ABSTRACT

ZERPA, JOSE LUIS. Understanding Forest Floor Accumulation and Nutrient Dynamics in a Loblolly Pine Plantation Regenerated with Varying Forest Floor and Slash Retention. (Under the direction of H. Lee Allen.)

The effects of varying forest floor and slash retention at time of regeneration were evaluated in a loblolly pine study established near Millport, Alabama 10 years after the retention treatments were imposed. The objectives were to determine the effects of removing, leaving unaltered, or doubling the forest floor and slash material, on forest floor mass, nutrient dynamics, litterfall, foliar nutrition, mineral soil properties, and stand yield. The parameters measured included ash-free weight, nitrogen (N), carbon (C), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), sulfur (S), boron (B), copper (Cu), and zinc (Zn) concentrations in the forest floor, litterfall, and foliar samples, N extracted from ion exchange membranes (IEM) from the forest floor, potential mineralized N and IEM-N, total C and N, exchangeable Ca, Mg, K, and sodium (Na), extractable P and Mn, pH, and bulk density from the mineral soil, and tree volume. Forest floor mass and nutrient content in the doubled treatment were significantly greater than in the other two treatments. The doubled accumulated 25, 45 and 350% more forest floor mass and 56, 56, and 310% more N than the control treatment in the L, F, and H layers, respectively, the other nutrients followed similar accumulation patterns. IEM and potential mineralized NO_3^--N in the mineral soil were significantly higher in the doubled treatment. No significant treatment differences were found in the mineral soil properties assessed. The positive effect of doubling the forest floor on soil N availability was well reflected by the fact that the greatest foliage production (indicated by litterfall) and stand yield were found on this treatment. In addition, this linkage was indicated

by strong positive correlations among stand yield, litterfall, potential nitrification, and IEM extractable NO_3^--N. Greater amounts of available N in the mineral soil and most likely in the forest floor on the doubled treatment apparently resulted in a feed forward effect with greater growth and in turn greater litterfall and accumulation of new forest floor material (L and F layers). In addition, the retention of more forest floor material (at least in the manner it was done in this study) apparently resulted in slower decomposition of the retained material in a non linear proportion relative to its original mass. This in turn has resulted in long term increases in soil available N through the 10th year following plantation establishment.

UNDERSTANDING FOREST FLOOR ACCUMULATION AND NUTRIENT DYNAMICS IN A LOBLOLLY PINE PLANTATION REGENERATED WITH VARYING FOREST FLOOR AND SLASH RETENTION

by

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BIOGRAPHY

Jose Luis Zerpa was born in 1971 in Mérida, a small city in the Venezuelan Andes surrounded by cloud forests and 16,000 ft. high peaks. He graduated from high school in 1987 and then went to Ohio, US to spend one year as a foreign exchange student. He entered the University of Los Andes at Mérida in 1989 and received a Bachelor of Science degree with a major in forestry in June 1996.

From 1996 to 1998 he worked for Smurfit Cartón de Venezuela managing Eucalyptus, Gmelina, and Caribbean Pine plantations on the west plains of Venezuela where intensive silviculture is practiced for the production of wood fiber for pulp and paper.

In 1998 he moved to the United States to manage a small company that provided supplies and services for the wood flooring industry and in 2003 he entered the graduate program in the Department of Forestry at North Carolina State University under the guidance of Dr. Lee Allen with an interest in the areas of silviculture and forest soils. In 2004 he was awarded the Hofmann Forest Graduate Fellowship, which will allow him to continue his research in these areas.

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INTRODUCTION

Intensively managed plantations of loblolly pine (*Pinus taeda L.*) in the Southeast US have become one of the most efficient ways to produce the wood and fiber required to satisfy the demands of our growing society (Sedjo 2001). The productivity of these plantations strongly depends on the ability of the sites to provide essential nutrients. However, most loblolly pine plantations in the Southeast are limited by low nutrient availability (Ducey and Allen 2001; Valentine and Allen 1990), which hinders the possibility to obtain the growth rates required to make these plantations profitable and competitive with other markets. To overcome these limitations, fertilizer application has become common practice. As a result, increased forest floor accumulation occurs because increases in litterfall associated with fertilizer application have not been matched by similar increases in forest floor decomposition and nutrient release (Gurlevik et al. 2003). Nitrogen (N) accumulations contained in the forest floor of 100, 300, and up to 700 kg-N ha^{-1} have been reported for loblolly pine plantations in the southeast US at ages 15 (Switzer and Nelson 1972), 22 (Tew et al. 1986), and 34 years (Urrego 1993), respectively. Similarly, forest floor N and Phosphorus (P) accumulations were reported to be 2.6 to 3 and 1.9 to 2 times greater than the above-ground biomass N and P contents, respectively. Nutrient accumulation in the forest floor, at levels comparable or greater than those occurring in the above-ground biomass highlight the importance of the forest floor as a source of nutrients for current and subsequent rotations.

Nutrient release dynamics studies have shown that the forest floor mineralizes (Covington 1981; Jorgensen et al. 1980; Switzer and Nelson 1972) , as well as retains nutrients through

immobilization (Piatek and Allen 2001; Vitousek and Matson 1985), making the forest floor both a sink and a source of nutrients depending on the nutrient, tissue type (e.g. branches, foliage), and time since deposition. At a large scale, climatic factors such as temperature and moisture have explained most of the differences in decomposition (Carey et al. 1982; Cortina and Vallejo 1994) especially in recently deposited material (McHale et al. 1998; Rustad and Fernandez 1998). On the other hand, litter quality (Berg et al. 1993; De Santo et al. 1993; Piatek and Allen 2001), lignin content (Berg 1986; Sariyildiz and Anderson 2003; Scott and Binkley 1997), and the type of colonizing fungal species during microbial succession (Cox et al. 2001) have been associated with differences in decomposition at smaller scales. Based on these factors, the amount and quality of forest floor in a stand are expected to influence its decomposition and nutrient dynamics, thus the nutritional status of the stand as a whole.

In contrast to forest floor removal, common in past site preparation practices such as shearing, piling, and burning, forest floor retention is now much more common. Unfortunately, little information is available concerning the effect that this retention has on nutrient dynamics in the subsequent stand. Forest floor removal has resulted in no (Fox et al. 1986; Li et al. 2003; Vitousek and Matson 1985) to negative effects (Burger and Pritchett 1984; Smethurst and Nambiar 1990b) in nutrient availability. However, most of these studies included other confounding effects such as tillage and compaction. These effects can also influence soil N availability in ways different than the forest floor retention treatments.

On sites with low nutrient levels, retention of residuals can have a positive effect (Ellert and Gregorich 1995) as it increases soil nutrient levels and consequently stand productivity

(Henderson 1995). It has also been reported that on low fertility sites, doubling the amount of harvest residue left from one rotation to another can improve tree growth (Mendham et al. 2003). With these precedents in mind, it is important to understand the effects that different levels of forest floor and slash retention have on nutrient dynamics and consequently on stand productivity.

It was hypothesized that increased retention levels of forest floor and slash material will have a directly proportional effect on nutrient availability and stand development.
The specific objectives of this study were:

1. To assess the effects of varying forest floor and slash retention treatments imposed at time of regeneration on:
    - forest floor mass, nutrient concentrations and contents
    - exchangeable cations, pH, extractable P in the mineral soil, and total soil C and N
    - available N in the forest floor and mineral soil
    - foliar nutrition
    - litterfall, nutrient concentrations and contents
    - stand yield

2. To understand the interrelationship among measures of forest floor mass, litterfall, N availability, and stand yield.

METHODS

Site and Study Description

The study site was located in the Upper Coastal Plain physiographic province in Lamar County near the town of Millport, Alabama (33°32'22.87"N, 88°7'7.53"W). Thirty year (1971-2000) mean annual temperature is 15.9 °C with mean monthly temperatures ranging from 4.6 °C in January to 26.3 °C in July. Mean annual precipitation is 1,398 mm with a fairly uniform distribution throughout the year, with September being the driest month with 85 mm, and January the wettest month with 157 mm (NOAA 2003). The soils are deep, well drained Ruston soil series classified as fine-loamy, siliceous, semiactive, thermic Typic Paleudults. The A horizon is a 23 cm deep sandy loam followed by a clay loam Bt horizon.

The study was established by Weyerhaeuser in winter of 1994 after harvesting a 34 year old loblolly pine plantation with a site index of 17 m at age 25. Twelve – 0.16 ha plots were established in a randomized complete block design with 3 treatments and 4 replications or blocks. The treatments were imposed after harvest and immediately before planting the current rotation as follows: removed treatment, all forest floor and slash material were removed using rakes to remove and tarps to carry the material, control treatment, the forest floor and slash material were unaltered, and doubled treatment, all forest floor and slash material coming from the removed treatment were uniformly added. Loblolly pine were planted at 4.3m x 3m spacing in each plot and only the inner 81 trees were considered for measurement purposes, leaving the trees in the treated perimeter as buffer.

Forest Floor Sampling

The forest floor was collected from five randomly located points per plot in mid April of 2004 using a 30.5 cm diameter round sampler with which the forest floor layer were cut until the mineral soil was reached. For each sampling location, the forest floor was separated in the field based on its degree of decomposition into three distinguishable layers designated as litter (L), fermentation (F), and humus (H) (Kendrick 1959) These correspond with the more recent classification of forest floor layer O_i O_e and O_a, respectively (Guthrie and Witty 1982).

The litter or L layer are recently fallen, relatively undecomposed needles which accumulate in a loosely arrangement in the uppermost stratum of the forest floor.

The fermentation or F layer is composed of partially fragmented needles which lay in a more closely packed layer immediately below the L layer.

The humus or H layer is a darker colored layer that accumulates immediately above the mineral soil, composed of more or less amorphous materials due to the complete physical decomposition of the organic residues. Sampled layers were handled and stored separately and the five samples per plot were combined to obtain a composite sample by layer per plot.

Forest Floor Mass

Forest floor samples were oven dried at 70 °C until constant weight was reached, and then weighed for dry weight and moisture content determinations. The lost-on-ignition method (Nelson and Sommers 1996) was used to determine the ash-free weight of the L, F and H

layers. This procedure consisted of incinerating a 5 g sample of forest floor for 12 hours in a muffle furnace at 450 °C and then calculating by weight difference the organic and mineral fractions of the sample. Based on the area of the forest floor sampler, these estimates were scaled up to a per hectare basis.

Forest Floor Nutrient Concentration and Content

Oven dry samples of L, F, and H material were ground to pass a 1mm mesh sieve and analyzed for N and carbon (C) concentration using the CHN elemental analyzer (CE Instruments-NC 2100, CE Elatech Inc., Lakewood, NJ). P, potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), sulfur (S), boron (B), copper (Cu), and zinc (Zn) concentrations were determined by digesting 0.8 g of ground, oven dry material with nitric acid (Zarcinas et al. 1987) followed by spectrometry analysis using an inductively coupled plasma atomic emission spectrometer (IPS-AES, Varian ICP, Liberty Series 2, Varian analytical instruments, Walnut Creek, CA). All analyses were conducted with 10% sample duplication. The pine standard from the National Institute of Standards and Technology (standard reference material No. 1575) was used. A maximum coefficient of variation of 20% within duplicates was permitted for quality control. Nutrient concentrations of the forest floor as a whole (using all layers of the forest floor) were calculated using a weighted average that accounted for the relative weight contributions of each layer to the forest floor. Total nutrient content of the forest floor as a whole and by layer was calculated as concentration multiplied by forest floor mass.

Mineral Soil Sampling

A-horizon samples and thickness estimates were collected at 5 randomly located points per plot in mid April 2004. Samples were composited in the field by plot, stored in plastic bags and transported in refrigerated containers to the lab. Once in the lab, a portion of each of these samples was immediately sieved through 4 mm mesh size to remove the coarser fraction and used for the potential N mineralization experiment. The other portion was ground, sieved through 2 mm mesh size and left to air dry for further nutrient and pH analyses. Three bulk density samples were also collected per plot using the core method (Grossman and Reinsch 2002).

Mineral Soil Properties

A 10 g sub-sample of air-dry soil per plot was weighed and oven dried at 105 °C for 24 hours to determine air dry moisture content (Gardner 1986). Total soil C and N concentrations were determined by analyzing a 50 mg air-dry soil sample in the CHN elemental analyzer. To determine exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}), 4 g of air dry soil sample were extracted with 40 ml of 1 M NH_4Cl (Shuman and Duncan 1990). The samples in the solution were shaken at high speed for one hour and centrifuged for 15 minutes at 4,000 rpm. The centrifuged solution was filtered using Whatman No. 40 filter paper previously soaked in the same extracting solution. The filtered solution was then analyzed for the cations previously mentioned using an inductively coupled plasma atomic emission spectrometer (IPS-AES, Varian ICP, Liberty Series 2, Varian analytical instruments, Walnut Creek, CA). Determinations of pH were performed using a pH meter equipped with a glass electrode (Mettler DL 12 Tritator, Mettler-Toledo, Inc., Hightstown, NJ) which measured the H^{+}

activity of slurry composed of 10 g of soil sample and 10 ml of deionized water (Thomas 1996).

Extractable P was determined by adding 20 ml of Mehlich-3 extracting solution (Tucker 1992) to 2 g of air dry soil, shaking at high speed for 5 minutes, filtering using Whatman No. 40 filter paper , and finally analyzing for P in solution using the inductively coupled plasma atomic emission spectrometer (IPS-AES, Varian ICP, Liberty Series 2, Varian analytical instruments, Walnut Creek, CA). All the extractions performed on mineral soil samples were done in duplicates.

Bulk density was estimated by the core method using three replications to obtain an average per plot, contents of all the extractions described in this section were scaled up to a per hectare basis considering the averaged bulk density and depth of the A-horizon.

Available Nitrogen

A 28-day aerobic incubation was used as an index of potential N mineralization in the mineral soil (Hart et al. 1994b). Five 10 g sub samples of each mineral soil sample were weighed and prepared for this incubation; one was used for moisture content determinations, two were used for the N extraction values at time zero, which also represented the extractable N on fresh soil samples, and the last two were left to incubate at field moisture content and 25 °C for 28 days. Changes in the moisture content of the incubated samples were monitored every other day and deionized water was added when they dropped 5% below their initial levels. Soil samples, at time zero, were extracted in 35 ml of 2M KCl by shaking at high

speed for one hour and centrifuging for 15 minutes at 4,000 rpm. The centrifuged solution was filtered using Fisherbrand G8 glass fiber filters and analyzed for inorganic N through a colorimetric technique using the Lachat Autoanalyzer (Quick-Chem 8000, Zellweger Analytics, Inc., Milwaukee, WI). The same procedure was used for the incubated samples. Potential N mineralization per plot was calculated by subtracting the time zero averaged values of NO_3^--N and NH_4^+-N from the incubated average values.

Ion exchange membranes were used as another way to assess available N in the field. Ion exchange membranes allow the estimation of a nutrient supply through the exchange of ions in the soil solution with the active surfaces of the membrane in a similar way as it occurs with root surfaces (Hangs et al. 2004; Huang and Schoenau 1996). The rate is expressed as weight of nutrient per surface area of membrane per time of exchange rather than weight of nutrient per unit weight of soil (Johnson et al. 2005). Two cation (CR67) and two anion (AR204-SXZL-386) membranes (46 cm * 102 cm) were obtained from Ionics, Inc. These were washed with deionized water to remove the glycol coating that protects them from dehydration and were cut into 16 cm * 5 cm rectangles. A nylon string was sewn to one corner of the membranes and on the other extreme of the string a yellow flag was attached for easier identification in the field. The membranes were submerged to charge in 1 M NaCl solution the night before their installation in the field.

Two of the anion and two of the cation membranes were installed per plot in the forest floor–mineral soil interface to capture N coming from the forest floor and a similar set was inserted at 16 cm depth in the A-horizon to capture N coming from the mineral soil. The location of

these membranes within each plot was randomly assigned. The membranes were left in the field to exchange ions with the soil solution for 20, 59, and 47 days for the first, second, and third sampling periods respectively. The membranes were replaced, but the same sampling locations were kept from one period to the next. Immediately after retrieval from the field, the membranes were washed and cleaned of soil residues with deionized water and placed in a sealed plastic bag. The membranes were placed in the same plastic bag if they were of the same type (anion or cation) and the same position (forest floor or mineral soil) within the same plot. Once in the laboratory, the pooled membranes (two per plot) were eluted with 40 ml of 1M NaCl using the same plastic bag to contain the solution. The membranes were placed in the shaker at low speed for one hour and then the solution was transferred to a clean vial. The resulting solutions from these extractions were analyzed for NO_3^--N and NH_4^+-N^+ using the Lachat Autoanalyzer (Quick-Chem 8000, Zellweger Analytics, Inc., Milwaukee, WI)

Foliar analysis

Foliar samples were collected in January of 2005 from the upper third of the live crown of 5 dominant or codominant trees in each plot. A total of 100 complete and healthy fascicles (20 fascicles from each selected tree) were collected from the first flush produced during the 2004 growing season. The samples were analyzed for N concentration using a CHN elemental analyzer, other nutrient concentrations were determined by digesting 1.0 g of ground, oven dry foliage material with nitric acid (Zarcinas et al. 1987) followed by spectrometry analysis using an inductively coupled plasma atomic emission spectrometer. These analyzes were performed by SureTech laboratories in Indianapolis, IN.

Litterfall analysis

Litterfall was estimated using five - 1 m^2 littertraps randomly located in each plot. The littertraps were installed in the second week of April of 2004, the litter was collected approximately bimonthly, and the last collection was on April 29, 2005. Annual litterfall was the sum of these collections which represented the foliage cohort produced in 2003. Litterfall was oven dried at 70 °C until constant weight was reached, and then weighed. Nutrient concentrations were determined using the same methodology described for the forest floor material. The ash content of these samples was determined by the loss-on-ignition technique and used to adjust the weights and nutrient concentrations to an ash-free basis.

Stand Yield

Diameter at breast height and total tree height were measured in January 2005. Using these data, individual tree volume was calculated with the following volume equation: Volume (cu ft) = 0.34864 + 0.00232 * dbh^2 (in) * height (ft) (Burkhart 1977). Plot volume was calculated by summing individual tree volumes and scaled to per hectare values based on the plot size.

Data Analysis

Analyses of variance using the general linear model (SAS 2000), SAS Institute Inc., Cary, NC) were performed to test for treatment effects on mass, nutrient concentrations, and nutrient contents of the forest floor and litterfall, nutrient concentrations of foliage, total C and N, exchangeable cations, extractable P and Mn, pH, depth of the A-horizon, and potential N mineralization of the mineral soil, extractable N from ion exchange membranes

from both the forest floor and the mineral soil, nutrient remobilization, decomposition indexes, and stand yield. Significance was accepted at $p \leq 0.10$ for all analysis. The data from the ion exchange membranes were transformed to log scale to provide for homogeneity of variance. Remobilization for each nutrient was calculated as (foliar nutrient concentration – litterfall nutrient concentration)/foliar nutrient concentration x 100. These remobilization estimates were approximations, because the nutrient data were from different foliage cohorts (2003 for litterfall and 2004 for foliage).

Two decomposition indexes were also calculated. One index described litter decomposition and was calculated as litterfall mass/L layer mass and the other was the ratio of L layer mass to F layer mass. Relationships among measures of forest floor mass, litterfall, N availability, and stand yield were examined using Pearson correlation coefficients. The Mitscherlich equation, a curvilinear asymptotic model with the form: $Y = a\ (1 - e^{-b(x + c)})$ was used to model the nonlinear relationships between wood production and forest floor total mass, H layer mass and potential nitrification. For this model, (Y) was the volume at age 10 ($m^3\ ha^{-1}$), (X) was either forest floor total mass, H layer mass, or potential nitrification, (a) was the asymptotic wood production, (b) was the shape parameter, and (c) was the intercept.

RESULTS

Forest Floor Mass

Forest floor mass on the doubled treatment was significantly greater than on the control and removed treatments for L, F, and H layers and for the sum of all layers (figure 1, tables 1 and 2). Total forest floor mass increased non-linearly with the amount of forest floor and slash initially retained (figure 1). The doubled treatment had 19,000 kg ha^{-1} – a 96% increase over the control (9,700 kg ha^{-1}) as a result of 25, 45, and 350% more mass in the L, F, and H layers, respectively. Forest floor masses in the removed and control treatments were very similar and averaged 4,800, 2,900, and 1,700 kg ha^{-1} for the L, F, and H layers, respectively.

The two indexes of decomposition were not affected by treatment indicating similar rates of decomposition for litterfall and L layer materials as they decomposed to F layer material. The litterfall /L layer ratio averaged 1.05 and the L layer/F layer ratio averaged 1.63.

Forest Floor Nutrient Concentrations

Not surprisingly, C concentrations averaged 500 g kg^{-1} and were not significantly different across treatments or forest floor layers (tables 1 and 2). N was the only element that was consistently affected by treatment with significantly higher concentrations in the doubled, for the L, F, and all layers combined, than in the control and removed treatments (tables 1 and 2). For the L layer, N concentration in the doubled treatment was 6.4 g kg^{-1}, 25 and 31% greater than the control (5.1 g kg^{-1}) and removed (4.9 g kg^{-1}) treatments, respectively. For the F layer, N concentration in the doubled treatment was 9 and 23% greater than the control and

removed treatments, respectively. N concentration averaged 18.3 g kg^{-1} in the H layer with no differences among treatments. For all layers combined, N concentration in the doubled treatment was 31 and 62% greater than the control and removed treatments respectively.

The significantly different N but constant C concentrations resulted in significantly different C:N ratios among treatments and also among forest floor layers. The L, F and combined layers had lower C:N ratios in the doubled as compared to the other two treatments. C:N ratios dropped from 94 to 48 and finally to 25 as forest floor material decomposed from the L to the F and finally to the H layer (table 1 and 2).

In the L layer, P and K concentrations in the doubled and removed were significantly higher than in the control treatment. Ca concentration in the doubled was significantly lower than in the control treatment (tables 1 and 2). In the F layer, Cu concentration in the removed was significantly lower than in the control and doubled treatments (tables 1 and 2). In the H layer, K concentrations were significantly lower in the doubled treatment only when compared to the removed treatment. Finally, for all layers combined, P, B, and Zn concentrations in the doubled were significantly higher than in the control and removed treatments (table 1 and 2).

Forest Floor Nutrient Contents

Forest floor nutrient contents followed similar trends as for forest floor mass (table 1). For the L layer, C, N, P, K, Mg, S, B, and Cu contents in the doubled were significantly higher than in the control and removed treatments. For example, N content averaged 257, 98, and 76 kg ha^{-1} for the doubled, control and removed treatments, respectively (table 1). No significant

differences in Ca, Mn, or Zn content were found among any of the treatments (tables 1 and 2). Contents of all nutrients for the F, H and for all layers were significantly higher in the doubled treatment than in the other two treatments (tables 1 and 2). N contents in the doubled treatment were 60, 67, 417, and 195% higher than the average N content in the other two treatments for the L, F, H, and all layers, respectively. No significant differences in nutrient contents were found between the control and the removed treatment for these layers.

Mineral Soil Properties

Mineral soil properties were not significantly different across treatments. Total C and N, exchangeable P and Mn, exchangeable cations (Ca^{2+}, K^{+}, Mg^{2+}, and Na^{+}) in the A-horizon of the mineral soil averaged 21,000, 1,500, 20, 75, 6, 5, 8, and 0.6 kg ha^{-1} respectively. The pH, bulk density, and depth of the A-horizon had averages of 4.8, 1.3 g cm^{-3}, and 23 cm respectively (table 3).

Nitrogen Availability Indexes

For the aerobic incubations, NH_4^{+}-N dominated the extractable-N fractions in the initial samples and NO_3^{-} - N dominated in the incubated samples (table 3). Initial NO_3^{-} - N and NH_4^{+}-N values showed no significant differences among treatments (tables 3 and 4). However, potential nitrification was significantly increased (>300%) in the doubled (10.8 kg NO_3^{-}-N ha^{-1}) as compared with the control (2.6 kg NO_3^{-}-N ha^{-1}) and removed (-0.06 kg NO_3^{-}-N ha^{-1}) treatments (tables 3 and 4). Potential Nitrification values on the control and removed treatments were not significantly different from 0. Potential ammonification values did not significantly differ from zero and consequently showed no significant differences among

treatments (tables 3 and 4). Summing the potential ammonification and nitrification values resulted in significantly higher potential N mineralization on the doubled as compared to the control and removed treatments (tables 3 and 4). The doubled treatment mineralized 72% more N than the control treatment (8.33 vs. 4.84 kg NO_3^- + NH_4^+-N ha^{-1}).

NO_3^--N but not NH_4^+-N extracted from the ion exchange membranes (IEM) showed significant treatment differences (table 3 and 4). The NH_4^+-N values from the forest floor and the mineral soil IEM averaged 1 and 0.4 µg-N cm^{-2} 126 $days^{-1}$, respectively and were variable (table 3). The NO_3^--N extracted from the IEM installed in the forest floor-mineral soil interface was significantly greater in the doubled treatment than in the control and removed treatments, but only at the first sampling period (20 days, data not shown). For the total sampling period, IEM extracted NO_3^- in the forest floor averaged 1.4 µg-N cm^{-2} 126 $days^{-1}$ and showed no significant differences among treatments, although IEM extracted NO_3^- in the doubled treatment was 43 times greater than in the removed treatment (table 3).

NO_3^--N extracted from the membranes installed in the mineral soil was significantly greater in the doubled treatment than in the other two treatments for the first and second sampling periods (data not shown), as well as for the total NO_3^--N extracted from the entire 126-days sampling period (tables 3 and 4). The NO_3^--N values from the doubled treatment were approximately 28 and 52 times greater than the values for the control and the removed treatment, respectively (table 3).

Foliage, Litterfall, Remobilization

No significant differences among treatments were found in foliar nutrient concentrations (tables 4 and 5). Foliar concentrations averaged 14.5, 1.2, 4.7, 2.4, and 1.1 g kg^{-1} for N, P, K, Ca and Mg, respectively.

Litterfall mass was significantly increased (30%) for the doubled (6,565 kg ha^{-1}) as compared to the control (5,058 kg ha^{-1}) and removed (4,807 kg ha^{-1}) treatments (table 6). Litterfall N and B concentrations in the doubled treatment were also significantly higher than in the control and removed treatments. In contrast, P concentrations in the removed were higher than in the control and doubled treatments and Ca concentrations in the control and removed treatments were higher than in the doubled (tables 4 and 6). Litterfall nutrient contents were significantly increased for C, N, P, K, Mg, S, and B in the doubled as compared to the other two treatments (tables 4, and 6).

Foliar concentrations were higher than litter concentrations for all nutrients except for Ca, Mg, Mn, and B which are known to be very immobile elements within foliage. For the other nutrients, remobilization rates were: N=68%, K=69%, S=32%, Cu=41% and Zn=28%. Remobilization was only affected by treatment for P. P remobilization in the removed (50%) was significantly lower than the control (67%) treatment only ($p=0.040$), P remobilization for the doubled treatment was 63%.

Stand Yield

Stand volume in the double treatment was significantly greater than in the control and removed treatments (p=0.008). Volume increased by 19 and 37% in the doubled (108 m^3 ha^{-1}) as compared to the control (91 m^3 ha^{-1}) and the removed (79 m^3 ha^{-1}) treatments, respectively (table 7). Stand density at age 10 averaged 727 trees ha^{-1} across all treatments.

Relationships among Variables

Potential nitrification and potential mineralization rates were positively and significantly correlated with forest floor mass and N content (figure 6 and table 8). NO_3^--N from IEM installed in the mineral soil was also positively correlated with the potential nitrification rates (figure 2 and table 8). Volume growth was strongly correlated with litterfall (figure 3), forest floor mass, potential nitrification, IEM extractable NO_3^--N from the mineral soil, and litterfall (table 8).

Total forest floor mass accounted for 61% of the variation in volume using the Mitschelich equation. Parameter estimates were a=118.4, b=0.000177, and c=-2337.3 (figure 4). H layer mass accounted for 64% of the variation in volume and parameter estimates were a=110.2, b=0.000702, and c=509.5 (figure 5). Potential nitrification accounted for 64% of the variation in volume and parameter estimates were a=105.5, b=0.9618, and c=1.45 (figure 7).

DISCUSSION

The 9,400 kg ha^{-1} of forest floor mass and 87 kg ha^{-1} of N content found on the removed and control treatments in this 10-year-old loblolly pine plantation (table 1) are comparable to those reported by Larsen et al. (1976) for a 13-year-old loblolly pine plantation established in the hilly costal plain of Alabama. The 19,047 kg ha^{-1} and 257 kg ha^{-1} of N content found on the doubled treatment are more typical of the 20+ year plantations reported by Shepard (1985). Apparently today's plantations may have higher forest floor mass and nutrient accumulations than plantations established in the past. Interestingly, the H layer in the doubled treatment was the largest component of forest floor even in this young stand accounting for 46% of the mass and 65% of the N content. Thus, it appears that the large forest floor accumulations are in part a function of better growth and higher litterfall inputs (all treatments) and residual material from the previous stand's forest floor and slash (doubled treatment). Plantations established on old fields or following hot site preparation fires typical of the 1960s would not have had any residual forest floor at planting.

The non linear pattern of forest floor mass and nutrient contents observed across treatments (figure 1 and table 1) is interesting because the amount of forest floor material retained at time of planting was linearly related to treatment (0, 1x, and 2x, for the removed, control, and doubled treatments, respectively). This is especially true for the H layer mass where the doubled treatment was >400% than control or removed treatments. Several factors may account for this non linear pattern including: 1) greater inputs of litterfall, 2) slower decomposition rates of this rotation's litterfall, and 3) slower decomposition of the retained

material from the previous rotation for the doubled treatment. Litterfall was over 30% greater on the doubled treatment (table 6) indicating greater inputs. Litterfall was also closely linked quantitatively to the observed increases in stand yield (figure 3 and table 7). However, the lack of treatment differences in the decomposition indexes for L and F layers indicate that decomposition rates were similar and could not account for the non linear pattern. Apparently, slower decomposition of the retained material on the doubled as compared to the control treatment may account for much of the observed non linear pattern in forest floor accumulation and nutrient content.

A possible explanation for the lack of differences in between the control and removed treatments may be the rapid rate of forest floor and slash decomposition on the control treatment during the early stages of the plantation. Accelerated litter decomposition has been previously reported after harvest (Bengston 1981; Gadgil and Gadgil 1978; Pritchett and Fisher 1987). This decomposition could have released large amounts of nutrients in a time when the root systems of the trees were not developed enough to capture the nutrients released from the forest floor, leaving the removed and the control treatment with similar levels of N availability. Meanwhile the doubled treatment still would have had sufficient amounts of forest floor to continue decomposing providing needed nutrients for stand growth when demand for nutrients increased (Allen et al. 1990).

In addition, differences in moisture, temperature, and aeration caused by the layering of retained material on the doubled as compared with control treatment may be responsible for the apparent reduction in decomposition and large difference in H layer mass and nutrient

content. During the 10th year, forest floor moisture content did not significantly differ by treatment (data not shown). Other environmental parameters were not measured. We can only speculate that large differences in environmental factors may have existed earlier in the rotation that reduced decomposition of the retained material.

The L and F layers not only exhibited significantly greater mass and nutrient content in the doubled treatment but also significantly better quality as indicated by higher N concentrations and lower C:N ratios (table 1). The higher N concentration in the litterfall (table 6) may be in part responsible for the improved quality of the L and F layers.

The N contained in the forest floor accounted for only 5% of the combined N of the forest floor and A horizon in the removed and control treatments and 15% of the N in the doubled treatment. In order to understand the contributions of the forest floor and mineral soil N pools to N availability, several fluxes were quantified using commonly accepted methods including extractions of fresh soil, aerobic incubations, and ion exchange membranes. Significant treatment effects were only found for potential nitrification, potential N mineralization (due to the effect of nitrification), and extractable NO_3^--N from ion exchange membranes in the mineral soil and no treatment effects were found for the low NO_3^--N levels in the initial extractions from fresh soil (tables 3 and 4). High variability in the forest floor assessments also resulted in non significant treatment effects even though the magnitude of treatment differences were similar to those found in the mineral soil (table 3).

The low initial values of extractable NO_3^--N observed are typical of loblolly pine systems (Gurlevik et al. 2004; Piatek and Allen 1999) and they apparently reflect the preference that

microbial populations have for NH_4^+ since it is a more energy efficient, already reduced form of N. If the microbial populations are provided with high and constant C inputs as occurs in undisturbed forests, they will tend to immobilize most of the NH_4^+ available and little NO_3^- would be produced (Davidson et al. 1992; Hart et al. 1994a). Other reasons for the low levels of NO_3^--N observed in the initial extractions could be attributed to low nitrifier populations, low initial NH_4^+ levels which lead to low nitrification rates, and the higher mobility of NO_3^- which may lead to leaching losses.

The high extractable NO_3^--N values following the 28-day lab incubation on the doubled treatment (table 3) may have resulted from eliminating C inputs that would have been present from the large forest floor mass in the field. The reduction in C inputs would reduce the NH_4^+ demand from heterotrophic microbes and leaving it available for oxidation by the nitrifiers (Davidson et al. 1992; Hart et al. 1994a). The significant increases in NO_3^--N absorbed on IEM on the doubled treatment and the positive correlations between the NO_3^--N values from incubation and IEM methods (figure 2) suggest that these two indexes may be measuring similar processes and may be effective at detecting biologically relevant differences in available N among treatments.

The positive effect of the doubled treatment on soil N availability was well reflected by the fact that the greatest foliage production (indicated by litterfall) and stand yield growth were found on this treatment (tables 3, 6, and.7). In addition, this linkage is indicated by strong positive correlations among stand yield, litterfall, potential nitrification, and IEM extractable NO_3^--N (table 8).

The relationship between volume at age 10 and total forest floor mass was curvilinear (figure 4) suggesting no additional increase in volume with increasing forest floor accumulation above 18,000 kg ha^{-1}. This relationship was very similar when the humus layer mass, instead of total forest floor mass, was used (figure 5), which indicates the important contributions of this layer to the total forest floor.

The strong positive linear relationship between potential nitrification and humus layer mass (figure 6) suggests increasing levels of nitrogen availability with greater humus accumulation. Based on the asymptotic relationship between volume and forest floor mass, it appears that the high levels of available nitrogen (4 kg ha^{-1} 28 $days^{-1}$) present with high forest floor masses may not be fully used by the stands (figure 7).

The lack of significant treatment effects on foliar nutrient analyses was not surprising as mid rotation pine plantations exhibiting a range in productivity typically have similar foliar nutrient concentrations (Valentine and Allen 1990). Available nutrient levels are most commonly reflected in the production of foliage and not its concentration (Vose and Allen 1988). Additionally, at age 10 enough crown has formed to contribute to the remobilization of nutrients such as N, P, and K letting the biochemical cycle take a more important role in meeting nutrient demands (Switzer and Nelson 1972).

Greater amounts of available N in the mineral soil and most likely in the forest floor on the doubled treatment apparently resulted in a feed forward effect with greater growth and in turn greater litterfall and accumulation of new forest floor material (L and F layers) (figure 1). In

addition, the retention of more forest floor material (at least in the manner it was done in this study) apparently resulted in slower decomposition of the retained material in a non linear proportion relative to its original mass. This in turn has resulted in long term increases in soil available N through the 10th year following plantation establishment (figure 6).

The fact that the doubled forest floor treatment (without incorporation into the underlying mineral soil) was still making an impact on stand productivity 10 years after imposition, and that other studies (Sanchez et al. 2003; Sanchez and Eaton 2001) have shown that incorporation of the forest floor and slash material may accelerate decomposition, emphasizes the importance of evaluating the long term effects of retention and incorporation treatments on stand nutrition. Interesting lines of research lie ahead as the factors regulating decomposition and nutrient release are better understood, and have the potential to be manipulated at the operational level to provide adequate and timely nutrition to the stands.

REFERENCES

Allen, H. L., P. M. Dougherty, and R. G. Campbell. 1990. Manipulation of Water and Nutrients - Practice and Opportunity in Southern U.S. Pine Forests. Forest Ecology and Management 30:437-453.

Bengston, G. W. 1981. Nutrient conservation in forestry: a perspective. Southern Journal of Applied Forestry 5:50-58.

Berg, B. 1986. Nutrient Release from Litter and Humus in Coniferous Forest Soils - a Mini Review. Scandinavian Journal of Forest Research 1:359-369.

Berg, B., M. Berg, P. Bottner, E. Box, A. Breymenyer, R. Calvo de Anta, M. M. Couteaux et al. 1993. Litter mass loss rates in pine forests of Europe and Eastern United States; some relationships with climate and litter quality. Biogeochemistry 20:127-159.

Burger, J. A., and W. L. Pritchett. 1984. Effects of Clearfelling and Site Preparation on Nitrogen Mineralization in a Southern Pine Stand. Soil Science Society of America Journal 48:1432-1437.

Burkhart, H. D. 1977. Cubic-Foot Volume of Loblolly Pine to Any Merchantable Top Limit. Southern Journal of Applied Forestry 1:7-9.

Carey, M. L., I. R. Hunter, and I. Andrew. 1982. Pinus Radiata Forest Floors: Factors Affecting Organic Matter and Nutrient Dynamics. New Zealand Journal of Forestry Science 12:36-48.

Cortina, J., and V. R. Vallejo. 1994. Effects of clearfelling on forest floor accumulation and litter decomposition in a radiata pine plantation. Forest Ecology and Management 70:299-310.

Covington, W. W. 1981. Changes in forest floor organic matter and nutrient content following clear cutting in northern hardwoods. Ecology 62:41-48.

Cox, P., S. P. Wilkinson, and J. M. Anderson. 2001. Effects of fungal inocula on the decomposition of lignin and structural polysaccharides in Pinus sylvestris litter. Biology and Fertility of Soils 33:246-251.

Davidson, E. A., S. C. Hart, and M. K. Firestone. 1992. Internal cycing of nitrate in soils of a mature coniferous forest. Ecology 73:1148-1156.

De Santo, A. V., B. Berg, F. A. Rutigliano, A. Aleani, and A. Fioretto. 1993. Factors regulating early stage decomposition of needle litters in five different coniferous forests. Soil Biology & Biochemistry 25:1423-1433.

Ducey, M., and H. L. Allen. 2001. Nutrient supply and fertilization efficiency in midrotation loblolly pine plantations: A modeling analysis. Forest Science 47:96-102.

Ellert, B. H., and E. G. Gregorich. 1995. Management-induced changes in the actively cycling fractions of soil organic matter *in* W. W. M. a. J. M. Kelly, ed. Carbon forms and functions in forest soils. Madison, WI, Soil Science Society of America.

Fox, T. R., J. A. Burger, and R. E. Kreh. 1986. Effects of Site Preparation on Nitrogen Dynamics in the Southern Piedmont. Forest Ecology and Management 15:241-256.

Gadgil, R. L., and P. D. Gadgil. 1978. Influence of clearfelling on decomposition of *Pinus radiata* litter. New Zealand Journal of Forestry Science 8:213-224.

Gardner, W. H. 1986. Water Content, Pages 503-507 *in* A. Klute, ed. Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods. Madison, WI, Soils Science Society of America.

Grossman, R. B., and T. G. Reinsch. 2002. The Solid Phase, Bulk Density and Linear Extensibility, Pages 201-228 *in* J. H. Dane, and G. C. Topp, eds. Methods of Soil Analysis Part 4 - Physical Methods. Madison, WI, Soil Science Society of America.

Gurlevik, N., D. L. Kelting, and H. L. Allen. 2003. The effects of vegetation control and fertilization on net nutrient release from decomposing loblolly pine needles. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 33:2491-2502.

—. 2004. Nitrogen mineralization following vegetation control and fertilization in a 14-year-old loblolly pine plantation. Soil Science Society of America Journal 68:272-281.

Guthrie, R. L., and J. E. Witty. 1982. New designations for soil horizons and layers and the new Soil Survey Manual. Soil Sci Soc Am J 46:443-444.

Hangs, R. D., K. J. Greer, and C. A. Sulewski. 2004. The effect of interspecific competition on conifer seedling growth and nitrogen availability measured using ion-exchange membranes. Canadian Journal of Forest Research 34:754-761.

Hart, S. C., G. E. Nason, D. D. Myrold, and D. A. Perry. 1994a. Dynamics of gross nitrogen transformations in an old growth forest: the carbon connection. Ecology 75:880-891.

Hart, S. C., J. Stark, M., E. A. Davidson, and M. K. Firestone. 1994b. Nitrogen Mineralization, Immobilization, and Nitrification, Pages 985-1018 *in* R. W. Weaver, J. S. Angle, and P. S. Bottomley, eds. Methods of Soil Analysis, Part 2, Microbiological and Biochemical Properties. Madison, WI, Soil Science Society of America.

Henderson, G. S. 1995. Soil organic matter: A link between forest management and productivity *in* W. W. M. a. J. M. Kelly, ed. Carbon forms and functions in forest soils. Madison, WI, Soil Science Society of America.

Huang, W. Z., and J. J. Schoenau. 1996. Microsite Assessment of Forest Soil Nitrogen, Phosphorus, and Potassium Supply Rate In-field Using Ion Exchange Membranes. Communications in Soil Science and Plant Analysis 27:2895-2908.

Johnson, D. W., P. S. J. Verburg, and J. A. Arnone. 2005. Soil extraction, Ion exchange resin, and Ion exchange membrane measures of soil mineral nitrogen during incubation of a tallgrass prairie soil. Soil Sci Soc Am J 69:260-265.

Jorgensen, J. R., C. G. Wells, and L. J. Metz. 1980. Nutrient changes in decomposing loblolly pine forest floor. Soil Sci Soc Am J 44:1307-1314.

Kendrick, W. B. 1959. The time factor in the decomposition of coniferous leaf litter. Canadian Journal of Botany 37:907-912.

Larsen, H. S., M. C. Carter, J. W. Gooding, and D. M. Hynk. 1976. Biomass and Nitrogen Distribution in Four 13-year-old Loblolly Pine Plantations in the Hilly Coastal Plain of Alabama. Canadian Journal of Forest Research 6:187-194.

Li, Q. C., H. L. Allen, and C. A. Wilson. 2003. Nitrogen mineralization dynamics following the establishment of a loblolly pine plantation. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 33:364-374.

McHale, P. J., M. J. Mitchell, and F. P. Bowles. 1998. Soil warming in a northern hardwood forest: trace gas fluxes and leaf litter decomposition. Canadian Journal of Forest Research 28:1365-1372.

Mendham, D. S., A. M. O'Connell, T. S. Grove, and S. J. Rance. 2003. Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalyptus. Forest Ecology and Management 181:357-372.

Nelson, D. W., and L. E. Sommers. 1996. Total Carbon, Organic Carbon, and Organic Matter, Pages 1004-1005 *in* SSSA, ed. Methods of Soil Analysis Part 3 Chemical Methods. Madison, WI, Soil Science Society of America, Inc.

NOAA. 2003. Climatography of the United States, Report No. 81, Pages 1-12. Ashville, NC, National Oceanic and Atmospheric Administration.

Piatek, K. B., and H. L. Allen. 1999. Nitrogen mineralization in a pine plantation fifteen years after harvesting and site preparation. Soil Science Society of America Journal 63:990-998.

—. 2001. Are forest floors in mid-rotation stands of loblolly pine (Pinus taeda) a sink for nitrogen and phosphorus? Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 31:1164-1174.

Pritchett, W. L., and R. F. Fisher. 1987. Properties and Management of Forest Soils. New York, Wiley.

Rustad, L., and I. Fernandez. 1998. Soil warming: consequences for foliar litter decay in a spruce-fir forest in Maine, USA. Soil Sci Soc Am J 62:1072-1080.

Sanchez, F. G., E. A. Carter, and J. F. Klepac. 2003. Enhancing the soil organic matter pool through biomass incorporation. Biomass & Bioenergy 24:337-349.

Sanchez, F. G., and R. J. Eaton. 2001. Sequestering carbon & improving soils - Benefits of mulching and incorporating forest slash. Journal of Forestry 99:32-36.

Sariyildiz, T., and J. M. Anderson. 2003. Interactions between litter quality, decomposition and soil fertility: a laboratory study. Soil Biology & Biochemistry 35:391-399.

SAS. 2000.SAS Software version 8.2.SAS Institute Inc., Cary, NC.

Scott, N. A., and D. Binkley. 1997. Foliage litter quality and annual net N mineralization: comparison across North America forest sites. Oecologia 111:151-159.

Sedjo, R. A. 2001. The role of forest plantations in the world's future timber supply. Forestry Chronicle 77:221-225.

Shepard, J. P. 1985. Relationships Between Nutrient Cycling and Net Primary Productivity in Loblolly Pine Plantation Ecosystems of The East Gulf Coastal Plain. Dissertation thesis, Mississippi State University.

Shuman, L. M., and R. R. Duncan. 1990. Soil Exchangeable Cations and Aluminum Measured by Ammonium-Chloride, Potassium-Chloride, and Ammonium Acetate. Communications in Soil Science and Plant Analysis 21:1217-1228.

Smethurst, P. J., and E. K. S. Nambiar. 1990b. Effects of Slash and Litter Management on Fluxes of Nitrogen and Tree Growth in a Young Pinus-Radiata Plantation. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 20:1498-1507.

Switzer, G., and L. Nelson. 1972. Nutrient accumulation and cycling in loblolly pine (Pinus Taeda L.) plantation ecosystems: The first twenty years. Soil Science Society of America Proceedings 36:143-147.

Tew, D. T., L. A. Morris, H. L. Allen, and C. G. Wells. 1986. Estimates of Nutrient Removal, Displacement and Loss Resulting from Harvest and Site Preparation of a Pinus-Taeda Plantation in the Piedmont of North-Carolina. Forest Ecology and Management 15:257-267.

Thomas, G. W. 1996. Soil pH and Soil Acidity, Pages 475-490 *in* D. L. Sparks, ed. Methods of Soil Analysis, Part 3, Chemical Methods. Madison, WI, Soil Science Society of America.

Tucker, M. R. 1992. Determination of phosphorus by Mehlich 3 extractant, Pages 9-12 *in* S. J. Donohue, ed., Reference Soil and Media Diagnostic procedure for the southern region of the United States. Backsburg, VA, Va. Agric. Exp. Station.

Urrego, J. B. 1993. Nutrient accumulation in biomass and forest floor of a 34-year-old loblolly pine plantation. Thesis (M.S.) thesis, North Carolina State University.

Valentine, D. W., and H. L. Allen. 1990. Foliar Responses to Fertilization Identify Nutrient Limitation in Loblolly-Pine. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 20:144-151.

Vitousek, P. M., and P. A. Matson. 1985. Intensive harvesting and site preparation decrease soil nitrogen availability in young plantations. Southern Journal of Applied Forestry 9:120-125.

Vose, J. M., and H. L. Allen. 1988. Leaf-Area, Stemwood Growth, and Nutrition Relationships in Loblolly-Pine. Forest Science 34:547-563.

Zarcinas, B. A., B. Cartwright, and L. R. Spouncer. 1987. Nitric-Acid Digestion and Multielement Analysis of Plant-Material by Inductively Coupled Plasma Spectrometry. Communications in Soil Science and Plant Analysis 18:131-146.

Table 1. Treatment means for forest floor mass, nutrient concentrations, and nutrient contents by layer in a 10-year-old loblolly pine plantation regenerated under different forest floor and slash retention treatments.

Forest Floor Layers	Litter (L)				Fermentation (F)				Humus (H)				Total (All Layers)			
Treatments	Removed	Control	Doubled	(RMSE)	Removed	Control	Doubled	(RMSE)	Removed	Control	Doubled	(RMSE)	Removed	Control	Doubled	(RMSE)
Forest Floor Mass																
Ash-free wt. (kg ha^{-1})	4831	4841	6033	(577)	2849	2950	4262	(729)	1500	1947	8752	(1663)	9180	9738	19047	(2148)
Concentrations																
C (g kg^{-1})	506	506	510	(5)	511	503	509	(9)	412	504	433	(63)	494	505	479	(24)
N (g kg^{-1})	4.9	5.1	6.4	(0.4)	9.7	10.9	11.9	(1.2)	15.8	20.8	18.2	(2.4)	8.1	10.0	13.1	(1.5)
P (g kg^{-1})	0.49	0.40	0.48	(0.04)	0.80	0.80	0.87	(0.11)	1.60	1.43	1.27	(0.30)	0.70	0.70	0.90	(0.10)
K (g kg^{-1})	0.6	0.5	0.6	(0.1)	0.8	0.9	0.9	(0.1)	1.8	1.6	1.2	(0.3)	0.9	0.8	0.9	(0.1)
Ca (g kg^{-1})	5.3	5.6	4.7	(0.4)	6.4	7.6	6.8	(0.8)	5.5	8.0	6.9	(1.5)	5.7	6.6	6.1	(0.6)
Mg (g kg^{-1})	1.0	1.0	1.1	(0.1)	1.0	1.1	1.1	(0.1)	1.6	1.8	1.2	(0.4)	1.1	1.2	1.1	(0.1)
S (g kg^{-1})	0.69	0.69	0.76	(0.05)	1.20	1.34	1.42	(0.15)	2.63	2.62	2.11	(0.92)	1.10	1.30	1.50	(0.36)
Mn (mg kg^{-1})	795	790	716	(108)	812	964	1088	(238)	1201	1588	1427	(558)	837	1006	1127	(188)
B (mg kg^{-1})	9.7	10.1	10.2	(0.5)	13.5	13.2	13.9	(1.1)	34.2	40.5	36.2	(10.4)	14.4	17.2	22.6	(3.2)
Cu (mg kg^{-1})	2.0	2.1	2.5	(0.4)	7.2	9.5	8.8	(0.9)	54.2	39.3	37.3	(27.7)	11.7	11.8	19.0	(7.6)
Zn (mg kg^{-1})	24	28	26	(5)	42	50	48	(6)	102	126	105	(17)	41	54	67	(8)
C:N ratio	103	99	80	(7)	54	47	43	(5)	26	24	24	(4)	75	68	47	(5)
Contents																
C (kg ha^{-1})	2446	2453	3075	(299)	1454	1485	2167	(367)	627	992	4027	(1245)	4527	4930	9267	(1454)
N (kg ha^{-1})	24	25	39	(5)	28	32	50	(9)	24	41	168	(54)	76	98	257	(62)
P (kg ha^{-1})	2.4	2.0	2.9	(0.4)	2.3	2.4	3.6	(0.7)	2.2	2.8	11.7	(3.4)	6.8	7.1	18.2	(3.6)
K (kg ha^{-1})	3.0	2.5	3.8	(0.4)	2.4	2.7	3.8	(0.7)	2.6	3.1	10.5	(3.0)	8.0	8.2	18.1	(2.9)
Ca (kg ha^{-1})	25	27	28	(3)	18	22	28	(4)	8	15	61	(12)	52	64	117	(12)
Mg (kg ha^{-1})	4.9	5.0	6.3	(0.5)	2.9	3.2	4.4	(0.7)	2.0	3.4	11.1	(3.1)	9.8	11.6	21.8	(3.6)
S (kg ha^{-1})	3	3	5	(1)	3	4	6	(1)	4	5	21	(9)	11	12	31	(10)
Mn (kg ha^{-1})	3.8	3.8	4.3	(0.7)	2.2	2.9	4.5	(1.0)	1.4	3.2	13.0	(4.0)	7.4	9.9	21.7	(4.7)
B (kg ha^{-1})	0.05	0.05	0.06	(0.01)	0.04	0.04	0.06	(0.01)	0.05	0.08	0.30	(0.05)	0.13	0.17	0.42	(0.06)
Cu (kg ha^{-1})	0.010	0.010	0.015	(0.003)	0.020	0.028	0.036	(0.006)	0.083	0.075	0.311	(0.117)	0.113	0.113	0.362	(0.117)
Zn (kg ha^{-1})	0.12	0.14	0.16	(0.03)	0.12	0.15	0.20	(0.03)	0.15	0.25	0.93	(0.20)	0.39	0.53	1.29	(0.21)

(RMSE) = root mean square error.

Table 2. Summary of statistical significance (Pr > F) from ANOVA analyses on forest floor nutrient concentrations, C:N ratio, nutrient contents, and mass in a 10-year-old loblolly pine plantation regenerated under different forest floor and slash retention treatments.

Nutrient Concentrations and C:N ratio

	Source	C	N	P	K	Ca	Mg	S	Mn	B	Cu	Zn	C:N ratio
Layer (L)	Treatment	0.469	**0.005**	**0.056**	**0.034**	**0.037**	0.747	0.173	0.546	0.331	0.246	0.487	**0.006**
Layer (F)		0.405	**0.091**	0.571	0.519	0.187	0.573	0.187	0.327	0.669	**0.028**	0.220	**0.052**
Layer (H)		0.175	**0.072**	0.363	**0.087**	0.141	0.251	0.671	0.638	0.695	0.660	0.183	0.715
Total (All Layers)		0.373	**0.009**	**0.045**	0.496	0.182	0.515	0.345	0.171	**0.029**	0.361	**0.009**	**0.001**

Nutrient contents and mass

	Source	C	N	P	K	Ca	Mg	S	Mn	B	Cu	Zn	Mass
Layer (L)	Treatment	**0.039**	**0.012**	**0.064**	**0.009**	0.500	**0.011**	**0.055**	0.511	**0.046**	**0.073**	0.191	**0.041**
Layer (F)		**0.057**	**0.022**	**0.048**	**0.059**	**0.039**	**0.056**	**0.019**	**0.044**	**0.042**	**0.026**	**0.021**	**0.060**
Layer (H)		**0.016**	**0.018**	**0.012**	**0.017**	**0.002**	**0.012**	**0.069**	**0.013**	**0.001**	**0.049**	**0.003**	**0.001**
Total (All Layers)		**0.007**	**0.012**	**0.007**	**0.004**	**0.001**	**0.006**	**0.041**	**0.011**	**0.001**	**0.037**	**0.002**	**0.001**

Table 3. Treatment means for mineral soil variables and available nitrogen in a 10-year-old loblolly pine plantation regenerated under different forest floor and slash retention treatments.

Treatments	Removed	Control	Doubled	(RMSE)
Mineral Soil				
Total C (kg ha^{-1})	19563	24514	19063	(4837)
Total N (kg ha^{-1})	1352	1704	1406	(338)
Mehlich-3 extractable P (kg ha^{-1})	18.9	11.7	30.3	(10.2)
Mehlich-3 extractable Mn (kg ha^{-1})	72.5	67.5	85.3	(63.9)
NH_4Cl extractable Ca (kg ha^{-1})	7.2	7.2	4.7	(3.7)
NH_4Cl extractable K (kg ha^{-1})	4.3	7.2	4.7	(2.6)
NH_4Cl extractable Mg (kg ha^{-1})	7.5	8.9	6.8	(2.7)
NH_4Cl extractable Na (kg ha^{-1})	0.6	0.7	0.6	(0.1)
pH	4.8	4.8	4.9	(0.1)
Bulk Density (g cm^{-3})	1.25	1.32	1.30	(0.05)
Depth A-Horizon (cm)	21.2	23.5	24.3	(6.7)
Available N				
Initial KCl extractable NO_3^- (kg ha^{-1})	0.41	0.17	0.35	(0.29)
Initial KCl extractable NH_4^+ (kg ha^{-1})	4.36	3.26	4.26	(1.73)
Potential NO_3^- Mineralization (kg ha^{-1} $28days^{-1}$)	-0.06	2.61	10.79	(3.97)
Potential NH_4^+ Mineralization (kg ha^{-1} $28days^{-1}$)	-0.57	2.24	-2.46	(3.02)
Potential Tot. N Mineralization (kg ha^{-1} $28days^{-1}$)	-0.63	4.84	8.33	(3.46)
IEM in forest floor NO_3^-(μg N cm^{-2} 126 $days^{-1}$)	0.09	0.18	3.92	(4.21)
IEM in mineral soil NO_3^-(μg N cm^{-2} 126 $days^{-1}$)	0.07	0.13	3.62	(3.24)
IEM in forest floor NH_4^+(μg N cm^{-2} 126 $days^{-1}$)	0.98	1.38	0.96	(1.11)
IEM in mineral soil NH_4^+(μg N cm^{-2} 126 $days^{-1}$)	0.36	0.31	0.63	(0.37)

(RMSE) = root mean square error.

Table 4. Summary of statistical significance (Pr > F) from ANOVA analyses on mineral soil, available nitrogen, foliage, and litterfall variables in a 10-year-old loblolly pine plantation regenerated under different forest floor and slash retention treatments.

Mineral soil

Source	Total C	Total N	P	Mn	Ca	K	Mg	Na	pH	Bulk Density	Depth-A
Treatment	0.286	0.349	0.104	0.921	0.565	0.290	0.560	0.427	0.304	0.170	0.794

Available N

Source	Initial NO_3^-	Initial NH_4^+	Potential NO_3^-	Potential NH_4^+	Potential N	Forest floor Log IEM NO_3^-	Forest floor Log IEM NH_4^+	Mineral soil Log IEM NO_3^-	Mineral soil Log IEM NH_4^+
Treatment	0.522	0.634	**0.020**	0.167	**0.029**	0.531	0.855	**0.062**	0.560

Foliar Nutrients Concentration

Source	N	P	K	Ca	Mg	S	Mn	B	Cu	Zn
Treatment	0.801	0.125	0.105	0.570	0.961	0.275	0.403	0.716	0.957	0.251

Litterfall

Source		C	N	P	K	Ca	Mg	S	Mn	B	Cu	Zn
Treatment	**Concentration**	0.709	**0.017**	**0.029**	0.280	**0.007**	0.555	0.110	0.166	**0.031**	0.865	0.259
	Content	**0.005**	**0.002**	**0.082**	**0.058**	0.254	**0.001**	**0.001**	0.632	**0.003**	**0.070**	**0.082**

Table 5. Treatment means for foliar nutrient concentrations in a 10-year-old loblolly pine plantation regenerated under different forest floor and slash retention treatments.

Treatments	Removed	Control	Doubled	(RMSE)
Foliar nutrient concentrations				
N (g kg^{-1})	14.4	14.3	14.7	(0.9)
P (g kg^{-1})	1.25	1.2	1.25	(0.03)
K (g kg^{-1})	4.8	4.7	4.5	(0.2)
Ca (g kg^{-1})	2.2	2.6	2.3	(0.4)
Mg (g kg^{-1})	1.13	1.15	1.15	(0.14)
S (g kg^{-1})	0.88	0.95	0.93	(0.06)
Mn (mg kg^{-1})	524	581	497	(83)
B (mg kg^{-1})	9.8	10.5	11.0	(2.1)
Cu (mg kg^{-1})	5.5	5.3	5.3	(1.4)
Zn (mg kg^{-1})	38	43	44	(5)

(RMSE) = root mean square error.

Table 6. Treatment means for litterfall mass, nutrient concentrations, and nutrient contents in a 10-year-old loblolly pine plantation regenerated under different forest floor and slash retention treatments.

Treatments	Removed	Control	Doubled	(RMSE)
Literfall (kg ha^{-1})	4807	5058	6565	(496)
Litterfall nutrient concentrations				
C (g kg^{-1})	529	531	531	(4)
N (g kg^{-1})	4.4	4.4	5.1	(0.3)
P (g kg^{-1})	0.62	0.39	0.46	(0.09)
K (g kg^{-1})	1.6	1.4	1.4	(0.2)
Ca (g kg^{-1})	4.9	4.7	3.9	(0.3)
Mg (g kg^{-1})	1.06	1.07	1.10	(0.05)
S (g kg^{-1})	0.614	0.595	0.655	(0.034)
Mn (mg kg^{-1})	906	861	705	(135)
B (mg kg^{-1})	9.2	9.1	10.0	(0.4)
Cu (mg kg^{-1})	2.9	3.0	2.9	(0.5)
Zn (mg kg^{-1})	25	32	31	(5)
C:N ratio	124	124	109	(6)
Litterfall nutrient contents				
C (kg ha^{-1})	2546	2687	3484	(265)
N (kg ha^{-1})	21	22	34	(3)
P (kg ha^{-1})	2.9	2.0	3.1	(0.6)
K (kg ha^{-1})	7	7	9	(1)
Ca (kg ha^{-1})	23	24	26	(2)
Mg (kg ha^{-1})	5.1	5.5	7.3	(0.4)
S (kg ha^{-1})	2.9	3.0	4.3	(0.3)
Mn (kg ha^{-1})	4.2	4.3	4.6	(0.6)
B (kg ha^{-1})	0.044	0.046	0.067	(0.006)
Cu (kg ha^{-1})	0.014	0.016	0.019	(0.003)
Zn (kg ha^{-1})	0.129	0.162	0.201	(0.036)

(RMSE) = root mean square error.

Table 7. Treatment means for stand yield in a 10-year-old loblolly pine plantation regenerated under different forest floor and slash retention treatments.

Treatments	Removed	Control	Doubled	(RMSE)
Stand Yield				
dbh (cm)	15.8	17.5	18.6	(0.8)
Height (m)	10.8	11.2	11.3	(0.4)
Volume (m^3 ha^{-1})	79	91	108	(9)

(RMSE) = root mean square error.

Table 8. Pearson correlation coefficients from a 10-year-old loblolly pine plantation regenerated under different forest floor and slash retention treatments.

r values	L layer mass	F layer mass	H layer mass	Total forest floor mass	Forest floor N content	C:N ratio	Litterfall	Volume	Potential nitrification	Potential ammonification	Potentinal N mineralization	Forest floor IEM nitrate	Mineral soil IEM nitrate
L layer mass		**0.58199**	**0.71947**	**0.80566**	**0.76517**	**-0.61135**	**0.77984**	**0.73402**	**0.63162**	-0.40252	0.50453	**0.6042**	**0.63018**
F layer mass			**0.78823**	**0.84579**	**0.78966**	**-0.6708**	**0.68955**	**0.66564**	**0.74101**	-0.51278	0.5595	**0.64578**	**0.69637**
H layer mass				**0.98402**	**0.97083**	**-0.90685**	**0.76647**	**0.68664**	**0.76938**	-0.38472	**0.69894**	**0.73287**	**0.76384**
Total forest floor mass					**0.9728**	**-0.87645**	**0.81438**	**0.74504**	**0.79636**	-0.44054	**0.68963**	**0.74841**	**0.78426**
Forest floor N content						**-0.85381**	**0.76078**	**0.70921**	**0.81267**	-0.41704	**0.72974**	**0.85983**	**0.88171**
C:N ratio							**-0.6233**	-0.55748	**-0.75622**	0.30304	**-0.747**	-0.53509	-0.58497
Litterfall								**0.97187**	**0.75629**	-0.4435	**0.63485**	0.54421	**0.59276**
Volume									**0.75333**	-0.38056	**0.68127**	0.55089	**0.59516**
Potential nitrification										**-0.64556**	**0.79216**	**0.70408**	**0.77468**
Potential ammonification											-0.04529	-0.38439	-0.44434
Potentinal N mineralization												**0.61379**	**0.65824**
Forest floor IEM nitrate													**0.99299**

Significance (n = 12) r=0.497 for p < 0.10; r=0.576 for p < 0.05 (bold numbers); r=0.708 for p < 0.01

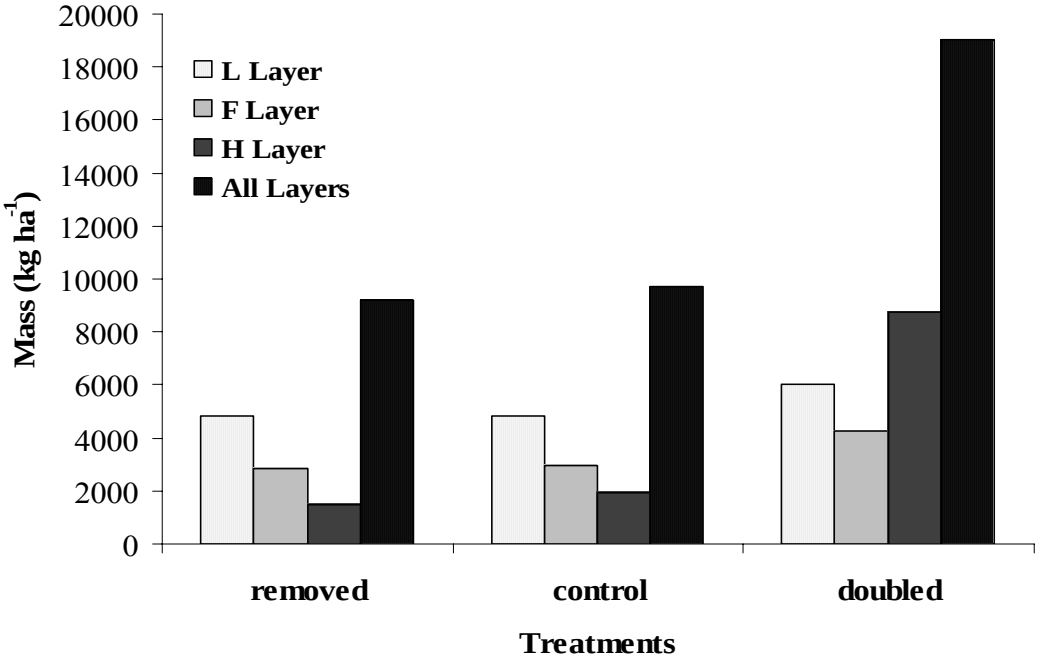

Figure 1. Forest floor biomass mass in a 10-year-old loblolly pine plantation regenerated under different forest floor and slash retention treatments.

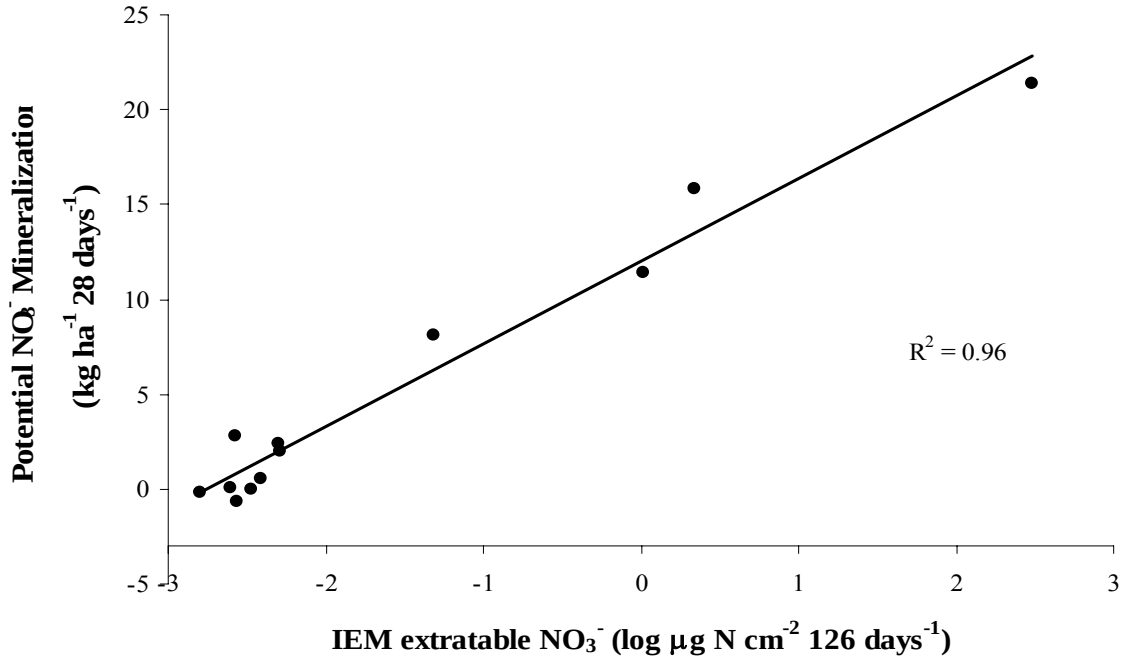

Figure 2. Relationship between two indexes of nitrogen availability from the surface mineral soil of a 10-year-old loblolly pine plantation regenerated under different forest floor and slash retention treatments.

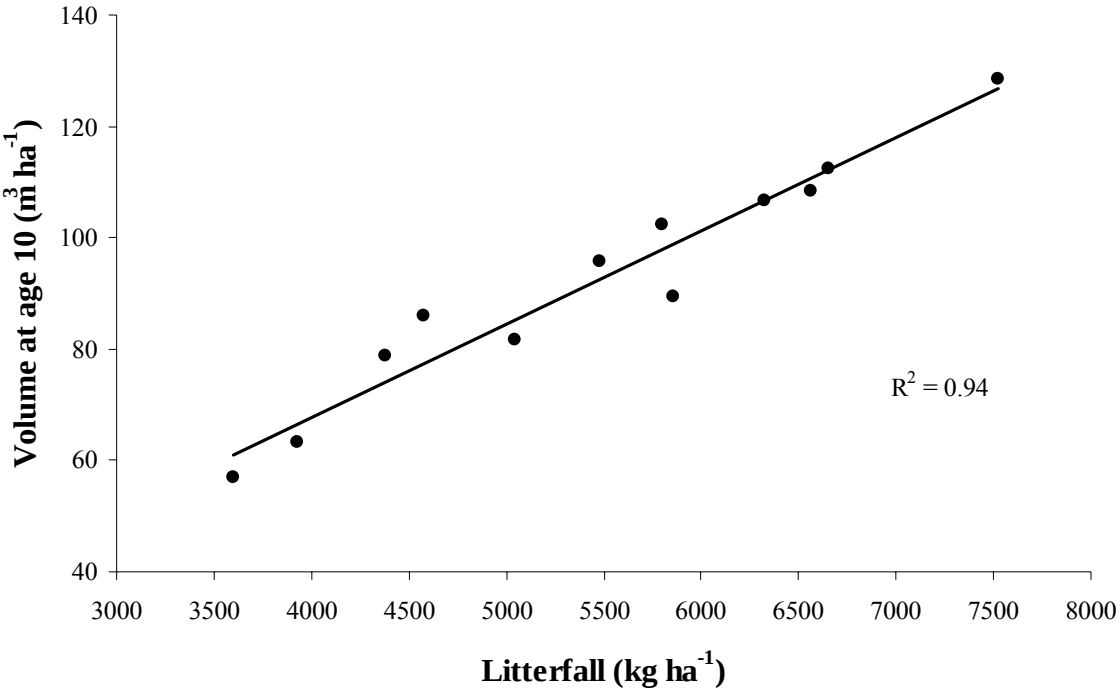

Figure 3. Relationship between volume at age 10 and annual litterfall for a loblolly pine plantation regenerated under different forest floor and slash retention treatments.

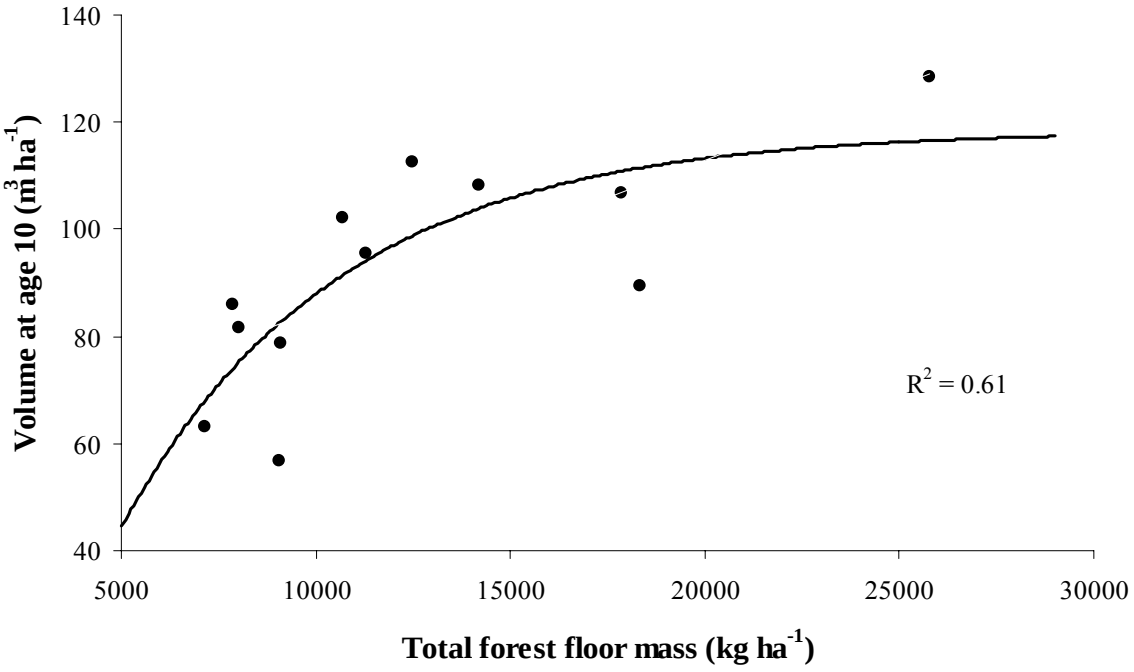

Figure 4. Relationship between volume at age 10 and total forest floor mass for a loblolly pine plantation regenerated under different forest floor and slash retention treatments.

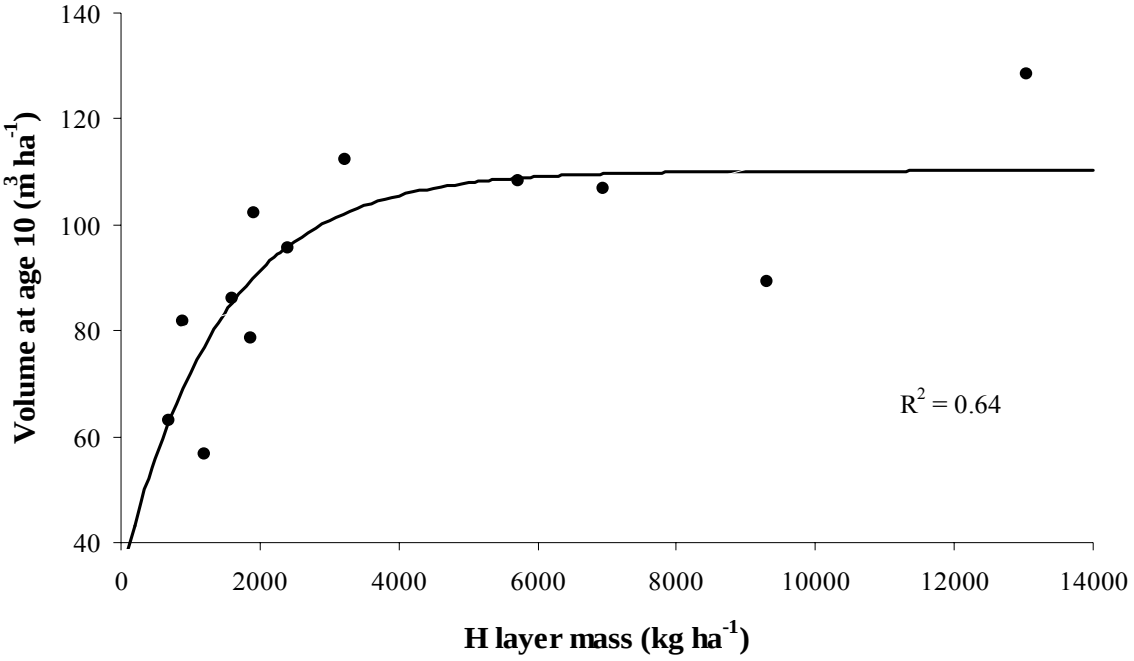

Figure 5. Relationship between volume at age 10 and humus layer mass for a loblolly pine plantation regenerated under different forest floor and slash retention treatments.

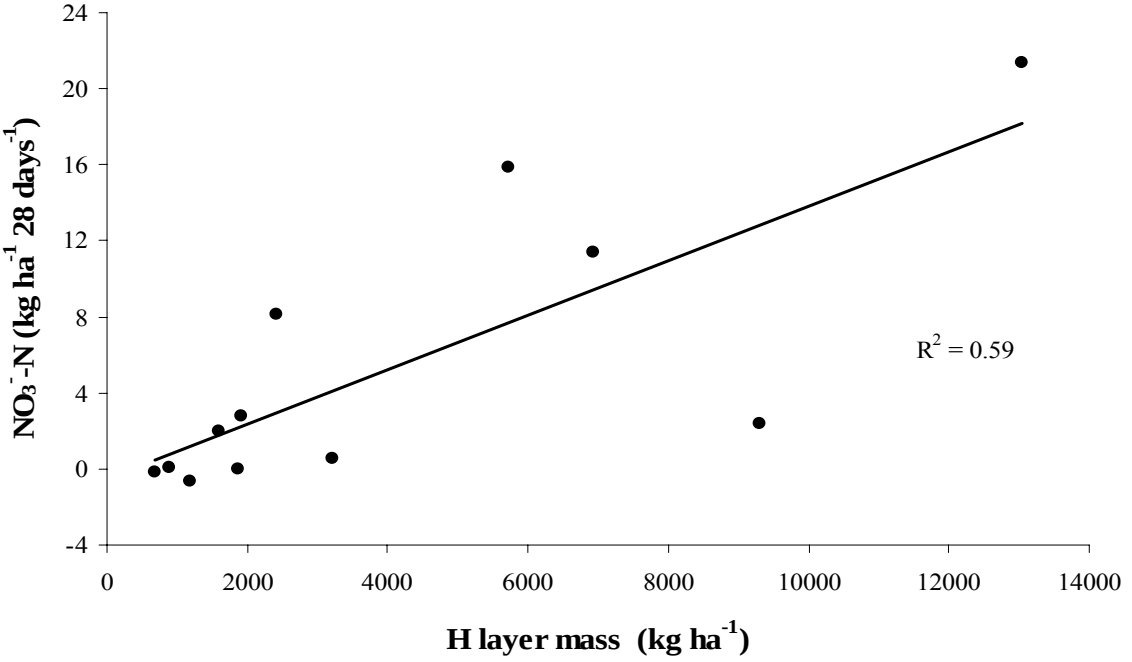

Figure 6. Relationship between potential nitrification in the mineral soil and humus layer mass for a loblolly pine plantation regenerated under different forest floor and slash retention treatments.

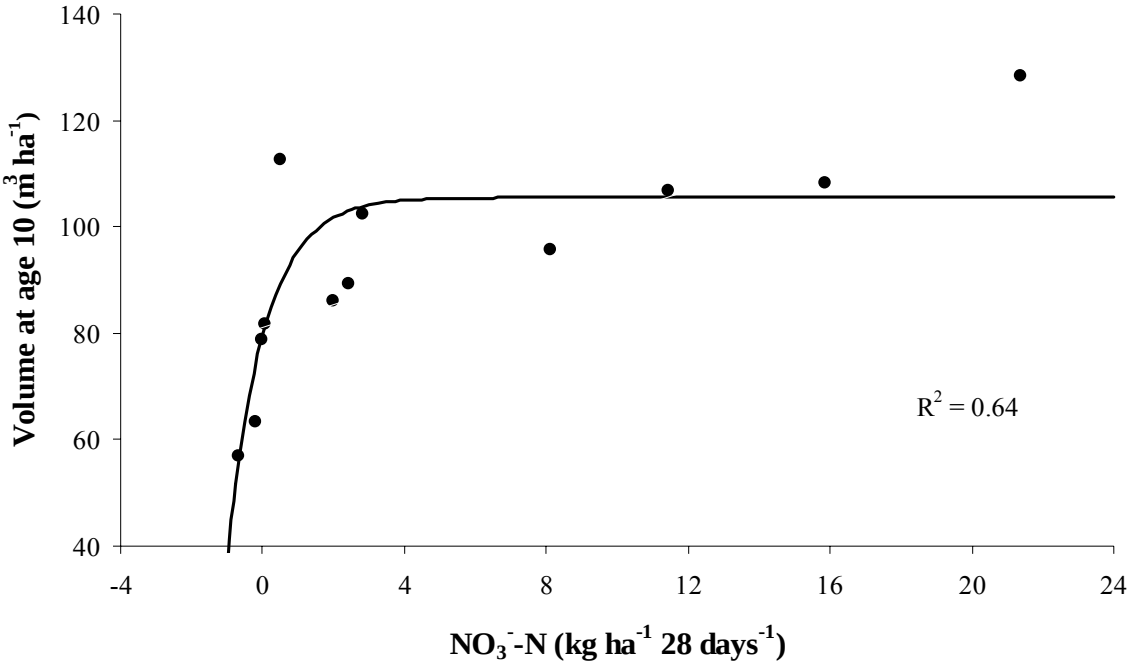

Figure 7. Relationship between volume at age 10 and potential nitrification in the mineral soil for a loblolly pine plantation regenerated under different forest floor and slash retention treatments.