NITROGEN ACCUMULATION AND CHANGES IN NITRATE LEACHING AFTER 4 YEARS OF INTENSIVE FOREST CULTURE ON MARGINAL AGRICULTURAL LAND*

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ABSTRACT

Loblolly pine (*Pinus taeda* L.) and sweetgum (*Liquidambar styraciflua* L.) were grown with irrigation, continuous fertiliser application, and insect pest control on a 1-year-old abandoned peanut (*Arachis hypogaea* L.) field. Wells and tension lysimeters were used to measure nitrate-nitrogen (NO_3-N) in soil moisture and groundwater on three replicate transects for 4 years. Each replication had five treatments: maximum plantation management, minimum plantation management, old field, natural forest, and lake edge. Maximum plantation management included improved genetic stock, irrigation, fertiliser, complete elimination of competing vegetation, and insect pest control. Minimum plantation management included improved genetic stock and complete elimination of competing vegetation. The old field was the abandoned peanut field with no treatment. The natural forest was 50-year-old longleaf pine (*Pinus palustris* Mill.) forest. The lake edge was a narrow wetland transition from the longleaf pine forest to the lake. During the first 2 years of plantation management, groundwater nitrate-nitrogen concentrations exceeded drinking water standards throughout the abandoned field and were highest on plantation plots. During years 3 and 4, groundwater nitrate-nitrogen concentrations declined. The greatest reduction of nitrate-nitrogen concentration occurred in soil moisture, at the shallowest depths, in the plantation treatments. After four growing seasons, biomass accumulation ranged from 7.5 Mg/ha for the sweetgum minimum treatment to 57 Mg/ha for loblolly pine maximum treatment.

Keywords: irrigation; fertiliser; nitrate-nitrogen; groundwater; soil moisture; nitrogen accumulation; *Pinus taeda*; *Liquidambar styraciflua*.

INTRODUCTION

Pine silviculture in the southern United States has utilised plantation management on industrial forest lands for the past four decades. During those four decades the harvest rates and growth rates have steadily increased (Sheffield *et al.* 1985). Growth rate increases were due primarily to intensified pine plantation management during this period. Intensified

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management included mechanical and chemical site preparation, genetic improvement of growing stock, chemical seedling release, and fertiliser application at both planting and mid-rotation. However, widespread intensive plantation management is not consistent with ecosystem management concepts being implemented on public lands. Forest industry has recognised the need for greater emphasis on endangered species protection, wetland protection, water quality protection, and enhanced biodiversity on their lands. The large industrial owners are also practising their versions of ecosystem management, which generally reduces the area where plantation management is practised. It is likely that the area of plantation management will not expand, and may even contract, on forested lands.

Expanding plantation management on to marginal agricultural lands can have several advantages. Vitousek (1991) suggested that planting marginal agricultural land in plantations is the only way that forest management is likely to influence global carbon dioxide (CO_2) levels. Forest planting can reduce carbon dioxide by both direct sequestration of carbon into long-lasting forms and as a replacement to fossil fuels (Hohenstein & Wright 1994). Conversion of marginal agricultural land to forest crops may also result in a decrease in run-off of sediment and nutrients into the nation's waters (Pimental & Krummel 1987). Natural forests cycle nitrogen tightly to control nitrate-nitrogen leaching (Vitousek *et al.* 1982), a common problem in agricultural production. Forest plantations can also be used to control nitrate-nitrogen leaching in land-based sewage disposal (Cole *et al.* 1986). Fredrick *et al.* (1998) demonstrated enhanced growth and survival of a number of hardwood species in plantations treated with swine waste. Plantations on marginal agricultural land could free more forestland for non-commodity uses. Plantations could help reduce carbon dioxide by sequestration of carbon into long-lasting products and displacement of fossil fuels. Plantations may also improve water quality by reducing sediment and controlling nitrogen losses.

In 1995, International Paper Company began an experimental planting of loblolly pine and sweetgum under highly intensive conditions on a field that had been used to grow peanuts before planting in trees. The study examined four levels of intensive management. The minimum treatment included pre-planting subsoil ripping, complete elimination of competing vegetation with herbicide, and planting improved genetic material. Three more treatments were: addition of daily irrigation, daily irrigation + fertiliser, and irrigation + fertiliser + insect pest control. The maximum treatment was essentially an effort to grow trees without water, nutrient, or insect pest limitations.

During the first 2 years of growth, nitrate-nitrogen in groundwater beneath the entire abandoned field exceeded drinking water standards (10 mg NO_3-N/litre) (Williams 1999). Plantation establishment also exacerbated the problem with groundwater nitrate-nitrogen concentrations significantly higher in the plantation treatments. Maximum concentrations ranged from 18 to 45 mg NO_3-N/litre in plantation replications and 10 to 15 mg NO_3-N/litre in the fallow field. Nitrate-nitrogen concentration in soil moisture revealed increased leaching in the plantation plots but no significant differences between the maximum and minimum treatments. These results had three features in common with other forest treatments where nitrate-nitrogen leaching has been noted. Peanuts fix nitrogen, even in the absence of photosynthesis (Siddique & Bal 1991), similar to stands of red alder (*Ulnus rubra* Bong) where higher concentrations of nitrate-nitrogen were found (van-Miegroet & Cole 1985). Soils were sandy and sandy soils are also common in other sites where higher nitrate-nitrogen concentrations have been identified (Likens *et al.* 1969; Johnson *et al.*1991; Munson *et al.*

1993). Finally, all treatments included herbicide elimination of competing vegetation. High nitrate-nitrogen concentrations have also been associated with herbicide treatments that eliminated vegetation at a watershed scale (Likens *et al.* 1969) and with repeated herbicide applications (Munson *et al.* 1993).

By the end of the fourth growing season, tree growth had become a significant factor, with several treatments already reaching crown closure. This paper outlines changes in nitrate-nitrogen concentrations in soil moisture and groundwater during the first 4 years. Fourth year accumulations of biomass and nitrogen will also be contrasted between three of the treatments.

METHODS

Field Installation

The experiment was designed to test cultural methods to increase growth of loblolly pine and sweetgum at International Paper's Silver Lake farm near Bainbridge, Georgia (30°51′ north, 84°45′ west). The experiment was installed on an abandoned field that had grown a variety of crops, ending with peanuts in summer of 1994. The field was on a small hill (<10 m) with a Lakeland sand (Typic Quartzipsamments) soil (Fig. 1). The experimental

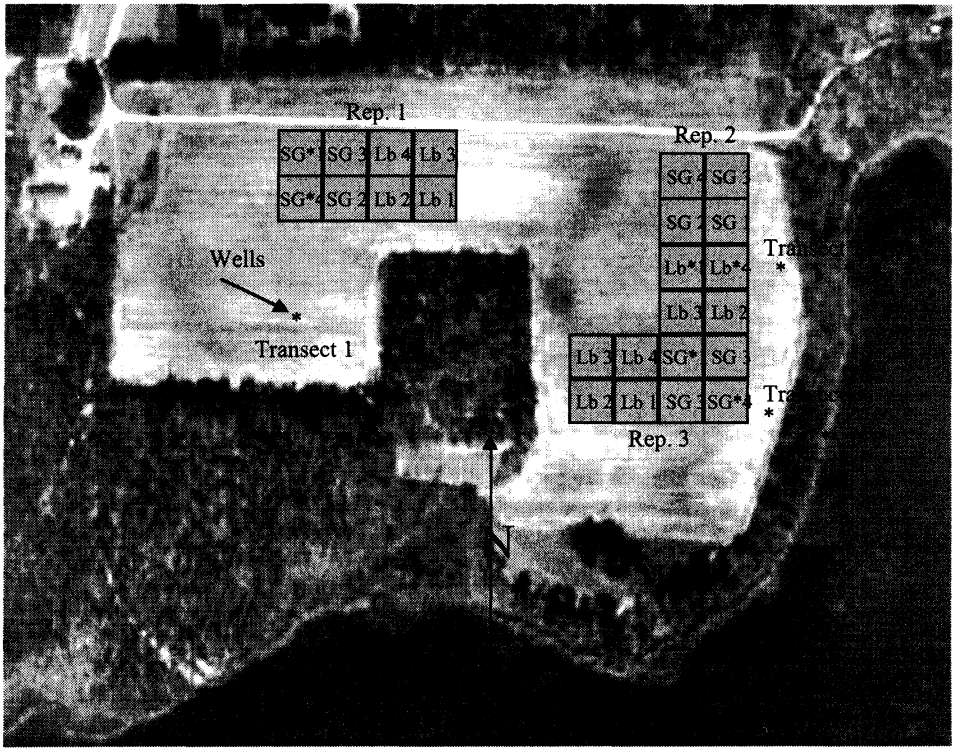

FIG. 1–Map of site with treatment layout. Species are sweetgum (SG) and loblolly pine (Lb) and treatments are minimum (1), irrigated (2), irrigated + fertiliser (3), and irrigated + fertiliser + pest control, maximum (4). Location of three transects of soil moisture and groundwater sampling stations (*).

design was three replications of a 2 × 4 factorial with two species and four levels of management intensity as factors. Each replication was a 182 × 88-m rectangle with eight 44 × 48-m treatment plots and they were maintained competition-free with repeated herbicide applications. Planting rows were 3.7 m apart and subsoiled by ripping at 60 cm to fracture the plough layer. The minimum treatment consisted of planting 1-year-old seedlings from improved seed sources of loblolly pine and sweetgum. Daily trickle irrigation was added as the second treatment. Liquid fertiliser was added to irrigation (fertigation) as the third treatment and the maximum treatment included repeated insect pest control. Nantucket pine tip moth (*Rhyacionia frustrana* Comstock) was the most prevalent insect pest on loblolly pine and was effectively controlled during the first 3 years. Sweetgum at this site has not had any significant insect pest problems and so the fertigation and maximum treatments were indistinguishable.

Water samples were collected from both soil moisture and groundwater (unconfined water table aquifer), using transects from each of the three replicates (Fig. 1). Each transect had five stations: the centre of the maximum treatment plot, the centre of the minimum treatment plot, in the old field downhill from the minimum treatment, in the surrounding forest downhill from the old field, and near the edge of Silver Lake downhill from the forest station. At each station a 15-cm hole was augered to 1.5 m below the water table. A 2.5-cm × 1-m well screen was placed into the well bottom and covered with washed sand and a bentonite seal. At depths of 1.5, 3.0, 4.6, and 6.1 m tension lysimeters (2 × 10-cm porous cups) were placed 30 cm from the central shaft by horizontal drilling. Each lysimeter was connected to a sample bottle and vacuum reservoir by 5-mm polyethylene tubing. After each lysimeter was completed the central shaft was filled to the next depth with a mixture of bentonite and auger cuttings.

Water Sampling

Between May 1995 and November 1996, a continuous 0.07 MPa tension was maintained on the lysimeters and water was collected biweekly. Groundwater samples were also collected during each site visit. Sampling was re-initiated as quarterly samples in the fall of 1997 in the third growing season and continued through 1998. Quarterly sampling consisted of three site visits over a 4- to 6-week period. At the first visit only groundwater samples were taken and the vacuum pump was started. Tension of 0.07 MPa was then maintained and the site was visited twice after rains, with sampling conducted as was done during the first 2 years. After the second group of soil moisture samples were collected the vacuum pump was then shut off until the next quarter sampling. 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, and a 60-ml sample was collected from any of the small screened samplers that were below the water table. All samples were placed in coolers and returned to the Baruch Institute Lab in Georgetown, South Carolina, and nitrate-nitrogen determinations were made within 24 hours. Nitrate analyses were done using cadmium reduction technique on a Technicon Autoanalyser (Greenberg *et al.* 1992).

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 analysed as a factorial with four treatments, four depths, and three blocks. Treatment differences in groundwater, and year and depth differences in soil moisture were tested by the Tukey multiple range test.

Plant Biomass and Nutrient Sampling

Tree growth was measured on three treatments: minimum, irrigated, and maximum. 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. All 80 trees in Replicate 1 of the maximum and minimum plots were measured. After examining error rates and spatial distribution, only 40 trees were measured on the remaining plots by sampling every second tree along each row rather than every tree.

Biomass and nutrient accumulation were determined for the maximum and minimum treatments. The irrigation treatment was also sampled for biomass and 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 loblolly pine trees from the maximum plot and 10 from the minimum plot were harvested, separated into stems, unfoliated branches, dead branches, and foliated branches, and weighed green. Subsamples were dried (60°C) and weighed to obtain moisture content; subsamples of foliated branches were separated into branches and needles before drying. Dry weight proportions from subsamples were used to determine dry weight of trees in the following components: stem, live branches, dead branches, and leaves. Portions of each subsample were subsequently ground for nutrient analysis. Sweetgum was measured in the same way. The maximum loblolly pine treatments were the only trees where crown closure had led to production of dead branches.

Simple linear biomass regressions were calculated for each component and total biomass equations were based on measures of basal diameter (BD), diameter at breast height (dbh), and height. These regressions were combined with the growth data collected on each treatment to estimate treatment biomass means.

Forest floor biomass was estimated on the maximum and minimum plots for each species. All litter (humus layers had not yet formed in any treatment) was removed from 14 1-m^2 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 centres) and interrows (greater than 1 m from either row centre). Seven areas were collected from each row and interrow. All litter was carefully scraped from the soil surface and placed into paper bags. Bags were dried (60°C) and weighed. Subsamples of each bag were ground for nutrient analysis.

All dried subsamples were ground to pass a 1.0-mm sieve. The bole samples were chipped prior to grinding in the Wiley mill. Ground materials were Kjeldahl digested (Isaac & Johnson 1976; Labconco 1987; Jones & Case 1990; Jones 1991), diluted with DDW, and colorimetrically analysed 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 colour reaction between ammonium and alkaline sodium salicylate with a chlorine source (Crooke & Simpson 1971; Technicon Industrial Systems 1978; Nelson & Sommers 1980). The ascorbic acid method (Murphy & Riley 1962) was used to analyse the diluted digestate for phosphate. Averaged nutrient concentrations were then multiplied by biomass estimates to estimate nutrient quantities.

RESULTS

Groundwater Nitrate-nitrogen

Nitrate-nitrogen concentrations in groundwater can be examined as differences between treatments. During the first year there was a difference between the plantation treatments and the old field (Table 1). This difference was also significant if Years 1 and 2 were combined (Williams 1999). However, during Years 2, 3, and 4 the differences declined and there were no significant differences, although a consistent pattern continued. There was a clear and significant difference between the field and the forest and lake edge plots. These two stations behaved similarly for the entire 4-year period.

TABLE 1–Average and maximum nitrate concentrations (mg NO_3-N/litre) in shallow groundwater measured during each year and for each treatment. Averages in each year followed by the same letter are not significantly different $\alpha = 0.05$.

Treatment	1995	1996	1997	1998
Average concentration				
Minimum	6.62 a	8.82 a	6.92 a	7.42 a
Maximum	4.82ab	6.60 a	6.18 a	6.47 a
Old field	2.46 b	5.46 a	5.41 a	5.09 a
Forest	0.40 c	0.24 b	0.17 b	0.15 b
Lake edge	0.26 c	0.34 b	0.04 b	0.04 b
Maximum concentration				
Minimum	19.93	17.99	9.64	17.89
Maximum	13.93	27.89	9.90	15.98
Old field	8.49	10.67	7.75	12.48
Forest	1.48	4.36	0.48	0.36
Lake edge	0.44	1.40	0.07	0.09

The most important aspect of nitrate-nitrogen concentrations is not the average concentration but whether drinking water standards are violated. Individual occurrences of concentrations over the 10 mg NO_3-N/litre are violations of the EPA Standard for safe drinking water, and the stations throughout the field continued to violate the standard (Table 1). None of the samples in 1997 violated the standard but sampling in 1997 was limited to the fall period when concentrations have been least. The 1998 data indicate that all plots in the old field continued to violate drinking water standards.

Soil Moisture Nitrate-nitrogen

During the first 2 years of measurements, soil moisture nitrate-nitrogen concentrations were high and quite variable. Soil moisture nitrate-nitrogen concentrations were significantly higher under the maximum and minimum treatment than the old field which was significantly higher then the natural forest (Williams 1999). During this period there were no significant differences between depths or between years at a single depth (Table 2).

In the 4 years of sampling there were no significant changes in the natural forest. Concentrations remained below 1 mg NO_3-N/litre throughout the period (Table 2a) These concentrations were not significantly different due to uniformity between depths and years.

TABLE 2–Average nitrate-nitrogen concentrations (mg NO_3-N/litre) in soil moisture by depth and by year for each treatment except the lake edge where the water table was close to the surface. Lowercase letters in each column indicate averages are not significantly different between depths; capital letters in rows indicate average are not significantly different between years ($\alpha = 0.05$)

Depth (m)	1995	1996	1997	1998
(a) Forest treatment*				
1.5	0.82	0.30	0.08	0.25
3.0	0.12	0.15	0.01	0.38
4.6	0.51	0.46	0.17	0.20
(b) Old field treatment*				
1.5	3.70	8.93	2.95	6.33
3.0	7.13	5.24	3.96	4.32
4.6	4.56	8.67	5.84	3.70
6.1	4.98	5.85	7.80	4.02
(c) Maximum treatment				
1.5	11.12 aA	10.75 aA	2.80 B	5.46 bA
3.0	9.50 aA	6.53 aA	8.60 A	2.77 bB
4.6	11.33 aA	14.43 aA	6.12 A	9.63 aA
6.1	9.48 aA	14.22 aA	8.07 A	10.98 aA
(d) Minimum treatment				
1.5	9.88 aA	10.51 aA	0.79 B	0.23 cB
3.0	11.54 aA	10.32 aA	5.45 A	6.37 bA
4.6	12.97 aA	13.39 aA	11.01 A	12.61 aA
6.1	6.43 aA	10.57 aA		6.89 bA

* No significant differences by depth or year

The old field treatment also showed no significant changes over the 4 years of measurement (Table 2b). However, the field showed considerable variation between years and depths. The high rates of variability obscure any changes that may be happening in the field.

The maximum and minimum treatments contrast sharply with the old field plots. The maximum treatment showed significant differences between depths during the fourth year (Table 2c). At the 1.5 m depth, the third-year concentration was significantly less than that of the first 2 years, and the fourth year concentration at the 3 m depth was also significantly less than the first three. In Year 4, the concentrations at 1.5 and 3.0 m were both significantly less than the deeper depths. The minimum treatment showed an even clearer change during Years 3 and 4 (Table 2d). At the 1.5 m depth, soil moisture concentrations dropped below 1 mg NO_3-N/litre during both Year 3 and Year 4. These values are significantly lower than at deeper depths and significantly lower than for Years 1 and 2.

Biomass and Nitrogen Accumulation

The following regressions were developed:

Loblolly pine
Bole Biomass $= 13.94\ D^2H + 3481$ $r^2 = 0.92$
Branches Biomass $= 4.80\ D^2H + 3670$ $r^2 = 0.43$
Leaf Biomass $= 3.36\ BD + 1486$ $r^2 = 0.35$
Total Biomass $= 29\ D^2H + 9868$ $r^2 = 0.91$

Sweetgum

Bole Biomass $= 27.36\ D^2H + 772$ $r^2 = 0.95$
Branch Biomass $= 12.52\ D^2H + 682$ $r^2 = 0.71$
Leaf Biomass $= 4.44\ D^2H + 141$ $r^2 = 0.31$
Total Biomass $= 44.3\ D^2H + 1594$ $r^2 = 0.31$

Biomass is in kilograms, D (dbh) and BD (basal diameter) are in centimetres, and height is in metres.

Component biomass estimates sums agreed well with total biomass estimates for all treatments except the maximum loblolly treatment. This treatment was the only one in which the trees were large enough to have unfoliated and dead branches. However, there were not sufficient trees harvested (three with unfoliated branches, five with dead) to produce reliable estimates of these two components. Since total biomass estimates in this treatment consistently exceeded the sum of leaf, bole, and branches, the difference was divided equally between unfoliated and dead branches.

Because this paper is concerned with nitrate-nitrogen only the nitrogen analyses will be presented here. There are a number of errors compounded during the estimation of biomass and nutrient accumulation on a per hectare basis, thus estimates of significance are not justified. However, there were very large differences in the estimated biomass and nitrogen accumulation between treatments. Biomass accumulation varied from 7.5 Mg/ha for the sweetgum minimum treatment to 57 Mg/ha for the loblolly pine maximum treatment (Fig. 2). The pattern of nitrogen accumulation between treatments was similar to biomass

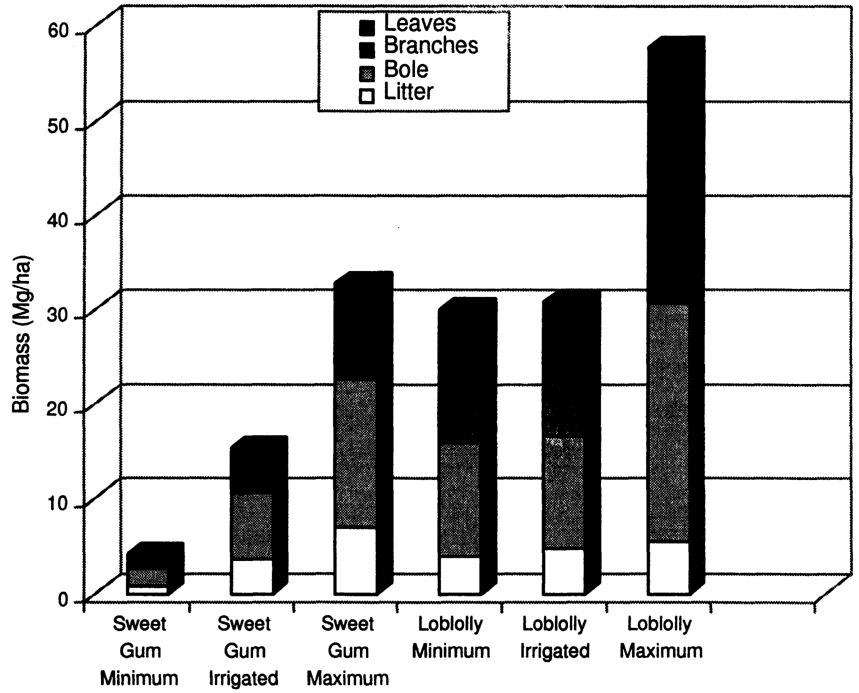

FIG. 2–Biomass accumulation after 4 years on three management treatments. Litter estimates were not made on the irrigated plots; an average between the minimum and maximum was assumed.

with the exception of the sweetgum maximum treatment (Fig. 3). Nitrogen accumulation in litter under this treatment was considerably higher. Higher nitrogen in this treatment was a combination of more litter of the deciduous tree and a high nitrogen concentration (>1%) in the litter.

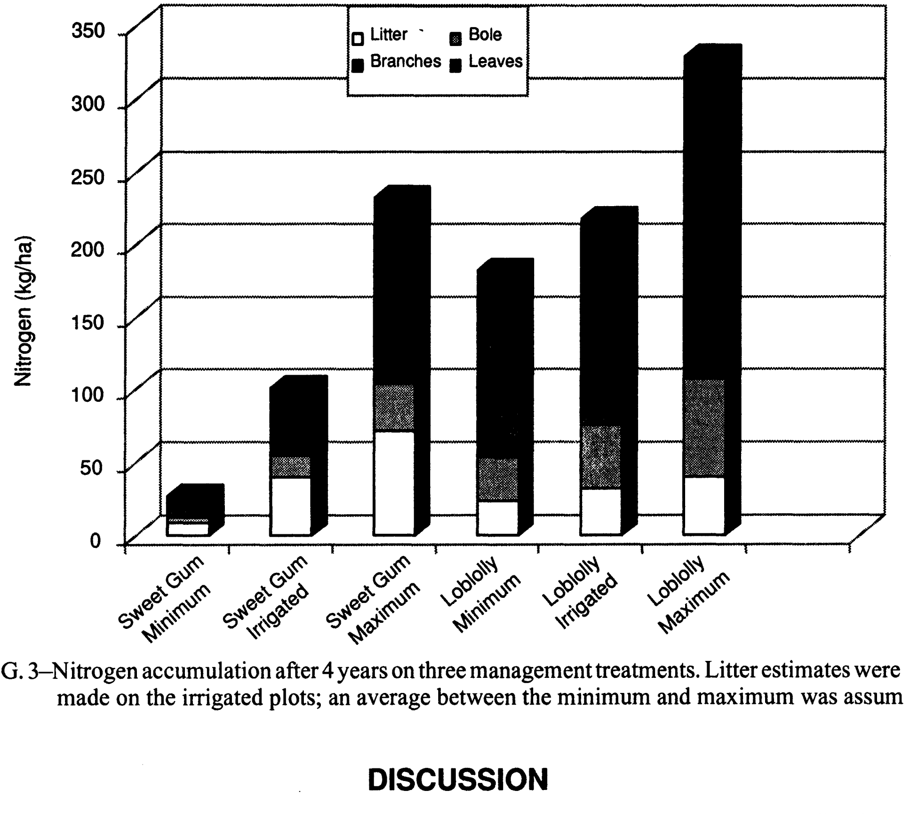

FIG. 3–Nitrogen accumulation after 4 years on three management treatments. Litter estimates were not made on the irrigated plots; an average between the minimum and maximum was assumed.

DISCUSSION

Four-year results showed a number of trends that can be interpreted as reflections of nitrogen cycling in the conversion of marginal cropland to forest plantation. Nitrate-nitrogen continued to leach from the entire fallow field for 4 years with concentrations averaging above 5 mg NO_3-N/litre throughout the period. The field soils had sufficient nitrogen for the irrigated loblolly pine treatment to accumulate over 200 kg N in above-ground pools. The concentration of nitrate-nitrogen in the upper soil moisture showed a consistent decline during Years 3 and 4 in the plantation treatments. The lowest concentrations were found at 1.5 m in the minimum treatment.

Following the results of devegetation at Hubbard Brook (Likens *et al.* 1969), with nitrate-nitrogen concentrations peaking at 10.5 mg NO_3-N/litre, nitrogen cycling after forest disturbance was closely examined. Experimental disturbances produced a variety of results with concentrations varying over three orders of magnitude, from 10 μg NO_3-N/litre (Richardson & Lund 1975) to 25 mg NO_3-N/litre (Edwards & Todd 1979). Vitousek & Melillo (1979) proposed nine processes that may prevent nitrate-nitrogen leaching to groundwater or streams. They were: (1) immobilisation of ammonium in decomposing material with high C:N ratio, such as wood; (2) ammonium uptake by rapid regrowth;

(3) ammonium could be fixed in 2:1 clays; (4) ammonium could be transformed to ammonia and volatilised; (5) ammonium could accumulate on cation exchange sites; (6) nitrate-nitrogen could be denitrified to nitrous oxide or nitrogen; (7) nitrate-nitrogen could be used in nonassimilatory reduction to ammonium; (8) nitrate-nitrogen could be retained in soils by anion exchange; (9) there may be insufficient water to transport nitrate-nitrogen from the soil profile. To these nine, uptake of nitrate-nitrogen by regrowth may also be added as Nadelhoffer *et al.*(1984) found that nitrate-nitrogen was the dominant form of nitrogen taken up by vegetation in eight of nine temperate hardwood stands studied. Since studies have found 10 separate mechanisms that can prevent nitrate-nitrogen movement into groundwater or streams, it is not surprising that nitrate-nitrogen is not often found after disturbance of natural forests.

In the south-eastern United States, many of these mechanisms are not likely to be common. Most south-eastern soils are dominated by kaolinitic clays. Cation exchange capacities of most soils are rather low. Most soils are acidic and ammonia volatilisation is not likely. Nonassimilatory reduction of ammonia to ammonium hasn't been found. Soils also have relatively small anion exchange capacity, and there is certainly enough growing season rain to move nitrate-nitrogen. That leaves ammonium immobilisation and uptake by plants of either ammonium-nitrogen or nitrate-nitrogen as the most likely mechanisms active in south-eastern forests. Using labelled nitrogen additions, Vitousek & Matson (1985) showed that heterotrophic bacteria were the primary sink of nitrogen following intensive site preparation in loblolly pine. Swank & Douglass (1977) also found relatively low (0.64 mg NO_3-N/litre) concentrations in a watershed that had been converted from forest to grass. Waide & Swank (1977) discussed a high and rapid turnover of nitrogen in the microbial pool in Appalachian hardwood stands. Southern forests also display rapid regrowth after disturbance. Although concentrations were often under 100 μg NO_3-N/litre, higher nitrate-nitrogen concentrations were associated with disturbances to the vegetation (Swank & Douglass 1977), even small ones such as insect defoliation (Swank *et al.* 1981). Complete elimination of vegetation has often been associated with the few studies with nitrate-nitrogen concentrations over 10 mg NO_3-N/litre: Likens *et al.*(1969) 10.5 mg NO_3-N/litre; Davis (1987) 19 mg NO_3-N/litre; Edwards & Todd (1979) 25 mg NO_3-N/litre, while control of hardwoods in a mixed pine-hardwood stand produced one of the largest nitrate-nitrogen concentrations found in streams draining southern pine forests, 5.3 mg NO_3-N/litre (Neary *et al.* 1993). It is most likely that both processes are common in south-eastern forests. Johnson (1992) suggested that microbial uptake may be the common short-term response, with heterotrophic bacteria out-competing nitrifiers, but that trees may be the most effective competitors over time scales of years.

How do the 4-year results of this pilot study compare to what we know about nutrient cycling in forest systems?

Nitrate leaching has continued throughout the period and the old field site has continued to show high nitrate-nitrogen concentrations throughout the profile. This suggests that there is still residual nitrogen in the soil 4 years after cessation of agricultural production, and that nitrifying bacteria are still active. Van Miegroet *et al.* (1992) found nitrate-nitrogen concentrations declined drastically 3 years after cutting of nitrogen-fixing red alder. They found nitrification approximately equal to mineralisation and both were significantly lower in cut plots than in an uncut alder stand, although this did not account for all of the observed decrease in nitrate-nitrogen leaching. The old field plot showed large variations with a consistent average around 5 mg NO_3-N/litre for the entire 4-year period. Groffman *et al.* (1986) investigated nitrogen cycling in field crops in central Georgia and found rapid uptake and release of nitrogen by agricultural weeds, up to 40 kg N/ha in 3 months. They concluded rapid uptake and release of nitrogen, along with low use efficiencies, characterise agricultural crops and associated weeds. The old field plot still seems to be following this type of loose nitrogen cycling with nitrogen losses as nitrate-nitrogen continuing as long as mineralisable nitrogen exists in the profile. Nutrient accumulations in the treatment plots have shown that the field soil was quite rich in nitrogen. The irrigated treatments have received no nitrogen additions but the sweetgum has accumulated over 90 kg N/ha and the loblolly pine over 200 kg N/ha in the past 4 years. Also, the irrigated loblolly pine had needle nitrogen concentrations of 1.19%, indicating that nitrogen was not a limiting nutrient (Allen 1987).

On the sites that are now supporting rapid tree growth, nitrate-nitrogen concentrations have shown a significant decline in the upper soil profile. Soil solution concentrations at 1.5 m in the minimum treatment are now similar to the natural stand. In the maximum treatments both the 1.5 and 3.0 m depths show reduced nitrate-nitrogen concentrations, although values are still higher than the in the minimum treatment. There are several reasons why these results indicate that uptake has been the most important factor in regulation of nitrate-nitrogen concentration. Most of the discussion will deal with the loblolly pine plots since nutrition and water relations of sweetgum on upland sites are not as well understood (Lockaby *et al.* 1997).

Heterotrophic bacteria are generally associated with decomposition of litter and forest floor materials. On the minimum treatment plots very little forest floor decomposition has occurred. Both plots began as bare soil in 1985. The sweetgum plots now have a litter layer of only 817 kg/ha, which does not even cover 50% of the ground. The loblolly pine plots have a litter layer of 4 Mg/ha. However, most of that was litter produced during the third growing season and was not on the ground during the fourth growing season. This was apparent with a litter nitrogen content of 0.502%, which is indistinguishable from fresh litter. In contrast, the maximum plots had 7.0 (sweetgum) and 5.6 (loblolly pine) Mg/ha forest floor material and the nitrogen content of the loblolly litter (0.7%) suggests some decomposition. Given the nitrogen content of this litter, and assuming a 50% carbon content in biomass, the C:N ratios were 86, 71 , 46, 48 for the loblolly pine minimum and maximum and sweetgum minimum and maximum, respectively. These values suggest that only the pine litters would immobilise nitrogen (Berg & Ekbohm 1983). However, they are well above a value of 9–11 that Verhagen & Laanbroek (1991) found that the heterotroph *Arthrobacter globiformus* would out compete the nitrifying bacteria *Nitrosomonas europaea* and *Nitrobacter winogradskyi*. It is difficult to see how the nitrate-nitrogen concentration below sparse litter of the minimum treatments would be expected to be less than the maximum if the immobilisation in the litter was the main control of nitrate-nitrogen concentrations.

Without additional nitrogen, tree growth has been very rapid on this field. Lockaby *et al.* (1997) reported an average height of sweetgum at age 4 of 3.45 m with 150 kg N/ha and 2.5 cm/week irrigation. The sweetgum minimum treatment had an average height of 3.12 m and the irrigated was 5.40 m. Loblolly pine growth also compares well with that reported by Swindel *et al.* (1988). Their plot with 240 kg N/ha added, irrigation, and competition control had an average height of 5.6 m at age 4 while the minimum treatment in this study had an average height of 5.0 m. The irrigation-only treatment in this study had a mean height of 5.9 m. The minimum and irrigation treatments were growing as well as or better than studies with 150 and 240 kg N added. There is little doubt that the field was supplying ample nitrogen for rapid growth. It does not seem unlikely that the minimum treatments were withdrawing this nitrogen from the upper 1.5 m of soil, resulting in the lower nitrate-nitrogen concentrations. Uptake may have been directly as nitrate-nitrogen or as ammonium-nitrogen. Gijsman (1991) showed Douglas-fir (*Pseudotsuga menziesii* Mirb.) utilised nitrate-nitrogen when soils were dry and ammonium-nitrogen when soils were damp. It could be that on the drier minimum treatment soils, loblolly pine behaved similarly. It may also be that this study behaved as Johnson (1992) predicted, i.e., over a longer period trees are more effective competitors for ammonium-nitrogen than heterotrophic bacteria.

CONCLUSIONS

This study was a pilot study of intensive forestry on marginal agricultural land. During the first 2 years the primary finding was that this particular field had a high amount of residual nitrogen in the soil profile and nitrate-nitrogen leaching was a problem. Soil moisture nitrate-nitrogen concentrations also indicated that the bare ground of the treatments resulted in higher nitrate-nitrogen concentrations than the agricultural weeds growing in the fallow field. There were no differences between the plantation treatments, presumably because the trees were too small to have an environmental impact. The age 4 results indicate that there was indeed a large pool of residual nitrogen in this field. Nitrate-nitrogen concentrations in groundwater continue high, as do those in soil moisture in the fallow field and at depths greater than 4.5 m. This is longer than found after removal of a nitrogen-fixing forest. Also, nitrogen concentrations in the irrigated loblolly pine indicate sufficient nitrogen nutrition despite accumulation of over 200 kg N in the above-ground biomass. Tree growth on both the minimum and maximum plots appears to have reduced soil moisture nitrate-nitrogen concentration. The pattern of withdrawal seems most consistent with nitrate-nitrogen control by vegetation uptake.

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