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Poultry Litter Application to Loblolly Pine Forests: Growth and Nutrient Containment

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ABSTRACT

Forestland application of poultry manure offers an alternative to the conventional practice of pastureland application. Before such a practice is considered viable, however, it must be demonstrated that the forest ecosystem is capable of absorbing the nutrients contained in poultry manure, especially nitrogen (N) and phosphorus (P). From the forestry perspective, it must also be demonstrated that tree growth is not diminished. We investigated these questions using loblolly pine (*Pinus taeda* L.) stands growing in central Mississippi in an area of high poultry production. Stockpiled broiler litter was applied to newly thinned, 8-yr-old stands at 0, 4.6, and 18.6 dry Mg ha^{-1}, supplying 0, 200, and 800 kg N ha^{-1} and 0, 92, and 370 kg P ha^{-1}, respectively. Levels of nitrate in soil water, monitored at a 50-cm depth with porous cup tension lysimeters, exceeded 10 mg N L^{-1} during the first two years after application in the 18.6 Mg ha^{-1} rate but only on two occasions in the first year for the lower rate of application. Phosphate was largely absent from lysimeter water in all treatments. Other macronutrients (K, Ca, Mg, S) were elevated in lysimeter water in proportion to litter application rates. Soil extractable nitrate showed similar trends to lysimeter water, with substantial elevation during the first year following application for the 18.6 Mg ha^{-1} rate. Mehlich III–extractable phosphate peaked in excess of 100 μg P g^{-1} soil during the third year of the study for the 18.6 Mg ha^{-1} rate. The 4.6 Mg ha^{-1} rate did not affect extractable soil P. Tree growth was increased by the poultry litter. Total stem cross-sectional area, or basal area, was approximately 20% greater after 2 yr for both rates of litter application. Overall, the nutrients supplied by the 4.6 Mg ha^{-1} rate were contained by the pine forest and resulted in favorable increases in tree growth. The higher rate, by contrast, did pose some risk to water quality through the mobilization of nitrate. These results show that, under the conditions of this study, application of poultry litter at moderate rates of approximately 5 Mg ha^{-1} to young stands of loblolly pine offers an alternative disposal option with minimal impacts to water quality and potential increases in tree growth.

Water pollution from excess nutrients is of great current concern throughout the world. The principal problems are ground water contamination by N, as NO_3^-, and surface water eutrophication by N and P in various forms (Daniel et al., 1998; Sims and Wolf, 1994). Intensive and concentrated animal production has been implicated as a significant threat to both water quality problems but especially to eutrophication (Mallin, 2000). In the case of poultry production, animal waste has traditionally been applied to pasturelands with little environmental concern. However, as demand for poultry products increases and pasturelands become nutrient saturated, water quality concerns are being reported (Gallimore et al., 1999; Sauer et al., 1999; Vervoort et al., 1998).

Forestland offers an attractive alternative to the conventional practice of pastureland application. Several advantages exist. First, poultry production facilities are often located in rural areas with abundant forestland within range of economic transport of poultry waste. Most of the top poultry-producing counties of the Southern United States also have an abundance of southern pine forests (Fig. 1). Second, forests are frequently nutrient limited and routinely fertilized with N and P (Binkley et al., 1999). Third, actively growing forests have an immense potential for rapid nutrient uptake (O'Neill and Gordon, 1994), immobilization (Vitousek et al., 1992), and sediment trapping (Taylor et al., 1990). Previous studies in the southeastern United States have observed promising growth responses of forests to poultry litter application (Samuelson et al., 1999); however, little information exists about the degree to which these forest ecosystems retain the associated nutrients and prevent eutrophication.

Trees absorb nutrients in direct proportion to their growth rate (Coleman et al., 1998; Ingestad, 1982). However, forests have additional mechanisms for nutrient retention such as immobilization (Vitousek et al., 1992) and retention of ions on the soil exchange complex (Pritchett and Fisher, 1987). Forest ecosystems are highly buffered with respect to the amount of nutrients lost to stream or ground water after nutrient addition. With the exception of forests saturated with N due to atmospheric deposition and low soil buffering capacity, fertilized forests generally release minimal N or P to streamwater (Binkley et al., 1999). In the Pacific Northwest, large applications of N (700 kg N ha^{-1}) and P (500 kg P ha^{-1}) to Douglas-fir [*Pseudotsuga menziesii* (Mirbel) (Franco)] stands in the form of municipal biosolids resulted in minimal impacts to streamwater quality (Grey and Henry, 2002). Biologically available P, PO_4–P, and NH_4–N were the same before and after biosolids application. Nitrate N, while doubled in association with the application, was less than 1 mg N L^{-1} or one-tenth of the USEPA standard for drinking water. In summary, established, fast-growing forests have a large potential for retaining nutrients, especially when applied as biosolids.

We anticipated that poultry manure could be applied to pine forests at rates in excess of tree growth demands due to the high potential of forests to retain nutrients. Two concerns shed doubt on this potential, however. First is the concern that large amounts of inorganic N in poultry litter would lead to more N leaching than the

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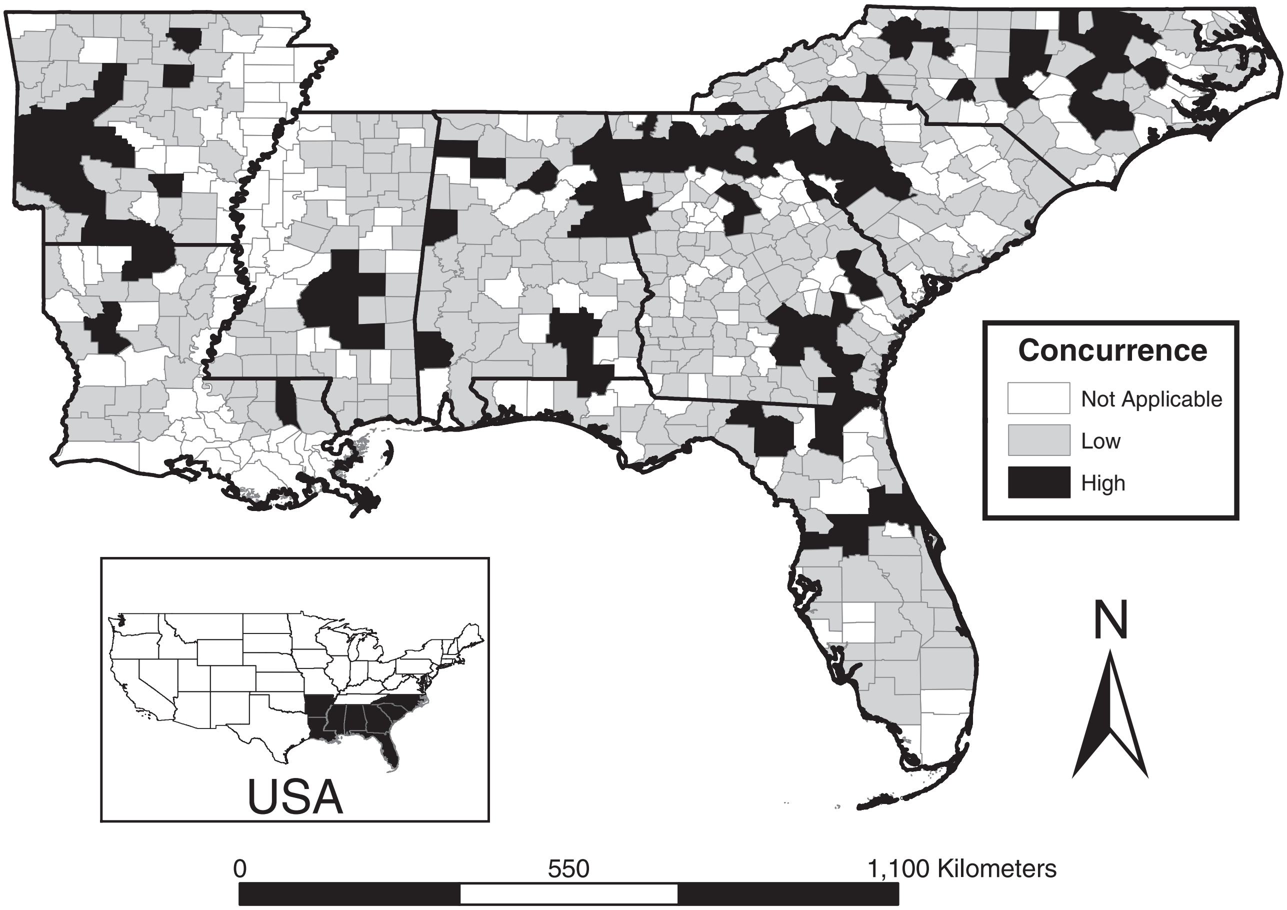

Fig. 1. Concurrence of poultry production and the distribution of southern pine forests, by county. Light and dark shading indicate low and high concurrence, respectively, for the presence of southern pine forest land and the abundance of chickens in birds ha^{-1}. For details see Materials and Methods.

same amount of N applied in purely organic form. Poultry litter can contain 25 to 50% of total N as ammonia (Williams et al., 1999), and the use of inorganic N fertilizers (e.g., NH_4NO_3) has resulted in greater leaching of N than organic N fertilizers (e.g., urea) (Binkley et al., 1999). Second is the concern that the control of understory vegetation, as is commonly practiced in southern pine stands (Clason, 1993; Lauer et al., 1993), could undermine ecosystem nutrient retention by eliminating the nutrient retention of vigorously regrowing woody and herbaceous understory plants (Jokela et al., 1990). Vigorous proliferation of competing vegetation following biosolids application is well documented, and is often controlled with herbicides (Torbert and Johnson, 1993; Young et al., 1993). To address this concern, we used an intensive herbicide regimen to control competing vegetation, thus helping ensure that the nutrient retention we report is representative of what intensively managed pine forests could retain. Consequently, the results reported in this study represent the most conservative case.

The objective of our study was to evaluate the potential for using loblolly pine stands for poultry litter application in poultry producing regions of the South. Loblolly pine was selected because of its abundance (Fig. 1) and its economic importance. Two questions were addressed: (i) Will these forests retain the nutrients associated with poultry waste?, and (ii) Will litter application enhance tree growth? Representative pine stands were thinned to permit access and given one-time litter applications at rates designed to meet and exceed tree nutrient demand. Containment was addressed by analyzing macronutrients in soil water, available N and P in soil extracts, and N and P content of the foliage and forest floor. Growth was addressed by measurements of tree heights and stem diameters. Measurements were collected over 5 yr.

MATERIALS AND METHODS

Land Cover–Land Use Analysis

We mapped the concurrence of poultry production and forest coverage in southern pine for counties in Arkansas, Louisiana, Mississippi, Alabama, Georgia, Florida, South Carolina, and North Carolina, USA (Fig. 1). Poultry production is based on the number of chickens older than 3 mo per hectare as reported in the U.S. Geological Survey Distributed Spatial Library, using 1987 poultry data, categorized as C1 (0–0.62 birds ha^{-1}), C2 (0.63–4.94 ha^{-1}), and C3 (4.95–51.87 ha^{-1}). Standardized southern pine area (hectares of loblolly–short leaf pine or longleaf–slash pine types per hectare of land in each county) is based on Smith et al. (2004) using 2002 forest data, categorized as P1 (0–0.115 ha ha^{-1}), P2 (0.116–0.289 ha ha^{-1}), and P3 (0.290–0.642 ha ha^{-1}) classes. The figure presents concurrence as: (i) not applicable: counties with no pine or no chickens reported, (ii) low: counties with either low chickens (C1) or low pines (P1), or (iii) high: counties with moderate to high chickens (C2 or C3) and moderate to high pine (P2 or P3).

Study Site

The study site was a young loblolly pine stand near Newton, Mississippi, USA (32°20′ N, 89°04′ W), growing on a fine sandy loam in the Shubuta series (fine, mixed, semiactive, thermic Typic Paleudults) (USDA, 1960). Measured soil properties before treatment were 65% sand, 22% silt, 13% clay, pH 5.1 in water, and pH 4.4 in $CaCl_2$ for the 0- to 8-cm layer; and 59% sand, 17% silt, 24% clay, pH 4.9 in water, and pH 4.0 in $CaCl_2$ for the 8- to 24-cm layer. Soil nutrient availability before treatment is represented by the control values of experimental results (Table 1, Fig. 2–5). Average annual daily high temperature for Newton County is approximately 24° and the low is approximately 11°C. Annual precipitation is approximately 1400 mm. The setting was gently sloping with 2 to 5% slopes and an elevation of 125 m. The stand was cut in 1990 and planted, though vigorous regeneration from seed resulted in excessively high stem densities.

Nine 20- × 20-m plots were established in the winter of 1999–2000. Each plot was manually thinned to a basal area of approximately 11 m^{-2} ha^{-1}. All trees from the thinning operation were carefully removed from the plots by hand to minimize disturbance to the litter and soil organic horizons. Non-pine vegetation was controlled annually through manual application of Arsensal (77 mL, 53% active ingredient; BASF, Ludwigshafen, Germany) and Escort (5.7 g, 60% active ingredient; DuPont, Wilmington, DE) with a surfactant in a water mix of 15 L per 0.04 ha plot. The plots were positioned on the landscape with independent drainage. All sampling and measurements were taken from the inner 10- × 10-m portion of each plot.

Poultry litter was applied on 13 Mar. 2000 using stockpiled cake collected from a local broiler growing operation near Newton, MS. Each plot receiving a litter treatment was divided into 16 sections. Litter was applied manually by evenly spreading the appropriate amount to each section. At the time of field application the moisture content of the litter was 21%. Elemental composition on a dry weight basis was C 38%, N 4.3%, P 2.0%, K 3.2%, Ca 2.8%, Mg 0.7%, S 0.6%, Zn 590 ppm, B 60 ppm, Mn 680 ppm, Fe 987 ppm, and Cu 969 ppm. Three experimental rates of manure were applied to three plots each in a completely randomized design: 0, 4.6, and 18.6 dry Mg ha^{-1}. These rates were based on the N assay of the litter to supply 0, 200, and 800 kg N ha^{-1} and resulted in P additions of 0, 92, and 370 kg P ha^{-1}. The 200 kg N ha^{-1} rate is representative of conventional forest fertilization practices (Allen, 1987) and the 800 kg ha^{-1} rate was used to intentionally push the soil plant N uptake system by applying more N than usual.

Sampling and Analyses

Soil water was sampled using porous cup suction lysimeters (5-cm diameter; Soilmoisture Equipment, Santa Barbara, CA) installed at three locations within each plot. Lysimeters were installed at a 50-cm depth by hand auger and sealed at the soil surface with bentonite (Morrison, 1983). The depth was selected to be below the argillic horizon (20- to 45-cm depth) and representative of water likely to escape root uptake. Installation took place between January and February 2000. Soil water samples were collected under a tension of approximately 60 kPa the week before manure application, and every month thereafter when soil moisture was adequate. To account for seasonal variability in lysimeter yield, datasets from a given collection date were only analyzed if samples could be collected from at least seven of the nine possible lysimeters in each treatment. Solution samples were analyzed for cations (NH_4, K, Mg, Ca) and anions (NO_3, PO_4, SO_4) using a DX500 ion chromatograph (Dionex, Sunnyvale, CA). All ionic concentrations are expressed on an elemental basis (i.e., NH_4–N, NO_3–N, and PO_4–P). Elemental concentrations were highly variable among lysimeters in a given plot, with some missing values. Evaluation of treatment effects was made using a mixed

Table 1. Characteristics of current year foliage for three rates of litter application.

Date	0 Mg litter ha^{-1}		4.6 Mg litter ha^{-1}		18.6 Mg litter ha^{-1}	
			Nitrogen concentration (g N kg^{-1} dry wt.)			
June 2000	15.1 ± 0.8ab†		14.7 ± 0.8b		17.3 ± 0.6a	
December 2000	13.6 ± 0.2b		13.9 ± 0.3b		16.4 ± 0.6a	
June 2001	13.4 ± 0.4b		13.0 ± 0.2b		14.6 ± 0.6a	
December 2001	13.6 ± 0.3b		14.3 ± 0.1ab		14.8 ± 0.2a	
June 2002	11.7 ± 0.3b		12.9 ± 0.5a		13.0 ± 0.2a	
December 2002	14.4 ± 0.4a		14.9 ± 0.3a		15.2 ± 0.5a	
			Carbon to nitrogen ratio (g g^{-1})			
June 2000	35.5 ± 1.7ab		36.7 ± 1.8a		30.9 ± 1.0b	
December 2000	41.3 ± 0.7a		40.0 ± 0.6a		34.3 ± 1.1b	
June 2001	43.1 ± 1.0a		44.3 ± 1.1a		39.4 ± 1.8b	
December 2001	41.2 ± 0.9a		39.1 ± 0.4ab		37.4 ± 0.5b	
June 2002	47.0 ± 1.3a		42.6 ± 1.7b		42.2 ± 0.8b	
December 2002	38.3 ± 1.0a		36.8 ± 0.6a		36.0 ± 1.1a	
			Phosphorus concentration (g kg^{-1})			
	Flush 1	Flush 2	Flush 1	Flush 2	Flush 1	Flush 2
June 2000	1.03 ± 0.03b‡	1.83 ± 0.13b	1.57 ± 0.03a	2.23 ± 0.10ab	1.60 ± 0.10a	2.50 ± 0.21a
December 2000	0.83 ± 0.03b	0.87 ± 0.03b	1.37 ± 0.09a	1.33 ± 0.07a	1.33 ± 0.09a	1.43 ± 0.12a
June 2001	0.77 ± 0.03b	1.00 ± 0.06b	1.60 ± 0.12a	1.87 ± 0.09a	1.53 ± 0.20a	1.83 ± 0.17a
December 2001	0.77 ± 0.03b	0.73 ± 0.03b	1.20 ± 0.06a	1.30 ± 0.06a	1.33 ± 0.07a	1.37 ± 0.03a
June 2002	0.57 ± 0.03b	0.90 ± 0.06b	0.97 ± 0.03a	1.50 ± 0.06a	0.97 ± 0.07a	1.37 ± 0.09a
December 2002	0.87 ± 0.03b	0.97 ± 0.07b	1.37 ± 0.03a	1.47 ± 0.03a	1.33 ± 0.03a	1.53 ± 0.03a

† Values presented are means ± standard error. Similar letters within a row indicate no significant treatment differences ($\alpha = 0.05$) for that date according to Duncan's Multiple Range Test. Nitrogen concentration and carbon to nitrogen ratio means average Flush 1 and Flush 2 as flush differences were not significant.

‡ Mean separation letters for phosphorus indicate differences, as discussed above, but within the same flush.

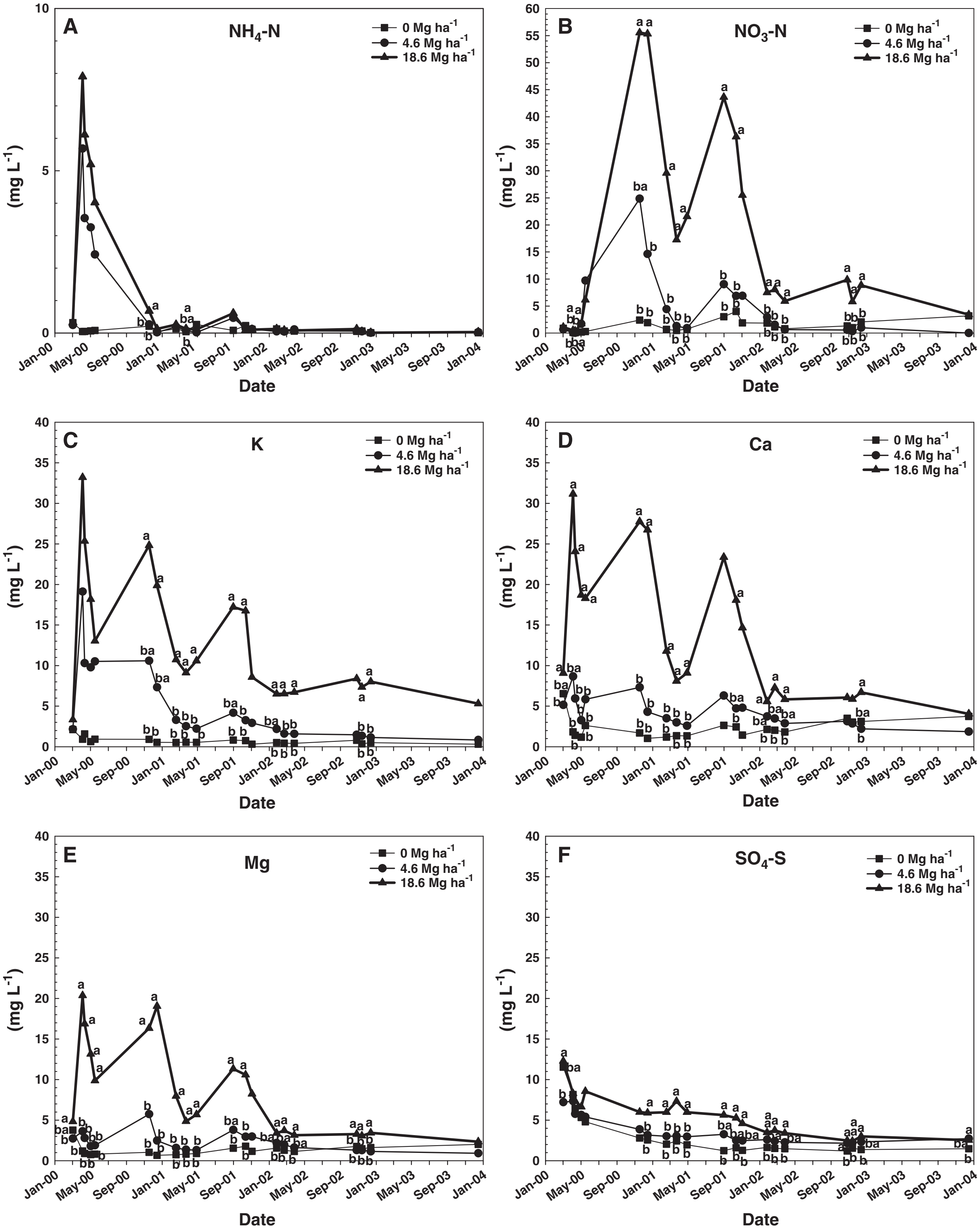

Fig. 2. Poultry litter treatment effects on soil solution concentrations from suction lysimeters installed at a 50-cm depth in each plot. Means are shown by sampling date for (a) ammonium, NH_4–N, (b) nitrate, NO_3–N, (c) potassium, K, (d) calcium, Ca, (e) magnesium, Mg, and (f) sulfate, SO_4–S. Similar letters (or no letters) among the three treatments indicate no significant treatment effects according to Tukey's test ($\alpha = 0.05$).

models approach, allowing for unequal treatment population variances. Pairwise least squares means comparisons were performed in SAS ($\alpha = 0.05$) (SAS Institute, 2001).

Available N and P from soil were determined monthly. Mineral soil was collected from upper (0–8 cm) and lower (8–24 cm) depths from five random locations in each plot using a 2.5-cm-diameter push tube. Samples were dried at 32°C to a constant weight (48 h) and sieved to remove any coarse fraction (>2 mm). Available N was determined by extracting soil with 2 *M* KCl followed by spectrophotometric analysis on an

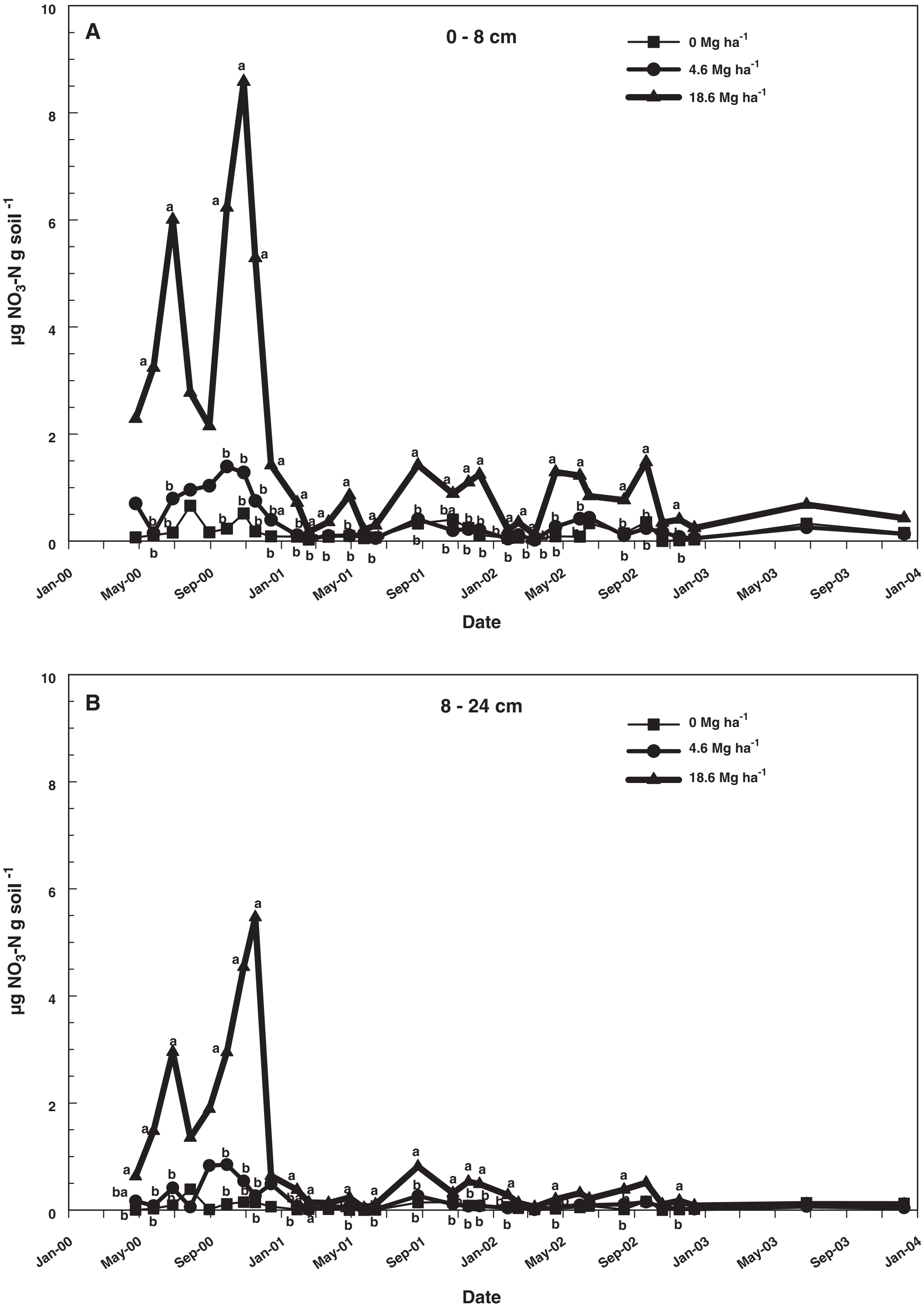

Fig. 3. Poultry litter treatment effects on soil KCl extractable NO_3 from the (a) 0- to 8-cm depth (excluding O horizon) and (b) 8- to 24-cm depth presented as micrograms of N per gram of soil. Plotted are treatment means for each sampling date. Similar letters (or no letters) among the three treatments indicate no significant treatment effect at that date according to Tukey's test ($\alpha = 0.05$).

Auto Analyzer II (Technicon, Tarrytown, NY) following standard procedures (Maynard and Kalra, 1993). Available P was determined by acid extraction with a Mehlich-III solution (see Tran and Simard, 1993) followed by analysis using inductively coupled plasma spectrometry techniques (Jones and Case, 1990) with a 3200DV Optima ICP (PerkinElmer, Wellesley, MA).

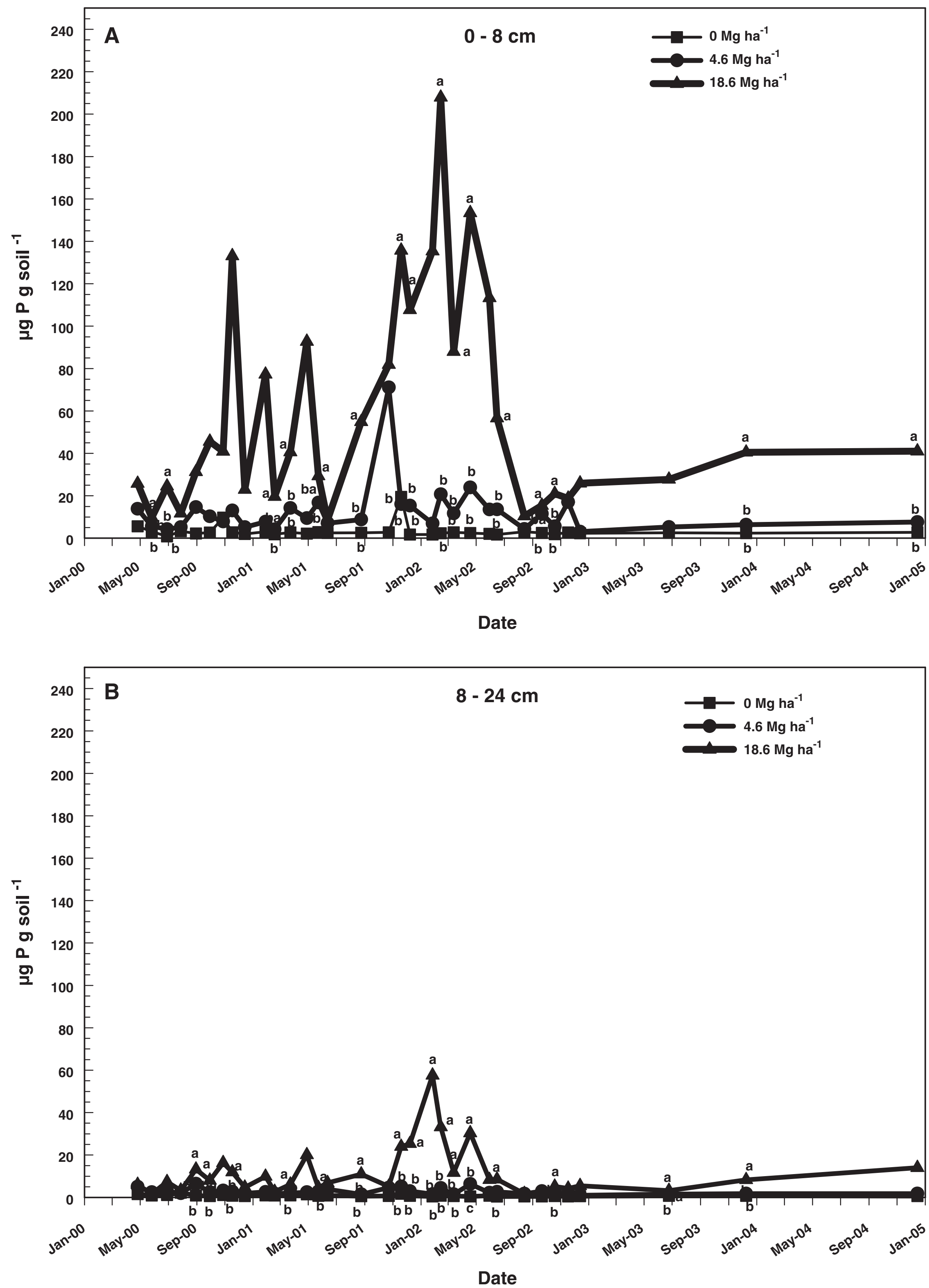

Fig. 4. Soil Mehlich III–extractable PO_4–P from the (a) 0- to 8-cm depth (excluding O horizon) and (b) 8- to 24-cm depth presented as micrograms of P per gram of soil. Plotted are treatment means for each sampling date. Similar letters (or no letters) among the three treatments indicate no significant treatment effect at that date according to Tukey's test ($\alpha = 0.05$).

Treatment effects were analyzed separately for each depth using a completely random design and the GLM procedure in SAS ($\alpha = 0.05$) (SAS Institute, 2001).

Foliage and forest floor were sampled for determinations of total N and P in June and December of each year. Current year foliage was collected from the upper-third of three tree crowns

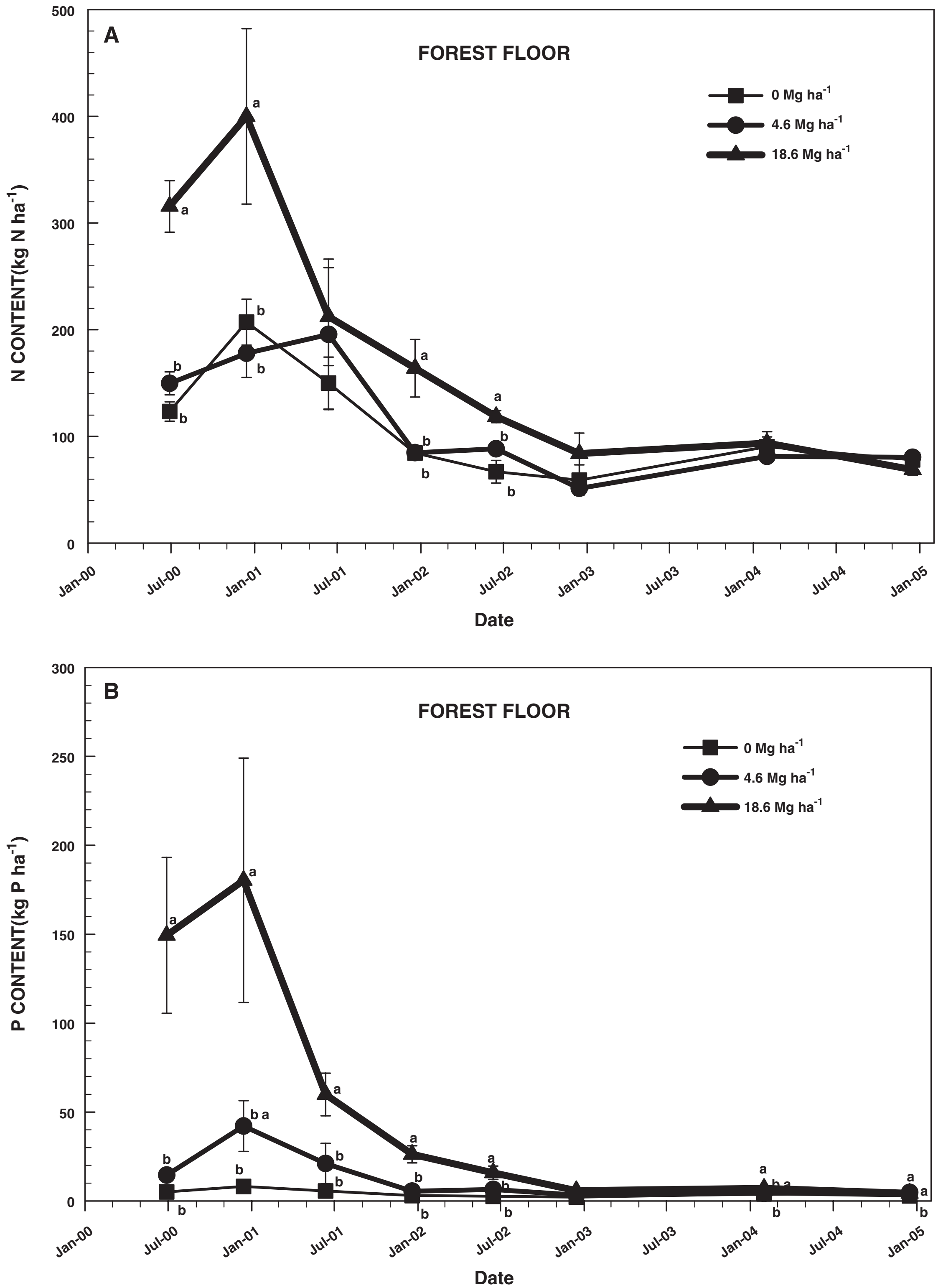

Fig. 5. Nitrogen and phosphorus content of forest floor (O horizon) collected from plots treated with poultry litter. Plotted are the treatment mean values during the first five growing seasons after application. Similar letters (or no letters) among the three treatments indicate no significant treatment effect at that date according to Tukey's test ($\alpha = 0.05$). Error bars indicate $\pm$ one standard error of the mean.

per plot, and separated into first- and second-flush foliage. Forest floor was collected from three 0.25-m^2 frames in each plot. All foliage and forest floor subsamples were collected from random locations and composited into one sample per plot. Samples were dried at 65°C to a constant weight (48 h) and ground through a 60-mesh sieve. Total N and C were analyzed with a Fisons 1500 NA NCS Analyzer (ThermoQuest Italia, Milan, Italy) using Dumas combustion techniques

(Jones and Case, 1990). Total P was analyzed from resolubilized ash using inductively coupled plasma spectrometry as described above. Mineral soil was analyzed for total N and total C using the methods described above.

Tree growth was recorded before treatment and at the end of each growing season by measuring stem diameter (at 1.3 m height above the soil surface) and the total height of every tree within the interior 10 × 10 m of each plot. Basal area, the cross-sectional area of a tree stem at 1.3 m, was calculated for each tree. Plot basal area (m^2 ha^{-1}) was derived from the sum of the basal areas of all trees on a plot. Plot average tree height, quadratic mean stem diameter, and plot basal area were analyzed using a completely random design and the GLM procedure in SAS ($\alpha = 0.05$) (SAS Institute, 2001).

RESULTS AND DISCUSSION

Soil Lysimeter Water

The first measurable effect of the added litter on soil water was a spike in ammonium concentration in the first 2 mo after application (Fig. 2a). The statistical significance of this effect was marginal (p values from 0.06 to 0.14) because it was observed sporadically; nonetheless, it occurred consistently during the first four sample periods. Ammonium N is abundant in poultry litter (Williams et al., 1999), but is readily immobilized by soil microbes and on the soil exchange complex, making the detection of abundant ammonium at a 50-cm depth an unusual finding. We speculate that some lysimeters were collecting soil water that drained rapidly through soil macropores following precipitation events, with little exposure to the soil exchange complex. With the exception of this transitory elevation associated with plots receiving litter, ammonium N remained below 1 mg L^{-1} for all plots throughout the study.

Nitrate N showed no treatment effects until 8 mo after litter application (Fig. 2b) when soil water showed a large pulse of nitrate N for both the 4.6 and 18.6 Mg ha^{-1} treatments. The fall pulse occurred again during the second year after application, but was only significant for the 18.6 Mg ha^{-1} treatment. Nitrate was apparently generated in the soil during the growing-season months, especially in the litter plots, but was only detected in the fall when site water balance became positive. It should be noted that lysimeters were dry from at least June to August of each year, so concentrations are reported for spring and fall only. Three years after application, nitrate in the 18.6 Mg ha^{-1} treatment remained elevated relative to control, although concentrations were below 10 mg L^{-1} and there was not a distinctive fall pulse.

Similar results have been reported for large applications of poultry litter or biosolids to other forest lands. Minkara et al. (1995) found nitrate N concentrations of 150 mg N L^{-1} at 61 cm after applying 800 kg N ha^{-1} from poultry litter to a newly planted loblolly pine stand. Similarly, Brockway and Urie (1983) found nitrate N concentrations of 24 mg N L^{-1} at 1.2 m after applying 1380 kg N ha^{-1} from municipal sludge to a 40-yr-old white (*Pinus strobus* L.) and red pine (*Pinus resinosa* Soland.) stand. It should be noted, however, that lysimeter measurements do not necessarily reflect export from the system. A 16-yr-old Douglas-fir stand receiving 700 kg N ha^{-1} from municipal sludge generated nitrate N concentrations of less than 1.5 mg L^{-1} from stream discharge water (Grey and Henry, 2002).

The basic cations, K, Ca, and Mg, were all elevated in lysimeter water immediately after litter application, by more than an order of magnitude in 18.6 Mg ha^{-1} plots compared with control plots (Fig. 2c, 2d, 2e). After the initial leaching of cations from March to May 2000, there was a consistent seasonal pattern of elevated concentrations in the fall associated with the recharge of soil moisture, then a decrease and leveling off through winter and spring. Elevated concentrations of K, Ca, and Mg were pronounced for the first two years after litter application, beyond which, with the exception of K, the treatment effects were significant but concentrations were on the same order of magnitude as in control plots. Four years after litter application, K in lysimeter water remained elevated by fivefold (Fig. 2c). Interestingly, the intermediate litter application rate (4.6 Mg ha^{-1}) showed a similar trend as 18.6 Mg ha^{-1} for all cations, but was statistically indistinguishable from the control plots. The elevation of cations in leachate from this study was comparable to that of similar studies, with a maximum increase of about 10-fold between treatment and control (Medalie et al., 1994; Sauer et al., 1999; Shepard and Bennett, 1998).

Phosphate P was less than 0.4 mg P L^{-1} throughout the study (not graphed). Treatment differences existed only in October 2001, when phosphate was 0, 0.03, and 0.07 mg P L^{-1} in 0, 4.6, and 18.6 Mg ha^{-1} treatments, respectively. Sulfate S was elevated by about 1.5-fold in 18.6 Mg ha^{-1} relative to the other two treatments. This trend lasted for the first two years after application, then SO_4–S returned to near-control levels (Fig. 2f).

Soil Nitrogen and Phosphorus Extracts

Unlike soil water, which showed early treatment effects, there were no treatment effects on KCl-extractable ammonium N. There was an initial spike in ammonium N in May 2000 across all treatments and depths. Ammonium N was elevated to 40 μg N g^{-1} soil at both soil depths (0–8 and 8–24 cm), but by June 2000 levels had returned to approximately 6 μg N g^{-1} soil in the upper depth and 3 μg N g^{-1} soil in the lower depth (data not shown). We attributed this spike in soil ammonium to a pulse of N mineralization associated with the thinning of all plots that took place over the winter of 1999–2000, resulting in a large input of organic N and conditions favorable to N mineralization. The spike was not large enough, however, to impact ammonium in the lysimeter water of the control plot which remained near zero for the entire study (Fig. 2a).

Soil KCl extractable nitrate N was elevated in the 18.6 Mg ha^{-1} treatment during the first month after litter application and remained elevated throughout the first year (Fig. 3). Seasonally, there were peaks of nitrate N in June and October, both of which followed periods of warm moist conditions favorable to N mineralization. Similar patterns were observed in both upper and lower soil depths. The 18.6 Mg ha^{-1} treatment also resulted in elevated nitrate in the second and third years after application but the magnitude of the effect was minor in comparison with the first year, especially in the lower soil depth. These results are generally consistent with patterns observed in the lysimeter water, except that the elevation of nitrate in 2000 soil water was nearly the same as in 2001 whereas soil extractable nitrate dropped substantially from 2000 to 2001. Such differences in magnitude of effect could be explained by a dilution–concentration phenomenon for soil water, or by a substantial transport of nitrate produced in organic horizons and moving directly to lysimeter water through macropores.

Extractable soil phosphate P was substantially elevated by the 18.6 Mg ha^{-1} treatment (Fig. 4) compared with 4.6 Mg ha^{-1} or control. Unlike nitrate, however, phosphate P appeared to be largely retained within the system. There was a strong attenuation of available P with depth, with nearly 10-fold less at the 8- to 24-cm depth (Fig. 4b) compared with the 0- to 8-cm depth (Fig. 4a). Furthermore, PO_4–P collected from lysimeters was less than 0.4 mg L^{-1} (data not shown). Even in the 18.6 Mg ha^{-1} treatment plots, peak levels of available P were much lower than those seen under intensive hayfield applications. For example, annual applications of poultry (Sistani et al., 2004) or swine (Novak et al., 2000) manure delivering approximately 300 kg P ha^{-1} yr^{-1} to soils supporting bermuda grass result in nearly twice the level of Mehlich-extractable P in the surface soil (400–800 μg P g^{-1}) than we reported with a one-time application of 370 kg P ha^{-1} to forestland (Fig. 4a). It is also important to recognize that Mehlich-extractable P is not necessarily representative of P vulnerable to leaching. Maguire and Sims (2002) developed a phosphorus saturation index based on extractable P relative to extractable Al + Fe that correlated well with phosphorus leaching from soil, using the Mehlich-III extraction for both P and Al + Fe. The index is based largely on Ultisol soils, as in our study. They found that the molar P to [Al + Fe] ratio must be in excess of 0.2 for P to be leached. Therefore, in our system, with a peak P value of 60 μg g^{-1} in the 8- to 24-cm depth, aluminum concentrations would need to be less than 300 μg g^{-1} for P to leach. Since Maguire and Sims (2002) found no values less than 400 μg g^{-1} in a range of soils comparable to our study, leaching of phosphate from our system is unlikely. In addition, much of the concern with pasture application stems from overland flow directly into surface water. In forest systems, with well-developed forest floors, overland flow is far less common (Brooks et al., 1997).

The seasonal pattern of P availability showed sporadic spikes, but in general treatment effects were greatest during the third year after application (Fig. 4). The lag in phosphate availability contrasts with nitrate, which was abundant early and became much less abundant by 2002 (Fig. 3). This 2-yr lag in inorganic P availability likely reflects the P deficient nature of the soil and persistent immobilization of P in soil organic matter. High rates of P immobilization were reported by Piatek and Allen (2001) in loblolly pine leaf litter. Because the current stand was thinned heavily immediately before litter application, normal immobilization by litter was likely enhanced by the presence of dead roots and stumps.

Foliage and Litter Nitrogen and Phosphorus

Poultry litter application had greater impacts on foliar P than on foliar N concentrations. Treatments did result in increased foliar N and decreased C to N ratios in all sampling dates except the final one (Table 1). However, foliar N was relatively high in all three treatments throughout the three years of monitoring. All of our mid-winter values were above the critical value of 12 g N kg^{-1} for loblolly pine (Allen, 1987; Colbert and Allen, 1996) and well above those reported for nutrient stressed sites (Gough et al., 2004). The lack of nitrogen limitation is ascribed to inherent fertility, organic N inputs (i.e., fine root turnover) associated with thinning immediately before plot treatments, control of competing vegetation, and reduced N demand from the residual stand after thinning. Foliar P, by contrast, was consistently below the critical level of 1 g P kg^{-1} (Allen, 1987) at mid-winter for all three years in plots that received no litter (Table 1), reflecting the P deficient nature of these sites. Litter application substantially increased foliar P concentration, doubling it in many cases. Phosphorus demand was apparently satisfied with the 4.6 Mg ha^{-1} treatment, as the 18.6 Mg ha^{-1} treatment resulted in no additional increase in P concentration over the 4.6 Mg ha^{-1} treatment. Our findings with foliar P are consistent with the widespread responses of loblolly pine to P additions on Ultisols of the upper Gulf Coastal Plain (Allen, 1990).

Nutrient responses of the forest floor followed trends similar to those in the foliage. Nitrogen and P concentrations were elevated by poultry litter addition resulting in substantially elevated pools of N and P in the forest floor (Fig. 5). In the first year after application, N was elevated by twofold and P was elevated more than 20-fold with 18.6 Mg ha^{-1} of litter compared with the control. As with foliage, the C to N mass ratio was less (approximately 30) at 18 Mg ha^{-1} than in the control (approximately 50) during the first two growing seasons (data not shown). Forest floor N and P pools returned to control levels by the end of the third growing season (Fig. 5). This illustrates the importance of the litter layer in forests as a buffering mechanism for nutrient retention. In our case, nearly 200 kg N ha^{-1} and 150 kg P ha^{-1} were retained via immobilization in the litter layer during the first growing season. This represents 25% of the N and 50% of the P applied in the poultry waste.

Mineral soil was analyzed for total N, total C, and C to N ratio for the same months that are reported for forest floor N and P; however, no treatment effects were found. Total N content was approximately 1 g N kg^{-1} in the 0- to 8-cm layer and approximately 0.5 g N kg^{-1} in the 8- to 25-cm layer. Carbon content varied in similar proportions with approximately 20 g C kg^{-1} in the 0- to 8-cm layer and 10 g C kg^{-1} in the 8- to 25-cm layer. The C to N ratio varied from 20 to 25, over both depths, with no treatment effects.

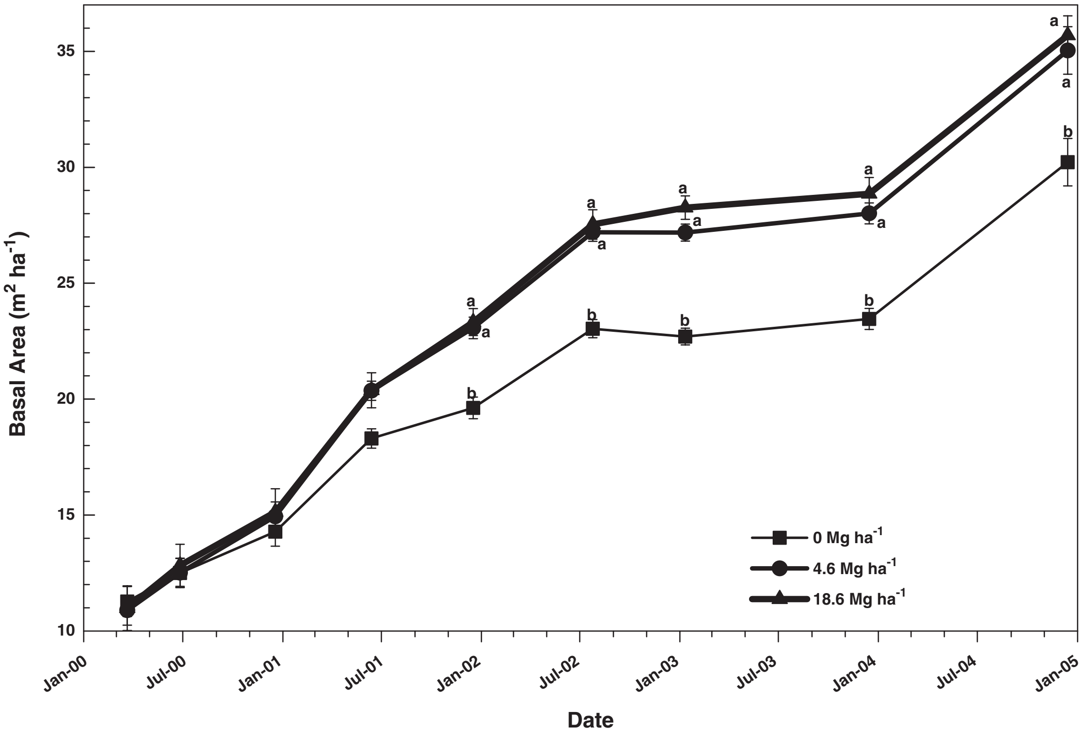

Fig. 6. Total basal area (cross-sectional area of all trees) of loblolly pine from plots treated with poultry litter. Plotted are the mean values, by treatment, following the first five growing seasons after litter application. Similar letters (or no letters) among the three treatments indicate no significant treatment effects according to Tukey's test ($\alpha = 0.05$). Error bars indicate $\pm$ one standard error of the mean.

Tree Growth

Poultry litter increased tree growth appreciably. During the year in which litter was applied, standing basal area increased by about 5% (not significant) for both treatments compared with the control. During the second year, treatment effects became significant and the size difference widened to about 20% (Fig. 6) and remained at that margin from the third through the fifth years. Interestingly, height was not affected by litter application but did increase over time, from a range of 6 to 7 m in the first year to a range of 9 to 13 m in the fifth year (data not shown). Our results were similar to those reported by Samuelson et al. (1999) for 18-yr-old loblolly pine growing on a similar soil in the adjacent state of Alabama. After two growing seasons, they found that stem diameter increment at a 1.3-m height increased from 1.1 cm in control plots to 1.5 cm in plots treated with poultry litter that supplied 240 kg N ha^{-1} and 100 kg P ha^{-1}. This is a 40% increase in growth rate. We found 2-yr diameter increment increased from 1.15 cm in control plots to 1.76 cm in plots treated with poultry litter supplying 200 kg N ha^{-1} and 92 kg P ha^{-1} (4.6 Mg litter ha^{-1}), which is a 53% increase in growth rate over the same time period. Standing volume after 4 yr in our study was 76, 97, and 106 m^3 ha^{-1} in 0, 4.6, and 18.6 Mg litter ha^{-1} treatments, respectively (Roberts et al., 2006).

CONCLUSIONS

Loblolly pine forests offer considerable potential for the application of poultry litter in the southeastern United States. Nutrients were contained and applied litter had positive effects on tree growth. Nutrients in the 4.6 Mg ha^{-1} treatment were almost entirely contained. At the high application rate (18.6 Mg ha^{-1}) nutrients were still contained remarkably well. Nitrate N in soil water for this treatment exceeded 10 mg L^{-1} during the first two growing seasons after application; however, NO_3 was below 10 mg L^{-1} after the second season. The USEPA standard for drinking water is 10 mg L^{-1} and applies to ground water and stream water. This standard is not applicable to soil water from a 50-cm depth but the comparison illustrates the success with which our system retained nitrate despite the application of 18.6 Mg ha^{-1} of poultry litter. In addition, vegetation regrowth would normally respond more rapidly than the pine and accumulate the initial pulse of nutrient availability (Jokela et al., 1990). We repeatedly controlled competing vegetation to evaluate the nutrient removal potential of the pine system; therefore, our conclusions concerning nutrient containment are conservative.

In reference to tree growth, litter applications of 200 kg N ha^{-1} and 92 kg P ha^{-1} (4.6 Mg litter ha^{-1}) resulted in an appreciable growth stimulation. An increase of 20% in basal area will greatly increase the value of the stand by shortening the rotation age or increasing the volume harvested, thereby increasing the net worth of the stand. These responses are comparable to what we might expect from a commercial application of chemical fertilizers. Despite the obvious economic benefits of fertilizing southern pine (Williams and Farrish, 2000), one study has found that social barriers may be more important considerations to implementing this practice than economics (Lynch and Tjaden, 2004). We will continue to monitor the site to see if the 18.6 Mg ha^{-1} treatment maintains its increased growth for a longer period than the 4.6 Mg ha^{-1} treatment.

Overall, our results indicate that poultry litter applications of approximately 5 dry Mg ha^{-1} to mid-rotation loblolly pine stands will be easily contained by the ecosystem and may result in significant increases in tree growth. Previous work has shown that techniques exist for land applying biosolids, including poultry litter, on an operational scale (Grey and Henry, 2002; Samuelson et al., 1999). The extent to which this practice can be repeated in subsequent rotations is unknown; however, there is an abundance of forestland with no history of litter application, and a single 4.6 Mg ha^{-1} application per rotation (approximately every 30 yr) would be consistent with current N fertilization practices, though in excess of P needs (Allen, 1987). Our results with the higher rate (approximately 20 Mg ha^{-1}) suggest repeated applications of approximately 5 Mg ha^{-1} over several rotations would be sustainable; however, long-term studies of forest application should be used to evaluate the long-term sustainability of this practice. Forest land provides a valuable alternative to pasturelands that have received repeated applications of litter and are becoming saturated with respect to N or P.

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