Pine Nutrition

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BIOMASS, NITROGEN, AND PHOSPHORUS ACCUMULATION IN 4-YEAR-OLD INTENSIVELY MANAGED LOBLOLLY PINE AND SWEETGUM PLANTATIONS

Charles A. Gresham and Thomas M. Williams[1]

Abstract—Knowing the nutrient uptake potential of plantations of fast-growing species is essential to designing land-based tertiary water treatment facilities. This study was conducted to estimate the biomass of 4-year-old, intensively managed loblolly pine (*Pinus taeda)* and sweetgum (*Liquidambar styraciflua)* plantations and to estimate the N and P contained in that biomass. The cumulative effects of competition control only and competition control, irrigation, fertilization and pest control were investigated on an abandoned peanut field in Decatur County Georgia on a Lakeland sand soil. Planted at 1,157 trees/ha, loblolly pine accumulated 57.3 mg/ha dry biomass 4 years after planting and sweetgum accumulated 26.5 mg/ha dry biomass in the maximum treatment plots. Sweetgum was more responsive to the maximum treatment with a biomass increase of 388 percent compared to a 217 percent increase in loblolly pine biomass. In the maximum treatment plots, loblolly pine accumulated 330 kg N/ha and 35 kg P/ha compared to sweetgum accumulation of 137 kg N/ha and 15 kg P/ha.

INTRODUCTION

In 1994 International Paper Company installed their Forest Growth Maximization Study to determine the potential of highly intensive tree culture on abandoned agricultural land. The most likely motivation for such a study would be to determine the economic feasibility of cultural treatments that are known to increase tree growth. From previous research we know that competition control, soil moisture management, nutrient amendment all increase the growth rate. Pest control also contributes to an increased individual tree growth rate by maintaining the terminal shoots and minimizing defoliation. If the growth response is large enough, these treatments can be made operational over large areas at a cost.

We recognized another opportunity in this study; using plantations of pine or fast-growing hardwoods for tertiary sewage treatments. Land application of secondary treated sewage is not new, but it does require knowledge of how rapidly the applied nutrients can be assimilated into biomass. If the application rate exceeds the assimilation rate, then excess nutrients will not be fixed in biomass and could leave the system by leaching. Our interest in this study was to estimate the N and P fixed into tree biomass that will provide an estimate of the nutrient loading possible without exceeding uptake. Although the design of the experiment is not a land application study, we recognized the potential to derive loading rates. The objective of this research was to estimate the aboveground biomass, N, and P pools of both loblolly pine (*Pinus taeda)* and sweetgum (*Liquidambar styraciflua)* in the control and maximum treatments.

MATERIALS AND METHODS

The field installation was on abandoned agricultural peanut (*Arachis hypogaea)* field in Decatur County Georgia, approximately 16 km southwest of Bainbridge Georgia. The soil was a Lakeland sand (a Typic Quartzipsamment) on International Paper Company's Silver Lake Farm. This installation was a randomized complete block design with three replications of four cumulative treatments. A fourth replication, designated for destructive sampling, contained only the control and maximum treatments. The control treatment consisted of ripping to a 60-cm depth and constant competition control. The irrigation treatment was the control treatment with trickle irrigation of 24 l/day/tree of water pumped from the near-by Silver Lake. The fertigation treatment was the irrigation treatment with the addition of 135 kg N/ha/yr, 33 Kg P/ha/yr and 130 kg K/ha/yr. The maximum treatment was the fertigation treatment with insect pest control, primarily, tip moth (*Rhyacionia frustrana*) for loblolly pine. Each of the complete replications had eight plots; all four treatments with both loblolly pine and sweetgum.

The trees were planted in March 1995 on a 2.4 m X 3.6 m spacing in plots with 12 rows of 18 trees per row.
In December 1998 we systematically selected 40 measurement trees in the center of each plot in replications 1,2, and 3 and 80 trees in replication 4. Diameter outside bark at groundline, breast height, and at the base of live crown was measured with a diameter tape or with calipers. The base of live crown was defined as the base of the lowest live branch on the tree. Distance from the ground to the

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base of live crown and to the top of the terminal bud was measured with a fiberglass tape attached to a telescoping pole. An observer with an unobstructed view of the terminal bud at approximately a 45 degree angle, determined when the pole tip was level with the top of the terminal bud.
In March 1999 ten randomly selected loblolly pine trees in both the control and maximum plots of Replication 4 were destructively sampled. Diameter at groundline and breast height were measured, the tree was felled by cutting at groundline and the distances to the base of live crown and the top of the terminal bud were measured. Branches were then removed from the bole and both components immediately weighed. Bole and branch sub-samples were taken and weighed. This same procedure was repeated in April 1999 with sweetgum trees in the control and maximum plots of replication 4.

In the laboratory, bole and branch samples were dried at 65 degrees Celsius in a forced-air oven to a constant weight. The bole samples were reweighed and the branch samples were separated into foliage and branches and these components reweighed. Tissue samples were prepared and analyzed for total Kjeldahl N and P by the procedure described in Williams and Gresham (2000). Biomass and nutrient pool sizes were estimated by calculating the average diameter at breast height (dbh) and total tree height by treatment and block. Simple linear regression equations were calculated to predict tree dry foliage weight, branch weight, crown weight, bole weight and total tree weight from dbh squared times total height. Nitrogen and P concentrations of the foliage, branch and bole samples were averaged by treatment for each species and these averages were combined with the biomass estimates to estimate N and P pool sizes on an area basis.

RESULTS

Foliage N and P concentrations were most affected by species and treatment (Table 1). Sweetgum foliage N and P were much higher than for loblolly pine and sweetgum foliage concentrations were much more affected by the maximum treatment compared to loblolly pine. For the branch component, there was little difference in concentrations between sweetgum and loblolly pine in the control treatment and only loblolly pine N showed much maximum treatment response. There was little response to treatment in both sweetgum and loblolly pine bole N and P, and loblolly pine did have more N that did sweetgum.

Loblolly pine was larger and accumulated more N and P compared to sweetgum, but sweetgum was more responsive to the treatments (Table 2). Loblolly pine averaged 13 cm dbh 4 years after planting with the maximum treatment. The 10 cm dbh of trees in the control plots probably reflected an old field effect of residual fertilizer. The total height of loblolly pine in the maximum plots was 7 m compared to 6.1 m for sweetgum. Although much smaller, sweetgum showed an almost 300 percent dbh response to treatment. Sweetgum in the control plots averaged 3 cm dbh and 3 m tall after 4 years with competition control, but without irrigation and fertilization. The height response of sweetgum to treatment was less than the diameter response (206 percent versus 298 percent) but still greater than loblolly pine's response (139 percent). The crown, bole and total aboveground biomass pools (Table 2) reflect the same trends seen in the height and diameter data. After 4 years in the field, loblolly pine produced over 57 mg/ha oven dry, above ground, biomass with the maximum treatment, but only 46 percent was in the bole. Sweetgum in the maximum treatment produced less biomass (27 mg/ha) more bole biomass (60 percent) and was much more responsive to treatment. The bole biomass increased 535 percent and total biomass increased 388 percent comparing the control to maximum treatments.

The distribution of N between species and treatments reflected the biomass differences. Loblolly pine accumulated 330 kg N/ha after 4 years in the field with the maximum treatment compared to 137 kg N/ha for sweetgum. As was the case with biomass, sweetgum N accumulation was more responsive to treatment; crown N increased by 322 percent, bole N increased by 519 percent and total sweetgum N increased by 350 percent. Phosphorus

Table 1—Average (and one standard error) Kjeldahl N and P concentrations (percent) in foliage, branches and boles of 5-year-old loblolly pine and sweetgum trees in plots receiving competition control only (Control) and competition control, irrigation, fertilization, and pest control (Maximum)

Component	Treatment	Species	percent N	percent P
Foliage	Control	Loblolly pine	1.33 (0.03)	0.13 (0.00)
		Sweetgum	2.21 (0.08)	0.26 (0.02)
	Maximum	Loblolly pine	1.40 (0.02)	0.14 (0.00)
		Sweetgum	3.07 (0.08)	0.40 (0.04)
Branch	Control	Loblolly pine	0.44 (0.04)	0.06 (0.01)
		Sweetgum	0.47 (0.03)	0.06 (0.01)
	Maximum	Loblolly pine	0.53 (0.02)	0.06 (0.00)
		Sweetgum	0.44 (0.02)	0.04 (0.00)
Bole	Control	Loblolly pine	0.25 (0.01)	0.03 (0.00)
		Sweetgum	0.19 (0.01)	0.02 (0.00)
	Maximum	Loblolly pine	0.26 (0.01)	0.03 (0.00)
		Sweetgum	0.19 (0.01)	0.02 (0.00)

Table 2—Average (and one standard error) dbh, height, biomass, and N and P accumulation of 5-year-old loblolly pine and sweetgum trees in plots receiving competition control only (Control) and competition control, irrigation, fertilization, and pest control (Maximum)

	Loblolly pine				Sweetgum			
	Control		Maximum		Control		Maximum	
DBH (cm)	9.7	(.1)	13.7	(.1)	3.1	(.3)	9.4	(.3)
Total height (m)	5	(.2)	7	(.1)	3	(.1)	6.1	(.1)
Crown Biomass (kg/ha)	15,216	(470.0)	31,312	(326.0)	3,816	(889.0)	10,552	(803.0)
Bole Biomass (kg/ha)	11,192	(504.0)	26,020	(284.0)	2,983	(598.0)	15,981	(1,153.0)
Total Biomass (kg/ha)	26,410	(974.0)	57,332	(609.0)	6,829	(1,486.0)	26,533	(1,956.0)
Crown N (kg/ha)	143	(4.0)	261	(2.0)	33	(7.0)	107	(13.0)
Bole N (kg/ha)	28	(1.0)	69	(1.0)	6	(1.0)	30	(2.0)
Total N (kg/ha)	171	(6.0)	330	(2.0)	39	(9.0)	37	(15.0)
Crown P (kg/ha)	15	(0.5)	27	(0.2)	4	(1.0)	13	(1.5)
Bole P (kg/ha)	3	(0.1)	8	(0.1)	1	(0.1)	3	(0.2)
Total P (kg/ha)	18	(0.6)	35	(0.3)	5	(1.0)	15	(1.7)

accumulation results are similar to the N results. Loblolly pine accumulated 35 kg P/ha compared to sweetgum's 15 kg P/ha for the maximum treatment.

DISCUSSION

Loblolly pine height growth in the control plots indicates that the estimated site index (25-year base age) would be 60 (Pienaar and Shiver 1980) to 70 (Trousdell and others 1974). Site index for the maximum treatment plots is estimated to be 87 (Pienaar and Shiver 1980).
Sweetgum productivity in the maximum plots exceeded the sycamore (*Platanus occidentalis)* productivity on fertilized plots reported by Steinbeck and Brown (1976). They reported a green weight biomass of 105 Mg/ha after 4 years at a 1.2 by 1.2 m spacing. Assuming a 50 percent dry weight, this is 52 mg/ha at 5.8 times the planting density of our sweetgum that produced 26 mg/ha after 4 years in the field.

One of the reasons for doing this research was to determine the feasibility of slow-rate land application of wastewater on plantations of fast-growing species. Although leaching data are needed to provide a more complete picture, these data provide a useful framework. In the loblolly pine plots receiving the maximum treatment, N was applied at 135 kg/ha/yr and after 4 years 330 kg N/ha was accumulated. The N accumulated in tree biomass is 61 percent of the N applied during that 4-year period. A typical N loading rate for land application would be 3 to 5 kg N/ha/d (Kadlec and Knight 1996) which equates to pumping for 27 to 45 days a year to achieve the 135 kg/ha/yr applied in this experiment. This rough comparison indicates that from 8 to 13 ha will be needed for every ha to receive wastewater if pumping were year around. Another major consideration is whether the site could handle the high hydraulic loading of 208 l/tree/d (Kadlec and Knight 1996) compared to the loading of this study (24 l/tree/d).

CONCLUSIONS

These data present biomass, N and P accumulation rates for fast-growing species and provide several implications for intensive management of loblolly pine and sweetgum. The growth rate of loblolly pine with competition control only indicates that an old-field effect was present. If irrigation and fertilization treatments are added, loblolly pine will grow to 7 m tall and 13 cm dbh after 4 years in the field. At the planting spacing of 1,157 trees/ha loblolly pine can accumulate 57 mg/ha dry biomass. However, sweetgum biomass and nutrient accumulation was much more responsive to the treatment than was loblolly pine. The increase in sweetgum biomass and nutrient accumulation ranged from 267 to 535 percent compared to 181 to 261 percent for loblolly pine. Sweetgum leaves from the maximum treatment had a high N (3 percent) and P (0.4 percent) concentrations and could be used as an organic fertilizer. Finally the treatments did not affect the bole N or P content, but in most cases for branch biomass, N and P was higher in trees from the control plots. We speculate that although the branches and boles did accumulate more nutrients in the maximum plots, the concentration was decreased by the great increase of biomass.

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INTER- AND INTRA-SPECIFIC DIFFERENCES IN FOLIAR N CONCENTRATIONS OF JUVENILE LOBLOLLY AND SLASH PINE IN NORTH FLORIDA

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Abstract—Differences in foliar N concentrations among species, families, and clones may contribute to variation in relative growth performance under varying environmental conditions. Only limited information exists regarding the importance of genetic vs. environmental controls on the nutritional characteristics of loblolly and slash pine. Knowledge of these processes may provide a better understanding of growth strategies among pine taxa and aid in selection and breeding of superior genotypes. This paper will summarize the results of a study designed to investigate the effects of taxa, genotype, site and silvicultural treatments on levels of foliar N concentrations over an entire leaf cycle. Three different pine taxa were investigated (genetically improved loblolly pine, genetically improved slash pine and unimproved slash pine) at two locations in north Florida. Each study consisted of two silvicultural treatments (non-intensive, intensive), three complete blocks within each treatment, three taxa, and 16 open-pollinated families within each taxon. In these juvenile (3-4 yr old) stands, loblolly pine was the most productive species. In comparison to improved and unimproved slash pine, loblolly pine consistently maintained 1) higher foliar N concentrations over time; and 2) higher family variations in N concentrations.

INTRODUCTION

The productivity of loblolly (*Pinus taeda* L.) and slash pine (*P. elliottii* Engelm. var. *elliottii*) stands has been greatly improved since the 1950's. The increases in production are primarily due to the application of intensive silvicultural treatments and the utilization of genetically improved seedlings that offer increased volume gain and disease resistance. Further increases in stand production may result from an improved understanding of how nutritional characteristics vary among species or genotypes in relation to different environments. Several studies, using clones as experimental materials, have also shown that some nutritional traits are under strong genetic control. Forrest and Ovington (1971) reported large differences in foliar nutrient levels (P, Ca, K, Mg, Mn, and Zn) among six clones of radiata pine (*Pinus radiata*). Broad-sense heritabilities among radiata pine clones for foliar nutrients were higher for K, Mg and Ca (Beets and Jokela 1994). Raupach and Nicholls (1982) observed that some nutrients (N, K, Mg, Zn) were significantly different among radiata pine clones in their study. These studies have demonstrated that foliar nutrient levels were controlled by genetic factors, and that nutritional differences were genotype specific. For nutrient use efficiency (amount of dry weight produced per unit weight of nutrients absorbed), Sheppard and Cannell (1985) found 10 - 30 percent differences among 8-year-old clones of *Picea sitchensis* and *Pinus contorta*, which were closely related to the nutrient concentration of foliage. They proposed an ideotype for high nutrient use efficiency as trees having an inherently low nutrient concentrations in needles. Such trees might be well-suited to grow on nutrient poor sites.

From the standpoint of forest genetics, it would be informative to know whether nutritional traits could be incorporated as direct or indirect selection criteria in tree improvement programs to achieve more genetic gain. Additionally, we need to understand if selection on growth traits (DBH, height, and volume) has any indirect effects on the nutrient status of trees. At present, information regarding the genetic architecture (heritabilities, genetic - environmental interaction, and genetic correlation) for the two southern pine species is limited. The objectives of this study were to 1) Examine temporal foliar N dynamics among three southern pine taxa as influenced by site and silvicultural treatments; and 2) Determine the magnitude of variation in foliar N concentrations among families with a taxon.

METHODS

Two field experiments, previously established by the University of Florida's Cooperative Forest Genetics Research program, were sampled in north central Florida (Dunnellon, Levy County, 29°20' N, 82°50' W and Palatka, Putnam County, 29°40' N, 81°42' W). Sixteen open-pollinated families from each of three pine taxa (genetically improved loblolly pine, and improved and unimproved slash pine) were planted at both sites in a five-tree row plot in each of three complete blocks using a split-split plot experimental design. Two levels of silvicultural treatments (intensive vs. non-intensive) were applied. Prior to study establishment, each site was chopped and bedded. Understory vegetation in the intensive silvicultural treatment blocks was controlled during the first growing season

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using a combination of mechanical and pre- and post-plant directed spray applications of glyphosate applied at labeled rates. Containerized seedlings were planted in December 1994 at a 5 x 11 ft spacing at Palatka, and a 6 10 ft spacing at Dunnellon. Fertilizers were broadcast applied in the high intensity treatment as a balanced mix of macro- and micronutrients during year 1 (250 lbs/ac DAP + 200 lbs/ac KCl) and year 3 (535 lbs/ac 10-10-10 + micronutrients). Insecticides were applied 3-4 times during the first growing season to control tip moth (*Rhyacionia* spp.) on the high intensity treatment. The low intensity treatment did not receive herbicide, fertilizer or insecticide applications.

Two sample trees within a 5-tree row-plot in each family from each block were randomly selected. Sample trees were healthy and free of disease. In total, 192 sample trees (2 treatments × 3 blocks × 16 families × 2 trees) were chosen for each taxa and site. Overall, 1,152 trees (2 locations × 2 treatments × 3 blocks × 3 taxa × 16 families × 2 trees) were sampled across the two sites. Needle samples were collected eight times over a two-year period from the same branch of every sample tree through the life cycle of the same needle cohort. Approximately 9,216 total leaf samples (2 locations × 2 treatment × 3 blocks × 3 taxa × 16 families × 2 trees × 8 times) were processed for chemical analyses.

Needle N concentrations were measured using the method as outlined in Thomas and others (1967) and Jones and others (1991). Nitrogen concentrations were determined using an Aipkem Flow Solution IV analyzer.

SAS procedures, GLM and MIXED, were used to analyze the data (SAS Institute 1996). Means for foliar N concentrations among the three taxa were compared using the LSMEANS statement in PROC MIXED. A default level of a = 0.05 was used to test significance among the means unless otherwise specified.

RESULTS AND DISCUSSION

Variation of Foliar N Concentrations at the Taxa Level

Nitrogen concentrations generally decreased over a complete leaf life cycle among the three pine taxa (figure 1). Differences in N concentrations were consistent among taxa across locations and treatments, with loblolly pine

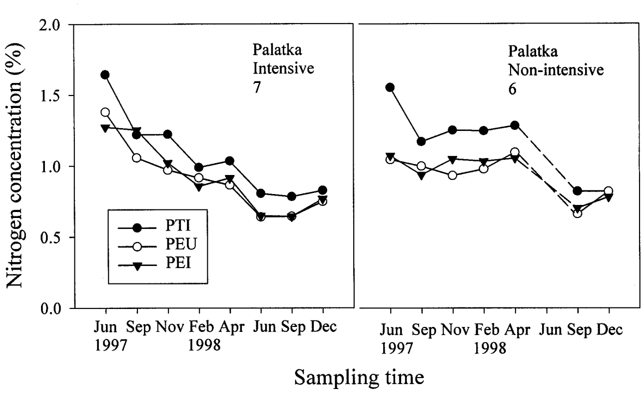

Figure 1—Inter- and Intra-specific Differences in Foliar N concentrations of juvenile loblolly and slash pine in North Florida.

Table 1—Family variation in foliar N concentrations (percent) of the three pine taxa managed under two levels of silvicultural treatments planted at two locations in north-central Florida

Site Treatment Taxa	Interfamily statistics	Mean	Minimum	Maximum
Sampling time: June 1997				
Dunnellon				
High	PTI	1.35	1.02	1.61
	PEU	1.10	0.98	1.20
	PEI	1.21	1.09	1.34
Low	PTI	1.00	0.87	1.12
	PEU	0.90	0.84	0.98
	PEI	0.88	0.73	0.97
Palatka				
High	PTI	1.64	1.38	1.92
	PEU	1.38	1.25	1.47
	PEI	1.28	1.13	1.44
Low	PTI	1.55	1.35	1.80
	PEU	1.05	0.94	1.11
	PEI	1.07	0.98	1.29
Sampling time: December 1998				
Dunnellon				
High	PTI	0.72	0.66	0.77
	PEU	0.74	0.64	0.79
	PEI	0.70	0.64	0.77
Low	PTI	0.81	0.72	0.90
	PEU	0.69	0.63	0.74
	PEI	0.68	0.61	0.74
Palatka				
High	PTI	0.82	0.74	0.91
	PEU	0.75	0.69	0.83
	PEI	0.77	0.68	0.85
Low	PTI	0.82	0.72	0.95
	PEU	0.82	0.74	0.89
	PEI	0.78	0.67	0.90

Note: high = intensive treatment, low = non-intensive treatment; PTI = improved loblolly pine, PEU = unimproved slash pine, PEI = improved slash pine;

having significantly higher concentrations than slash pine. For example, loblolly pine had an average N concentration of 1.64 percent (1.17 and 2.29 percent for minimum and maximum observations, respectively), while improved and unimproved slash pine had N concentrations of 1.28 percent (0.88 - 1.96 percent) and 1.38 percent (1.09 - 1.89 percent), respectively, in June 1997 under the intensive treatment at Palatka. The foliage N concentrations for loblolly pine were significantly higher than either slash pine taxa in seven of the eight sampling periods (88 percent) under the intensive culture treatment and 6 of 8 sampling periods (75 percent) under the non-intensive treatment. Differences in nutrient concentrations for N between improved and unimproved slash pine were generally non-significant. Location × treatment interactions for foliar N concentrations were significant under most sampling periods, showing differential responses among taxa to treatments across locations. Treatments generally did not significantly influence N concentration differences between loblolly and slash pine. Significant treatment × taxa interactions were caused by differential treatment responses between improved and unimproved slash pine, with improved slash pine having lower nutrient concentrations under the non-intensive treatment, but higher concentrations under the intensive treatment compared to unimproved slash pine.

Variation of Foliar N Concentrations at the Family Level

Foliar N concentrations not only showed significant seasonal changes over time at the taxa level, but also varied at the intraspecific (family) level over time (table 1). Family variation in N concentrations (the ratio between the maximum and minimum values of N concentrations) was higher for loblolly than the two slash pine taxa. For example, averaged across locations and treatments, family variation for loblolly, improved and unimproved slash pine was 40, 29, and 19 percent, respectively, in June 1997. Family variation within a taxon decreased from the early fascicle development stage (June 1997) to the later stage (December 1998) for all taxa. Variation in foliar N concentrations among families within a taxon also converged to a similar level for all three taxa. Averaged across locations and treatments, family variation for loblolly, improved and unimproved slash pine was 24, 25, and 20 percent, respectively, in December 1998. The intensive silvicultural treatment increased the foliar N levels at both locations, while loblolly pine still maintained higher N concentrations than the two slash pine taxa across both locations and treatments.

More detailed examination of the relationships between nutrient attributes and growth characteristics at the family level will be helpful to form a better understanding of growth strategies. Estimation of genetic parameters (heritability, genetic-environmental interaction, and genetic correlation coefficients) for various nutritional traits such as nutrient use efficiency, nutrient retranslocation efficiency, and crown nutrient content are planned in the future to quantify the importance of genetic vs. environmental controls on these attributes. Knowledge gained through an understanding of nutritional traits and their relations to growth performance will prove useful in the application of future breeding efforts designed to select superior genotypes for a range of silvicultural management intensities (Xiao 2000).

The potential implications of our findings in the changing nature of foliage N concentrations at the family level suggest that selection could be considered for the two species during the early stages of fascicle development (maturation) if desired in tree improvement programs. For example, N concentrations in the first month that current year foliage attains full length (June, 1997) could be an important sampling period for estimating heritabilities because family variation was most pronounced.

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ALTERATION OF NUTRIENT STATUS BY MANIPULATION OF COMPOSITION AND DENSITY IN A SHORTLEAF PINE-HARDWOOD STAND

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Abstract—Uneven-aged management is used to promote adequate pine reproduction and control species composition of shortleaf pine (*Pinus echinata* Mill.)-hardwood stands in the Interior Highlands of the southern United States. The modification of pine-hardwood composition in these stands has the potential to alter nutrient pools and availability since nutrient uptake, retranslocation, and/or cycling significantly differs in pines and hardwoods. Nutrient status and availability were monitored in a study investigating the effects of different residual pine and hardwood densities on pine reproduction in a mature shortleaf pine-hardwood stand located in the Ouachita Mountains of Arkansas. In 1989 pine basal area was reduced to 13.8 m^2/ha. and hardwood basal area was reduced to 0.0, 3.4, or 6.9 m^2/ha using single-tree selection. A portion of the unaltered stand was used as a control. Nutrient contents of and concentrations in litterfall, forest floor, and soils were monitored 3 and 11 years after harvesting. Nutrient contents and concentrations were then compared among treatments using these data to determine short and long-term changes of nutrient status resulting from the alteration of pine-hardwood composition and density.

INTRODUCTION

Partial cuttings of shortleaf pine (*Pinus echinata* Mill.)-hardwood stands in the Ouachita Mountains are used to regenerate and maintain shortleaf pine as well as to control pine-hardwood composition to meet various wildlife, aesthetic, and diversity objectives. Changes in species composition due to silviculture or natural processes such as succession can alter nutrient regimes, cycling, and availability in forest ecosystems. For example, Alban (1982) compared nutrient levels in soils, forest floor, and litterfall in adjacent 40-year-old plantations of aspen (*Populus tremoloides* Michx.), white spruce (*Picea glauca* Moench), red pine (*Pinus resinosa* Ait.), and jack pine (*Pinus banksiana* Lamb.). Levels of Ca and Mg were generally lower in the soils but higher in the litterfall and forest floor of the aspen than the pine stands (Alban 1982). Binkley and Valentine (1991) found greater accumulations of several base cations and lower net mineralization rates in soils 50 years after an old field was planted to green ash compared to white pine. In the southern United States, Hinesley and others (1991) documented increased nutrient levels in late succession oak-hickory forests compared to early successional pine forests. Switzer and others (1979) found that as old field succession proceeds from pine to oak-hickory communities, soil surface contents of C, N, P, Ca, and Mg increase as does forest floor contents of Ca and Mg. Rates of decomposition nutrient mineralization, or nutrient immobilization are also altered with species composition. Lockaby and others (1995) found that changes in N and P concentration in litter were more dynamic in mixed pine-deciduous stands than in pine-only stands. Decomposition rates appeared to be greater for the mixed stands than pine-only stands (Lockaby and others 1995). Results from these studies suggest that manipulation of the composition of shortleaf pine-hardwoods by partial cutting may potentially alter nutrient cycling and regimes. To better quantify the effects of partial cutting and stand composition on nutrient cycling and regimes, we monitored nutrient concentrations/contents in litterfall, forest floor, and soils 3 and 11 years after application of several uneven-age reproductive cutting prescriptions in a shortleaf pine-hardwood stand. Prescriptions retained 13.8 m^2/ha of overstory pine basal area and 0.0, 3.4, or 6.9 m^2/ha of overstory hardwood basal area. Pine/hardwood composition differed among prescriptions and during the two study periods.

METHODS

Study Site

The study area is located in Perry County Arkansas (34° 52' 12" N Latitude and 92° 49' 30" W Longitude) near Lake Sylvia on the Winona Ranger District of the Ouachita National Forest. Elevations at the site range from 195 to 240 m above mean sea level. Slopes within the study site range from 8 to 21 percent and soils are classified as Typic Hapludults of the Carnasaw and Pirum series and are well drained and moderately deep (Townsend and Williams 1982). Treatment plots were established along an east-west running ridge typical of Ouachita Mountains physiography.

Vegetation in the study area is typical of the Ouachita Mountains where upland forests are dominated by shortleaf pine and mixed oak species (Guldin and others 1994). The site index for shortleaf pine in the study area averaged 17.4 m at 50 years. White oak (*Quercus alba* L.) is the most prevalent hardwood and had an average site index of 16.2 m

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at 50 years. Smaller quantities of post oak (*Q. stellata* Wangenh.), black oak (*Q. velutina* Lamarch), blackjack oak (*Q. marilandrica* Muenchh.), and southern red oak (*Q. falcata* Michx.) are present on the site along with ash (*Fraxinus* spp.), hickory (*Carya* spp.), red maple (*Acer rubrum* L.), serviceberry (*Alemanchier arborea* [Michx. f.] Fern.), blackgum (*Nyssa sylvatica* Marsh.), and dogwood (*Cornus florida* L.). Understory vegetation consists mainly of shade tolerant shrubs such as huckleberries (*Vaccinium* spp.) and hawthorns (*Crataegus* spp.) (Shelton and Murphy 1997).

Typical of a number of stands located in the Ouachita Mountains, the stand at the study site developed after intensive harvesting of virgin pine forests in the early twentieth century. Harvesting in the early twentieth century removed high quality pines and oaks with stump diameters of 36 cm or more but left smaller, poorer quality trees (Shelton and Murphy 1991). Establishment of fire suppression during the 1930's resulted in the reestablishment of hardwoods in the understory of these forests. As a result, 90 percent of pines and oaks present prior to the study establishment ranged in age from 50-80 and 40-70 years, respectively (Shelton and Murphy 1991). The youngest age classes found in the overstory for both pines and oaks

Table 1—Mean litterfall and forest floor mass (O_i and O_e) for each harvesting treatment and component in a shortleaf pine-hardwood stand located Perry County, Arkansas

Component	0.0[a]	3.4	6.9	Uncut
	Litterfall Mass (kg/ha) 1991			
Pine Foliage	1,871a[b]	1,481a	1,367a	2,210a
Hardwood Foliage	30c	889b	1,647a	1,361ab
Total Foliage	1,902c	2,370bc	3,014ab	3,571a
Woody Debris	488a	529a	712a	1,017a
Reproductive	287a	274a	444a	387a
Total Litterfall	2,676c	3,173bc	4,171ab	4,975a
	Litterfall Mass (kg/ha) 1999			
Pine Foliage	2,913a	2,580a	2,132a	3,160a
Hardwood Foliage	1,170b	1,744ab	2,480a	1,735ab
Total Foliage	4,083a	4,324a	4,613a	4,896a
Woody Debris	1,528a	1,294a	1,327a	1,576a
Reproductive	628a	669a	730a	619a
Total Litterfall	6,239a	6,287a	6,669a	7,091a
	Forest Floor Mass (kg/ha) 1991			
O_i	7,157a	6,317a	4,939a	5,892a
O_e	14,022a	13,580b	9,150b	12,542ab
Total	21,180a	19,898a	14,090b	18,435ab
	Forest Floor Mass (kg/ha) 1999			
O_i	5,018a	4,802a	4,846a	5,762a
O_e	17,012a	17,963a	18,315a	16,331a
Total	22,031a	22,765a	23,162a	22,094a

[a] Retained hardwood basal area (m²/ha) after harvesting the pine component to 13.8 m²/ha.
[b] Treatments with the same letter for a given component and year are not significantly different at $\alpha = 0.05$.

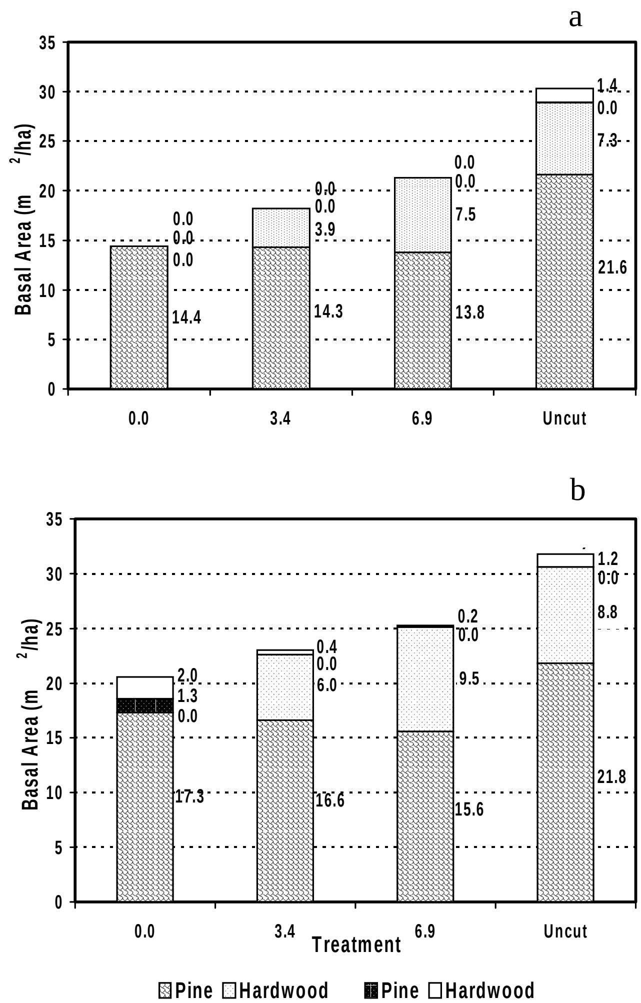

Figure 1—Basal area of pine and hardwood overstory and saplings in a) 1991 and b) 1999 by harvesting treatment (retained hardwood basal area in m²/ha) in a shortleaf pine-hardwood stand located in Perry County, Arkansas.

suggests that regeneration of overstory species had been inhibited 30-40 years prior to the initiation of the study. Average basal areas of shortleaf pine and hardwoods were respectively 21.5 and 6.9 m²/ha prior to harvesting in 1988.

Study Design and Treatment

In late winter of 1988 and spring of 1989, three harvesting treatments were established in four different slope/aspect blocks in a randomized block design. In the three harvested treatments, overstory pine basal area was reduced to 13.8 m²/ha while hardwood basal area was reduced to 0.0, 3.4, or 6.9 m²/ha. Higher quality white and red oaks were retained in a uniform distribution within treatments that maintained residual hardwoods. The basal area-maximum diameter-quotient method of single-tree selection was used to regulate the pine component on each of the harvested treatments (Farrar 1984). The selection targets were 13.8 m²/ha of basal area, 45.7-cm maximum d.b.h., and a 1.2 quotient for 2.5-cm d.b.h. classes. Pine after felling was yarded using mules. No markets were available for the hardwoods, thus all unwanted hardwoods ≥2.5 cm d.b.h.

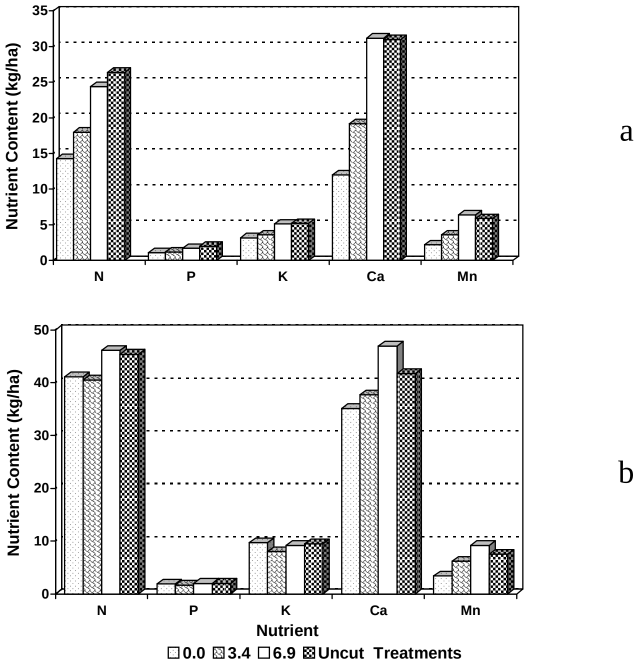

Figure 2—Selected nutrient contents of litterfall in a) 1991 and b) 1999 by harvesting treatment (retained hardwood basal area in m^2/ha) in a shortleaf pine-hardwood stand located in Perry County, Arkansas. For a given nutrient, treatments with the same letter are not significantly different $\alpha = 0.05$.

were injected with triclopyr amine during April 1989. A 0.2-ha net plot surrounded by a 17.7-m isolation strip was established in each harvesting treatment and block. Net plots were established in a portion of the uncut stands in each block in 1990. The uncut plots have no isolation strip as the surrounding undisturbed stand acts as an isolation strip.

Sample Collection and Preparation

Litterfall was collected on a 1 to 3 month interval for nutrient analysis and mass determination during 1991 and 1999. Litterfall was collected in four 0.08-m^2 circular traps in each net plot during 1991 and in two additional 0.08-m^2 circular trap plus three 0.5-m^2 square traps in each net plot during 1999. All litter was sorted into four components: hardwood foliage, pine foliage, woody debris, and reproductive material. Woody branches and stems greater than 1.25 cm in diameter were excluded from sampling in 1991 while in 1999 only debris greater than 7.50 cm were excluded.

Forest floor was collected on the border of each net plot using three 0.1-m^2 frames in 1991 and six 0.1-m^2 frames in 1999. Forest floor samples were separated into the O_i and the O_e horizons. The O_i was further separated into hardwood foliage, pine foliage, woody debris, and reproductive material in 1999. In 1991 samples were not separated by component but the proportion of O_i in each component determined in 1990 was used to estimate component mass from each treatment using total 1991 O_i mass. Maximum branch or stem size included in the samples for 1991 was 2.5 cm and in 1999 was 7.5 cm. Nutrient concentrations for each component for 1991 were determined from the separated samples collected in 1990. Since no sampling was performed in the uncut treatment in 1990, nutrient concentrations for each component in the 6.9-m^2/ha treatments were used to estimate the uncut nutrient concentrations.

Mineral soil was collected at the border of the net plot and isolation strip for each plot. In 1991 mineral soil from the 0–15.0 cm depth was collected using a shovel at two locations at the border of the harvested net plots and outside the border of the isolation strips. The samples collected from outside the isolation strips were used as the uncut treatment samples in 1991. Mineral soil was collected from six locations to a depth of 7.5 cm along the border of each net plot using an 8.5 cm impact soil sampler in 1999. Samples were collected from both harvested and uncut control plots.

Litterfall and forest floor samples were dried at 65 °C for at least 48 hours after collection. Samples for each collection period were weighed and then subsamples from each component and type were ground to pass a 1-mm sieve for chemical analysis. Mineral soil was air-dried and passed through a 2-mm sieve. Samples from a given depth, plot, and year were then composited prior to chemical analysis.

Chemical and Statistical Analysis

For litterfall and forest floor samples, P, K, Ca, Mg, S, and micronutrients were determined using inductance coupled plasma (University of Arkansas, Soil Test Laboratory 1990a) after a perchloric acid digestion (Alder and Wilcox 1985). N concentration was determined using micro-Kjeldhal techniques (University of Arkansas, Soil Test Laboratory 1990b). Mineralizable N (Powers 1980), total N, P, K, Ca, Mg, and micronutrients were determined for the mineral soil samples in 1999 but only P, K, Ca, Mg, S, and micronutrients were determined in 1991. P, K, Ca, Mg, S, and micronutrients were determined using inductance coupled plasma (University of Arkansas, Soil Test Laboratory 1992) after a Mehlich 3 soil extraction (Mehlich 1984). N was analyzed using a Skalar autoanalyzer after digestion by Kjeldhal techniques (Bremner 1982).

Analysis of variance was used to evaluate differences in nutrient concentrations, nutrient contents, or mass among treatments. Where differences were significant, Tukey's Honestly Significant Difference test was used to separate treatments means. An a=0.05 was used except where noted.

RESULTS AND DISCUSSION

Litterfall

Three years after harvesting total, total foliage, and hardwood litterfall amounts were significantly lower in the 0.0-m^2/ha residual hardwood treatment than in any of the other three treatments (table 1). Generally hardwood foliage, total foliage, and total litterfall amounts reflected differences in basal area and composition among treatments (figure1a). By 1999 the total amounts of litterfall and litterfall foliage did not differ among treatments but the amount of hardwood litterfall was still significantly less in the 0.0-m^2/ha treatment than that in the 6.9-m^2/ha treatment (table 1). Total and hardwood tree basal area in 1999 still reflected the initial residual densities of the treatments but differences

Table 2—Average forest floor contents and mineral soil concentrations for selected nutrients in each harvesting treatment during 1991 and 1999 in a shortleaf pine-hardwood stand in Perry County, Arkansas

Nutrient	0.0[1]	3.4	6.9	Uncut
Forest Floor Content (kg/ha) 1991				
N	195a[2]	183a	129a	172a
P	13a	11a	9a	12a
K	22a	17a	14a	18a
Ca	194a	148a	145a	181a
Mn	23a	20a	20a	25a
Forest Floor Content (kg/ha) 1999				
N	181a	204a	212a	181a
P	10a	10a	11a	9a
K	11a	13a	16a	13a
Ca	137a	147a	165a	147a
Mn	16b	26ab	32a	28ab
Mineral Soil (mg/kg) 1991[3]				
P	13a	13a	13a	13a
K	48a	42a	30a	44a
Ca	174a	142a	174a	131a
Mn	66a	67a	63a	60a
Mineral Soil (mg/kg) 1999[4]				
Total N	1102a	944a	903a	846a
Mineralizable N	58a	41a	54a	45a
P	4a	4a	5a	4a
K	57a	47a	54a	48a
Ca	246a	98b	119ab	100b
Mn	58a	36a	54a	34a

[1] Retained hardwood basal area (m^2/ha) after harvesting the pine component to 13.8 m^2/ha.
[2] Treatments with the same letter for a given nutrient and year are not significantly different at $\alpha = 0.05$.
[3] 0-15 cm depth.
[4] 0-7.5 cm depth.

were reduced among treatments compared to those observed in 1991 (figure 1). Approximately 3.3 m^2/ha of sapling (1.5-8.9 cm d.b.h.) basal area was present in the 0.0-m^2/ha treatment. The amount of hardwood foliage litterfall collected in the 0.0-m^2/ha treatment during 1999 was 39 times more than that collected during 1991 and reflected the partial recovery of the hardwoods in this treatment. The total amount of litterfall collected in the uncut treatment was respectively 42 percent more in 1999 than 1991. A portion of this increase reflected the larger diameter of woody litterfall included in collections from 1999 ($\leq$7.5 cm) compared to 1991 ($\leq$1.25 cm). However total foliar litterfall also increased by 37 percent during this period. Thus it seams likely that the increased levels of litterfall in 1999 compared to 1991 reflected natural variation in litterfall amounts and the continuing growth of trees in the plots.

Total litterfall nutrient contents in 1991 were generally greatest in the uncut and 6.9-m^2/ha treatments than in the 0.0- or 3.4-m^2/ha treatments (figure 2a). Nutrient contents of litterfall in 1991 closely reflected the differences in the amount of litterfall and basal area among treatments (figure 1; table 1). Removal of pine and hardwoods reduced the inputs of foliage and reproductive material in the litterfall thereby reducing nutrient contents. However, differences in nutrient concentrations of litterfall were evident. Concentrations of Ca and Mn were significantly lower while concentrations of K were significantly higher in the 0.0-m^2 treatment than the uncut and/or the 6.9-m^2/ha treatments. Concentrations in the 0.0-m^2/ha treatment differed from those in the uncut and 6.9-m^2/ha treatment by as much as 30 to 70 percent. These differences were in part related to the changes in the pine/hardwood foliage proportions in the litterfall after applying the harvesting treatments. However, concentrations of K in pine foliage litterfall were also significantly higher in the 0.0-m^2/ha treatment (0.15 percent) than in either the 6.9-m^2/ha treatment (0.11 percent) or uncut (0.11 percent) treatments. These results suggest that harvesting treatments had altered the availability, competition for, or retranslocation of K, Ca, or Mn within these treatments during 1991.

In 1999, 11 years after harvesting treatment application, litterfall nutrient contents generally did not differ among treatments (figure 2b). The similar nutrient levels among treatments reflect the rapid recovery of foliar production in the treatments since harvesting (table 1). Litterfall contents of Mn were still significantly lower in the 0.0-m^2/ha treatment than the uncut or 6.9-m^2/ha treatments. The differences in Mn content are primarily related to the lower concentrations of Mn in the litterfall of the 0.0-m^2/ha treatment. Mn concentrations in the foliar litterfall of the 0.0-m^2/ha treatment (0.10 percent for hardwood and 0.06 percent for pine) were significantly lower than concentrations in the 6.9-m^2/ha treatment (0.17 percent for hardwood and 0.12 percent for pine) and uncut (0.16 percent for hardwood and 0.11 percent for pine) treatment. Mn concentrations in 1991 and 1999 were strongly correlated to the amount of hardwoods retained and basal area harvested. Apparently, reduction of hardwoods alters cycling of Mn by shortleaf pine and hardwoods for a number of years after harvesting.

Forest Floor

Forest floor mass in 1991 was generally the least in the treatments that had little or no hardwood removal, and greatest in treatments that had the greatest hardwood removal. Increased mass of the forest floor in the 0.0- and 3.4-m^2/ha treatments appeared to reflect bark and woody inputs from hardwoods that were killed with herbicide. Eleven years after harvesting in 1999, forest floor mass did not significantly differ among treatments. Recovery of the forest floor mass in the 0.0-m^2/ha treatment was evident, and mass generally varied by less than 10 percent among treatments.

Differences in forest floor nutrient contents among treatments in 1991 were not significant (table 2). However, like forest floor mass, nutrient contents were consistently greatest in the 0.0-m^2/ha treatment. In 1999 differences among treatments were significant for Mn contents but not for N, P, K, or Ca. Differences in forest floor Mn like litterfall can be attributed to lower concentrations of Mn in the 0.0-m^2/ha treatment. Forest floor Mn concentrations were significantly lower in the 0.0-m^2 treatment (0.07 percent) than in the uncut (0.13 percent) or 6.9-m^2/ha treatments

(0.14 percent). Forest floor Mn concentrations were twice as great in the 6.9-m^2 treatment than the 0.0-m^2 treatment. These differences were similar to those observed in the litterfall and generally reflect differences in litterfall Mn concentrations.

Mineral Soil

Mineral soil concentrations with the exception of Ca in 1999 did not significantly differ among treatments (table 2). Frequently, nutrient concentrations were greatest in the 0.0-m^2/ha treatment during 1999, but differences between this treatment and the others were not significant for any nutrient other than Ca. These results suggest that although nutrient cycling may have been altered by the harvesting treatments, this alteration has had minimal impacts on the nutrient levels in the soils in these treatments. It should however be noted that the statistical power of the study design and sampling scheme was lower for the mineral soil component than for either the litterfall or forest floor.

SUMMARY

Changes in stand density and composition due to harvesting treatments significantly impacted the levels of specific nutrients in this study. Impacts were generally greatest in 1991 due to the changes in litterfall and forest floor amounts. However, differences in K and Mn concentrations in litterfall or forest floor altered total amounts of these nutrients in the treatments. By 1999 differences in nutrient contents were minimal among treatments. However, litterfall and forest floor Mn levels in the 0-m^2/ha treatment were still lower than those in the uncut or 6.9-m^2/ha treatments. Any changes in litterfall or forest floor nutrient contents did not appear to alter nutrient concentrations in soils. Concentrations of nutrients did not significantly differ among treatments either 3 or 11 years after harvesting.

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EFFECT OF A ONE-TIME BIOSOLIDS APPLICATION IN AN OLD-FIELD LOBLOLLY PINE PLANTATION ON DIAMETER DISTRIBUTIONS, VOLUME PER ACRE, AND VALUE PER ACRE

E. David Dickens[1]

Abstract—A forest land application of biosolids study was initiated in 1991 in the lower Coastal Plain of South Carolina (SC). A major objective of this project was to quantify the magnitude and duration of old-field loblolly pine (*Pinus taeda*, L.) growth response to a one-time biosolids application after canopy closure. The study area is located on Alcoa property in Berkeley County, SC. The soil series, Goldsboro (Fine-loamy, Aquic Paleudults) was delineated by a NRCS soil mapper in a 1982 planted loblolly pine stand. Gross treated and interior permanent measurement plots were installed in a randomized complete block design. Forty feet of untreated buffer was maintained between plots. All living loblolly pines were tagged, numbered, and measured for dbh and total height in February-March 1992. Berkeley County Water and Sanitation Authority (BCW&SA) biosolids (5.7 percent total-N, 15 percent solids, extended aeration treated) were applied one-time in April 1992 at 0, 650, and 1300 pounds of total-N per acre (5.7 and 11.4 dry tons/acre). The stand was operationally thinned (third row with logger select in between) in August 1993 reducing SPA from 560 to 300 (BA/ac from 120 to 65 square feet). Stand data from age 10-years-old to age 17-years-old show a dramatic growth increase in mean dbh increment (0.5 and 1.0 inch), total height increment (2.0 and 2.7 feet), volume/tree (30-35 percent), and volume/acre increment (37-38 percent) in the biosolids versus the control plots. Diameter distributions 7 years after biosolids application favored more chip and saw (8-9 cords/acre) and less pulpwood (1-3 cords/acre) in the biosolids versus control plots. Total wood value/acre was increased by $555 to $595 (at $19/cd pulpwood and $73/cd chip and saw (Timber Mart-South 2000) in the biosolids plots versus the control plots by age 17-years-old.

INTRODUCTION

Total demand for forest products is anticipated to increase substantially by the year 2030 (USDA 1988). Pulpwood is projected to show the largest rise, with demand increasing 50 percent (GFC 2001). The southeastern US is estimated to produce 50 percent or more of the world's pulp and paper 30 years from now (USDA 1988). This increased demand for wood fiber coincides with the recent interest by the US congress and EPA to promote beneficial use of biosolids. Forest land application of biosolids can save large sums of money through landfill tipping fee cost avoidance and extensions in landfill life. These savings are estimated for South Carolina to range from $50,000 to $400,000 per year per county. Loblolly pine (*Pinus taeda,* L.), a principle southeastern US crop tree, will often respond to one-time N+P fertilization on most better drained Coastal Plain soils (NCSUFNC 1999). Forest wood and fiber products are not a part of the human food chain and forest land application scheduling and management is not as complicated as in other crop alternatives. There is an abundance of forest land in South Carolina where two-thirds of 19 million acres is forested (Tansley and Hutchins 1988).

METHODOLOGY

Permanent measurement plots were established in the fall of 1991 on Alcoa property in Berkeley County, SC. The study area was on an old field 10-year-old loblolly pine planted at 6x10 feet with 14 feet between every 5th row. The soil series throughout the study area was Goldsboro. The experimental design was randomized complete block with two replications (blocks) per treatment (0, 5.7, and 11.4 dry tons biosolids/acre) in the loblolly pine stand for a total of six experimental units (plots). Gross treated plots averaged 1/4 acre and internal permanent measurement plots averaged 1/10th acre. Forty feet of untreated buffer was maintained between each plot. Plot conversion factors were used to convert from volume per tree and number of trees to wood volume per acre for each plot and biosolids treatment. All living loblolly pine trees in each plot were affixed with a numbered aluminum tree tag at 4.5 feet above groundline then measured for diameter (Dbh with a d-tape) and total height (height pole except the last measurement was with a clinometer) in February-March 1992 prior to biosolids application and two (1/94), four (1/96), five (3/97), and seven (3/99) growing seasons after biosolids application. Extended aeration biosolids (80 percent domestic and 20 percent industry input, 15 percent solids, 5.7 percent total-N, table 1) were applied on 9-15 April 1992 at 0, 5.7 dry tons (200 PAN) and 11.4 dry tons

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Table 1—Concentrations and application levels for the BCW&SA biosolids applied to an old-field loblolly pine plantation in Berkeley County, SC on a Goldsboro soil

Component	Concentration	Application Level Low		Application Level High	
	--mg/kg dry basis--	kg/ha	(lb/ac) dry basis	kg/ha	(lb/ac) dry basis
Biosolids		2800	(11400)	25,500	(22800)
Kjeldahl-N	57000	728	(650)	1460	(1300)
NH_4-N	1660	21.1	(18.9)	42.3	(37.8)
NO_3-N	53	0.67	(.60)	1.3	(1.2)
elemental-P	11500	147	(131)	293	(262)
elemental-K	3770	48.2	(43)	96	(86)
Ca	18600	237	(212)	475	(424)
Mg	6400	81.8	(73)	164	(146)
As	3.0	0.038	(.034)	0.076	(.068)
Cr	10.0	0.128	(.114)	0.260	(.230)
Cu	380	4.85	(4.33)	9.70	(8.66)
Pb	33	0.421	(.376)	0.842	(.752)
Ni	38	0.476	(.433)	0.970	(.866)
Se	1.7	0.022	(.020)	0.045	(.400)
Zn	500	6.4	(5.7)	12.8	(11.4)

(400 PAN) per acre to randomly assigned plots. Plant available nitrogen (PAN) was estimated to be 30 percent of organic-N (TKN - NH_4-N), 50 percent of NH_4-N, and 100 percent of NO_3-N (SC-DHEC 1996). The low biosolids level (5.7 dry tons/acre or 38 wet tons/acre) was achieved by one pass with a tractor and pull behind side port spreader at a known speed with the port door set to a marked opening height and the PTO RPMs set at 540. Two passes achieved an average of 11.4 dry tons/acre (76 wet tons/acre). Fourteen feet between every fifth row allowed for ground access into the plots. The stand was operationally thinned (third row with logger select in between) in August 1993 from an average of 560 stems/acre (120 ft^2 BA/ac) to 300 SPA (65 ft^2 BA/ac). Winter prescribe backing fires were performed in the entire study area in February 1994, 1996, and 1998.

An analysis of covariance (SAS 1988) was run on 1994 data to ensure that a “common” starting point among the treatment levels after the thinning. Per acre basal area was used as the co-variate but it was not significant nor was the treatment effect. There were no significant treatment differences (5 percent alpha level) for mean dbh, total height, total volume/tree and total volume/acre the 1994 data. The number of stems in each diameter class was multiplied by the plot conversion factor to obtain the number of trees/acre by dbh class. Pre-thinning and pre-treatment (3/94) average stems/acre were 589 for the control, 555 for the low biosolids (200 PAN/ac) and 527 for the high biosolids (400 PAN/ac). Post thinning (1/94) stems/acre averages were 310 for the control, 300 for the low biosolids (200 PAN/ac) and 286 for the high biosolids (400 PAN/ac). Age 17-years-old average stems/acre were 297 for the control, 295 for the low biosolids (200 PAN/ac) and 271 for the high biosolids (400 PAN/ac). Diameter distributions at age 17-years-old were discerned by individual measured stems in one inch dbh classes from 4.0 - 4.9 to 12.0 and greater. The stem volume equations used (Pienaar and Grider 1984, Bailey and others, 1985) were:

$$TV_{(ib)} = 0.0014793\ D^{1.821} H^{1.1629}$$
$$MV_{(ib)} = TV_{(ib)}(1 - 0.4482\ D_m^{3.4580} D^{-3.1947})$$

where

$TV_{(ib)}$ = inside bark, total stem volume in cubic feet
$MV_{(ib)}$ = inside bark, merchantable stem volume in cubic feet
D = dbh in inches
H = total stem height in feet
D_m = outside bark, merchantable diameter in inches.

It was assumed that 100 percent of the tagged loblolly pines were pulpwood after biosolids application (age 10-years-old) and after the thinning (age 12-years-old). Product class distribution (either pulpwood or chip and saw) at age 17-years-old was estimated in the following manner. All living tagged loblolly pines in each plot that were 9.0 inches dbh and over were considered to be chip and saw trees. All living tagged trees that were 4.0 through 8.9 inches dbh were considered to be pulpwood trees. Where dbh was greater than or equal to 9.0 inches then D_m was 4.0 inches. Where dbh was less than 9.0 inches then D_m was 2.0 inches. Each individual measured living stem was therefore “merchandised” into either a “pulpwood” or “chip and saw” tree at age 17-years-old. Seventy-six cubic feet (ib) per cord was used as the conversion factor. A price of $19/cord for pulpwood and $73/cord for chip and saw

Table 2—Mean diameter (at 4.5 feet above groundline), total height, volume/tree (ib), and volume/acre in a 1982 planted old-field loblolly pine plantation where biosolids were applied (4/92) in Berkeley County, SC on the Goldsboro soil series

Year	Trt[a]	Dbh (in)	Tot Ht (ft)	Vol/tree (ft^3)	Vol/acre (ft^3)
1992	Control	5.05	26.7	1.29	760
	Low	5.33	27.2	1.45	805
	High	4.88	26.6	1.20	632
1994	Control	6.44	39.2	3.13	970
	Low	6.74	39.0	3.38	1014
	High	6.45	38.0	3.11	889
1996	Control	7.22	43.8	4.39	1317
	Low	7.69	45.4	5.13	1513
	High	7.54	43.8	4.75	1287
1997	Control	7.63	48.5	5.47	1625
	Low	8.17	49.5	6.34	1870
	High	8.12	49.2	6.22	1686
1999	Control	8.01	51.8	6.44	1913
	Low	8.82	54.3	8.12	2395
	High	8.83	54.4	8.15	2209
Culm.	Control	2.96	25.1	5.15	1153
grow	Low	3.49	27.1	6.67	1590
92-99	High	3.95	27.8	6.95	1577

[a]Treatments = biosolids treatments: control (no treatment), low (200 lb PAN/acre), and high (400 lb PAN/acre). The stand was operationally 3rd row thinned with select in between in August 1993 from 120 BA/acre to 65 ft^2 BA/acre.

(Timber Mart-South 2000) was used to determine value/ace by product class and total value/acre by treatment.

RESULTS

Loblolly pine mean diameters in the 1982 established stand were 4.88 inches (400 lb PAN/ac), 5.05 inches (control), and 5.33 inches (200 lb PAN/ac) in March 1992 prior to biosolids application and 8.01, 8.82, and 8.83 inches, respectively by March 1999 (table 2). Control plots mean diameter increased 2.96 inches, the 200 lb PAN/acre plots mean diameter increased 3.49 inches, and the 400 lb PAN/acre mean diameter increased 3.95 inches during the seven year measurement period. Average seven year diameter increment was increased by .07 and .14 inches/year in the biosolids plot trees compared to the control plot trees (table 2). Five year (94-99 post thin) average loblolly pine dbh increment was 0.314"/yr for the control, 0.416"/yr for the 200 PAN/acre, and 0.476"/yr for the 400 PAN/acre treatment.

Average loblolly pine tree heights prior to biosolids application were 26.7, 27.2, and 26.6 feet for the control, 200, and 400 lb PAN/acre plots, respectively at age 10-years-old (table 2). Average total heights seven years after biosolids application (3/99) were 51.8, 54.3, and 54.4 feet for the control, 200, and 400 lb PAN/acre plots, respectively. Average tree height growth during this seven year period since biosolids application was 25.1, 27.1, and 27.8 feet for the control, 200, and 400 lb PAN/acre plots, respectively. Biosolids plots height increment was 8 percent and 11 percent above the control seven years since biosolids application (table 2). Five year (94-99 post thin) average loblolly pine height increment was 2.52'/yr for the control, 3.06'/yr for the 200 PAN/acre, and 3.28'/yr for the 400 PAN/acre treatment.

Total inside bark wood volume per tree means prior to biosolids application (age 10-years-old) were 1.29, 145, and 1.20 cubic feet (inside bark) for the control, 200, and 400 lb PAN/acre plots, respectively (table 2). Wood volume per tree averages seven years after application (3/99) were 6.44 (control), 8.12 (200 lb PAN/acre), and 8.15 (400 lb PAN/acre) cubic feet. Wood volume per tree growth between 1992 and 1999 was 5.15 (control), 6.67 (200 lb PAN/acre), and 6.95 (400 lb PAN/acre) cubic feet. The biosolids plots mean wood volume per tree growth during the seven years since biosolids application was 30 percent (200 lb PAN/acre) and 35 percent (400 lb PAN/acre) greater than the control's. Five year (94-99 post thin) average loblolly pine volume/tree increment for the 200 and 400 PAN/acre biosolids treatments were 43 percent and 52 percent greater than the control, respectively. Post thin average annual volume/tree increment was 0.662 ft^3/yr for the control, 0.948 ft^3/yr for the 200 PAN/acre, and 1.01 ft^3/yr for the 400 PAN/acre treatment.

Total inside bark wood volume/acre means were 760, 805, and 632 cubic feet for the control, 200 PAN/ac, and 400 PAN/ac plots, respectively, prior to biosolids application

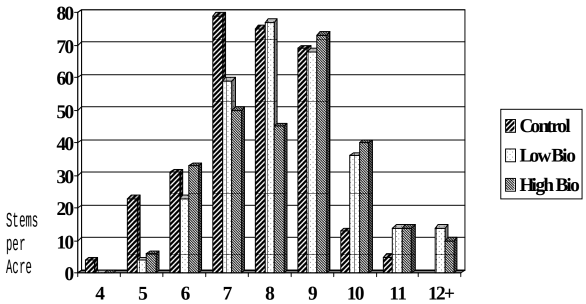

Figure 1—Old-field thinned loblolly pine plantation diameter distributions by treatment seven years after a one-time biosolids application in Berkeley County, SC on a Goldsboro soil series.

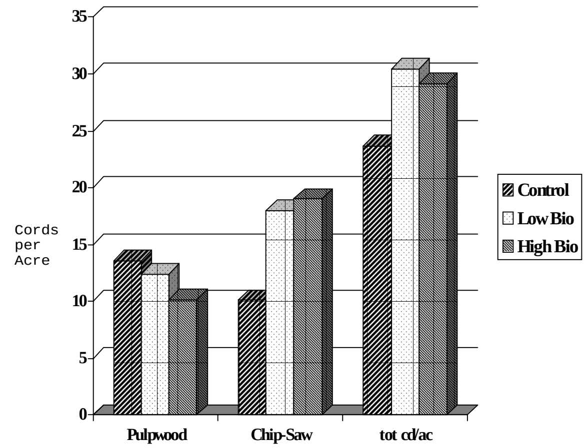

Figure 2—Old-field thinned loblolly pine plantation mean cords per acre production by treatment seven years after a one-time biosolids application in Berkeley County, SC on a Goldsboro soil series.

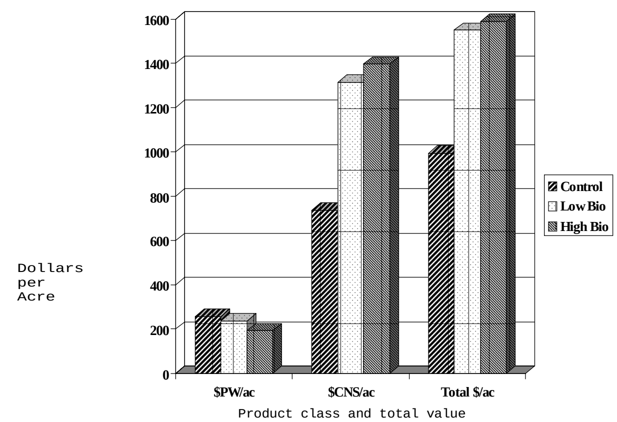

Figure 3—Old-field thinned loblolly pine plantation mean value by product class and per acre by treatment seven years after a one-time biosolids application in Berkeley County, SC on a Goldsboro soil series.

(3/92). Total inside bark wood volume means were 1913, 2395, and 2209 cubic feet for the control, 200 PAN/ac and 400 PAN/ac, respectively, seven years after the one-time biosolids application and five years after the thinning. Total wood volume(ib)/acre growth was 1153 (control), 1590 (200 PAN/ac), and 1577 (400 PAN/ac) seven years after biosolids application or 37-38 percent more wood volume increment in the biosolids plots. Five year (94-99 post thin) average loblolly pine volume/acre.year increment was 189 ft^3/yr for the control, 276 ft^3/yr for the 200 PAN/acre, and 264 ft^3/yr for the 400 PAN/acre treatment. Post thin average loblolly pine volume/acre for the 200 and 400 PAN/acre biosolids treatments were 46 percent and 40 percent greater than the control, respectively.

Diameter distributions in the low and high biosolids plots favored more chip and saw sized trees (9.0 inch dbh or greater) and less pulpwood sized trees (< 9.0 inch dbh) by age 17-years-old compared to the control plot diameter distribution (figure 1). Product class merchantable volumes in the biosolids plots had 8-9 more cords/acre in the chip and saw category and 1-3 cords/acre less pulpwood by age 17-years-old (figure 2). The pulpwood dollar value was greater in the control plots by $22 and $65 per acre compared to the low and high biosolids plots by age 17-years-old (figure 3). Chip and saw dollar value was $577 and $660 greater in the low and high biosolids plots, respectively, compared to the control seven years after treatment (figure 3). The net total revenue increase in the biosolids plots was $555 and $595 compared the the control plot mean (@ $19/cord for pulpwood and $73/cord for chip and saw) for the extra wood grown by product class. The internal rate of return ((Return/cost)$^{1/7}$-1) for the extra wood grown over seven years at a cost of $90/acre for one pass (the low biosolids level) and $180/acre for two passes (the high biosolids level) is 29.7 percent and 18.6 percent for the low and high biosolids treatment.

DISCUSSION

The literature is scarce documenting the magnitude and duration of response to biosolids when applied to old-field planted loblolly pine stands. Loblolly pine dbh, total height, volume per tree, and volume per acre biosolids plots means were greater than the control seven years after the one-time biosolids application (table 2). Biosolids plots wood volume per tree and volume/acre seven year increments were 30-35 percent and 37-38 percent greater than the control, respectively. Diameter distributions in the biosolids plots favored 8-9 cords more chip and saw and 1-3 cords less pulpwood by age 17-years-old. In this old-field trial the extra wood volume gain due to biosolids application was greater than 5 cords/acre. Dollar revenues were increased by an average of $575/acre in the biosolids plots seven years after application and five years after a thinning in the 1982 planted loblolly pine stand. Using a typical DAP+Urea fertilizer plus application cost of $90/acre for the one pass to achieve the 200 PAN/acre biosolids level and the extra $555 in wood grown over 7 years, the calculated rate of return was 29.7 percent. Assuming a cost of $180/acre for two passes to achieve the 400 PAN/acre biosolids level and the $595/acre extra wood grown, the calculated rate of return is 18.6 percent. The incremental growth gain (4 percent wood volume seven year increment increase over the low biosolids) and $40 extra dollars/acre generated in wood value from the high biosolids (two passes to achieve 76 wet tons/acre) in this case does not appear to be worth the extra time, cost, and labor compared the one pass low biosolids one-time application level.

The 200 pounds of plant available nitrogen (PAN) per acre biosolids application level is in line with the current nitrogen prescription (200 N+ 25-50 lbs P/acre) for loblolly pine stands after canopy closure (NCSUFNC 1999). This 200 PAN/acre application level includes 131 lbs elemental-P, 43 lbs elemental-K, 212 lbs Ca, 73 lbs Mg, 4.33 lbs Cu/acre and organic matter. Loblolly pine foliar N, P, and K were above sufficiency (1.2 percent N, 0.12 percent P, and 0.35 percent K) in all plots prior to biosolids (1992) application. Foliar levels of N and P by 1996 in the control plots were below sufficiency while the biosolids plot foliar levels were still above sufficiency. Top soil (0-2") soil organic matter was 2.5 percent in the control plots, 4.1 percent to 5.7 percent in the biosolids plots in 1997. Mehlich I soil P (0-6") was < 8 ppm in the control plots and 20-95 ppm in the biosolids plots in 1997.

Berkeley County, SC is over 77 percent forested with approximately 550,000 acres wooded (Tansley and Hutchins 1988). Thousands of acres of privately owned loblolly pine plantations are in close proximity to the Berkeley County Water and Sanitation Authority treatment plant. Using 1992 BCW&SA biosolids generation figures and the low application level (5.7 dry tons/acre) approximately 500 acres of land would be needed per year. If the biosolids are to be applied once every 7-10 years (in conjunction with a thinning regime) then 3,500 to 5,000 acres are needed for a seven to ten year cycle in near-by loblolly pine stands after canopy closure (with access) or just after a thinning.

CONCLUSIONS

Land application of BCW&SA biosolids in established loblolly pine plantations in Berkeley County, SC proved beneficial, increasing wood volume growth increment by 37-38 percent and value by $555 to $595 per acre seven years after application. A second objective in this study area was to determine the effect of the one-time biosolids application on local groundwater quality. Four year data showed no adverse effect of the one-time biosolids application on groundwater quality (Dickens and others 1997, Dickens 1999). Realistically, the low biosolids level (5.7 dry tons/acre or an estimated 200 lbs PAN/acre) achieved in one pass proved almost as beneficial in seven year wood volume growth, dollar acre increased revenue, and may be the closer to the amount of N needed for loblolly pine growth at this age class compared to the two pass high biosolids level (11.4 dry tons/acre or an estimated 400 lbs PAN/acre).

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NITRATE LEACHING FROM INTENSIVE FOREST MANAGEMENT ON ABANDONED AGRICULTURAL LAND: FIFTH-YEAR RESULTS

Thomas M. Williams, Charles A. Gresham[1]

Abstract—This report is on the fifth year results of a cooperative research project to examine water quality impacts of maximizing plantation growth on abandoned agricultural land, first reported after two years in the Ninth Southern Silvicultural Research Conference. The study, located on International Paper's Southland Experimental Forest at Bainbridge GA, examines growth of loblolly pine (*Pinus taeda* L.) and sweet gum (*Liquidambar styraciflua* L.) with complete vegetation control, irrigation, fertilization, and pest control as a factorial experiment on an abandoned agricultural field. Groundwater quality was measured in the maximum (all combined) and minimum (only vegetation control), the old field without plantation management, natural forest, and along the shore of Silver Lake. After two years groundwater nitrate concentrations in all the plots in the abandoned field violated drinking water standards (> 10mgN/l) and were significantly higher than the natural forest or lake edge. Soil moisture nitrate was significantly higher in the plots with vegetation control. After five years the number of violations and maximum nitrate concentrations have declined by roughly 50%. Soil moisture nitrate concentrations have declined significantly in the plantation plots in the last three years, at shallow depths. Concentrations at the five foot depth below the minimum treatment plots approached that found in the natural pine < 0.5mgNO_3-N /l. Growth rates have been large in all treatments except the sweet gum minimum treatment. Irrigated loblolly plots have accumulated over 250 kgN/ha from the soil pool in the abandoned field. The nitrogen pools within the soil have been sufficient to continue nitrate leaching for five years and supply 200-300 kg N/ha to the control and irrigated (only) pines.

INTRODUCTION

This paper updates a study first presented in the Ninth Southern Silvicultural Symposium (Williams 1999). The study has been following nitrate leaching on an abandoned peanut (*Arachis hypogaea* L.) field which has been used to grow loblolly pine and sweet gum at accelerated rates. International Paper has installed an experiment to examine highly intensive culture on marginal agricultural land on their Silver Lake experimental area near Bainbridge,GA. In this experiment three replications of four treatments have been applied to sweet gum and loblolly pine. The treatments are: complete competition control, plus irrigation, plus fertigation, plus fertigation and pest control for the maximum treatment. The goal of our section of this project was to evaluate the potential for contamination of groundwater or the adjacent Silver Lake. Groundwater and soil moisture were sampled from five locations in each replication: maximum treatment, minimum treatment, field with no treatment, adjacent natural pine stand, and hardwoods at the edge of Silver Lake. These plots were located as a transect from treated plots downhill to the lake.

Data collected during the first two years of the project confirmed that the direction of subsurface flow was not from the experimental area to the lake. However, the data also clearly showed high concentrations of nitrate nitrogen (NO3-N) beneath the entire old field. Groundwater concentrations peaks were over 27 mg NO3-N/ liter and exceeded EPA drinking water in all points below the field regardless of treatment. All groundwater NO3-N concentrations were significantly (> 10fold) higher than found in the natural forest plots. During the first year the minimum treatment concentration was significantly higher than the old field but this difference disappeared during the second year. Soil moisture NO3-N concentrations were significantly higher in the intensive treatments than in the fallow field and both were also 10 fold higher than the adjacent natural forest.

At that time, the best explanation of the results was tied to decomposition of peanut residues since they had been shown to rapidly release nitrogen (Smith and Sharpley 1990). Also, the higher soil moisture concentrations were thought to be associated with competition control which has been associated with other studies with higher NO3-N concentrations (Likens and others 1969, Munson and others 1993, Neary and others 1986).

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The study has been followed through the fifth growing season. During that period soil moisture and groundwater nitrate has been measured on a quarterly basis. In addition, trees and the forest floor have been measured for biomass and nitrogen uptake. The major questions to be answered have been: 1). Will nitrate leaching continue to be a problem? 2). Does plantation management have a significant impact on nitrogen cycling on the abandoned field?

METHODS

The study was done at International Paper's Silver Lake Experimental Forest near Bainbridge, GA on a former peanut field near the shore of Silver Lake. Silver Lake is a small stream valley that flooded subsequent to creation of Lake Seminole by a dam on the nearby Flint River. Soils of the site are Lakeland (Typic Quartzipsamments) and Eunola (Aquic Hapludult). In the old field, soils are excessively well drained fine sand to loamy sand.

The plantation management experiment is laid out as three replicates of a randomized block, 2x4 factorial experiment. Factors are species (loblolly and sweet gum) and management intensity (control, irrigation, irrigation + fertilizer, and irrigation + fertilizer + pest control). Since all the blocks had herbaceous competition control and genetically improved seedlings, the controls were still rather intensive cultural treatments.

Soil Moisture and Groundwater Sampling

Soil moisture and groundwater were examined using multi-level soil moisture and groundwater samplers on three transects, one from each replicate. Each transect consisted of five plots: Minimum treatment(control defined above), Maximum treatment, old field outside of the treatment plots, within a 50 year-old pine stand surrounding the field, and at the edge of the lake. In each replicate, the five plots were aligned perpendicular to the land slope from the field to the lake edge.

In April 1995 a 15 cm diameter hole was augured below the water table and a 5 cm PVC well screen was placed 60 to 120 cm below the water table at each sample location. All plots, except the lake edge, had water tables at approximately 6 meters depth and auger holes were 7 to 7.5 m deep. Horizontal drilling was used to place four (2.5 cm x 10 cm long) tension lysimeters in undisturbed soil approximately 30 cm from the central shaft. Tension lysimeters were connected to sample bottles in a box on the soil surface, and all sample bottles were connected to a central vacuum manifold.

Trees were planted in February 1995 and cultural treatments were begun in April 1995. Sampling of soil moisture and groundwater was begun in May 1995 and samples were collected twice each month until December 1996.

Tension lysimeters were maintained at tensions between 0.5 and 0.7 bar continuously throughout the period. At each sampling, water was poured from the lysimeter sample bottles into 60 ml polyethylene bottles, all 5 cm wells were pumped until clear and a 60 ml sample was collected.

Sampling was discontinued in December 1996 and was resumed in November 1997 and the sampling frequency was reduced. From November 1997 through December 1999 quarterly sampling was done. Groundwater was sampled three times and soil moisture was sampled twice each quarter. At the first visit during the quarter, a groundwater sample would be taken from all the wells. At that time the vacuum pump would be started and 0.5 to 0.7 bar tension would be placed on all of the lysimeters. After each of the next two rains the site would be revisited and samples taken from all wells and lysimeters. During the last visit the pump would be turned off until the first visit in the next quarter.

All samples were placed in coolers and returned to the Baruch Institute Lab in Georgetown SC and nitrate determinations were made within 24 hours. Nitrate analyses were done using cadmium reduction technique on a Technicon autoanalyser (Greenberg and others 1992).

Biomass and Nitrogen Content Sampling

Trees were planted in rows 3.7 m apart and spaced at 2.4 m within rows and each treatment plot consisted of 12 rows with 18 trees per row. A border 7.3 m wide was established in each plot using the inner 80 trees as a measurement plot. Forty of these were uniformly chosen by skipping every other tree on each row within the measurement plot. Tree growth was measured on three treatments: minimum, irrigated, and maximum, for each replication. For each tree, measurements were basal diameter, diameter at breast height, diameter at base of live crown, height of live crown, and total height. All measures were taken in January of 2000.

Biomass and nutrient accumulation were determined for the maximum and minimum treatments. In addition, the irrigation treatment was also sampled for nutrient content. Twenty trees of each species were sampled to determine biomass-size equations. A fourth replication of the maximum and minimum treatments of both species was designated for destructive sampling. Ten trees of each species from the maximum plot and 10 from the minimum plot were harvested, separated into: stems, dead branches, unfoliated branches, and foliated branches, and were weighed green. Subsamples were dried (60ºC) and weighed to obtain moisture content; subsamples of foliated branches were separated into branches and leaves before drying. Dry weight proportions from subsamples were used to determine dry weight of trees in the following components: stem, dead branches, live unfoliated branches, foliated branches, and leaves. Portions of each subsample were subsequently ground for nutrient analysis.

To assure that all trees measured during the fifth growing season were within the range of trees sampled for biomass, biomass equations were calculated on trees collected after the sixth growing season. Sweet gum trees were collected in September 2000 while loblolly were collected in February of 2001.

Forest floor biomass was estimated on the maximum, irrigated, and minimum plots for each species. In June 2000, all litter (humus layers had not yet formed in any treatment) was removed from 14, 1 m2 areas on a transect extending diagonally across each measurement plot as described above. Plots were stratified into rows (1 m on each side of the tree centers) and inter-rows (greater than 1 m from either row center). Seven areas were collected from each row and inter-row. All litter was carefully scraped from the soil surface and placed into paper bags. Bags were dried (60ºC) and weighed. Subsamples of each bag were ground for nutrient analysis.

All dried subsamples were ground to pass a 1.0mm sieve. The bole samples were chipped prior to grinding in the Wiley mill. Ground materials were Kjeldahl digested (Isaac and Johnson 1976, Labconco 1987, Jones and Case 1990, Jones 1991), diluted with DDW and colorimetrically analyzed for nitrogen and phosphorus with a Technicon AutoAnalyzer II using Industrial Method No. 329-74W/B (Nov. 78 revision) (Technicon Industrial Systems 1978). The nitrogen analysis method uses the sensitive color reaction between NH4+ and alkaline sodium salicylate with a chlorine source (Crooke and Simpson 1971, Technicon Industrial Systems 1978, Nelson and Sommers 1980). Averaged nutrient concentrations were then multiplied by biomass estimates to estimate nutrient quantities.

Statistical Analysis

Statistical analyses of the groundwater samples were as repeated samples of five treatments and three blocks. On the lake edge no tension lysimeters were installed, since the water table was so close to the surface. Soil moisture samples were analyzed as repeated samples of a factorial with four treatments, four depths, and three blocks. Treatment differences in groundwater within each year were tested by the Tukey multiple range test. Soil moisture concentration comparisons were made between years at a particular depth and across depths within a particular year. These analyses were also tested by Tukey multiple range tests.

Simple linear regressions were calculated for each component and total biomass. Equations were based on the same measures as taken in the growth plots. These regressions were combined with the growth data collected on each treatment to estimate treatment biomass means.

Loblolly equations were:

Bole	
biomass= 0.00958 D2h + 7.47	Rsq = .887
Dead Branch= 0.00372 D2h - 3.71	Rsq = .832
Unfoliated Branches= 0.076 BaBlc -1.82	Rsq = .624
Foliated Branches=0.0245 BaBlc -1.084	Rsq = .374
Leaves= 0.00401 BaBlc X Llc + 2.871	Rsq= .406
Total Biomass= 0.018 D2H + 14.62	Rsq = .926

Where biomass is in kilograms, D is diameter at breast height in cm, h is total height in m, Bablc is the basal area at the base of the live crown cm^2, Llc is length of live crown in m and is total height – height of live crown.

Sweet Gum equations were:

Bole= 0.0195 D2h + 1.53	Rsq = 0.96
Dead Branch= 2.1888 Hlc - 0.1892	Rsq = 0.86
Unfoliated Branch= 0.677 D - 2.47163	Rsq = 0.64
Foliated Branch= .00517 (BaBlc x Llc)+ 0.652	Rsq = 0.65
Leaves= 0.3026 BD - 1.4787	Rsq = 0.82
Total Biomass= 0.0305 D2h + 0.9581	Rsq = 0.96

Where units are as defined above and BD is basal diameter in cm and Hlc is height of live crown in m.

Tree part and total biomass were calculated by applying the above equations to each tree measured in the three measurement replication. Average values were then calculated from the aggregated measurements and expressed on a per hectare basis assuming full stocking (1125 t/ha). Nitrogen accumulation was taken by multiplying the appropriate nitrogen content to each tree part and calculation an average tree N content and expressed as per hectare values in the same way.

RESULTS

Groundwater nitrate nitrogen concentrations are the most important of this study in that NO3-N concentrations above 10 mg/l are above drinking water standards. Concentrations measured above this value represent contamination of the groundwater. Table 1 presents groundwater concentrations for each treatment during the five years on measurement.

Table 1—Nitrate-nitrogen concentrations in shallow groundwater for each year of measurement. Average concentration during each year followed by the same letter are not significantly different ($\alpha = .05$). Maximum concentrations in excess of 10 mg NO3-N/l are violations of EPA drinking water standard.

Average Concentrations mg NO3-N/l					
	1995	1996	1997	1998	1999
Lake Edge	0.26a	0.34a	0.04a	0.04a	0.02a
Forest	0.40a	0.24a	0.17a	0.15a	0.09a
Field	2.46ab	5.46b	5.41b	5.09b	3.43ab
Maximum	4.82bc	6.60b	6.18b	6.47b	7.57b
Minimum	6.62c	8.82b	6.92b	7.42b	8.09b
Maximum Concentrations mg NO3-N/l					
Lake Edge	0.44	1.40	0.07	0.09	0.07
Forest	1.48	4.36	0.48	0.36	0.22
Field	8.49	10.67	7.75	12.48	6.86
Maximum	13.93	27.89	9.90	15.98	10.84
Minimum	19.93	17.99	9.64	17.89	13.84

The table clearly shows that nitrate nitrogen leaching has continued in the field throughout the five years. There have been violations of the drinking water standard throughout the period also. One must regard the 1997 data with caution since it represents the fall period only during that year and fall samples showed lowest concentrations in all years. With that in mind there has been a decline in the maximum concentrations during the last two years. If this trend is real and continues drinking water violations may cease by year six or seven.

Soil moisture data shows patterns much more clearly than the groundwater data. Since the field was on a Lakeland sand the water table was in excess of six meters below the surface. Impacts of the treatments would most likely first appear at the soil surface and would be expected in the upper soil moisture before the groundwater.

Soil moisture NO3-N concentrations showed considerable variability in both time and space (table 2). Averaged over all depths the forest plot had significantly lower concentrations than the other treatments. There were no significant differences between the other treatments when all depths were considered. In the old field treatment there have been no significant trends in soil moisture NO3-N concentrations. However, there have been significant trends in soil moisture NO3-N concentrations in both the minimum and maximum treatment (table 2). In both treatments there has been a trend toward lower concentrations in the upper soil during the last two years. In 1997 there were fewer data and analyses between depths were not possible. However, at 1.5 meters both the maximum and minimum treatments showed significantly lower concentrations than during the previous years. At this depth the minimum treatment concentrations have remained significantly lower in 1998 and 1999. Also, during 1998 and 1999 the 1.5m depth has also had significantly lower concentrations than deeper depths on the same treatment. During these years the concentration at the 1.5 m depth has been in the same range as the forest treatment. The maximum treatment shows similar trends but the differences were not significant until 1999. Also the reduction in concentration on the maximum treatment appears to extend to the 3 meter depth.

Table 2—Soil moisture Nitrate – Nitrogen Concentrations (mg NO3-N/l) by depth and year. Within each treatment values followed by the same upper case letter are not significantly different between years within depths. Values with the same lower case letter are not significantly different between depths within years. (α = .05)

Depth (m)	1995	1996	1997	1998	1999
Forest Treatment*					
1.5	0.82	0.30	0.08	0.25	0.02
3.0	0.12	0.15	0.01	0.36	1.06
4.6	0.51	0.43	0.17	0.20	0.05
Old Field Treatment*					
1,5	3.70	8.93	2.95	6.33	2.13
3.0	7.13	5.24	3.96	4.32	1.24
4.6	4.56	8.67	5.84	3.70	8.74
6.1	4.98	5.85	7.80	4.02	6.09
Maximum Treatment					
1.5	11.12aA	10.75aA	2.808	5.46bA	0.96bB
3.0	9.50aA	6.53aA	8.60A	2.77bB	4.43abA
4.6	11.333A	14.43aA	6.12A	9.63aA	9.02BA
6.1	9.488A	14.22aA	8.07A	0.98aA	4.01abA
Minimum Treatment					
1.5	9.88aA	10.51aA	0.798	0.23cB	0.26bB
3.0	11.54aA	10.32aA	5.45A	6.37bA	9.39aA
4.6	12.97aA	13.39aA	11.01A	12.61aA	9.42aA
6.1	6.43aA	10.57aA	6.89bA	10.69aA	

* No significant differences between depths or years.

Nitrogen Uptake

During the five years that leaching has been measured the plantations have been growing at very high rates (table 3). Loblolly pine has been much more effective during the first five years in accumulation of both biomass and nitrogen. On the irrigated and minimum treatments these growth rates have been supplied entirely from nitrogen within the old field soil. The loblolly irrigated treatment has been the most effective in accumulating nitrogen form the field soil. The loblolly minimum treatment has accumulated nearly as much. The old field soil contained sufficient nitrogen to sustain rapid growth and accumulation of 173 kgN/ha and continue to show groundwater nitrate-nitrogen concentrations of 8.1 mg NO3-N/l.

The lowered NO3-N concentrations in the upper profile might indicate that uptake is beginning to deplete nitrogen reserves. Data now leaf nitrogen content may also tend to support that view. In table 4 leaf nitrogen contents in the fourth and fifth growing seasons are compared to those measured during the first and second (Samuelson 1998) when soil moisture NO3-N concentrations were uniformly near 10 mg/l. The data in table 4 are has some limitations in that Samuelson (1998) collected leaves in August while the fourth year leaves were collected in May and the fifth in June. McNeil and others (1988) found that loblolly pine

Table 3— Summary of fifth year growth on measurement plots in maximum growth study. Biomass and nitrogen are expressed assuming 1125 t/ha. Biomass represents only above ground living tree parts but total nitrogen includes nitrogen measured in the forest floor.

Treatment	Height	DBH	Total Biomass	Total Nitrogen
	m	cm	Mg/ha	kg/ha
Loblolly Maximum	8.63	15.6	72.7	282.8
Loblolly Irrigated	7.64	13.8	57.8	207.2
Loblolly Minimum	6.42	11.5	46.0	178.3
Sweet Gum Maximum	8.18	11.1	49.9	153.2
Sweet Gum Irrigated	6.16	7.6	22.5	66.9
Sweet Gum Minimum	4.29	4.7	10.4	43.3

needle nutrient content decreases as needles age suggesting that the leaves collected in May and June would be expected to have higher nitrogen content than those collected in August.

Although there was a clear decline in soil moisture NO3-N concentration in the control plots during the third year there were no declines in leaf nitrogen content until the fifth. During the fifth year the nitrogen content of both species in the minimum treatments are considerably lower than during the first four. The decline is larger in the irrigated treatments. This result would be expected since the irrigated treatments are growing considerably faster with the same soil nitrogen pool. The growth and leaf nitrogen data are consistent with the soil moisture NO3-N concentrations.

SUMMARY

After five years of growth the old field in this study continues to exhibit nitrate leaching. Groundwater NO3-N concentrations are significantly higher in all treatments in the old field than in the adjacent natural pine forest and the hardwoods along the lake edge. Groundwater NO3-N concentrations also continue to have peak values above 10 mg NO3-N/l in all of the old field treatments.

Soil moisture NO3-N concentrations do show significant changes after five years. The surface (1.5m) lysimeters in the minimum treatment shown a significant (both by year at that depth, and by depth within the last three years) declines. Concentrations are below 0.5 mg NO3-N/l and very similar to the surface concentrations found in the natural hardwoods.

Growth rates and nitrogen accumulation have been very rapid during the five years, with accumulations over 200 kgN/ha on sites receiving no fertilization. Leaf nitrogen content declines in the minimum treatment are consistent with depletion of the nitrogen pool within the surface soil. However, the nitrogen pool has been large enough to support accumulation of 173 kgN/ha and produce groundwater NO3-N concentrations that averaged 7.5 mg NO3-N/l for the entire five year period.

Table 4—Leaf nitrogen content of loblolly needles and sweet gum leaves on experimental plots during the first and second (Samuelson 1998) and fourth and fifth growing seasons. Nitrogen content of leaves (percent)*

Treatment	1995	1996	1998	1999
Loblolly Maximum	1.47	1.42	1.39	1.46
Loblolly Irrigated	1.22	1.28	1.20	1.03
Loblolly Minimum	1.10	1.28	1.31	1.09
Sweet Gum Maximum	2.17	2.60	3.13	2.01
Sweet Gum Irrigated	2.09	2.29	2.21	1.11
Sweet Gum Minimum	1.92	2.07	2.21	1.41

* First and second year leaves were collected in August, fourth year in late May, and fifth year in June

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DETERMINING NUTRIENT REQUIREMENTS FOR INTENSIVELY MANAGED LOBLOLLY PINE STANDS USING THE SSAND (SOIL SUPPLY AND NUTRIENT DEMAND) MODEL

Hector G. Adegbidi, Nicholas B. Comerford, Hua Li, Eric J. Jokela, and Nairam F. Barros[1]

Abstract—Nutrient management represents a central component of intensive silvicultural systems that are designed to increase forest productivity in southern pine stands. Forest soils throughout the South are generally infertile, and fertilizers may be applied one or more times over the course of a rotation. Diagnostic techniques, such as foliar analysis and soil testing are available, yet have not been highly successful in identifying fertilizer responsive sites. In most cases recommendations, based on these approaches, lack site-specificity. The Soil Supply And Nutrient Demand (SSAND) model is a mechanistic computer simulation model developed to: (1) diagnose nutrition limitations and (2) determine site-specific fertilization regimes necessary to achieve preset production goals. With this model, the user sets a desired level of production and the model is used to calculate stand nutrient demand. Using mass/flow diffusion theory, the model then simulates the soil supply and compares it to the demand. If the demand is more than supply, fertilization regimes can be tested in order to see which may be the most efficient in meeting plant nutrient demand. This paper provides an overview of the SSAND model and its application.

INTRODUCTION

Forest productivity of southern pine plantations is well below their biological potential (Farnum and others 1983, Neary and others 1990a), and low soil fertility is one of the major constraints to their potential being realized (Neary and others 1990b). It is not surprising, therefore, that during the last two decades genetic improvement, competition control, and water and nutrient management have increased productivity (Colbert and others 1990, Jokela and Martin 2000, Neary and others 1990a,b, Prichett and Comerford 1982).

Current fertilization recommendations are based on soil testing, foliar analysis, and field trials. However, recommendations lack site-specificity, which is most likely due to the empirical nature of these techniques. Consequently, a process-based assessment of the nutrient requirements of southern pine plantations and the bioavailability of soil nutrients are required. The Soil Supply And Nutrient Demand (SSAND) model is a process-based computer simulation model that combines the processes controlling nutrient uptake by plants and nutrient supply by soil in order to diagnose the depth of a nutrition limitation and to determine a site-specific fertilization regime. This paper provides an overview of the model and presents examples of how it is used.

MODEL STRUCTURE AND FUNCTIONS

SSAND is written in Microsoft Visual Basic 6.0, using Microsoft Excel worksheets and text files as inputs. Output is provided in *.txt files and Excel worksheets. Figure 1 shows the main interface of SSAND and the four steps that it performs.

Step 1. Desired Plant Growth

The user chooses the species of interest and inputs the production goal, called Desired Plant Growth. The Desired Plant Growth is provided, by the user, via an Excel worksheet and can be specified as biomass growth data over time (biomass input file; figure 2a). A second input file documents nutrient use efficiency (NUE) for producing the biomass over time (figure 2b). These input files are used to compute and generate a file of the nutrient demand necessary to achieve the production goal. Figure 3 shows an example of the output of nutrient demand with time.

Step 2. Nutrient Uptake Model

This step computes the soil supply and nutrient uptake by the plant using mass flow/diffusion theory for soil processes and root characteristics as the soil boundary condition definition. The model uses soil parameters (soil volume, bulk density, water content, nutrient diffusion coefficient in water, mineralization rate, and nutrient adsorption-desorption isotherm characteristics; figure 4a) and plant parameters (rate of water flux into roots, the

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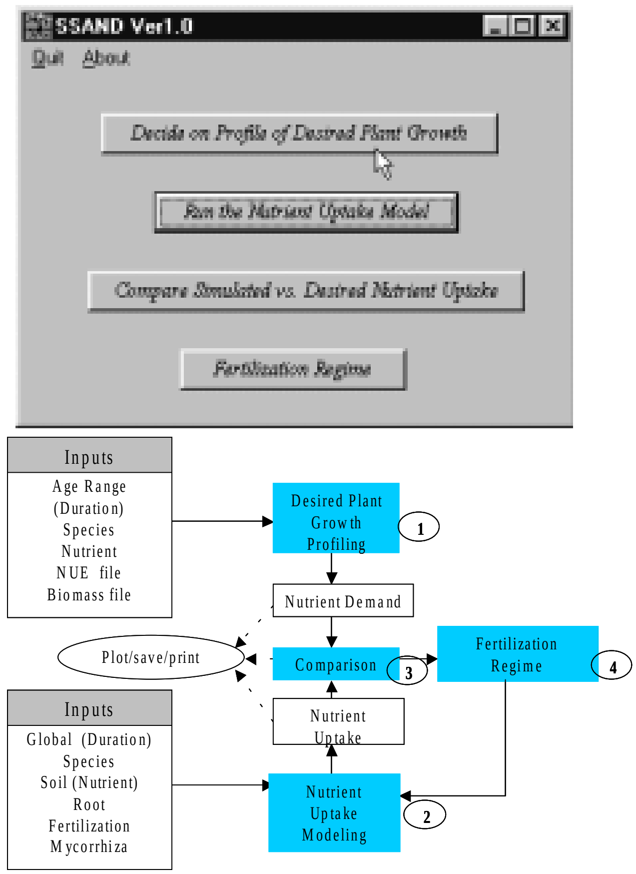


Figure 1—The SSAND model's main interface and structure.

average fine root radius, the root length density and nutrient uptake kinetics parameters; figure 4b) to evaluate the processes responsible for plant nutrient uptake by roots. Additional features allow the user to simulate nutrient uptake by extramatrical mycorrhizal fungi or the roots of a second, competing plant species, or both. The output from this step is the predicted nutrient uptake for which an example is found in figure 5.

Step 3. Comparison of Predicted Uptake and Demand

The third step compares the predicted nutrient uptake to the nutrient demand over time, as well as a user-defined limit around the result. If the predicted uptake is above or within the user-defined limit, the interpretation is that nutrient bioavailability is not a limitation to the desired productivity. If the uptake is below the user-defined limit of the uptake/demand curve, then the nutrient demand may be limiting productivity and fertilization should be useful. Such a nutrient limitation, beginning after 250 days, is shown in figure 6.

Step 4. Fertilization Regime

This fourth step allows the user to design a fertilization regime using multiple fertilization events. Each fertilization event is defined by the day of fertilization and the amount of elemental nutrient applied as fertilizer (figure 7a). A fertilization regime can have as many events as desired.

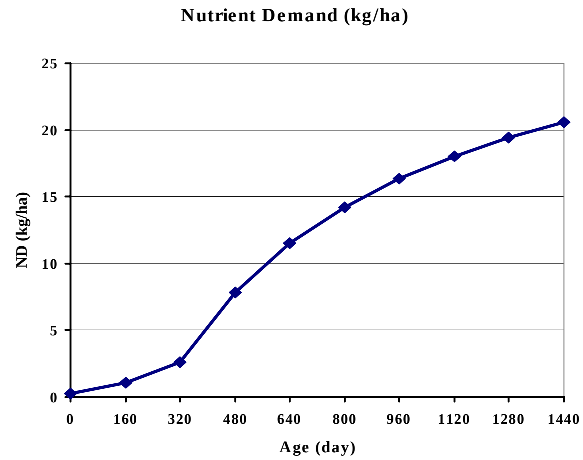


Figure 3—An example of the nutrient demand profile required to achieve predetermined production goals.

Final Modeling Outcome

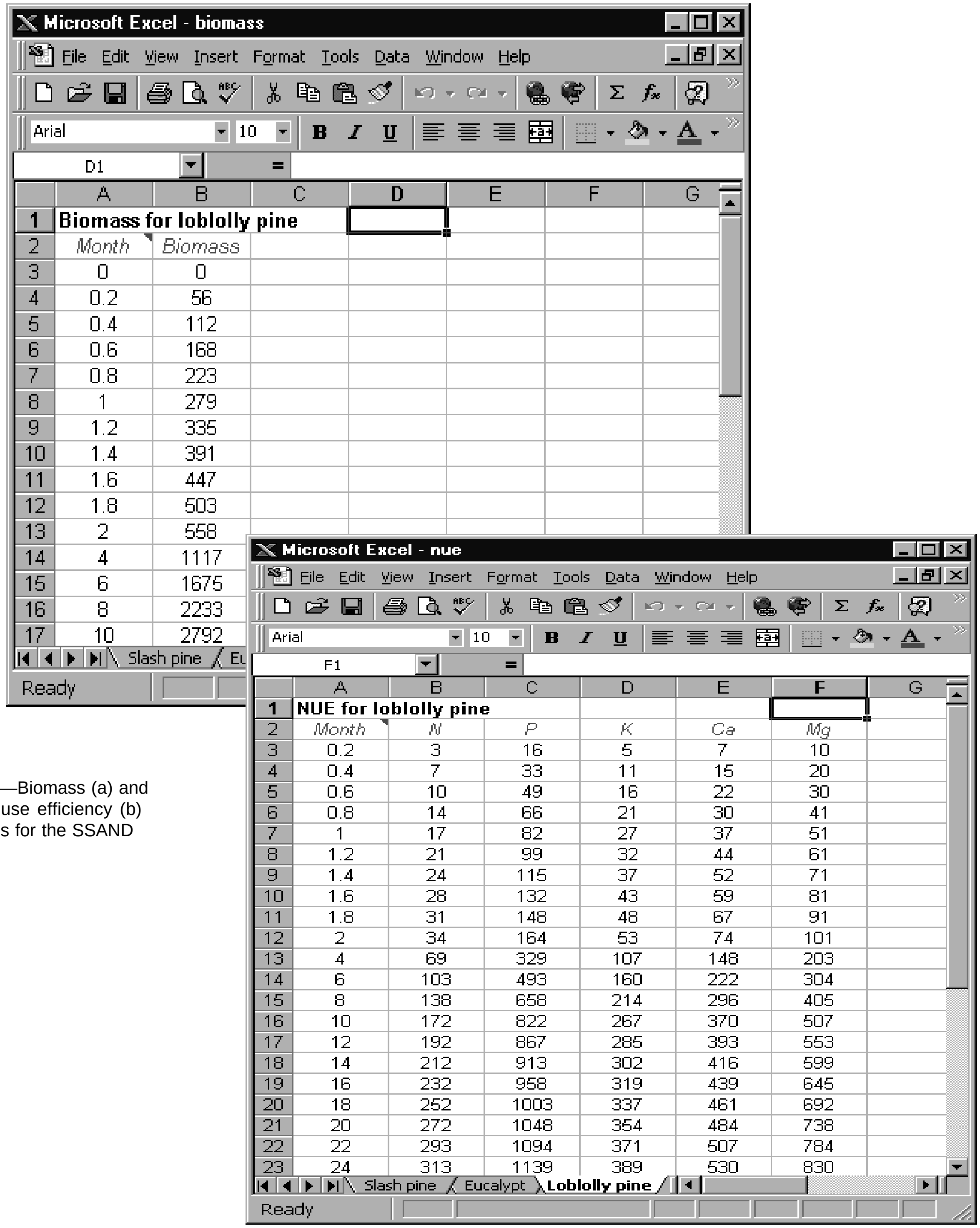
After inputing a fertilization regime, the nutrient uptake model (step 2) is run again and a new comparison is made between nutrient uptake and demand (step 3). The user can iteratively and interactively try various fertilization regimes until the predicted uptake meets the demand of the desired production. The example in figure 7b shows a fertilization regime that supplies the plant demand necessary to achieve the predetermined production goal.

TESTING AND VALIDATING THE SSAND MODEL

A process-based model requires detailed inputs from which the necessary processes can be simulated. Required data include:

- Temporal curves of total plant biomass for the desired level of production
- Nutrient concentrations of tree biomass components (including roots) and temporal curves of nutrient use efficiency
- Soil bulk density
- Water content changes by horizon over time
- Nutrient mineralization rates
- Fine root and/or mycorrhizal fungi characteristics (average fine-root radius by horizon, root length density by horizon, average water influx rate to roots by horizon, nutrient uptake kinetic parameters)
- Adsorption and desorption isotherms by horizon

During the past two years, our efforts have focused on acquiring the biomass, fine root data, plant tissue nutrient data and soil chemical and physical data necessary to test this model in intensively managed, juvenile (age 1 through 4) stands of loblolly pine growing on Spodosols of the Coastal Plain of southeastern Georgia. Above- and belowground components of 104 trees were harvested and



Biomass for loblolly pine

Month	Biomass
0	0
0.2	56
0.4	112
0.6	168
0.8	223
1	279
1.2	335
1.4	391
1.6	447
1.8	503
2	558
4	1117
6	1675
8	2233
10	2792

NUE for loblolly pine

Month	N	P	K	Ca	Mg
0.2	3	16	5	7	10
0.4	7	33	11	15	20
0.6	10	49	16	22	30
0.8	14	66	21	30	41
1	17	82	27	37	51
1.2	21	99	32	44	61
1.4	24	115	37	52	71
1.6	28	132	43	59	81
1.8	31	148	48	67	91
2	34	164	53	74	101
4	69	329	107	148	203
6	103	493	160	222	304
8	138	658	214	296	405
10	172	822	267	370	507
12	192	867	285	393	553
14	212	913	302	416	599
16	232	958	319	439	645
18	252	1003	337	461	692
20	272	1048	354	484	738
22	293	1094	371	507	784
24	313	1139	389	530	830

Figure 2—Biomass (a) and nutrient use efficiency (b) input files for the SSAND model

separated into sub-components for biomass and nutrient analysis. Fine root biomass, radius, and length were measured on 240 soil samples collected from 39 soil pits.

The development of the SSAND model is still in progress. After the model has been tested and validated for loblolly pine on Spodosols, the goal will be to evaluate its application to other soil types and forest tree species.

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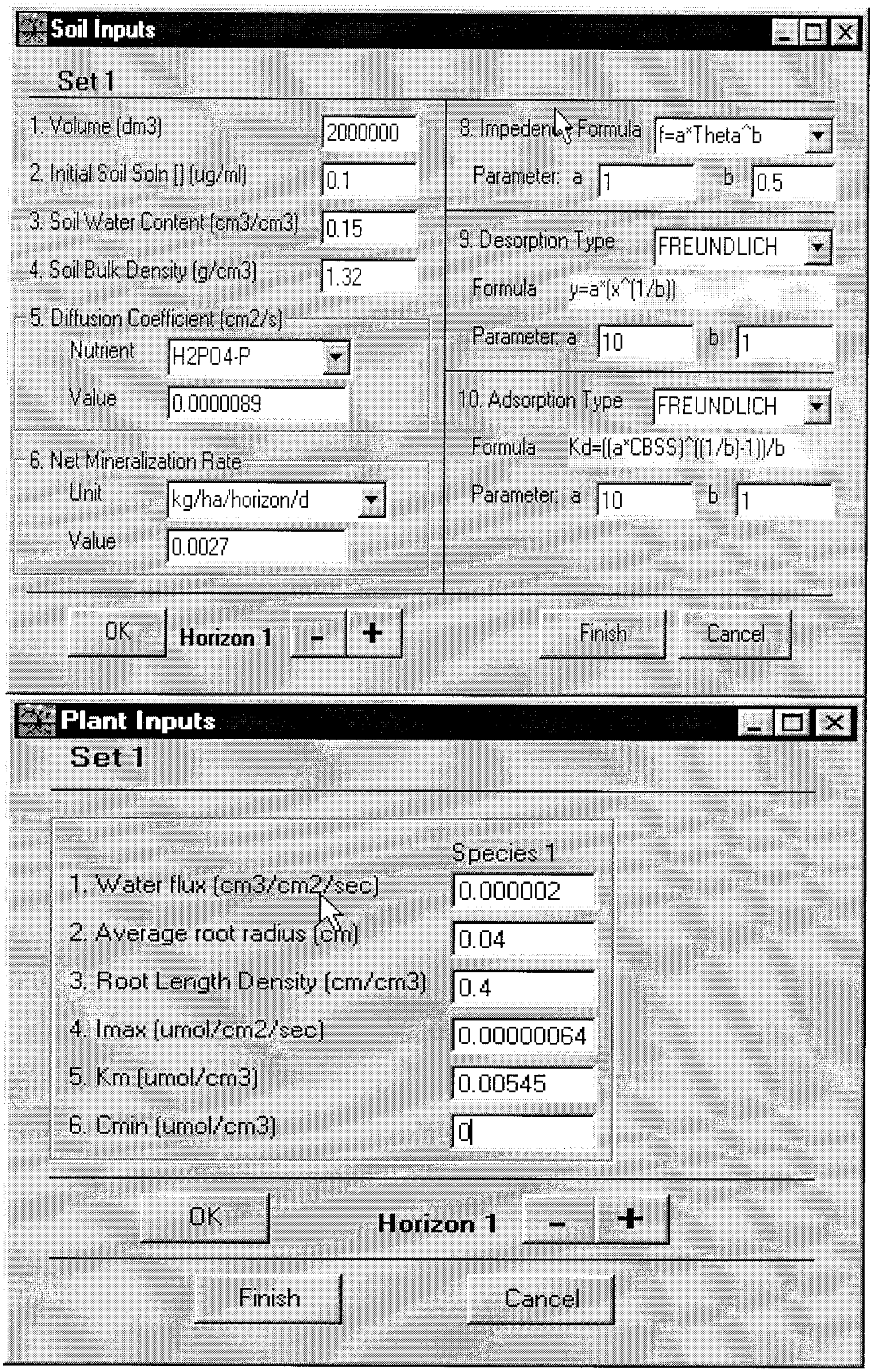

a

b

Figure 4—Parameters used in the SSAND nutrient uptake model: (a) soil inputs and (b) plant root and uptake kinetics inputs.

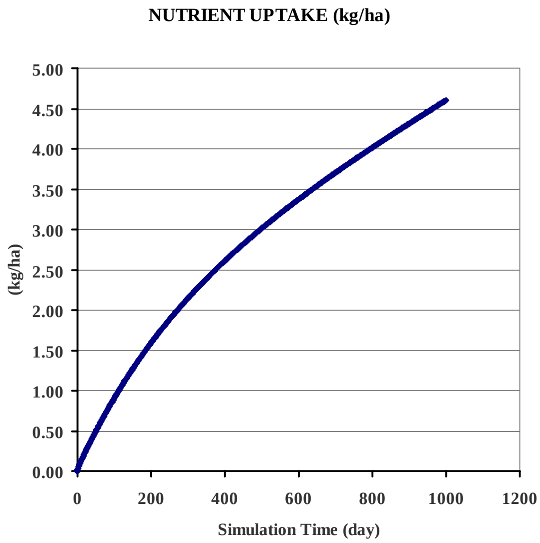

Figure 5—Simulated nutrient uptake over time for a hypothetical loblolly pine stand

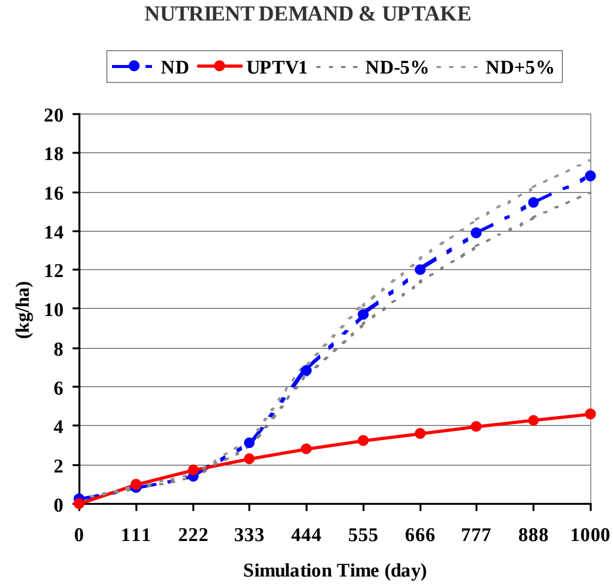

Figure 6—Comparison between required nutrient demand and simulated nutrient uptake. A nutrient limitation is shown to begin after 250 days. ND is nutrient demand and UPTV1 is simulated nutrient uptake.

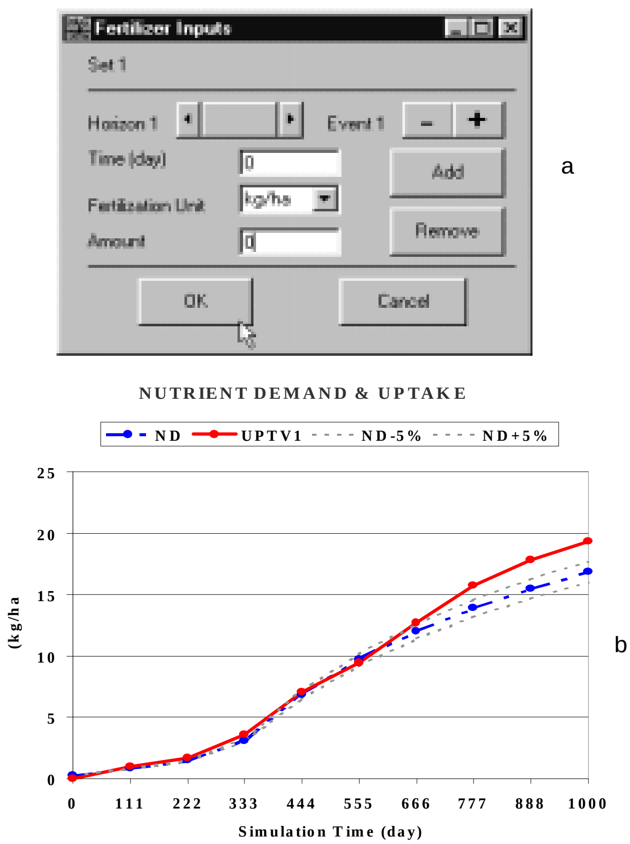

Figure 7—Fertilizer input interface (a) and an evaluation of a fertilization regime designed to meet the nutrient demand of a stand growing at a predetermined production goald (b). ND is nutrient demand and UPTV1 is simulated nutrient uptake.

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GROWTH RESPONSE OF LOBLOLLY PINE TO INTERMEDIATE TREATMENT OF FIRE, HERBICIDE, AND FERTILIZER: PRELIMINARY RESULTS

L.M. Marino, B.P. Oswald, K.W. Farrish, H.M. Williams, and Daniel R. Unger[1]

Abstract—Crown area is an important factor in determining stem development. This study examined the changes in stem diameter per unit area of crown due to treatment with fire, herbicide, fertilizer, and tree-thinning practice. The experimental sites were mid-rotation loblolly pine (*Pinus taeda*) plantations that were thinned one year before treatment. Site 1 was strictly row-thinned and Site 2 was thinned by and within each row. Five replicates were installed on each site. Each replicate consisted of 8 subplots (0.1 ha) containing a central 0.04 ha measurement plot. A randomized-block split-plot design was used at each site, with fertilizer as the whole-plot factor and vegetation control treatment as the subplot factor. The herbicide treatment (approximately 4.5 L ha^{-1} Chopper®, 2.5 L ha^{-1} Accord®, 11.2 L ha^{-1} Sun-It II oil, and 76.7 L ha^{-1} water) was applied in October, 1999. Prescribed burning was performed in March, 2000, and fertilizer (224 kg ha^{-1} N and 28 kg ha^{-1} P) was applied in April following the burn. The height and diameter of each tree was measured at plot establishment (1999) and in December, 2000. Individual tree crown area was measured in June, 2000. A leaves-to-tree (LT) metric, defined as the ratio of a tree's diameter (cm) in December, 2000 to crown area (m^2) in June, 2000 was used to examine the impact of the various factors. Herbicide affected growth differently at the two sites; growth was increased at Site 1, but decreased at Site 2, relative to their respective controls. The results were unaffected by the use of fertilizer. Fire had a negligible effect on growth at both sites, with and without fertilizer. Herbicide and fire were additive at Site 2 but antagonistic at Site 1. The results suggest that thinning practices can significantly alter the impact of herbicides and fire on tree growth. Data from the second (and final) year of the study will be available in December, 2001.

INTRODUCTION

Crown dimension measurements are commonly used to study habitat for wildlife, encroachment rates into tree gaps, and many other aspects of tree growth (Fajvan and Grushecky 1996, Vales and Bunnell 1988, Zeide and Gresham 1991). Larger crown area often translates into more photosynthetic surface area, which can increase stem development. Many factors can affect crown size, including silvicultural treatments, thinning (Smith and others 1997), chemical control of woody competitors (Ezell and others 1997), prescribed fire (Wade and Johansen, 1986), and fertilization (Williams and Farrish 1994).

Crown growth represents the biological basis for the desired outcomes of increased tree growth and optimal use of limited space. However, few studies have systematically examined the impacts of fire, herbicide, fertilizer, and thinning practice on individual tree growth. This is a preliminary report of such a study in mid-rotational loblolly pine in East Texas.

METHODS

Study Sites

The study area consisted of two sites on land owned by International Paper Company in northeastern Texas. Both sites were thinned in 1998, 1 year before plot establishment. Site 1 was hand-planted on 1.8 m by 3.1 m spacing, and row-thinned and thinned within the rows to a basal area of 13 m^2 per ha before plot establishment. Soils were of the Darco, Teneha, and Osier series; slopes ranged from 3-15 percent. The site index was 65 at base age 25 years.

Site 2 was machine-planted on 1.8 m by 3.7 m spacing, and row-thinned to a basal area of 22 m^2/ha one year before plot establishment. Soils were of the Ruston and Attoyac series, with slopes ranging from 3-15 percent. The site index was 71 at base age 25 years.

Five replicates at both sites were established in 1999. Each replicate consisted of 8 treatment subplots (40 plots per site)each 0.10 ha in size. A central 0.04 ha

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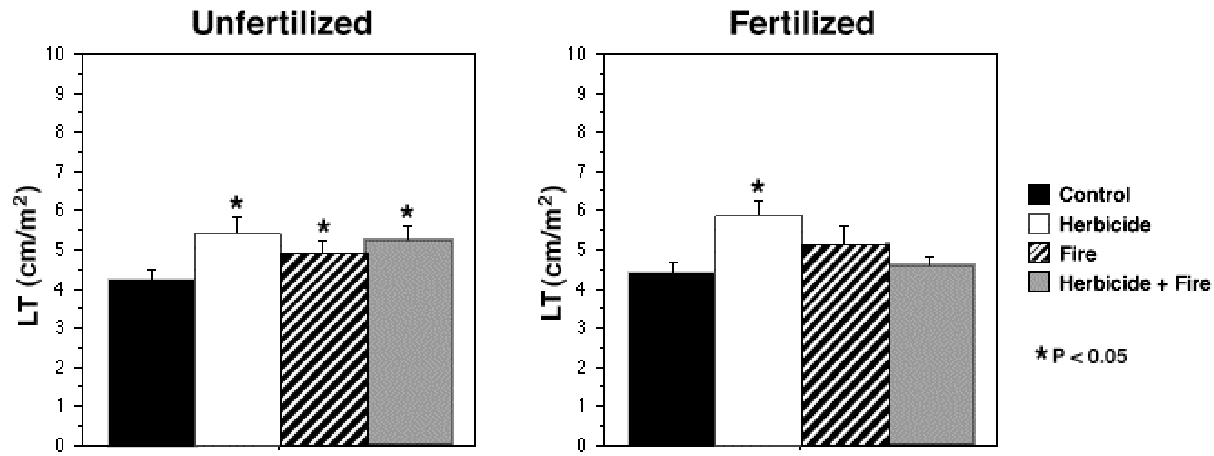

Figure 1—Effect of treatment on tree growth at Site 1, assessed using LT

measurement plot was established within each subplot. A randomized-block-split-plot design was used in which half of each replicate was randomly chosen for application of fertilizer, and each treatment (control, herbicide, prescribed fire, and herbicide/prescribed fire) was randomly assigned to the treatment subplots. A 10-m buffer separated each treatment subplot. All trees greater than 5 cm in diameter located within the subplots were tagged, identified to species, and measured for total height and DBH. There were approximately 20 and 35 trees per subplot at Sites 1 and 2, respectively.

Treatments

Due to a late summer drought, herbicide was applied in October, 1999. A herbicide mixture of 4.5 L/ha Chopper®, 2.2 L/ha Accord®, 11.2 L/ ha Sun-It® II oil, and 76.7 L /ha water was applied at Site 2. The same mixture was applied at Site 1, except that the amount of Accord® was increased to 2.5 L /ha, in an attempt to control a more dense understory. The mixtures were broadcast using a CO_2 backpack sprayer with a 3.66 m boom. Competing woody vegetation taller than 3.66 m was injected with a mixture of 100 ml Arsenal© AC diluted in 300 ml of water.

Firelines were installed around each burn plot to preserve the 10-m buffer. Prior to burning, ceramic tiles coated with strips of heat-sensitive paint (Tempilaq©) were installed at each plot center. The paint disintegrated at 100, 200, 400, 800, or 1000°C, thereby allowing for an estimate of fireline intensities. Four painted tiles per plot center were suspended from a rebar post at 4 levels: subsurface, surface, 0.3 m and 0.6 m aboveground.

The plots were prescribe-burned in March, 2000, using strip backfires. A backfire was used in an attempt to limit canopy damage due to scorch. Scorch heights (if any) were determined for each tagged tree.

In April following the burn, the fertilizer treatment was applied using a standard spreader. Diammonium

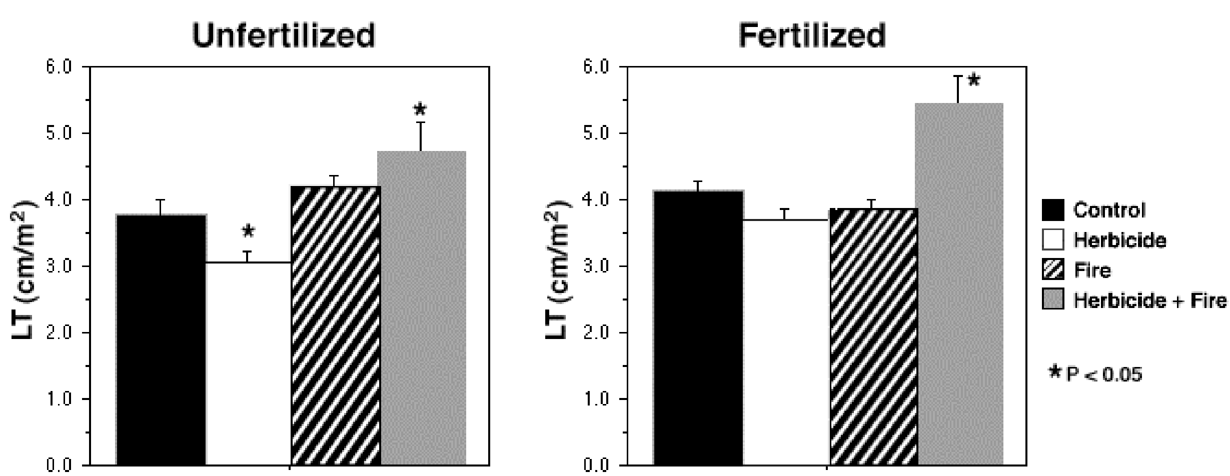

Figure 2—Effect of treatment on tree growth at Site 2, assessed using LT

phosphate (DAP) was and urea were applied at a rate of 224 kg/ ha N and 28 kg/ ha P, respectively.

Measurements

The crown area of each tree was determined in June, 2000 as follows (Farr and others 1989, Larocque and Marshall 1994, Peterson and others 1997). The length of the longest branch in each cardinal direction between the branch tip and tree stem was obtained using an electronic distance meter (Forestor Vertex, Haglof, Sweden). The area of the resulting polygon was calculated, after correcting for the radius of the tree. To ascertain the accuracy of the method, the results were compared with those calculated using 12 measurements per tree made at equal angular increments from a reference line. Use of 4 measurements consistently underestimated the crown area, but by less than 10 percent. The reproducibility of the measurement method was determined by making crown-area determinations on 10 different days, using 4 measurements per tree (5 trees). The average variation in the measurements was less than 7 percent.

The total height and outside bark DBH of each tagged tree were measured in December, 2000.

Study Metric and Statistical Analysis

To study the effect on tree growth of vegetative control (fire and herbicide), fertilizer, and thinning practice, it was necessary to control for any differences in tree diameter that existed prior to commencing the experiment. This was accomplished using a leaves-to-tree (LT) metric defined and calculated as follows. For each tree, the diameter (in cm) measured in December, 2000 was divided by the corresponding crown area (in m^2) measured in June, 2000. LT was, therefore, a simple measure of growth that related the diameter of the tree to its crown area measured 6 months earlier. The aim of the study was to determine how LT was affected by the study factors. For simplicity in interpretation, this was done on the basis of simple comparisons. Because LT was not normally distributed, differences were analyzed using the Mann-Whitney U test.

RESULTS AND DISCUSSION

At Site 1, herbicide treatment significantly increased growth, as assessed using LT (figure 1). The effect of fire was marginal, and it antagonized the effect of herbicide when the two treatments were combined (figure 1). Similar results occurred in both fertilized and unfertilized plots.

At Site 2, treatment with fire plus herbicide produced a significant increase in LT on both unfertilized and fertilized plots (figure 2). Either treatment alone had no beneficial effect.

Significant inter-site differences were seen in the response of the trees per unit of crown area to vegetative control. The differences could be due to the different thinning methods used at each site. Alternatively, they could be due to the slightly higher productivity at Site 1. the effect of thinning was likely more important because the addition of fertilizer had essentially no effect at either site.

There are at least two reasons that could explain why the prescribed fire was not as successful as herbicide treatment in promoting growth at Site 1. First, the dense understory was more easily controlled with the herbicide because the herbicides were selected specifically for control of the competing species actually present. In contrast, fire is known to affect some competing species more than others. Second, the relative humidity was 58 percent on the day the fire was applied. This could have reduced consumption of the competing vegetation. Analysis of post-burn fuel loading and temperature data may provide insight into the question.

Further Work

LT will be determined using stem diameters measured in December, 2001, thereby allowing assessment of the study hypotheses in the context of stem growth that occurred over a 2-year period. Stem maps and nearest-neighbor analysis will be used to examine individual tree growth response to treatment. Basal area growth and height growth will also be determined. This study is part of a larger study that is examining the physiological parameters, soil effects, and biodiversity changes in response to treatment.

Researchers will collaborate in order to fully characterize the response of mid-rotation loblolly pine to treatment with fire, herbicide, and fertilizer in East Texas.

ACKNOWLEDGMENTS

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EFFECTS OF MIDROTATION INTENSIVE SILVICULTURE ON FOREST SOILS IN EAST TEXAS: FIRST-YEAR RESULTS

S.A. Wilson, K.W. Farrish, B.P. Oswald, H.M. Williams, and J. L. Yeiser[1]

Abstract—Intensive forest management is becoming increasingly common in east Texas. Included in intensive management are such practices as mid-rotation fertilization, prescribed fire, and herbicide application. There is insufficient information about the effects of these treatments on soil physical, chemical, and biological properties when applied at mid-rotation. The objectives of this research are to evaluate the effects of these treatments on soil physical properties including organic matter content and bulk density; chemical properties including soil nitrogen and phosphorus; and on populations of resident earthworms. Five replications were installed in each of two loblolly pine (*Pinus taeda* L.) plantations aged 15 and 17. Both were thinned in 1998. Accord SP and Chopper emulsion were ground applied in the fall of 1999. The prescribed burn treatment occurred the following spring. Fertilizer was applied one to two weeks after completion of the burn to supply 224 kilograms per hectare of N and 28 kilograms per hectare of P. First-year results are presented.

INTRODUCTION

Intensive forest management, which is considered essential for meeting future timber production goals (Vann and Brooks, 1983), is becoming increasingly common in east Texas. Included in intensive management are such practices as mid-rotation fertilization, prescribed fire, and herbicide application. For example, as of 1996, fertilizer was applied to more than 150,000 hectares of loblolly pine (*Pinus taeda* L.) plantations in the United States each year (Zhang and Allen, 1996).

Each of these silvicultural practices has a number of potential effects on forest soils and tree nutrition. Fire, especially, has been shown to alter soil nutrient status, pH, and organic matter content. Fertilization and herbicide may have both indirect and direct effects on soil properties. These treatments may also impact earthworm populations, which can have long-term effects on soil fertility and structure (Francis and Fraser 1998, Thornes 1980). However, there is little information on the effects of these treatments when applied at mid-rotation in southern pine silviculture.

This study examines the individual and combined effects of fertilization, herbicide application, and prescribed burning on soils under two recently thinned mid-rotation loblolly pine plantations in Cherokee County, Texas. Baseline soil physical and chemical parameters were measured and monitored after treatment. The effects of intensive silviculture on earthworm populations are largely unknown; and this study evaluated effects of treatment on resident populations of earthworms.

MATERIALS AND METHODS

Study Sites

This study is located on two plantations in Cherokee County, Texas. The first site, referred to as the Cherokee Ridge site (CR), is on 78 hectares owned by the International Paper Corporation. The trees were planted in 1985, and were thinned to a basal area (BA) of 13.1 square meters in 1998. Soils on this site have sandy surface horizons, and include the Darco (Grossarenic Paleudult), Teneha (Arenic Hapludult), and Osier (Typic Psammaquent) series. The second site, referred to as the Sweet Union site (SU), is located on 45 hectares of land that is also owned by the International Paper Corporation. The trees were planted in 1982, and were row-thinned to a BA of approximately 22.0 square meters in 1998. The soils on this site have sandy loam surface horizons, and include the Ruston (Typic Paleudalf) and Attoyac (Typic Paleudult) series.

Experimental Design and Treatment Application

The experimental design is a split-plot, with fertilization as the whole plot treatment and competition control (herbicide, prescribed burning, both, or neither) as the sub-plot treatment. Five replications consisting of two 32 meter by 158 meter whole plots were installed at each site. Nested within each whole plot are four subplots measuring 32 meters by 32 meters (0.10 hectare), which are separated by 10 meter buffer strips. Within each sub-plot is an 11 meter radius (0.04 hectare) measurement plot.

Treatment application began in October of 1999. A mixture of 4.5 liters Chopper (imazapyr), 2.2 liters Accord SP (glyphosate), 11.2 liters Sun-It 2 oil, and 76.7 liters of water per hectare was applied at the Cherokee Ridge site using

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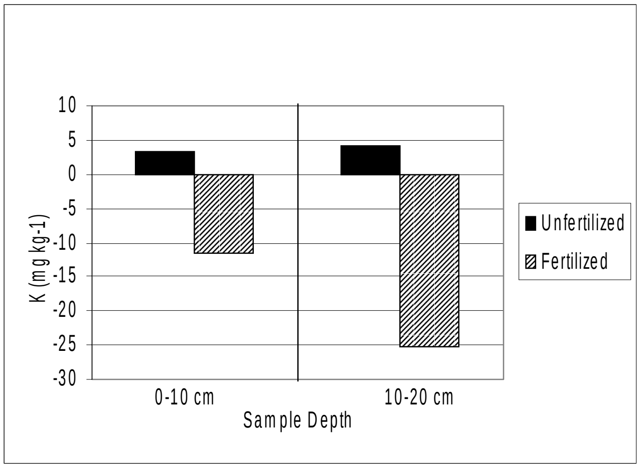

Figure 1-Change in K levels at the Cherokee Ridge site. In the fertilized plots, the level of K was greatly reduced by fertilization with urea and diammonium phosphate (DAP).

a backpack aerial sprayer with a 3.7 meter boom. At the Sweet Union site, a mixture of 4.5 liters Chopper, 2.5 liters Accord SP, 11.2 liters Sun-It 2 oil, and 76.7 liters of water per hectare was applied using the same backpack sprayer. Trees greater than 3.7 meters in height were injected with 100 milliliters of Arsenal AC (imazapyr) via the "hack and squirt" method; this is included in the total amount of imazapyr applied per plot. The prescribed burn treatment was applied in March of 2000, with fires applied as backfires to reduce damage from scorch. Tiles painted with heat-sensitive paints were installed in the center of each measurement plot to estimate temperatures at four levels: below the surface, ground level, 0.33 meter, and 0.66 meter. Fertilizers were applied in April of 2000, using diammonium phosphate and urea to supply 224 kilograms per hectare of nitrogen (N) and 28 kilograms per hectare of phosphorus (P).

Sampling Procedures

Soil samples were taken in July of 1999 and July of 2000 using an impact sampler and a bucket auger. Soil was sampled in three depth increments (0-10 centimeters, 10-20 centimeters, and the top 10 centimeters of the first B horizon), which were analyzed separately. The Soil, Plant, and Water Analysis Laboratory of Stephen F. Austin State University measured all micro- and macronutrients with the exception of N and P via the Ammonium Acetate EDTA method. P was measured using the Bray I method, and total N was determined via a LECO C/N Analyzer by the same lab. Earthworms were hand-sorted from a 0.25 meter sub-plot randomly located within each measurement plot. They were counted in the field, then were taken to the lab, re-counted, then oven-dried for biomass determination

RESULTS AND DISCUSSION

Cherokee Ridge

Competition control had no significant impact upon measured soil properties during the first year following treatment at this site. Soil pH was not affected by any of the treatments, nor was soil bulk density (Db). Organic matter content, measured as percent carbon, was also unaffected. Earthworm populations decreased at this site, from 376,000 per hectare in 1999 to 145,000 per hectare in 2000, a decrease of 61.4 percent. However, the population decrease was not correlated to forest management practices.

Total N was not affected by fertilization, but displayed a trend towards increasing in fertilized plots. Bray I-P remained constant regardless of fertilization. However, K dropped significantly (alpha = 0.05) as a result of fertilization in the top two samples (figure 1). The decrease

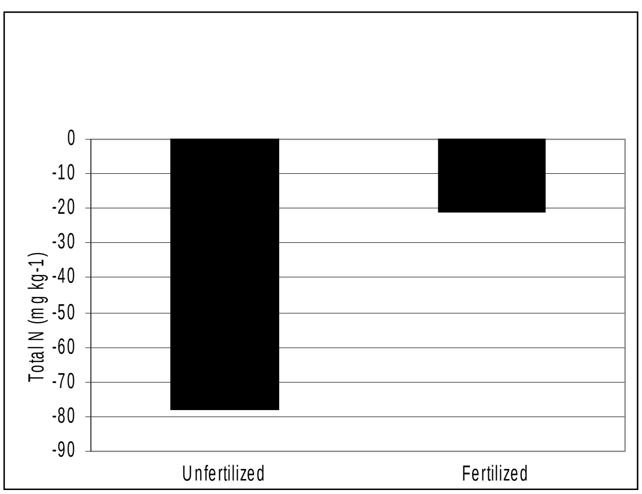

Figure 2-Change in total N at the Sweet Union site. Total N decreased in both fertilized and unfertilized plots, but decreased significantly less in the fertilized plots.

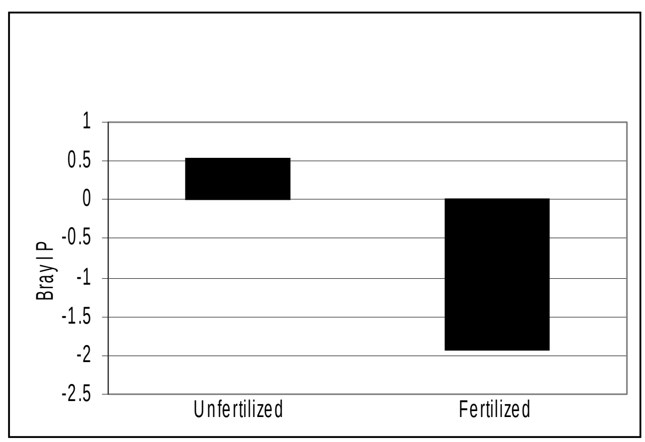

Figure 3-Change in Bray-I P at the Sweet Union site. Bray-I P increased in the unfertilized plots, and decreased in the fertilized plots, most likely due to uptake.

in K was most likely caused by leaching and was exacerbated by the sandy texture of the soils on this site.

Sweet Union

Soil bulk density and organic matter were unaffected by treatment at this site. Competition control had no significant effects on soil nutrient levels at this site. Earthworm populations decreased at this site as well, from 980,000 per hectare in 1999 to 734,000 in 2000, a decrease of 25.1 percent. This decrease was not correlated to management practices.

At this site, total N was unaffected by fertilization in the top 20 centimeters, but displayed a trend towards a decrease in fertilized plots. At the top of the B horizon, however, total N decreased significantly in both fertilized and unfertilized plots, but decreased less in plots receiving fertilization (figure 2).

Bray I-P was unaffected in the top 10 centimeters. In the 10-20 centimeter depth, P increased slightly in the unfertilized plots and decreased in the fertilized plots (figure 3). This is probably an uptake response.

At this site, magnesium was the only micronutrient that was significantly affected by fertilization; levels of Mg dropped in the 0-10 centimeter and B horizon depths. Leaching resulting from the influx of ammonium cations from fertilization probably caused this decrease. Soil pH also decreased in the 10-20 centimeter depth as a result of fertilization.

Both Sites

Of all of the treatments applied, fertilization was the only one to have significant impacts on the soils at these sites. Although fire can often have a number of effects on soils, the fires at these sites were relatively cool, which has minimized the fire impacts at these sites. The herbicides used in this study did not appear to have any effects on the soil properties that were measured.

The drought that the east Texas region has experienced for the last several years has almost certainly affected the outcomes of this project, especially the earthworm study. Although none of the treatments had statistically significant effects on earthworms, several trends became apparent during the course of sampling. Earthworm populations tended to be somewhat higher in plots that received herbicide and prescribed fire, either alone or combined, than in the control plots. Fire, especially, appeared to be beneficial; James (1988) found similar results in tallgrass prairie ecosystems. Furthermore, earthworm populations tended to be lower in plots that received fertilization than in the control plots. The number of sample plots for earthworms will be increased for the second sampling period of this study in the summer of 2001.

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NITROGEN AND PHOSPHORUS USE EFFICIENCY IN STANDS OF LOBLOLLY AND SLASH PINE

Christopher A. Dicus and Thomas J. Dean[1]

Abstract—Nitrogen and phosphorus use efficiency (NUE and PUE, respectively), the annual amount of stemwood produced per unit net N or P used in total aboveground production, were examined in 17-year-old pure stands of unthinned loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Englem.) planted at two spacings. Slash pine stands had a greater NUE and PUE than loblolly pine, which was attributed to greater relative allocation of aboveground production to stemwood, lower foliar N and P concentrations, and greater foliar retranslocation of N and P by slash pine. Compared to 2.4 x 2.4 meter spaced stands, denser 1.2 x 1.2m spaced stands had lower NUE and PUE, which may be related to a sustained drought. Results of this study imply that nutrient management should differ in stands of varying composition and structure.

INTRODUCTION

In the southeastern United States, stand production of loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.) forests are often limited due to highly weathered soils that have low N and P base saturation. Potential production of southern pine plantations has been estimated to be twice that which is currently realized (Albaugh and others 1998, Sampson and Allen 1998). To increase production, nutrient management has become increasingly common. For example, 650,000 hectares of southern pine forests were fertilized in 1999, a 35 percent increase over the previous year[1]. While the effects of increased nutrient supply on forest production are readily recognized, there is a need to better understand the underlying mechanisms of nutrient dynamics so as to maximize returns on nutrient management investments.

N and P use efficiency (NUE and PUE, respectively), the amount of stemwood produced per unit N or P used in total aboveground production, is a quantitative measure of how effectively stands use these often-limiting nutrients to produce merchantable stemwood. Knowledge of how NUE and PUE vary could facilitate more sound nutrient management decisions. Any factor that influences stemwood production also likely affects NUE and PUE. For example, the inherently greater percentage of aboveground production allocated to stemwood by slash pine compared to loblolly pine (Colbert and others 1990) could potentially contribute to greater NUE and PUE by slash pine if nutrient uptake was equivalent between species. Likewise, any factor that influences the amount of N or P used to produce new aboveground biomass, such as differences in N or P concentration among the various biomass components or differences in the foliar retranslocation of these nutrients, could also affect NUE or PUE. This study investigated the effects of species and spacing on NUE and PUE in midrotation stands of loblolly and slash pine. Further, differences in biomass allocation, nutrient concentrations, and foliar retranslocation were examined as potential factors that influence NUE and PUE.

METHODS

Site

The study was conducted in a species and spacing trial planted in 1981 on the Lee Memorial Forest in southeast Louisiana. The predominant soil type within the study area is a fine-loamy, siliceous, thermic typic Paleudult (Ruston series). Loblolly or slash pine was planted in 25 x 25 meter plots at spacings of 1.2 x 1.2 meters and 2.4 x 2.4 meters. Each species and spacing combination was replicated 3 times in contiguous blocks.

Understory woody vegetation on each plot was cut with a chainsaw prior to data collection to minimize interspecific competition with overstory pine. Felled stems were left on-site and residual stumps were treated with the herbicide picloram. Measurements were restricted to an inner plot approximately 20 x 20 meters to minimize edge effects between treatment plots. Actual inner measurement plot boundaries varied by plot to include the total crown of all trees whose boles fell within a 20 x 20 meter area. All plot measurements were converted to a per hectare basis.

Nitrogen and Phosphorus Use Efficiency

Aboveground biomass production was estimated with regression equations. Each tree in each plot was numbered in 1996 and was measured for outside bark diameter at breast height (1.37 meters), total height and height to the base of the live crown after the 1996, 1997,

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and 1998 growing seasons. Using these measurements, standing first-year foliage, second-year foliage, stemwood, and branchwood mass for each loblolly pine tree were estimated with equations developed by Baldwin (1987) and Baldwin and others (1997). Slash pine biomass components were calculated with regression equations developed by Lohrey (1984). Lohrey (1984) did not distinguish between first-year and second-year foliage; therefore, to obtain an estimate of first-year foliage, the estimated total foliage on each slash pine tree was multiplied by 53.62 percent, the mean percentage of total loblolly pine foliage that consisted of first-year foliage.

Annual foliage production on each tree for a given year was the first-year foliage in the current year. Annual needle litter production for each year (used to calculate foliar retranslocation) was the second-year foliage in the current year. Annual stemwood and branchwood production on each tree were calculated by subtracting the previous-year standing biomass in each respective component from current-year standing biomass. Per-tree biomass production for each respective component was summed by plot and expanded to a per hectare basis. Two-year periodic mean annual production by component is the mean stand-level biomass production for each respective component averaged over 1997 and 1998.

To obtain N and P concentrations, first-year foliage, second-year foliage, and branchwood samples were collected in mid-September 1997 by shooting a midcanopy branch from 4 trees in each plot with a 12-gauge shotgun and #4 shot. Stemwood samples were obtained by coring four trees in each plot at breast height during December 1997. Needle litter samples were obtained in December 1997 by placing four 1 x 1 meter plastic sheets on the ground in each plot and collecting needle litter after 1 week.

Each component type was combined for each plot, oven-dried at 60°C for 48 hours, ground to pass a 40-mesh screen, and the resulting powder thoroughly mixed. N and P concentration were determined on 3 replicates of the mixture. N concentration was determined with the Dumas-method with a Leco FP-428 Analyzer. P concentration was determined with inductively coupled plasma (ICP) spectrometry (Huang and Schulte 1985). N and P concentration for each component in each plot was the mean of the 3 replicates.

Annual stand-level N and P in new biomass production for each component in each plot in each year was calculated by multiplying the periodic mean annual biomass production in each component in each plot by its corresponding nutrient concentration. A portion of N and P in new biomass production was assumed to have been supplied by foliar retranslocation. The total amount of retranslocated N and P was assumed to come partially from first-year foliage before its second year and partially from second-year foliage before senescence. Thus, the annual per-hectare N and P supplied by foliar retranslocation in each plot in each year was calculated as the difference in N content in first-year foliage from the previous year and N content in second-year foliage from the current year plus the difference in N content in second-year foliage in the previous year and N content in needle litter that fell in the previous year.

Net N and P used in total aboveground production were calculated as the difference between N or P in new aboveground biomass minus N or P that was supplied by foliar retranslocation. NUE and PUE were calculated as mean annual stemwood production (kg/ha per year) per unit net N or P used in total aboveground production (kg/ha per year).

Analysis

Species and initial spacing effects on individual variables were analyzed in a randomized complete block design by analysis of variance with a general linear model procedure (Statistical Analysis System Version 8, SAS Institute Inc., Cary, NC, USA). The general linear model included a variable for block, species (loblolly or slash pine), initial spacing (2.4 x 2.4 meters or 1.2 x 1.2 meters), and the interaction between species and initial spacing. The critical value for significant effects was set at 0.10.

RESULTS AND DISCUSSION

Slash pine had a greater NUE than loblolly pine, producing more stemwood per unit net N used in total aboveground production (figures 1a). There were no significant species by initial spacing interactions for any of the variables measured. Several factors contributed to greater NUE by slash pine. First, while absolute production of stemwood did not vary between species (P = 0.233), slash pine allocated a greater percentage of total aboveground production to stemwood than loblolly pine (67 percent and 63 percent, respectively; P = 0.072). This pattern is apparently manifested early in development as Colbert (1990) reported similar results for 4-year-old seedlings. A

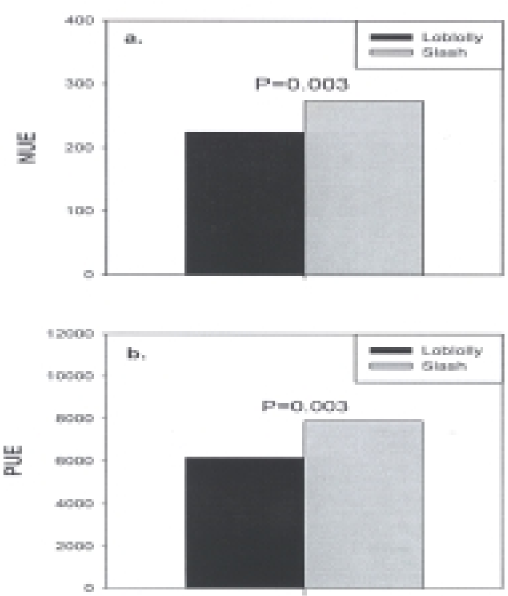

Figure 1—Nitrogen use efficiency (NUE) (a) and phosphorus use efficiency (PUE) (b) by species calculated as mean annual stemwood production (kg/ha per yr) per unit net N or P used in total aboveground production (kg/ha per yr). Data are from 17-year-old pure, unthinned stands of loblolly and slash pine in southeastern Louisiana.

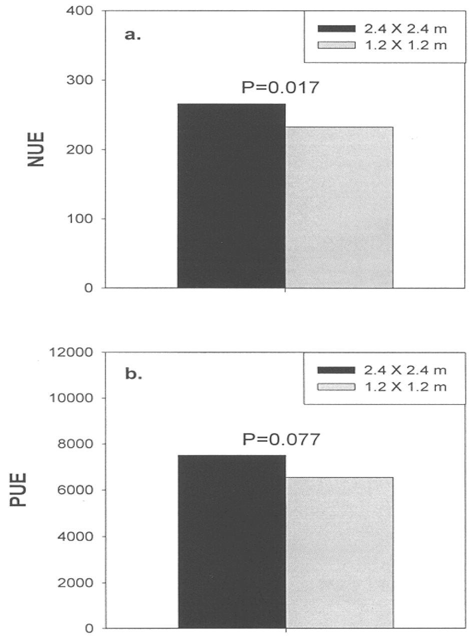

Figure 2—Nitrogen use efficiency (NUE) (a) and phosphorus use efficiency (PUE) (b) by initial spacing calculated as mean annual stemwood production (kg/ha per year) per unit net N or P used in total aboveground production (kg/ha per year). Data are from 17-year-old pure, unthinned stands of loblolly and slash pine in southeastern Louisiana.

lower N cost in new aboveground biomass also contributed to a greater NUE by slash pine as slash pine had lower N concentrations than loblolly pine in both first-year foliage (0.93 percent and 1.15 percent, respectively; P = 0.004) and branchwood (0.36 percent and 0.40 percent, respectively; P = 0.068). Further, slash pine foliage retranslocated a greater percentage of N during its lifespan than loblolly pine foliage (58.2 percent and 51.6 percent, respectively; P = 0.040).

Slash pine also had a greater PUE than loblolly pine (figure 1b). As with N, greater PUE by slash pine resulted in part from greater relative allocation to stemwood than loblolly pine. Again, slash pine had a lower P concentration in first-year foliage than loblolly pine (0.062 percent and 0.073 percent, respectively; P = 0.004). Although slash pine had greater P concentration in stemwood than loblolly pine (0.0045 percent and 0.0037 percent; P = 0.015), the relatively low concentration of stemwood did not appreciably affect total annual P demands. Slash pine foliage also had a greater percentage of P retranslocated during its lifetime than loblolly pine foliage (75.3 percent and 66.0 percent, respectively; P = 0.007).

Comparisons of initial spacing showed that NUE and PUE was greater in the 2.4 x 2.4 meter spaced stands than in the denser 1.2 x 1.2 meter spaced stands (figure 2), which was unexpected. Generally, foliar efficiency at producing stemwood increases with increasing stand density (Smith and Long 1989, Long and Smith 1990), and NUE and PUE were expected to follow a similar pattern. The decline in NUE and PUE in the denser 1.2 x 1.2 meter spaced stands may be related to a sustained drought that occurred during the study that likely caused intense intraspecific competition for water, particularly in the denser stands. As evidence for increased competition in the denser stands, 1.2 x 1.2 meters spaced stands had a significantly greater percentage of total volume lost each year to mortality than 2.4 x 2.4 meter spaced stands (1.32 percent and 0.08 percent per year, respectively; P = 0.001).

CONCLUSIONS

Slash pine stands had a greater NUE and PUE than loblolly pine, which was attributed to slash pine allocating a greater percentage of total aboveground production to stemwood, having lower foliar N and P concentrations, and retranslocating a greater percentage of N and P from foliage before senescence than loblolly pine. Both NUE and PUE declined with closer initial spacing, which was attributed to a drought that occurred during the study.

The results of this study illustrate how nutrient use efficiencies differ between stands of varying composition and structure. Thus, in light of the investment into intensive silviculture, it is apparent that forest managers must consider many variables in a sound nutrient management regime and a "one size fits all" approach is inappropriate.

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