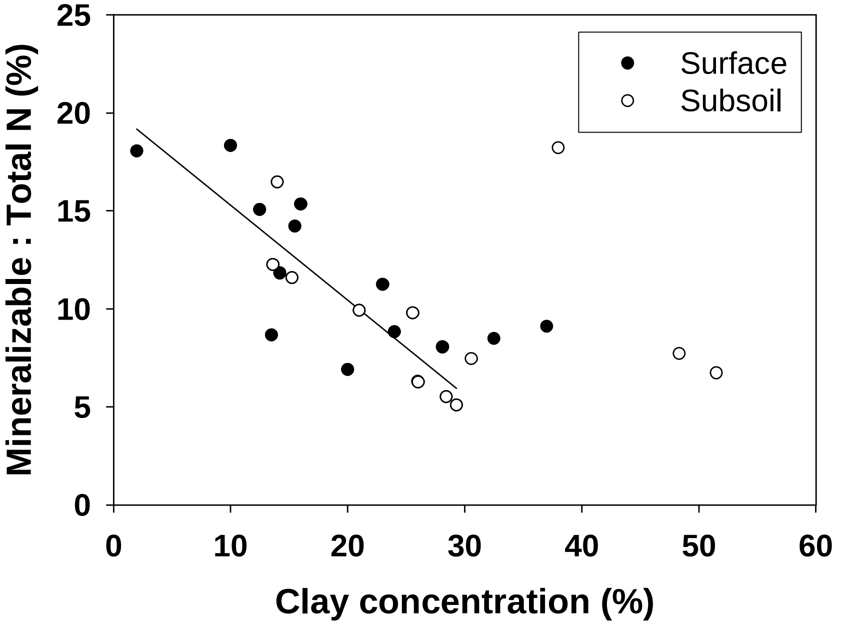

Figure VIII-6. Relationship of mineralizable N as a proportion of total N to clay content on 14 viable sweetgum plantations.

Because the amount of soil N supply is a function of not only the amount of mineralizable N but also its rate of mineralization, we projected the amount of N mineralized in 30 days at 25 °C and optimal moisture conditions using the first-order rate curves developed for each soil and modified for temperature with a Q_{10} approach (Stanford et al. 1973) (Figure VIII-7). In general, the results were very similar to mineralizable N, but the N_{30} value is a better measure of actual potential supply. The N_{30} of the surface soils was about 3 times greater on the cutovers (71 kg ha^{-1}) than on the ag fields (24 kg ha^{-1}). The subsoil N_{30} was 34 kg ha^{-1} on the cutover sites and 20 kg ha^{-1} on the ag fields.

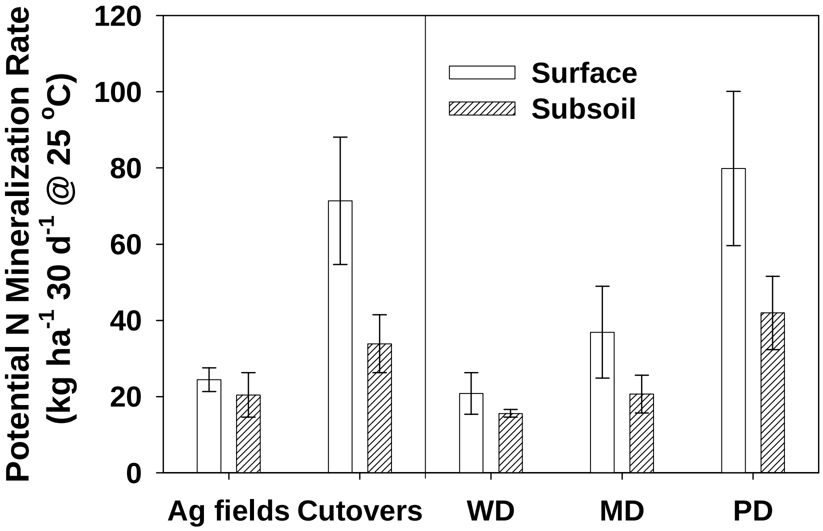

Figure VIII-7. Potential monthly N supply rate at 25 °C and optimal water content and assuming no immobilization or denitrification losses for 14 viable sweetgum plantations across land-use categories and drainage classes. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils. Error bars indicate one standard error.

The pattern across the drainage classes was similar to N_0 as well. The PD soils had an N_{30} of 80 kg ha^{-1}, which was almost 4 times the 21 kg ha^{-1} of the WD soils (Figure VIII-7). The MD soils were again intermediate, with 37 kg ha^{-1}. The subsoils had N_{30} of 42 kg ha^{-1} on the PD soils, 21 kg ha^{-1} on the MD soils, and 16 kg ha^{-1} on the WD soils.

Mineral Nutrient Fertility

Available soil P was similar between ag fields and cutovers in both surface soils and subsoils according to t-tests, but was very site-specific (Figure VIII-8, Table VIII-3). Available P of the ag field soils was about 2.5 and 1.5 times greater than the cutover soils for the surface and subsoils, respectively, but the variation on the ag fields was very high. With respect to soil P, the Wagram-VA818 site exhibited characteristics much more similar to other cutovers and its inclusion as an ag field caused some skewing of the data. If the Wagram site was analyzed as a cutover, the average surface soil available P was about 112 kg ha^{-1} on the ag fields and 35 kg ha^{-1} on the cutover sites. The range of the ag fields was over 230 kg ha^{-1}, while that of the cutover sites was only 35 kg ha^{-1}, even though we sampled 9 cutover sites and only 5 ag fields.

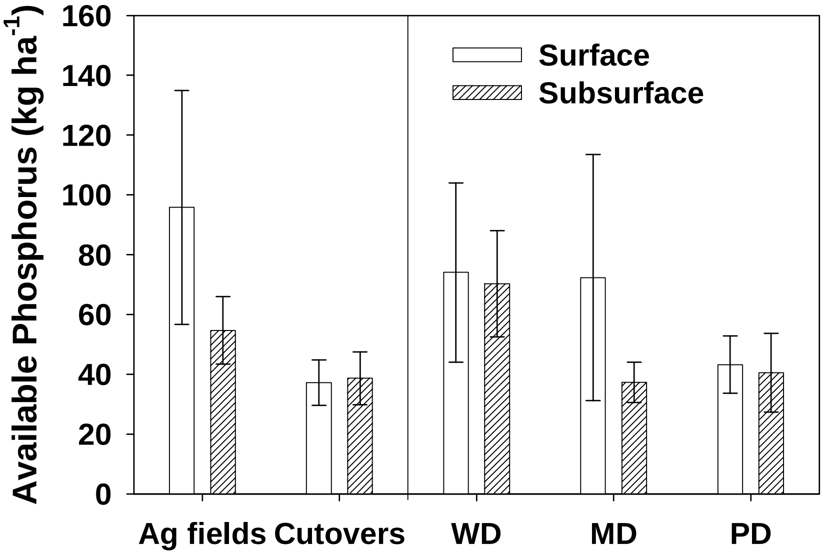

Figure VIII- 8. Available phosphorus (Mehlich I) for 14 viable sweetgum plantations across land-use categories and drainage classes. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils. Error bars indicate one standard error.

Surface soil available P was very similar across the WD soils and MD soils and averaged 73 kg ha^{-1}, but was only a little more than half that (43 kg ha^{-1}) on the PD soils (Figure VIII-8). Subsoil available P followed a different trend. The WD soils had about 70 kg ha^{-1}, but the MD soils and PD soils each had only about 39 kg ha^{-1}.

Exchangeable K was similar across both ag fields and cutovers in the surface soils, and averaged only about 200 kg ha^{-1} (Figure VIII-9). In the subsoils, however, exchangeable K was 739 kg ha^{-1} on the ag field soils and 545 kg ha^{-1} on the cutovers. Potassium increased in the surface soils from the WD soils and MD soils to the PD soils, but was similar across positions in the subsoils. The MD and WD soils averaged 144 kg ha^{-1} K in the surface soils, while the PD surface soils had over twice the exchangeable K (291 kg ha^{-1}). The subsoils averaged 636 kg ha^{-1} across drainage categories.

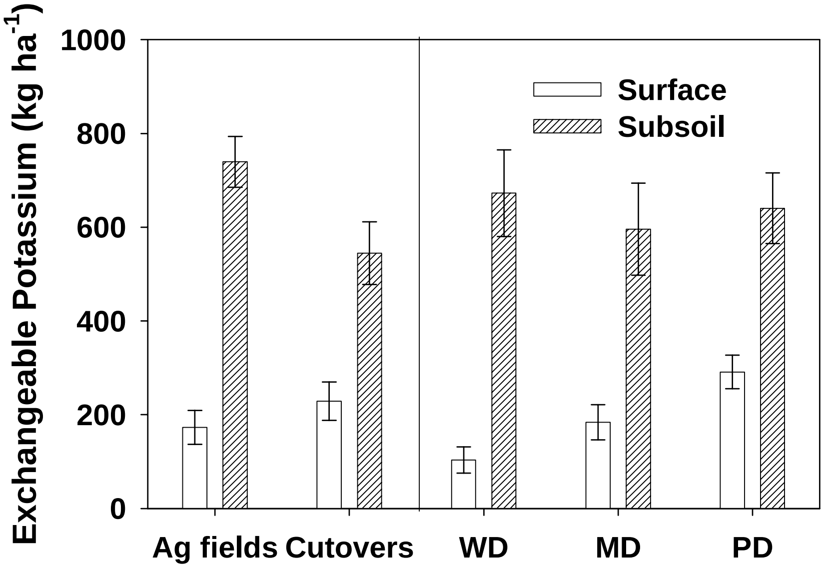

Figure VIII-9. Exchangeable potassium for 14 viable sweetgum plantations across land-use categories and drainage classes. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils. Error bars indicate one standard error.

Table VIII-3 Selected mineral nutrient status of 14 surface and subsoil soils supporting viable sweetgum plantations in the Atlantic coastal plain.

Site	Horizon	P		Ca		Mg		K		Al+ H	CEC	pH
		mg kg^{-1}	kg ha^{-1}	mg kg^{-1}	kg ha^{-1}	mgkg^{-1}	kg ha^{-1}	mgkg^{-1}	kgha^{-1}	cmol kg^{-1}		
Wagram-VA818	Surface	7.5	14	27	51	4.2	7.95	29.4	55.5	0.68	0.92	4.83
	Subsoil	5.1	64	34	459	10.3	138	37.8	489	0.67	1.08	4.94
Norfolk-BFF	Surface	24.4	104	54	229	4.6	19.7	35.8	152	0.53	1.05	5.21
	Subsoil	3.5	43	121	1470	19.5	237	64.3	781	0.56	1.97	5.23
Norfolk-Trice	Surface	37.5	104	90	251	8.4	23.2	36.3	101	0.35	1.19	5.23
	Subsoil	8.1	104	166	2120	9.8	125	58.5	748	0.63	2.28	5.43
Goldsboro-SC10	Surface	75.5	276	241	880	24.9	91.2	49.8	182	0.21	2.55	5.76
	Subsoil	2.3	30	229	2860	56.1	699	71.1	884	1.10	3.75	5.04
Golsboro-SOH	Surface	12.6	22	65	114	13.9	24.2	56.6	98.6	3.90	4.74	4
	Subsoil	4.3	50	12	114	11.8	116	46.2	428	2.96	3.27	4.36
Yemassee-FEB	Surface	11.5	35	118	354	14.4	44.4	45.2	148	1.76	2.95	4.71
	Subsoil	2.7	30	94	1020	33.5	362	37.0	404	4.26	5.33	4.80
Lynchburg-SC2	Surface	7.9	36	217	1000	41.0	191	59.2	275	0.18	2.52	5.94
	Subsoil	2.6	31	275	3190	88.1	1020	67.4	787	1.46	4.73	4.90
Yauhannah-BEH	Surface	8.7	54	341	2110	27.5	170	49.9	310	0.75	3.92	5.25
	Subsoil	8.6	64	257	2110	19.1	149	39.4	314	3.57	5.90	4.50
Argent-NC	Surface	6.0	11	509	906	206.2	367	50.2	89.4	0.56	6.57	5.56
	Subsoil	1.6	20	51	622	164.3	2050	60.8	755	8.22	10.2	4.86
Coxville-TR8	Surface	12.4	41	789	2570	97.6	318	83.0	271	0.03	7.75	6.14
	Subsoil	3.9	57	629	9050	85.3	1230	52.3	747	1.02	7.06	5.50
Myatt-VA221S	Surface	9.0	35	29	115	9.0	34.2	63.6	298	4.32	4.87	3.92
	Subsoil	1.1	14	21	251	4.4	50.4	34.9	407	4.35	4.56	4.31
Mouzon-DIW	Surface	18.6	57	1330	4180	169.9	534	134	423	3.66	16.8	4.59
	Subsoil	2.6	27	828	9410	77.9	864	69.2	774	14.8	22.5	4.45
Byars-POB	Surface	15.9	70	231	1030	26.9	119	47.5	208	2.07	4.30	4.63
	Subsoil	1.9	21	77	840	23.0	248	47.4	513	4.59	5.52	4.56
Meggett-JAB	Surface	3.0	14	991	4700	273.5	1340	53.9	257	1.42	12.0	4.90
	Subsoil	10.4	84	2290	18500	1540.9	12400	94.2	760	2.23	34.2	5.1

Soil pH was about 15 % greater on the ag fields compared to the cutover sites (Figure VIII-10). The surface soil pH averaged 5.52 on the ag fields and 4.70 for the cutovers. The subsoil pH was lower than the surface soil pH on both site types; 5.17 for the ag fields and 4.62 for the cutover sites. Neither surface or subsoil pH values were different across drainage classes, although the PD soils had an average surface pH of only 4.8, while the MD soils had a pH of 5.2.

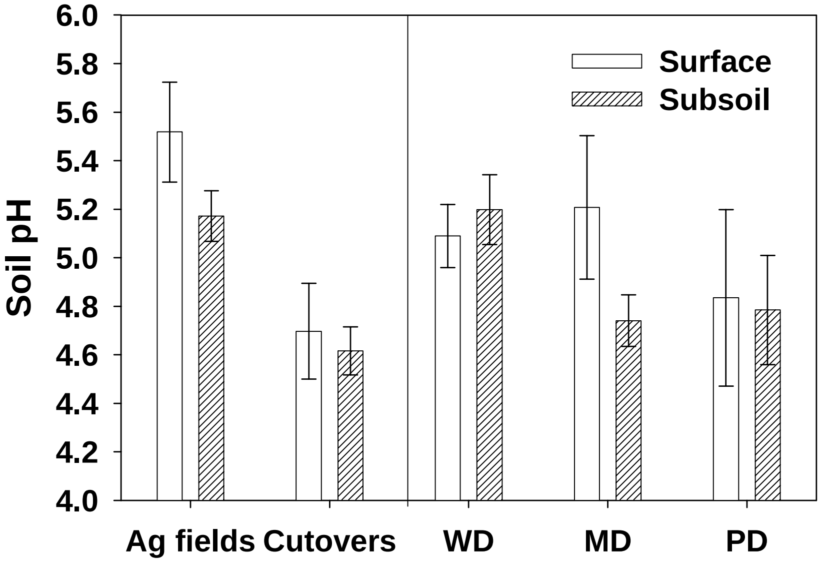

Figure VIII-10. Soil pH for 14 viable sweetgum plantations across land-use categories and drainage class. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils. Error bars indicate one standard error.

The effective CEC of the soil was calculated as the sum of the three main base cations Ca, Mg, and K and the two main acidic cations Al and H. The ag field soils had ECEC values of 2.66 and 3.48 cmol $^+$ kg^{-1} in the surface and subsoils, respectively (Figure VIII-11). The ECEC of the ag field surface and subsoils was primarily (88 and 74%, respectively) composed of base cations. The cutover sites had 7.02 and 11.4 cmol $^+$ kg^{-1} in the surface and subsoils, respectively, which were 2.5 and 3.3 times higher than the ag field soils. However, the proportion of ECEC due to base cations was much lower in the cutover soils. In the cutover surface and sub-soils, only 67 and 51% of the ECEC was occupied by Ca, Mg, and K.

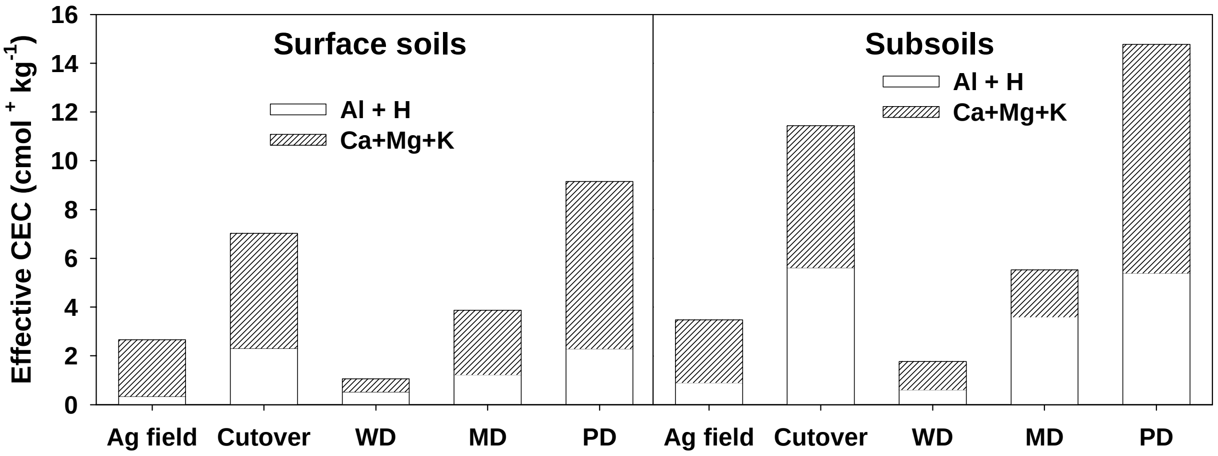

Figure VIII-11. Effective cation exchange for 14 viable sweetgum plantations across land-use categories and drainage classes. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils.

ECEC was much greater as relative elevation, and clay content, decreased; the surface soils had ECEC values of 1.05, 3.87, and 9.15 cmol $^+$ kg^{-1} in the WD soils, MD soils, and PD soils, respectively (Figure VIII-11). The pattern was even more pronounced in the subsoils. The WD subsoils had only 1.78 cmol $^+$ kg^{-1}, while the MD subsoils had about 3 times greater ECEC (5.53 cmol $^+$ kg^{-1}). The PD soils had the greatest subsoil ECEC of 14.8 cmol $^+$ kg^{-1}. The base saturation also increased in the surface soils as relative elevation decreased. Bases represented about half the ECEC in the WD soils, 68% in the MD soils, and 75% in the PD soils. In the subsoils, the WD soils and the PD soils both had about 65% base saturation, while the MD soils only had 35%.

Rooting Environment and Air/Water Balance

On average, the cutover soils were one textural class heavier (greater clay percentage) than the agricultural soils, and the subsoils of each category were about one class heavier than the surface soils. The average cutover surface and subsoil textures were sandy clay loams and clay loams, respectively, while those of the ag fields were sandy loams and sandy clay loams. Similarly, the soils increased in clay content by about one textural class for each decrease in slope position. In general, the WD soils had loamy sand surface soils and sandy loam subsoils, while the MD soils had sandy loam surface soils and sandy clay loam subsoils. The PD soils had the heaviest soils; the surface soils were sandy clay loams and the subsoils clay loams.

The surface soil bulk density was 1.52 on the ag fields, which was about 37% greater than the 1.11 g cm^{-3} bulk density of the cutover surface soils (Figure VIII-12, Table VIII-4). The average bulk density of the subsoils was 1.58 g cm^{-3}. Topography had little effect on bulk density; the surface soil bulk density averaged 1.31 g cm^{-3}, while the subsoil bulk density averaged 1.58 g cm^{-3} across all three drainage categories.

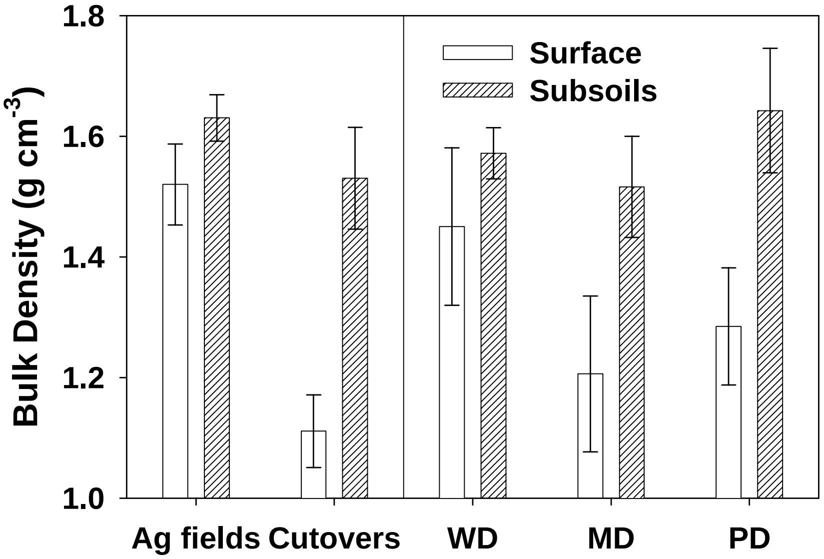

Figure VIII-12. Bulk density of 14 viable sweetgum plantations across land-use categories and drainage classes. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils. Error bars indicate one standard error.

Table VIII-4. Physical properties of the surface soils and subsoils of 14 surface and subsoil soils supporting viable sweetgum plantations in the Atlantic coastal plain.

Soil-Site	Horizon	Sand	Silt	Clay	Texture	Bulk Density	Total Porosity	Macro-Porosity	Avail. Water
		-------%-------				Mg m^{-3}	%	%	cm
Wagram-	Surface	90	0	10	ls	1.26	53	32	1.35
VA818	Subsoil	79	6	15	sl	1.49	44	20	6.96
Norfolk-	Surface	90	8	2	s	1.70	36	12	1.75
BFF	Subsoil	78	8	14	sl	1.63	38	19	6.25
Norfolk-	Surface	84	0	16	sl	1.39	48	22	2.00
Trice	Subsoil	76	10	14	sl	1.60	40	11	12.0
Goldsboro-	Surface	70	7	23	scl	1.59	40	12	3.45
SC10	Subsoil	50	24	26	scl	1.63	39	6	15.2
Goldsboro-	Surface	57	21	22	scl	0.87	67	21	6.20
SOH	Subsoil	55	22	24	scl	1.11	27	4	10.8
Yauhannah-	Surface	64	21	16	sl	1.07	60	23	3.45
FEB	Subsoil	44	30	26	l	1.56	41	7	8.40
Lynchburg-	Surface	84	4	13	ls	1.55	42	24	3.90
SC2	Subsoil	52	18	31	scl	1.66	37	5	11.0
Yemassee-	Surface	67	19	14	sl	1.27	52	16	9.85
BEH	Subsoil	56	18	26	scl	1.59	40	6	8.95
Argent-	Surface	61	19	20	l	0.89	68	31	4.60
NC	Subsoil	48	14	38	sc	1.55	42	6	16.4
Coxville-	Surface	61	2	37	sl	1.63	39	12	4.60
TR8	Subsoil	44	26	29	cl	1.78	33	1	19.3
Myatt-	Surface	53	34	14	sl	1.24	54	21	6.48
Block 221S	Subsoil	47	32	21	l	1.82	31	2	11.6
Mouzon-	Surface	32	36	33	cl	1.08	60	15	6.75
DIW	Subsoil	24	25	52	c	1.60	40	16	3.15
Byars-	Surface	69	3	28	scl	1.14	57	27	6.06
POB	Subsoil	56	16	28	scl	1.76	33	1	12.4
Meggett-	Surface	27	50	24	l	1.34	50	11	9.72
JAB	Subsoil	13	39	48	c	1.26	52	0	18.1

The macroporosity, or percentage of pores that are drained at -0.005 MPa, was about 20% across the surface soils, regardless of land-use type or position (Figure VIII-13). The subsoil of the cutovers, however, had only 5% macroporosity, which was about half that of the ag fields (10%). Similarly, the subsoils on the MD soils and PD soils had very low macroporosity (6 and 4%, respectively) compared to the WD soils (16%).

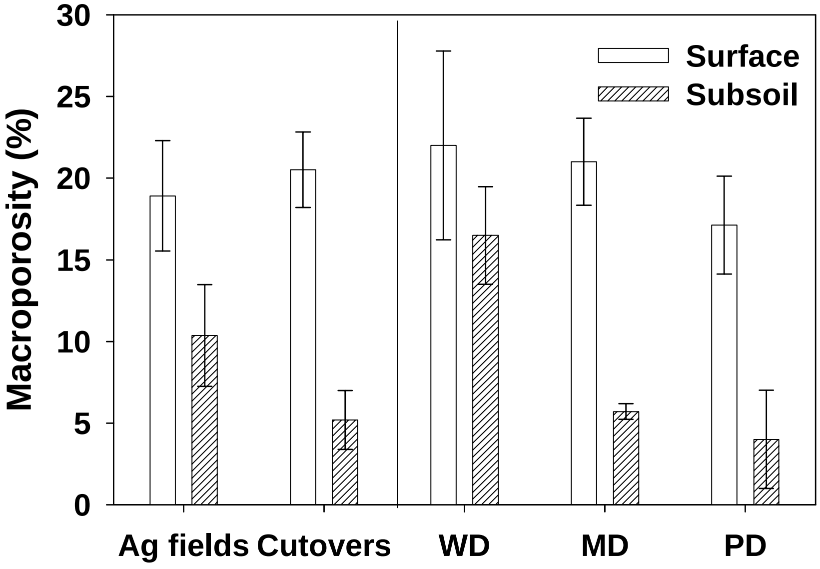

Figure VIII-13. Macroporosity of 14 viable sweetgum plantations across land-use categories and drainage class. WD soils include excessively well and well drained soils, MD soils include moderately-well and somewhat poorly drained soils, and PD soils include poorly and very poorly drained soils. Error bars indicate one standard error.

Water holding capacity (WHC) was calculated as the volumetric water held between field capacity (-0.03 MPa) and wilting point (-1.5 MPa). The subsoil WHC was not different between land-use categories or among drainage classes and averaged about 11 cm (Figure VIII-14). The surface soils, however, were different between the ag fields and cutovers and between the WD soils and lower sites. The cutover sites had about 6.6 cm of available water in the surface soil, on average, while the ag fields had less than half that (2.8 cm). The WD surface soils had only 1.7

cm available water, while the MD soils and PD soils averaged about 6 cm of available water. Overall, the total available water to a 1 m depth averaged about 16 cm across both ag field and cutover sites. The MD and PD soils averaged 18 cm available water, while the WD soils had just over half that (10.2 cm).

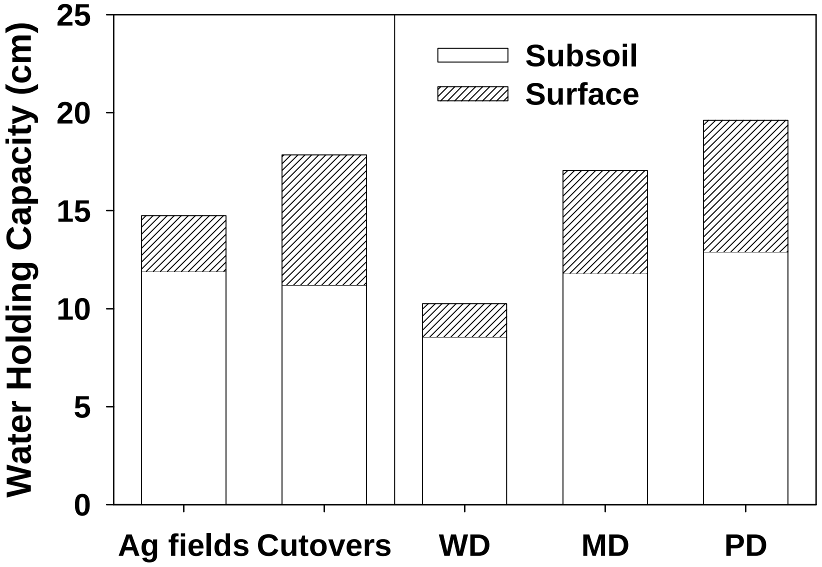

Figure VIII-14. Water holding capacity of 14 viable sweetgum plantations across land-use categories and drainage class.

DISCUSSION

Although hardwoods are in general more sensitive to site and soil conditions than conifers, sweetgum is one of the most general hardwood species in its site requirements (Baker and Broadfoot, 1979). Thus, site types suitable for plantation sweetgum range from well-drained, sandy upland soils to very poorly drained, heavy clay depressional soils. The primary limitations of the sites were hypothesized to be N availability on the WD ag fields and restricted rooting in the heavy clay PD soils. Across this range of sites several other characteristics were hypothesized to be important. We expected that some soils might have nutrient limitations other than N, low base fertility or aluminum toxicity, and low available water or restricted rooting volume.

The soils suitable for sweetgum plantations differed widely in many characteristics, but none more so than the surface soil organic matter. With only one exception (Wagram-VA 818), the surface soil organic matter of the cutover sites was greater than that of the ag field sites (Table VIII-2). The difference in soil organic matter was likely due to the land-use history, although other site factors probably modified the cultural effect. The lower SOM on the ag field soils was due to decreased organic inputs and increased SOM decomposition. The return of organic residues was decreased compared to the sites' natural systems due to the harvesting of the plant matter and a reduction in net primary productivity. Decomposition rates of the comparatively high quality agricultural residues (low C:N ratio, low lignin) were greater than decomposition rates of the natural coniferous and deciduous needles and leaves (Paul and Clark, 1996). Furthermore, repeated cultivation exposed the existing SOM to the soil microbial communities and increased the soil temperature, which increased SOM decomposition rates.

Because the ratio of soil C to N was relatively similar among sites except for the Argent soil (C:N=53) (Figure VIII-4, Table VIII-2), the pattern of total soil N was basically the same as for SOM, and for many of the same reasons. Other than C:N ratio, though, we found that soil clay content modified the proportion of SOM or total N that was mineralizable (Figure VIII-6). Because SOM binds to clay particles and becomes protected from microbial decomposition (Bosatta and Ågren, 1997), heavy-textured soils have less mineralizable N than expected given SOM or total N levels.

The potential monthly N supply rates in the surface soils may be useful to help determine the sites with the greatest potential for N limitations, but the absolute values can be misleading. The potential mineralization curves were performed in controlled laboratory setting at optimal climatic conditions (35 ^{o}C, -0.03 MPa). We adjusted the 30-day mineralization rate for 25 ^{o}C, which is more representative of the maximum growing season soil temperature in the region studied (Scott and Burger, 2002), with a Q_{10}=2 approach (Stanford et al., 1973). However, because the soils studied have very different water balances, we could not estimate the "average" water effect across the soils. Scott and Burger (2002) adjusted laboratory rates of potential N supply for soil temperature and water content on the Norfolk-Trice and Argent-NC sites. They found no evidence that adjusting the laboratory rates of potential N supply for actual soil temperature with a Q_{10}=2 relationship was inadequate. However, the response of *in situ* soil N supply to soil water content was not adequately described by a linear response to water content between field capacity and wilting point (Stanford and Epstein, 1974). Much of the inadequacy appeared to occur when the soils had soil water contents greater than field capacity, which was common on the poorly drained Argent site. In addition, they hypothesized that immobilization and denitrification were important processes regulating the actual soil N supply on these sites.

Although the cutover sites and PD soils had the greatest N_{30} (Figure VIII-7), both have greater potential for microbial N immobilization and denitrification due to their greater C content, which serves as a microbial energy source (Davidson and Swank, 1987). The N_{30} values indicate that the Norfolk-Trice, Argent-NC, Wagram-VA818, Goldsboro-SC10, Yemassee-FEB, and Lynchburg-SC2 would, in order, have the lowest soil N supply rates and be most responsive to N fertilization (Table VIII-2). Of these soils, the Argent and Yemassee soils had the highest C:N ratios (53 and 38, respectively) and have significant periods of wetness. These conditions would favor microbial N immobilization and denitrification. The water-holding capacity of both soils is relatively high (21 and 18 cm total, respectively) (Table VIII-4), so water is relatively plentiful for sweetgum growth on both soils. These conditions would make the Argent and Yemassee soils most responsive to N fertilizer. The Wagram, Goldsboro-SC10, and Lynchburg-SC2 soils may also be responsive to N fertilizer, but other conditions may limit their responsiveness. The Wagram soil may have water deficiencies that restrict sweetgum growth and N demand. The Goldsboro-SC10 and Lynchburg-SC2 soils have low N_{30} rates, but because they both have lower quantities of C substrate (1.39 and 2.89 % SOM, respectively), microbial immobilization and denitrification may not be as much of a factor as on the cutover soils with low N_{30}. The other soils, especially the PD soils, have high potential N supply rates. However, water contents are greater on these sites due to their wet nature, and denitrification may be high, as may immobilization. Further research needs to address the role of soil water content on soil N supply across this spectrum of site types.

The greater average P concentration and content and higher variability in available P across the agricultural surface soils was likely due to recent fertilization practices. Although none of the sites sampled had received P fertilizer within the past 2 years, some ag fields had received annual P applications prior to conversion to hardwood plantations while others had not. Across all the soils, the Argent, Wagram, Megget, and Goldsboro-SOH soils had the lowest soil P levels (Table VIII-3). Each had less than 25 kg ha^{-1} P content and 15 mg kg^{-1} P concentration in the surface soils. The Argent soil also had the least available P in the subsoil. The Goldsboro-SC10, Norfolk-BFF and Norfolk-Trice soils, which were all WD or MD agricultural soils, have the greatest contents and concentrations of available P in the surface soils and would be the soils least likely to need P fertilization for sweetgum production. Within the MD soils, only the Goldsboro-SOH soil was excessively low in available P. Of the WD soils, only the Wagram soil, which had not been cultivated recently, had low available P. However, generalizations could not be made across the PD soils. The Meggett and Mouzon soils represented the wettest, most poorly-drained site types in the study, yet they had very different P characteristics. The Meggett surface soil had the lowest concentration of P (3.04 mg kg^{-1}) of all the soils, while the Mouzon soil had the highest concentration (18.6 mg kg^{-1}) of any cutover site. The Meggett site had the highest subsoil concentration of any site (10.4 mg kg^{-1}). Based on these findings, P fertilization may be needed especially on sandy, well-drained cutover sites and some MD soils. Phosphorus, compared to N, is relatively easily managed. Because of its chemistry and reaction with the soil, P is retained in the system and remains available after several years (Pritchett and Comerford, 1982; Torbert and Burger, 1984). Therefore, P should be applied at planting at a rate of 50 kg P ha^{-1} to all but heavily fertilized converted agricultural fields to ensure adequate P supply (Jokela et al., 1991). Sites with very low P tests or low foliage P concentrations should be refertilized with 50 kg P ha^{-1} near canopy closure. This approach will ensure P is optimal without over-fertilization.

The soil chemistry reflected the differences in clay content caused by landscape position and in organic matter caused by land use history. Cation exchange capacity was greatest on the PD soils (Figure VIII-11) largely because they had the greatest clay concentrations and organic matter. Acidity was greatest on the cutover sites (Figure VIII-11) due to the production of organic acids through organic matter decomposition and from root exudates and decomposition. The Meggett soil had an extraordinarily high quantity of bases, which were largely calcium and magnesium (Table VIII-3). Although not present within the surface meter, calcium carbonate nodules were found near 1.5 m in the soil pit description, indicating that the site was located on marl or other calcareous deposits. However, the Myatt soil, another wet PD soil that was located within a pocosin, had very high levels of acidic cations (4.3 cmol $^{+}$ kg^{-1}) and very low levels of basic cations (Table VIII-3). The Myatt soil, with base saturation levels of 12 and 5 % and pH levels of 3.92 and 4.3 in the surface and subsoils, respectively, has the greatest potential for Ca and Mg deficiency and for aluminum toxicity, especially for planted seedlings. The cutover Goldsboro-SOH soil also had high soil acidity in the surface and subsoils, low base saturation, and low pH levels. Although this site was moderately well drained and located on the upper end of the catena in the region, it was located geographically near the Myatt soil in southeastern Virginia. No soils were found in South Carolina that approached the low levels of base saturation as these two soils, even though the Byars soil was located in a Carolina Bay, which are usually characterized as being very acidic. Therefore, cutover sites on the northern end of the Atlantic coastal plain may benefit from lime applications to reduce acidity and provide Ca and Mg. To date, only one author (Chang, 2000) has investigated Ca limitations in sweetgum plantations, and he found that only a few individual sites responded to liming. Thus, it appears that liming may be helpful on excessively acidic soils, but overall is not needed.

Root growth and gas exchange are greatly limited by excessive bulk densities, which cause soil strength to be too great for root growth, and a lack of macropores, which inhibits gas exchange (Greacen and Sands, 1980). Critical limits have been defined as 10% air-filled porosity and 3 MPa penetration resistance for aeration and soil strength (Gliñski and Staeniewski, 1985). Unfortunately, using bulk density alone is too simplistic; soil physical limitations to root growth and gas exchange are due to texture, structure, and organic matter as well as compaction (Håkanson and Lipiec, 2000).

Daddow and Warrington (1983) determined the influence of texture on root-limiting bulk densities for many species. Simmons and Pope (1987) studied root length in a silt loam soil that, according to Daddow and Warrington (1983), had a root-limiting bulk density of about 1.43 Mg m^{-3}. Simmons and Pope (1987) found that sweetgum root length was less than half at 1.45 Mg m^{-3} than at 1.25 Mg m^{-3}, suggesting that Daddow and Warrington's (1983) relationship between root growth and bulk density holds, at least reasonably, for sweetgum. Using Daddow and Warrington's (1983) relationship and 10% air-filled porosity as guidelines, we determined horizons that may be limiting root growth or aeration (Table VIII-5.). Few physical limitations were found in the WD soils. The Wagram and Norfolk-Trice soils had macroporosities less than 10% (7 and 9 %, respectively) in their deepest soil layer, which occurred at 82 and 71 cm from the surface, respectively. Because both soils are well-drained and root growth is minimal at these depths on any soil, these soils probably had little physical limitations to growth. At the other end of the spectrum, the Meggett and Mouzon soils had relatively low bulk densities as well. All of the other soils had potentially root-growth limiting bulk densities. The ag field sites especially had high bulk densities, probably as a result of cultivation and equipment traffic. The Myatt soil had especially high bulk densities and low macroporosities from 18 cm through 100 cm. The Coxville, Myatt, and Mouzon soils each had low macroporosities near the surface (18 to 36 cm), and all of the MD soils and PD soils had low macroporosities in the subsoils. While sweetgum has been shown to tolerate stronger (excessive bulk density) and less-well aerated soils than other hardwood species, such as sycamore and cottonwood (Baker and Broadfoot, 1979), the restricted rooting ability and gas exchange on the wetter end of the site spectrum may be limiting growth. When rooting ability is limited to the surface soils, the volume of soil exploited for water and nutrients becomes limited. Water, P, and base cation availability in the surface soil becomes even more important if root growth is limited. On average, only 32% of the available water holding capacity was in the surface soil of the MD soils and PD soils, while 68% was in the subsoil.

Table VIII-5. Individual soil layers with potentially root-growth limiting bulk density or macroporosity. Bulk density values with a * indicate potentially root-growth limiting values based on Daddow and Warrington, 1974.

Soil series (Site)	Layer	Upper Boundary	Sand	Silt	Clay	Bulk Density	Macro-porosity
		cm	-------%	-------		Mg m^{-3}	cm^{-3} cm^{-3}
Wagram-NOH	4	82	69	9	23	1.67	0.07
Norfolk-BFF	--	--	--	--	--	--	--
Norfolk-TR	4	71	74	14	12	1.61	0.09
Goldsboro-SC10	2	23	61	25	14	1.78*	0.08
	3	43	47	25	29	1.68*	0.04
	4	64	46	24	31	1.51	0.06
Goldsboro-SOH	2	20	60	16	24	1.50	0.07
	3	45	53	22	25	1.70*	0.04
Yauhannah-BEH	3	30	52	27	22	1.60	0.06
	4	60	38	33	29	1.53*	0.08
Lynchburg-SC2	3	30	61	12	27	1.72*	0.11
	4	50	48	19	32	1.64*	0.03
Yemassee-FEB	4	74	50	21	29	1.76*	0.01
Argent-NC	4	60	44	15	40	1.65*	0.01
Coxville-TR8	2	20	56	18	26	1.83*	0.03
	3	36	44	28	28	1.87*	0.00
	4	66	39	30	32	1.67*	0.02
Myatt-Block	2	18	53	33	14	1.90*	0.01
221S	3	36	48	31	21	1.76*	0.02
	4	65	46	34	21	1.68*	0.04
Meggett-JAB	3	30	27	24	50	1.38	0.01
Byars-POB	3	38	58	17	26	1.82*	0.01
	4	70	54	16	31	1.69*	0.01
Mouzon-DIW	2	18	26	47	26	1.26	0.00
	3	36	14	43	43	1.26	0.00
	4	66	12	35	53	1.52	0.07

These results have implications for management. Care must be taken on all soils, but especially on MD soils and PD soils, to avoid excessive trafficking during harvest and site preparation operations. Discing and ripping (subsoiling) may be needed to alleviate soil compaction caused by plowpans on converted ag fields that are MD (Goldsboro-SC10, Lynchburg) or PD (Coxville). Some pine cutover sites, especially those in pocosin or Carolina bay landforms (Myatt and Byars series) may also need subsurface tillage in combination with bedding to increase the effective rooting area and aeration.

CONCLUSIONS

The soil characteristics of viable sweetgum plantations varied widely across soil types, but in general, many distinctions were made between converted agricultural fields and pine cutover sites and across a topographic gradient. Phosphorus availability was generally greater on the converted ag fields due to past fertilization practices, but some cutovers had high quantities of available P in both surface and subsoils. Except for repeatedly fertilized, converted ag fields, all sites should be P fertilized at planting to remove any P limitations. Exchangeable K was generally low in all surface soils, but especially on sandy WD soils, where fertilization may be necessary. Most soils had moderate to high base saturation and exchangeable cations, but the sites located in southeastern Virginia had especially high extractable acidity and may benefit from liming to reduce aluminum toxicity and provide more calcium and magnesium.

As expected, converted ag fields had, in general, less soil organic matter than cutover pine stands. However, because of differential organic matter chemistry and physical protection of organic matter by clay particles, a greater proportion of the total soil N was mineralizable on WD ag field soils than on lowland cutover sites. Furthermore, because some cutover sites had high C:N ratios and some sites were located on wet sites, immobilization and denitrification may reduce the potential N supply. Further work needs to be done to elucidate the influence of soil water content on soil N supply, hardwood plantation growth and N demand, and ultimately, fertilizer need, but fertilizer requirements will likely be lower on cutover pine plantations than on converted ag fields as long as herbaceous and woody competition is controlled.

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CHAPTER IX. SUMMARY

This research was conducted in order to 1) improve N fertilizer prescriptions for sweetgum, a commonly planted short-rotation woody crop, and 2) create new knowledge regarding sweetgum nutrition and soil N dynamics. The specific research objectives were to:

1. Determine the plant growth and foliage nutrition response to repeated N fertilizer applications in two young sweetgum plantations with contrasting soil types;
2. Determine soil N supply, plant N demand, foliage N resorption, and soil and fertilizer uptake efficiencies in two young sweetgum plantations with contrasting soil types;
3. Develop and evaluate a N mineralization potential-based soil N supply model in two young sweetgum plantations with contrasting soil types;
4. Evaluate rapid methods for determining N mineralization potential across the spectrum of soils conducive to intensive sweetgum management in the Atlantic coastal plain; and
5. Characterize the soils and their silvicultural implications for the spectrum of soils conducive to intensive sweetgum management in the Atlantic coastal plain.

Sweetgum response to N fertilizer was site- and age-specific (Chapter IV). On a converted agricultural field, neither foliage biomass nor stem biomass growth was affected by N fertilization from age 3 to age 5. However, on a cutover pine stand, sweetgum foliage and stem biomass readily responded to N fertilization from age 4 to age 6. Foliage biomass doubled in response to N fertilization on the cutover pine stand at ages 4 and 6, the times of fertilizer application, but showed no response at age 5, when no fertilizer was applied. Stem biomass, on the other hand, increased by about 58% at age 5 and maintained the response at age 6. In general, diagnostic foliage N concentrations increased on the cutover pine site at ages 4 and 6 from about 1.1% to 1.8% in response to fertilizer N. By comparing stem biomass to diagnostic foliage N concentrations, it was estimated that about 1.75% N is required by young sweetgum for 90% of optimal growth.

In Chapter V, foliage biomass and N concentrations collected from the converted ag field and cutover pine site were used to calculate optimal N fertilization rates using a N-balance approach. Foliage N demand (total foliage N content) ranged from about 8 kg N ha^{-1} on a converted agricultural field at age 3 to 61 kg ha^{-1} N on a cutover pine plantation at age 6. Fertilization increased foliage N demand by 20% at age and 60% at age 6 on the cutover pine site, but had no effect on demand on the converted ag site. Nitrogen resorption efficiency prior to leaf senescence averaged about 40% on both sites, and was not affected by fertilization. Soil N supply was about 70 kg ha^{-1} on the converted ag field and 50 kg ha^{-1} on the cutover site. Foliage N uptake efficiencies from mineralized soil N were about 30 % on both sites. Foliage uptake of fertilizer N was about 20 % on the converted ag field and about 28 % on the cutover pine plantation. This chapter discussed the data and implications that N fertilizer applications are not warranted prior to age 4, and should increase from 70 kg ha^{-1} at age 4 to 95 kg ha^{-1} at age 6 on the cutover pine stand. Since tree biomass had not responded to N fertilizer at the converted ag field, presumably due to the 40% greater soil N supply, fertilizer was not warranted on this soil prior to age 5. While these recommendations are for only two soils, they indicate that, in order to prescribe N fertilizer, an accurate estimate of soil N supply is necessary.

In Chapter VI, a simple process model of cumulative soil N supply, based on the concept of potentially mineralizable nitrogen, was evaluated. Although the model may not have sufficiently accounted for the effects of soil water on N supply, it predicted annual soil N supply very well on the cutover pine site and underestimated soil N supply by 20% on the converted agricultural field. This approach was unlike most soil N supply modeling approaches, in that the model was not developed from observed soil N supply; it was developed from existing theories that relate cumulative N supply to the pool of mineralizable N, soil water, and soil temperature. Compared to regression-based models of soil N supply, this model can be more readily applied to additional soils without further calibration.

Because the main parameter (N mineralization potential) in the model evaluated in Chapter VI is a time-consuming and cumbersome procedure, three possible methods of estimating it were tested (Chapter VII) on thirteen soils that represent the range of soil types conducive for intensive sweetgum management in the Atlantic coastal plain. While a commonly used anaerobic incubation index and a hot salt extraction index provided poor estimates of mineralizable soil N, total N and a soil drying-rewetting CO_2 flush index worked quite well (R^2=0.90, 0.88, respectively). Total N had the best overall fit, but the agricultural soils were all grouped closely. The CO_2 flush index had almost as good of fit as Total N, but both converted agricultural soils and cutover pine plantation soils were equally well estimated. Because this flush is simple and can be used to estimate microbial biomass, it appears to be a good index of active soil organic matter and potentially mineralizable soil N.

In Chapter VIII, various soil properties were measured for fourteen successful sweetgum plantations in the Atlantic coastal plain in order to illustrate the range of site conditions possible for intensively managed sweetgum and to assist in interpreting soil information for management. The sites were analyzed on the basis of previous land use (agricultural fields versus loblolly pine plantations) and drainage class. Converted ag fields were more fertile than pine cutovers with respect to P and K, but cutover pine sites had almost 3 times the amount of potentially mineralizable N. Several soils, especially moderately drained ag fields and very poorly drained pine cutovers had physical conditions that potentially were an impediment to root growth.

Compared to traditional soil or foliage-based approaches to diagnosing nutrient deficiencies, this dissertation provided the information needed to pro-actively assess *potential* nutrient needs by intensively managed hardwood forests on various soil types and correct them with accurate fertilizer rates. More research needs to elucidate the role of litter decomposition on N release, the role of soil water on N supply in wet soils, and the response of older intensively managed stands to repeated fertilization. However, this work represents a significant contribution to forest science’s understanding of N dynamics and fertilizer prescriptions in young, intensively managed, short-rotation woody crops.

Vita

David Andrew Scott (Andy) was born on New Year's Eve 1972 in Crawfordsville, Indiana to Dave and Eleanor Scott. He graduated as salutatorian from Shoals Jr. Sr. High School in 1991 and then attended Purdue University, majoring in Forest Management. Following his freshman year, he began working as a research technician for Phil Pope's forest soils program. After graduation from Purdue with distinction in 1995, he attended Texas A&M University and received a M.S. in Forestry in December 1997 under the advisement of Mike Messina. He then traveled to Virginia Tech in January 1998 with his new bride, Deborah Lynn, and began a Ph.D. program in Forest Soils under the advisement of Jim Burger. He is currently employed as a Research Soil Scientist with the USDA Forest Service, Southern Research Station and will graduate with a Ph.D. in Forestry in December, 2002. He and his wife have two children: Madison Lynn, 2½ , and Luke Andrew, 5 months, and reside in Pineville, Louisiana.