ELSEVIER

Forest Ecology and Management 164 (2002) 67–88

Forest Ecology and Management

www.elsevier.com/locate/foreco

Short-term changes in soil C, N, and biota following harvesting and regeneration of loblolly pine (*Pinus taeda* L.)

Mason C. Carter[a,*], Thomas J. Dean[a], Minyi Zhou[a], Michael G. Messina[b], Ziyin Wang[c]

[a]*School of Forestry, Wildlife, and Fisheries, Louisiana State University, Baton Rouge, LA 70803-6202, USA*
[b]*Department of Forest Science, Texas A&M University, College Station, TX 77843-2475, USA*
[c]*Texas Parks and Wildlife, 4200 Smith School Road, Austin, TX 78744-3292, USA*

Received 26 February 2001; accepted 03 May 2001

Abstract

In affiliation with the USDA-FS long-term soil productivity program, a series of studies have been established in the US gulf coast region to monitor the effects of intensive silviculture on site productivity. This report presents early results of a study of the interactive effects of harvest intensity and cultural treatments on soil C, N, and biological processes following the regeneration of two stands of loblolly pine (*Pinus taeda* L.), a 19-year-old stand in St. Helena Pa., LA and a 27-year-old stand in Tyler Co., TX. Two harvesting intensities (MWT, mechanical whole-tree and HFBO, hand felled bole-only removed) were combined in a factorial assignment with bedding and herbaceous weed control (at St. Helena) or bedding and fertilization (at Tyler). Total C and N in 0–15 cm of soil were determined before, 9 and 21 months after harvesting. Total C and N in 0–60 cm were measured 2 years after harvesting at St. Helena and 3 years after harvesting at Tyler. At Tyler, N mineralization, soil respiration, and microbial populations were monitored before and for 2 years after harvesting. In the 19-year-old stand, MWT removed 67% of the above-ground biomass and 38% of the above-ground N compared to 46% and 10% for HFBO. In the 27-year-old stand, MWT removed 62% of the biomass and 35% of the N, while HFBO removed 48% and 13%. Harvesting method had no effect on total C or total N in surface soil but bedding resulted in higher levels of both 1 years after harvesting. The effect of bedding was still detected 3 years after treatment at Tyler but not at St. Helena. Herbaceous weed control at St. Helena had no effect on total N in the surface 60 cm of soil but significantly reduced total C at 30–60 cm 6 months after treatment. Sixteen months after application of 250 kg ha^{-1} of diammonium phosphate (DAP) at Tyler, the surface 60 cm of mineral soil in fertilized plots averaged 373 kg ha^{-1} more total N than did soil from unfertilized plots. Total C in the surface 60 cm was not effected by fertilization. Irrespective of harvesting or cultural treatment, total C and total N in the surface 15 cm of soil declined at both sites during the first year after harvesting. The declines were 8.2 Mg ha^{-1} total C, 361 kg ha^{-1} total N at St. Helena and 7.6 Mg ha^{-1} total C, 380 kg ha^{-1} total N at Tyler. After 2 years, total C and total N had returned to >90% of pre-harvest levels at both locations. Harvesting intensity had no effect on soil temperature, soil respiration, N mineralization, or microbial populations, but bedding significantly increased soil respiration and N mineralization during the first growing season after harvesting. Net N mineralization was not effected by treatments during the second year after harvesting, but was lower in the harvested plots than in the unharvested reference and inversely related to the pre-harvest rate. Fertilization with DAP increased mineral N flux for 2 months following application, but to a lessor extent than did bedding. Nitrification was significantly greater than ammonification in all treatments during the first year after harvesting but was equal to or less than ammonification during the second growing season and in unharvested plots. In these US gulf coast pine stands, harvesting and

* Corresponding author. Tel.: +1-970-206-4844; fax: +1-970-206-4845.
E-mail address: mcarter118@home.com (M.C. Carter).

PII: S0378-1127(01)00590-4

regeneration resulted in significant but transitory perturbation in soil processes. All of the processes studies returned to or near pre-harvest levels after two growing seasons. Differences in surface biomass removal, between whole-tree and bole-only harvesting, had no measurable effect on the monitored soil processes during the first two growing seasons after harvesting although differences may appear later in the rotation. Harvesting, per se, resulted in an increase in nitrification but no increase in net N mineralization. Bedding incorporated surface organic matter, accelerated microbial activity, and increased net N mineralization but before planted pine seedlings could benefit from the increased N availability. A prolonged release of nutrients from the undisturbed surface residues may be more beneficial to productivity of the pine regeneration than the rapid mineralization which followed bedding.

Keywords: *Pinus*; N mineralization; Soil respiration; Soil microbes

1. Introduction

Forest management can potentially impact site productivity through periodic removal of nutrients and alteration of soil physical and chemical properties during harvesting and site preparation (Powers et al., 1990, 1996). Soil nitrogen is of particular concern since availability of this element limits forest growth more frequently than any other nutrient (Fisher and Binkley, 2000). Since most of the N in forest soil (up to 95% in some soils) exists in an organic form and must be mineralized before it is available for root uptake, forest soil quality and productivity are more closely related to the rate of N mineralization than to soil total N (Landsberg and Gower, 1997; Reich et al., 1997; Burger and Kelting, 1999; Fisher and Binkley, 2000). Vitousek and Melillo (1979) cautioned that increased N mineralization caused by forest disturbances could lead to nitrate losses, reducing productivity and contaminating surface and ground waters. High levels of nitrate loss are seldom observed in practice (Grigal, 2000) but a number of forest management practices are known to alter N mineralization (Burger and Pritchett, 1984; Vitousek and Matson, 1985; Knoepp and Swank, 1993).

Concerns over escalating atmospheric C content has raised questions about the effects of forest management on soil C and the ability of a forest to perform as either a C sink or source (see Johnson, 1992). The combination of reduced input from photosynthesis, removal of above-ground biomass, and increased soil respiration, has led to speculation that intensified forest management will lead to a reduction in soil C (Harmon et al., 1990). Johnson (1992), after an extensive review of the literature, concluded that harvesting alone resulted in changes in soil C of smaller than ±10%, but cultivation could result in losses of up to 50%. Variation among reports was quite high leading Johnson (1992) to express the need for coordinated regional studies on the influence of forest management practices on soil processes and C dynamics.

In 1990, the USDA forest service initiated the long-term soil productivity program (LTSP) to monitor the impact of forest management on productivity and related issues (Powers et al., 1990). The group of scientist and managers who conceived and designed the LTSP concluded that soil compaction and soil organic matter were the properties most likely to be adversely impacted by forest management (Powers et al., 1990). The basic LTSP design combines three levels of soil compaction with three levels of organic matter removal into nine treatments. As of 1996, there were 62 installations of the LTSP plus more than 30 affiliated studies in North America (Powers, 1999).

However, before forest managers can utilize the results of the LTSP, they will need information about the extent of biomass removal and soil disturbance incurred by their practices which vary considerably (Morris et al., 1983; Vitousek and Matson, 1985; Tew et al., 1986; Fox et al., 1986). Also, most LTSP installations do not include site preparation or cultural practices which may exacerbate or mitigate effects of harvesting practices on soil productivity (Vitousek and Matson, 1985; Fox et al., 1986; Gent et al., 1986; McKee and Wilhite, 1986; Allen et al., 1990).

Monitoring productivity and environmental quality in southern pine plantations (MPEQ), a cooperative composed of forest industries, universities, and the USDA Forest Service, was formed in 1994 to compliment and help interpret the findings from LTSP (Powers et al., 1996). To date, MPEQ has installed four study sites and three more are in process or planned. All installations include two levels of harvest intensity combined with two or more cultural treatments applied using operational personnel and equipment. This report contains second and third year results from two study sites where the effects of harvesting and regeneration on soil C and N are being monitored.

2. Methods

2.1. Study areas

St. Helena site—this site is located in St. Helena Parish, LA on property owned by International Paper Company. The site lies at ~30.7°N latitude and 90.8°W longitude. Elevation ranges from about 28 to 32 m above sea level and annual precipitation is 168 cm. The soil is mapped as Toula, very deep, moderately well drained soils that have a fragipan. Permeability is moderate in the upper part of the subsoil and slow in the fragipan. These soils formed in a moderately thick mantle of loess over loamy Coastal Plain sediments. Slopes range from 0 to 3%. The taxonomic class is fine-silty, siliceous, thermic Typic Fragiudults. Texture is silt loam to a depth of >1 m. The site was probably cultivated and abandoned sometime prior to the 20th century. The existing 19-year-old plantation of loblolly pine (*Pinus taeda*) was established following clear-cutting of a pine–hardwood mixed forest. Site preparation methods, if any, are not known. The stand had not been thinned and had no known history of fire.

Tyler site—the study site is located in Tyler County, TX on the property of Temple–Inland Forest Products Corporation. The site lies at ~30.6°N latitude and 94.4°W longitude. Elevation ranges from about 17 to 19 m above sea level with microsite variation sufficient to influence plant species occurrence. The climate is warm and humid with an average annual temperature of 19.4 °C and a range in monthly means from 10 °C in January to 27 °C in July. The frost-free season is 241 days. Annual precipitation averages 136 cm and is generally well distributed throughout the year. The soil is mapped as Kirbyville, a very deep, moderately well drained, moderately permeable soil formed in loamy coastal plain sediments of mid-Pleistocene age. Slopes are 0–3%. The taxonomic class is fine-loamy, siliceous, semiactive, thermic Oxyaquic Paleudults. Soil texture is fine sandy loam to a depth of 50–75 cm where a transition to sandy clay begins. At time of harvest in August 1994, the site was occupied by a stand of loblolly pine direct-seeded in 1968 and thinned in corridors at age 15-year. There have been at least three harvests of pine from this site and no history of cultivation.

The phosphorus concentration in current year pine needles prior to harvest was 0.068% at St. Helena and 0.079% at Tyler, indicating that phosphorus was limiting at both sites (Wells et al., 1986).

2.2. Experimental design

The same high and minimum impact harvesting methods used in the LTSP (Powers et al., 1990) were employed at all MPEQ locations. Site preparation and other cultural treatments were selected in conjunction with local land managers and based on current operational prescriptions for each site. All cooperating land owners use aerial application of a tank mix of herbicides to suppress woody competition prior to planting pine seedlings. Since it is unlikely that aerial spraying impacts biomass removal or soil compaction, aerial spray was used as a zero or null site treatment at all locations. However, the herbicide mixture and application rates varied among study locations.

High impact harvesting was mechanical whole-tree harvesting (MWT) using feller-bunchers and rubber-tire skidders. All merchantable pine and hardwoods (and most unmerchantable pine and hardwoods) were felled, bunched and skidded to the loading deck where they were limbed and topped. Minimum impact harvesting (HFBO) consisted of hand-felling the trees with chain saws and limbing and topping them in place. Merchantable boles were lifted from the plots by a loader positioned outside the plot.

Prior to harvesting at St. Helena, three experimental blocks, based on soil structure and slope position, were established within an area of ~15 ha that was to be harvested. Each block was divided into a linear array of six plots, 42 m × 28 m (0.12 ha). The two harvesting methods were combined in a 2 × 3 factorial with three site preparation methods: (1) aerial spray; (2) aerial spray plus bedded; (3) aerial spray plus herbaceous weed control, in a randomized block design. The six treatment combinations were:

1	HFBO + aerial spray (AS)
2	HFBO + AS + bedded (Bd)
3	HFBO + AS + herbaceous weed control (HWC)
4	MWT + AS
5	MWT + AS + Bd
6	MWT + AS + HWC

Mechanical harvesting was conducted with three-wheel feller-bunchers (similar to a Franklin Model C3600) equipped with front mounted hydraulic shears. The stand was harvested in July 1995. Bedding was in October 1995, with D-7 tractor and a plow consisting of two gangs of three discs followed by an hour-glass packer. In July 1996, the harvested area was treated with an aerial application of a mixture of imazapyr and glyphosate (0.25 + 2.0 kg ha^{-1}, a.i. respectively). Hand planting was in December 1996 and herbaceous weed control (imazapyr + sulfometuron; 0.25 + 0.25 kg ha^{-1}) was applied in a band 1 m wide over the rows of planted pine in March 1997.

At Tyler, three blocks of eight 42 m × 28 m (0.12 ha) plots were established within a stand of ~12 ha. The two harvesting methods were combined with two site preparations methods (not bedded or bedded), and two fertilization treatments (none or 250 kg ha^{-1} diammonium phosphate) in a 2 × 2 × 2 factorial in a randomized block design. The eight treatment combinations were:

1	HFBO + aerial spray (AS)
2	HFBO + AS + bedded (Bd)
3	HFBO + AS + fertilized (DAP)
4	HFBO + AS + Bd + DAP
5	MWT + AS
6	MWT + AS + Bd
7	MWT + AS + DAP
8	MWT + AS + Bd + DAP

Harvesting at Tyler was conducted with a four-wheel feller-buncher (similar to a Franklin Hydrostatic Model C4500) equipped with a front mounted rotary cutter head during July to August 1994. In late September 1994, the harvested area was treated by helicopter with imazapyr and triclopyr (0.5 + 2.0 kg ha^{-1}). Bedding was conducted in October 1994 with a Savannah three-in-one plow, with two single discs and no packer, pulled by a D-7 tractor. The site was planted with improved loblolly pine seedlings in March 1995 but *Hylobius pales* Herbst caused >50% mortality in several plots. Therefore, in August 1995, the planted trees in all 24 plots were pulled up. The entire area was retreated with imazapyr and triclopyr in September 1995 and replanted in February 1996. On May 1996, fertilized plots received 250 kg ha^{-1} (~45 kg ha^{-1} N + 50 kg ha^{-1} P) diammonium phosphate (DAP), broadcast by hand.

2.3. Biomass and nutrient capital

All plots were inventoried prior to harvesting. Total height and diameter at 1.3 m (dbh) were recorded for all trees >5 cm dbh. Pine biomass by components was calculated using regression equations from Baldwin (1987). Three dominant or co-dominant pines were felled on each plot to document stand development by stem analysis and provide samples for nutrient analysis. Starting at ground line, a disc was removed every 0.5 m for 10 m and every 1 m from 10 m to the tip. From the 0, 5 and 10 m discs, a 22.5° wedge was removed. Wood and bark were separated and composited by plots. Samples of pine foliage and branches were collected from the upper, middle, and lower third of the crown of each felled tree and composited. Biomass equations and estimates of nutrient concentrations for hardwoods came from Clark et al. (1985), Messina et al. (1986), and Phillips et al. (1989).

Four 1 m × 2 m subplots were established in each main plot. All vegetation <5 cm dbh was clipped, weighed, and sub-sampled for moisture determination and elemental analysis. The litter was also weighed and sub-sampled for analysis.

Tissue samples were dried at 70 °C to a constant weight and ground to pass a 20 mesh stainless steel screen. Nitrogen concentration was determined with a Fison's Instruments Model EA 1108 CHN analyzer. For other elements, samples were wet-ashed in nitric acid–hydrogen peroxide (Huang and Shulte, 1985) and analyzed with an ICP emission spectrophotometer.

Biomass and nutrients removed and retained by MWT harvesting at St. Helena was estimated by subtracting whole-tree values for pine and hardwood ≥15 cm dbh from the plot totals. For HFBO harvesting, only the values for boles $\geq$15 cm dbh were subtracted. At Tyler, only pine was harvested and only pine $\geq$15 cm dbh whole-tree or bole values for were subtracted from plot totals.

During MWT harvesting, considerable disturbance and redistribution of surface organic matter occurred. To verify that estimates of biomass removal based on calculation from the pre-harvest inventory were valid, six MWT plots were selected at the Tyler site and residual biomass was determined for the 1 m $\times$ 2 m subplots used in pre-harvest sampling. Actual residue differed from estimated residue by less than 5%, although the coefficient of variation among subplots approached 100%.

2.4. Soil sampling and analysis

Soil bulk density was estimated 1 month before and 9 months after harvesting at both locations. Volumetric samples were taken at four locations on each plot at depths of 0–5, 10–15, and 20–25 cm. Samples were dried at 105 °C to a constant weight. The loess soil from St. Helena contained no gravel or stone. A portion of the Tyler samples contained fine iron concretions but no corrections were made for these inclusions.

In June, prior to harvesting and in May and November the first and second year after harvesting, four random push tube samples of mineral soil from 0 to 15 cm were collected from each plot for chemical analyses. In September 1997, 2 years after harvest at St. Helena and 3 years at Tyler, volumetric samples were collected in 30 cm increments to a depth of 150 cm at four locations in each plot and composted. Sub-samples were removed for chemical analyses and the remainder dried at 105 °C to a constant weight. Soil samples for chemical analyses were air-dried, ground, and sieved to pass 2 mm. Total N and total C were determined with an elemental analyzer (Fison Instruments Model EA. 1108). Total C and total N concentrations in Tyler soil samples below 60 cm were below the limits of our analytical method and are not included in the results. Available P was extracted with dilute acid–fluoride solution (Byrnside and Sturgis, 1958) and exchangeable cations with ammonium acetate, pH 7 (Thomas, 1982), then analyzed in an ICP spectrophotometer. Subsequent studies demonstrated that the P levels in the soil from the study sites were too low for reliable assay with the ICP. Therefore, extractable P was determined using a colorimetric procedure (Olsen and Sommers, 1982).

2.5. N mineralization

Mineral N flux to a depth of 15 cm was monitored at the Tyler site using 5 cm $\times$ 30 cm polyvinyl chloride tubes and mixed bed ion exchange resin (IER) packets at the bottom of the tube (Binkley and Matson, 1983, Hart and Binkley, 1985). Binkley (1984) suggested this technique was most appropriate for field estimation of both N-mineralization and transport. We confirmed that no transformation or loss of NH_4^+ or NO_3^- occurred once adsorbed by IER. The tubes were driven into the soil to a depth of 15 cm and carefully removed. Approximately 1.0 cm of soil was removed from the bottom of the tube and replaced with a bag of resin. The tube was then returned to the hole. The IER bags contained 8 g of Fisher no. R276-500 plus a perforated plastic disc ~5.1 cm diameter. Both disc and resin were wrapped in nylon mesh. Bags were assembled and stored frozen until transported to the field in an ice chest. Four tubes were placed in each plot, at random locations within randomly selected rows. Sampling tubes in bedded plots we placed at or near the crest of the bed. The scalped, inter-bed areas were not sampled.

Incubations were conducted from October 1993 to June 1994, prior to harvesting, May to November 1995, and May to November 1996, after harvesting. Resin bags were replaced every 8 weeks except that the bags placed in tubes in October 1993 were not exchanged until April 1994 since the high water table during the winter months prevented tube withdrawal. Ambient levels of mineral N from the top of the mineral soil to 15 cm were determined at the beginning and end of each incubation period for soil samples collected with a push-tube proximal to the incubation tubes.

In the laboratory, mineral N was determined by the same methods for both soil and resin. Ten grams of soil (or 8.0 g of resin) were placed in 80 ml 2 N KCl (20 g of soil was dried at 105 °C for moisture determination). Extracts were shaken at ~275 rpm for an hour, allowed to settle for an hour, filtered, and stored at 4 °C until analyzed. Ammonium and nitrate N were determined with an ammonia conductivity detector

(Alltech Model 320). Net N mineralization was determined by summing mineral N captured by IER bags plus soil mineral N at the end of the monitoring period and subtracting soil mineral N at the beginning of the monitoring period.

2.6. Soil respiration

In situ soil respiration at the Tyler site was determined at three sampling points in each experimental plot. Points were randomly located but had similar surface characteristics. CO_2 was measured in static chambers using soda-lime ($NaOH + Ca(OH)_2$) as the alkali absorbent (Edwards, 1982). Incubation chambers consisted of 2.9 l steel cans, each covering a soil surface area of 0.019 m^2. Chambers were coated with silver paint and covered with small plywood shelters to reduce unnatural heating of the soil surface. Soda-lime was pre-dried for 24 h at 100 °C and 30 g were weighed into a jar which was then placed under a chamber. The chambers were set ~1 cm into the soil to ensure a good seal between the soil and can, but to also minimize root severing. Any CO_2 flush that occurred from positioning the can was considered minimal or at least constant among treatments. Surface litter was left undisturbed. After a 24 h exposure period, the soda-lime was dried and re-weighed in the lab. The CO_2 respired was determined by the weight increase multiplied by a correction factor of 1.41 to account for water produced by chemical reactions and driven off by the drying process (Edwards, 1982). Soil temperatures were measured at a depth of 10 cm each time chambers were placed in the field. Two blanks were measured for each treatment to correct for ambient CO_2 levels inside the chambers. Blanks, consisting of sealed chambers containing soda-lime, were placed on the soil surface. Soil respiration measurements were terminated prior to fertilization, thereby permitting the evaluation of harvesting and bedding only.

2.7. Microbial populations

At the Tyler site, soil samples (without O layers) were collected near the incubation chambers to a depth of 15 cm with a standard bucket auger. Samples were collected four times during the study, twice to represent a "cool/wet" season, and twice to represent a "warm/dry" season. Bacteria were plated on 1/10th strength Tryptic Soy Agar (Difco), actinomycetes on Actinomycete Isolation Agar (Difco), and fungi on Acid Agar and Rose Bengal Streptomycin agar (Parkinson, 1994; Wellington and Both, 1994; Zuberer, 1994). All microbes were expressed as colony forming units (CFU) per gram of soil.

2.8. Reference plots

At both study sites, three reference plots were located in an adjacent, unharvested area. Plot dimensions and sampling regimes were identical to those used in the experimental plots except that biomass inventories were not taken. However, time and resources prevented the establishment of reference plots until April to May 1996, 1 year after harvesting at St. Helena and 2 years after harvesting at Tyler. Soil samples for C and N determination were collected in June 1996 and 1997 from the St. Helena reference plots. The N mineralization was monitored at the Tyler reference area during the 1996 growing season.

2.9. Statistical analyses

Data were analyzed using a General Linear Models Procedure as implemented by SAS (Ver 6.13, SAS Institute, NC) or ANOVA procedures as implemented by Systat 9 (SPSS Inc., Chicago, IL). All references to significance are based on $\alpha = 0.05$ unless otherwise stated.

3. Results

3.1. Biomass removal

Table 1 shows the mean values for above-ground biomass and nutrient capital of the two study sites prior to harvesting and Table 2 gives the estimated amounts removed and retained under the two harvesting systems. At the Tyler site, MWT harvesting removed 19, 168, 124, 67, 28, and 45% more biomass, N, P, K. Ca, and Mg, respectively, than HFBO harvesting. In the younger St. Helena stand, differences between MWT and HFBO were greater; 89, 315, 264, 153, 87, and 103%. Our differences between whole-tree and bole-only harvesting bracket those

Table 1
Pre-harvest biomass and nutrient pools

Component	Biomass (Mg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})
St. Helena site						
Pine	90.4	232.7	13.9	92.2	160.9	43.6
Bole	66.4	71.5	4.4	39.2	101.9	23.9
Branches	14.5	48.1	3.1	19.4	38.8	9.7
Foliage	9.5	113.1	9.4	33.5	20.1	10
Hardwoods	18.1	43.6	2.3	20.6	87.9	9.3
Bole	15	28	1.5	15.2	64.4	6.8
Branches	3.1	15.6	0.8	5.4	23.5	2.5
Understory	4.4	37.6	1.9	15.8	25.4	6.6
Forest floor	32.8	332.6	11.2	23.6	223.8	37.7
Above ground totals	145.7	646.5	29.3	152.2	498	97.2
Soil (0–15 cm) (pH 4.6)	33.9[a]	1431.8	3.9	48.2	401.3	76.3
Tyler site						
Pine	112.4	193.3	13.7	97.7	173.4	50.5
Bole	94.1	72.1	6.1	58.5	134.9	34.8
Branches	11.4	32.9	2.2	13.8	23.3	7.5
Foliage	6.9	88.3	5.5	25.4	15.2	8.2
Hardwoods	10.7	22.8	1.4	14.1	63.8	7.3
Bole	8.8	14.5	0.9	10	43.8	5.4
Branches	1.9	8.3	0.5	4.1	20	1.9
Understory	10.5	85.3	3.9	37.7	73.1	22.2
Forest floor	19.8	123.3	4.5	9.5	100.7	19
Above ground totals	153.4	424.7	23.5	159	411	99
Soil (0–15 cm) (pH 4.9)	21.1[a]	665.6	2.3	30.6	180.5	25.8

[a] Total C.

estimated by Tew et al. (1986) for a 22-year-old loblolly pine stand except for Ca and P. They estimated higher removal of Ca and P probably due to the higher component of hardwood in their stand (~30% of basal area compared to 14% at St. Helena and <1% at Tyler).

3.2. Soil C and N

Total C and N in the surface soil (0–15 cm) responded to harvesting in a similar way at both sites, declining during the first year after harvesting and increasing during the second year. There were no significant differences between harvesting systems (Table 3). At St. Helena, the mean decrease in soil total C was 8.2 ± 1.6 Mg ha^{-1} and the mean increase was 5.3 ± 2.1 Mg ha^{-1}. At Tyler, total C decreased 7.6 ± 1.6 Mg ha^{-1} followed by an increase of 5.2 ± 1.9 Mg ha^{-1}. Soil total N, at St. Helena, declined 361 ± 81 kg ha^{-1} the first year and increased 183 ± 84 Mg ha^{-1} the second year. At Tyler, the mean decrease was 381 ± 56 kg ha^{-1} followed by a mean increase of 370 ± 69 kg ha^{-1}. Table 4 summarizes ANOVA's where the yearly values are treated as repeated measurements. The quadratic contrasts for both C and N are highly significant ($P < 0.0001$) at both locations, indicating that the declines and recoveries are real. A comparison of annual means using the t-statistic resulted in the same conclusions. The linear contrasts for total N ($P = 0.0312$) at St. Helena and total C ($P = 0.0348$) at Tyler indicate that these parameters had not returned to pre-harvest levels 21 months after harvesting (Table 4). However, soil total C appears to have recovered to pre-harvest levels at St. Helena ($P = 0.0954$) as has soil total N at Tyler ($P = 0.7850$) (Table 4). At St. Helena, soil total

Table 2
Estimates of biomass and nutrients removed by harvesting and retained on site by the two harvesting systems: HFBO, hand felling bole-only removed; MWT, mechanical harvesting with whole-tree removal[a]

Component	Biomass (Mg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})
St. Helena site[b]						
HFBO						
Total	142 (6.8)	641 (31)	29.1 (1.6)	150 (10)	485 (20)	94.0 (4.3)
Removed	65.1 (4.0)	63.1 (4.5)	4.1 (0.3)	39.6 (2.5)	105 (8.2)	22.7 (1.6)
Retained	77.3 (3.7)	578 (79)	24.9 (1.4)	110 (8.6)	379 (17)	71.4 (3.4)
% Removed	46	10	14	26	22	24
MWT						
Total	150 (4.5)	645 (28)	29.2 (1.2)	153 (6.7)	505 (19)	96.1 (2.9)
Removed	100 (5.0)	244 (13)	14.5 (0.8)	102 (4.3)	202 (11)	46.8 (2.1)
Retained	50.0 (3.3)	401 (23)	14.7 (0.9)	51.1 (4.5)	303 (19)	49.3 (3.0)
% Removed	67	38	50	67	40	49
Tyler site[c]						
HFBO						
Total	160 (8.0)	448 (46)	28.1 (1.8)	188 (16)	470 (28)	101 (7.4)
Removed	77.5 (4.2)	58.5 (3.1)	8.4 (0.5)	66.1 (3.6)	154 (29)	37.4 (2.0)
Retained	82.4 (9.2)	389 (46)	19.6 (1.8)	122 (17)	315 (28)	63.9 (7.6)
% Removed	48	13	30	35	32	37
MWT						
Total	147 (6.3)	390 (21)	25.4 (1.1)	167 (8.4)	411 (14)	89.2 (3.8)
Removed	90.8 (5.0)	137 (7.8)	13.6 (0.8)	93.0 (5.2)	172 (5.9)	41.8 (2.3)
Retained	56.5 (7.6)	253 (19)	11.8 (0.7)	73.6 (7.1)	240 (12)	47.3 (3.1)
% Removed	62	35	54	56	42	47

[a] Standard errors shown in parenthesis.
[b] Merchantability limits: minimum dbh = 15 cm; minimum top diameter = 5 cm, for both pine and hardwoods.
[c] Merchantability limits: minimum dbh = 15 cm; minimum top diameter = 5 cm. Pine only harvested.

C and total N increased in the unharvested reference plots between year 1 and year 2 (Table 3) but sample size was small and differences between years did not exceed the 95% confidence level. The C/N ratio in the upper 15 cm of mineral soil remained fairly constant at St. Helena ranging from 22 to 27 (Table 3), but it varied considerably between years at Tyler, rising sharply the year after harvesting before returning to near or slightly below pre-harvest values (Table 3). The main effect of bedding was significant at Tyler but not at St. Helena (Table 3). However, the interaction between harvesting and bedding, which was not significant at Tyler, was significant at St. Helena for both total C and total N (Figs. 1 and 2).

The deeper soil samples, collected 24 months after harvesting at St. Helena and 36 months after harvesting at Tyler, still failed to show significant differences in soil total C or total N between harvesting intensities but significant effects due to cultural treatments were detected at both sites (Table 5). At Tyler, bedded soil was higher in total C (30–60 cm) but not total N, while fertilized soil was higher in total N (0–30 and 30–60 cm) but not total C (Table 5). Soil from the surface 60 cm of fertilized plots averaged ~371 kg ha^{-1} more total N than did soil from unfertilized plots. The DAP, applied 16 months prior to soil sampling, added only ~45 kg ha^{-1} N. At St. Helena, herbaceous weed control, applied 6 months prior to sampling, reduced total C in the 30–60 cm stratum. No interaction between harvesting and bedding on soil total C or total N was detected in these later, deeper samples.

Table 3

Effects of site treatments on the total C, N, and C/N ratio in the upper 15 cm of mineral soil. HFBO, hand felled bole-only removed; MWT, mechanical whole-tree harvesting; AS, aerial spray; HWC, herbaceous weed control

Main treatment[a]	Total C (Mg ha^{-1})			Total N (kg ha^{-1})			C/N ratio[b]		
	Before harvest	Nine months after harvest	Twenty-one months after harvest	Before harvest	Nine months after harvest	Twenty-one months after harvest	Before harvest	Nine months after harvest	Twenty-one month after harvest
St. Helena site									
HFBO	33.0	24.6	29.6	1402	1046	1189	24	24	25
MWT	34.9	26.7	32.4	1462	1095	1318	24	24	25
$P > F$	0.3281	0.161	0.3208	0.5493	0.4588	0.1576	–	–	–
AS	32.1	25.3	30.1	1433	1040	1314	22	24	23
AS + bedded	35.1	27.4	33.9	1413	1143	1259	25	24	27
AS + HWC 2	34.6	24.3	28.9	1448	1029	1187	24	24	24
$P > F$	0.3789	0.2277	0.3198	0.9572	0.3009	0.4953	–	–	–
Reference area (S.E.)	–	32.9 (1.7)	38.0 (3.4)	–	1402 (72)	1526 (102)	–	23	25
Tyler site									
HFBO	24.6	16.1	20.4	708	343	665	35	47	31
MWT	23.8	17	23.1	684	287	704	35	59	33
$P > F$	0.6083	0.5963	0.2351	0.6331	0.3838	0.6078	–	–	–
Not bedded	23.5	14.6	19.7	662	255	607	35	57	32
Bedded	24.9	18.6	23.9	730	375	762	34	50	31
$P > F$	0.3864	0.0315	0.0723	0.1902	0.0705	0.0558	–	–	–
Not fertilized	25.5	16.6	22.9	750	283	667	34	59	34
Fertilized (DAP 250 kg ha^{-1})	22.9	16.5	20.7	641	347	692	36	48	30
$P > F$	0.1073	0.8611	0.3175	0.0456	0.2048	0.8396	–	–	–

[a] HWC treatment applied 2 months prior to soil sampling. DAP applied 7–9 days prior to soil sampling.

[b] Ratios calculated from treatment means in columns to the left.

Table 4
Analyses of variance of soil total C and total N (0–15 cm) using a one-way repeated measures model and single d.f. orthogonal polynomials to compare the values for years, May 1994 (before harvest); May 1995 (first year after harvest); May 1996 (second year after harvest) at Tyler and June 1995 (before harvest); June 1996 (first year after harvest); June 1997 (second year after harvest) at St. Helena

Source	d.f.	SS	MS	*F*	*P*	d.f.	SS	MS	*F*	*P*
Single degree of freedom polynomial linear contrast						Single degree of freedom polynomial quadratic contrast				
St. Helena, soil C (0–15 cm)										
Year	1	80.85	80.85	3.12	0.0954	1	554.47	554.47	69.38	<0.0001
Error	17	440.76	25.93			17	440.76	25.93		
St. Helena, soil N (0–15 cm)										
Year	1	285866.66	285866.66	5.52	0.0312	1	888665.91	888665.91	63.03	<0.0001
Error	17	881184.94	51834.41			17	239696.32	14099.78		
Tyler, soil C (0–15 cm)										
Year	1	69.18	69.18	5.03	0.0348	1	658.17	658.17	67.08	<0.0001
Error	23	316.31	13.75			23	225.66	9.81		
Tyler, soil N (0–15 cm)										
Year	1	1468.44	1468.44	0.08	0.7850	1	2251570.00	2251570.00	112.15	<0.0001
Error	23	443315.43	19274.58			23	461756.03	20076.35		

Table 5
Effects of treatment on total C and total N in the upper 60 cm of soil 24 months after harvesting at St. Helena and 36 months after harvesting at Tyler

Main treatments	Total C (Mg ha^{-1})		Total N (kg ha^{-1})		C/N ratio[a]	
	0–30 cm	30–60 cm	0–30 cm	30–60 cm	0–30 cm	30–60 cm
St. Helena site						
HFBO	52.7	12.9	2279	958	23	13
MWT	44.4	11.6	2109	841	21	14
$P > F$	0.1302	0.4798	0.4854	0.1984	–	–
AS	50.4	12.4a[b]	2323	988	22	13
AS + bedded	51.9	14.8a	2243	864	23	17
AS + HWC	43.2	9.4b	2015	847	21	11
$P > F$	0.3541	0.0803	0.5571	0.3683	–	–
Tyler site						
HFBO	31.5	8.8	999	344	32	26
MWT	33.7	6.7	1101	404	31	17
$P > F$	0.6480	0.2365	0.4616	0.1500	–	–
Not bedded	29.0	5.2	962	350	30	15
Bedded	36.3	10.3	1138	398	32	26
$P > F$	0.1398	0.0102	0.2117	0.2297	–	–
Not fertilized	29.0	7.8	910	328	32	24
Fertilized (DAP 250 kg ha^{-1})[b]	36.3	7.6	1191	420	30	18
$P > F$	0.1407	0.8979	0.0548	0.0334	–	–

[a] Calculated from the means in columns to the left.
[b] Means followed by different letters are significantly different ($\alpha = 0.05$).

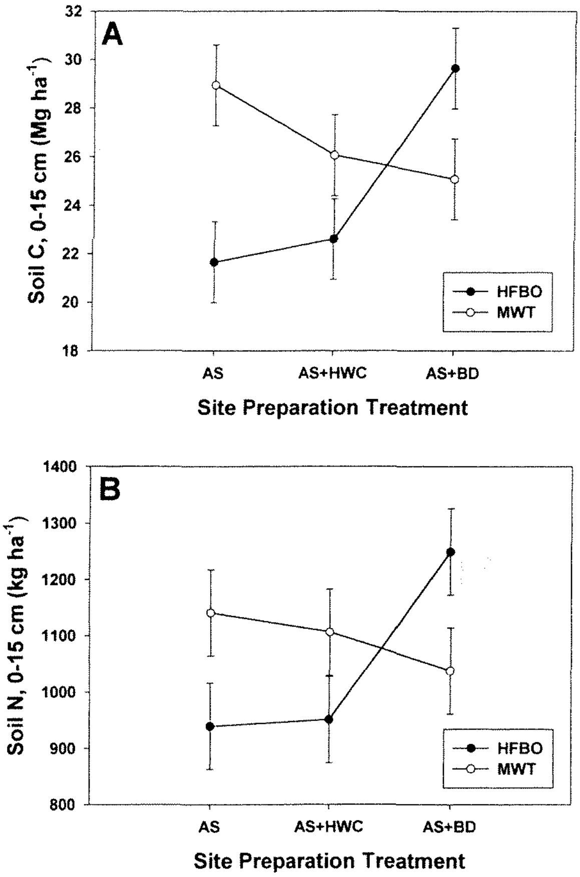

Fig. 1. The effect of harvesting method and site treatments on: (A) total C; and (B) total N, in the surface 15 cm of soil at the St. Helena site 1 year after harvesting. MWT, mechanical whole-tree harvesting; HFBO, hand felling bole-only removed; AS, aerial spray only; AS + HWC, AS + herbaceous weed control; AS + BD, AS + bedding. The interaction between harvesting method and site treatments was significant ($P = 0.0149$ for total C; $P = 0.0435$ for total N); error bars for $\alpha = 0.05$.

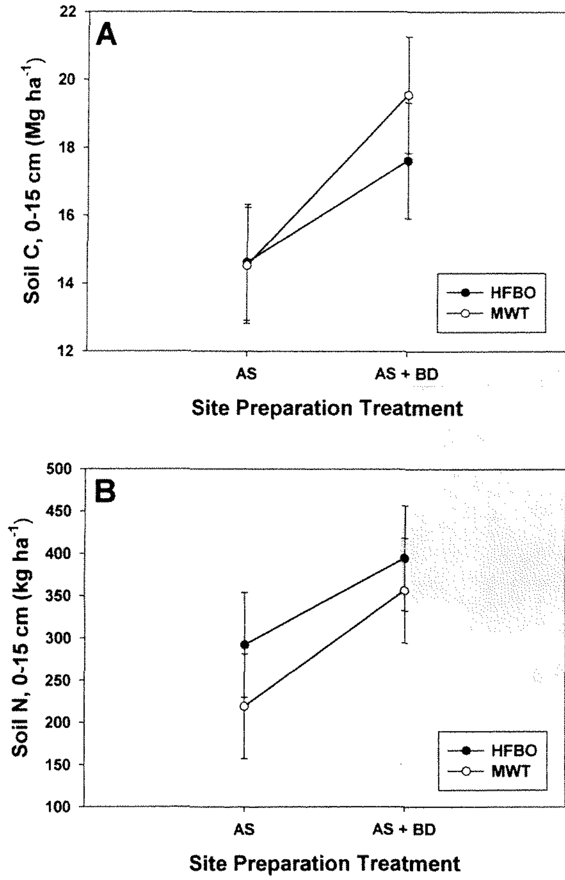

Fig. 2. The effect of harvesting method and site treatments on: (A) total C, and (B) total N, in the surface 15 cm of soil at the Tyler site 1 year after harvesting. MWT, mechanical whole-tree harvesting; HFBO, hand felling bole-only removed; AS, aerial spray only; AS, aerial spray only; AS + BD, AS + bedding. The interaction between harvesting method and site treatments was not significant ($P = 0.5624$ for total C; $P = 0.7836$ for total N); error bars for $\alpha = 0.05$.

3.3. N mineralization

Net N mineralization was higher the first growing season after harvesting than before or 2 years after harvesting or in the reference plot (Table 6). The increase was due almost entirely to a higher NO_3^- flux especially in bedded soil during the first year after harvest (Fig. 3a). There were no differences due to harvesting methods (Table 6, Fig. 3). During the 1 May to November after harvesting, NH_4^+ production averaged 2.5 kg ha^{-1} per month and was not affected by treatment while NO_3^- flux was 10.3 kg ha^{-1} per month in un-bedded soil and significantly higher ($P < 0.001$) at 14.7 kg ha^{-1} per month in bedded soil. During the second May to November period, net N mineralization in the harvested plots was below that in the unharvested reference area and NO_3^- flux was equal to or below that of NH_4^+ (Table 6, Fig. 3b). The 45 kg ha^{-1} N applied as DAP 10 days prior to soil sampling in May of year 2 resulted in significantly more mineral N in the May soil samples and in mineral N captured on the May to July resin samples. But mineral N flux following fertilizer application did not reach the levels recorded for bedded soil during the

Table 6

N mineralization ($NH_4^+ + NO_3^-$) at the Tyler site, before harvesting and mineral N flux and net mineralization during the first (1995) and second (1996) year after harvesting and site preparation

Main treatment effects	Net N minimum before harvest[a]	First year after harvesting (1996) (kg ha^{-1})						Second year after harvesting (1996) (kg ha^{-1})					
		Minimum N in soil, May	Resin, May to July	Resin, July to September	Resin, September to November	Minimum N in Soil, November	Net N minimum	Minimum N in soil, May	Resin, May to July	Resin, July to September	Resin, September to November	Minimum N in Soil, November	Net N minimum
HFBO	42.0	7.0	32.9	18.4	21.0	7.4	72.8	14.5	23.7	19.7	17.1	3.8	49.8
MWT	39.0	6.7	28.7	21.6	28.8	4.7	77.1	14.1	19.7	15.7	19.2	4.5	45.0
$P > F$	0.4340	0.8904	0.2438	0.2718	0.2420	0.2245	0.6727	0.8610	0.1466	0.4292	0.4200	0.4937	0.6058
Not bedded	39.9	5.4	25.4	17.1	20.0	4.6	61.6	11.8	20.8	17.9	20.7	3.6	51.1
Bedded	41.1	8.3	36.3	22.9	29.8	7.6	88.3	16.8	22.7	17.5	15.6	4.7	43.7
$P > F$	0.7456	0.1428	0.0066	0.0518	0.1545	0.1687	0.0021	0.1503	0.4855	0.9318	0.0870	0.3677	0.4596
Not fertilized	42.1	7.0	31.4	21.9	23.1	5.8	75.2	9.0	17.8	14.0	17.1	4.5	44.5
Fertilized[b]	38.9	6.8	30.3	18.2	26.7	6.3	74.8	19.5	25.6	21.4	19.2	3.7	50.4
$P > F$	0.3935	0.9210	0.7688	0.2015	0.5983	0.8001	0.9612	0.0057	0.0121	0.1545	0.4673	0.5029	0.5229
Reference area (S.E.)								2.0 (0.3)	13.8 (1.4)	21.9 (3.1)	25.6 (1.9)	8.3 (2.3)	67.6 (9.0)

[a] 1 October 1993 to June 1994.

[b] DAP not applied until second year (1996) after harvesting and 10 days prior to soil sampling.

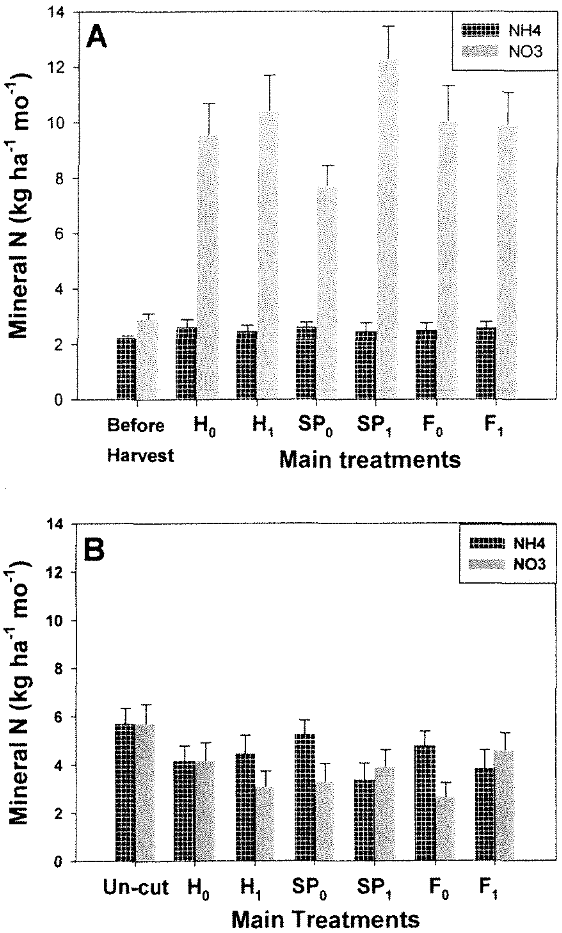

Fig. 3. Means for the main treatment effects on net N mineralization in 0–15 cm of soil at Tyler. Monitoring period was October to June before harvesting and May to November: (A) first year after harvesting; (B) second year after harvesting. H_0 = HFBO; H_1 = MWT; SP_0 = not bedded; SP_1 = bedded; F_0 = not fertilized; F_1 = 250 diammonium phosphate applied in May of second year. Error bars for $\alpha = 0.05$.

first season following harvesting (Fig. 3). No differences due to fertilization were detected after the July samples and net mineralization for the season was not altered (Table 6, Fig. 3b).

ANOVA of pre-harvest N mineralization data indicated no differences between blocks or treatments; therefore, the means presented in Table 6 were not adjusted for differences prior to harvesting. Regression analysis indicated no significant relationship between the N mineralization rate before harvest and that during the first season after harvest but a significant negative relationship was found between the before-harvest rate and the rate during the second growing season after harvesting (Table 7). There was also a significant block effect during the second year that was not detected earlier.

3.4. Soil respiration and temperature

As expected, pre-treatment soil respiration did not differ significantly among plots, even though the respiration rates for the plots to be bedded appeared to be slightly higher than those for the plots destined to be left un-bedded (Table 8). Respiration rates were significantly affected by bedding but not by harvesting method (Table 8). Bedded soil averaged 12.6 g CO_2 m^{-2} per day, whereas un-bedded soil averaged 9.7 g CO_2 m^{-2} per day. HFBO harvested plots averaged 11.7 g CO_2 m^{-2} per day and MWT harvested plots, 10.6 g CO_2 m^{-2} per day. Because the bedded plots had a slightly higher pre-treatment respiration rate than plots not bedded, a covariance analysis was performed on post-treatment respiration rate using pre-treatment rate as the independent variable. This showed that the increased respiration following bedding was indeed statistically significant (data not shown).

Treatment did not affect soil temperature. The mean soil temperature across all treatments for the six post-treatment sampling sessions was 17.8 °C with a range of only ±0.5 °C among treatments. During the same period, mean temperature in an adjacent unharvested area was only slightly lower at 17.0 °C. Before treatment, mean soil temperature across all treatments for the six sampling periods was 20.1 °C, with a range of only ±0.2 °C.

Fluctuations in soil respiration rates appeared to reflect seasonal trends in soil temperature both before and after treatment (Fig. 4). Higher soil temperatures usually resulted in higher rates of respiration. Application of the generally accepted Q_{10} exponential relationship between CO_2 efflux rate and soil temperature showed that soil temperature was a reasonably good predictor of soil respiration rates. However, the relationship between soil temperature and soil respiration was of a different form before treatment than it was after treatment (Fig. 5). For pre-treatment data, the relationship between respiration and temperature could be defined by the equation

Table 7
Regression analysis of net N mineralization during first and second growing seasons after harvesting at the Tyler site

Source	d.f.	SS	MS	F	$P > F$	Variable	Coefficient	S.E.	t	P
Year 1 after harvesting (May to November 1995)[a]										
Regression	6	6035.92	1005.99	1.90	0.1384	Intercept, b_0	46.25	28.75	1.61	0.1213
Residual	17	8980.39	528.26			N minimum before harvest, b_1	0.32	0.63	0.50	0.6217
						Blocks, linear, b_2	8.73	5.77	1.51	0.1440
						Blocks, quadratic, b_3	−3.25	3.45	−0.94	0.3559
						Harvesting method, b_4	5.35	9.56	0.56	0.5810
						Bedding, b_5	26.29	9.41	2.79	0.0103
Total	23	15016.31				Fertilization, b_6	0.50	9.60	0.05	0.9588
Year 2 after harvesting (May to November 1996)[b]										
Regression	6	6929.03	1154.84	4.46	0.0069	Intercept, b_0	111.43	20.12	5.54	<0.0001
Residual	17	4397.92	258.70			N minimum before harvest, b_1	−1.43	0.44	−3.24	0.0036
						Blocks, linear, b_2	−12.64	4.04	−3.13	0.0047
						Blocks, quadratic, b_3	−3.47	2.41	−1.44	0.1638
						Harvesting method, b_4	−8.90	6.69	−1.33	0.1968
						Bedding, b_5	−5.06	6.59	−0.77	0.4504
Total	23	11326.95				Fertilization, b_6	1.26	6.72	0.19	0.8523

[a] Regression: R^2 0.40; S.E. 22.98; Observations 24.
[b] Regression: R^2 0.61; S.E. 16.08; Observations 24.

Table 8
Pre- and post-harvest mean soil surface CO_2 efflux by treatment

Treatments[a]	1994 (pre-harvest) CO_2 efflux ($g\ m^{-2}$ per day)	1995 (post-harvest) CO_2 efflux ($g\ m^{-2}$ per day)
HFBO	10.87	11.70
MWT	10.68	10.56
$P > F$	0.7900	0.2400
Not bedded	10.16	9.66
Bedded	11.38	12.60
$P > F$	0.0900	0.0050

[a] Means for fertilized plots not included since DAP was not applied until after CO_2 monitoring ended.

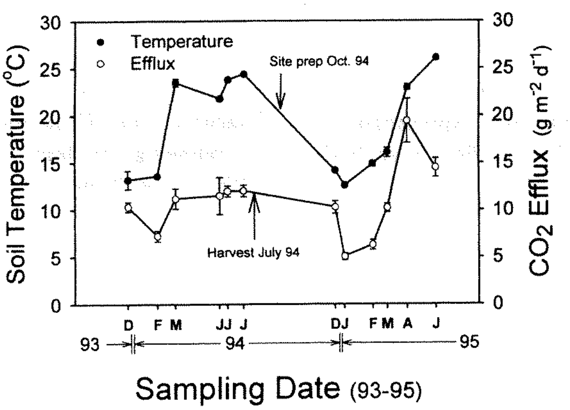

Fig. 4. Variation in soil surface CO_2 efflux and soil temperature through time before and after harvesting and site preparation at Tyler. Data are the means of all harvesting and site preparation treatment combinations except un-cut reference plots. Error bars for $\alpha = 0.05$.

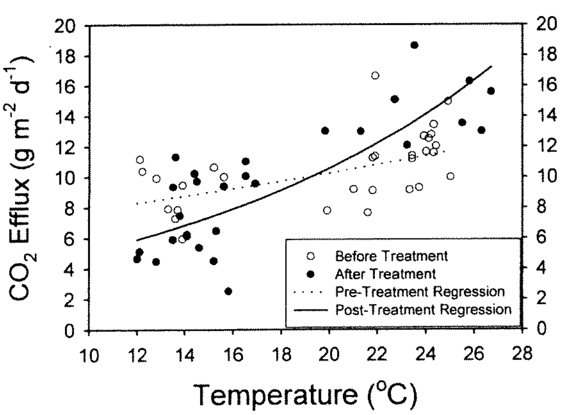

Fig. 5. Relationship between soil surface CO_2 efflux and soil temperature before and after harvesting and site preparation of the loblolly pine stand at Tyler.

$CO_2 = 6.049 \times 1.302^{T/10}$, with an $R^2 = 0.30$ ($P = 0.002$). Post-treatment, the respiration-temperature relationship was defined by $CO_2 = 2.462 \times 2.072^{T/10}$, with an $R^2 = 0.52$ ($P = 0.0001$).

3.5. Microbial populations

Harvesting and bedding had no effect on populations of bacteria, actinomycetes, or fungi (Fig. 6). Populations varied among sampling sessions in a

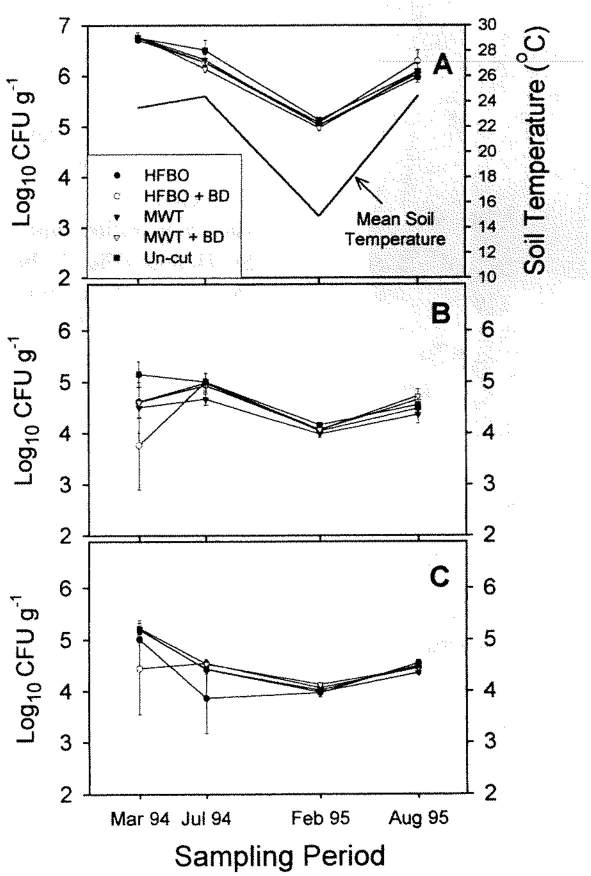

Fig. 6. Variation in: (A) bacteria; (B) actinomycetes; and (C) fungi populations at the study site (CFU, colony forming units). The first two sampling dates: March and July 1994, were before harvesting and the second two: February and August 1995, were after harvesting and site preparation. Mean soil temperature at sampling time: March 1994 = 23.5 °C; July 1994 = 24.4 °C; February 1995 = 14.9 °C. August 1995 was not determined but was approximately same as July 1994. Error bars for $\alpha = 0.05$. HFBO, hand felled bole-only harvesting not bedded; HFBO + BD = bedded; MWT, mechanical whole-tree harvesting not bedded; MWT + BD = bedded.

similar manner in all treatments, and appeared to respond more to soil temperature than to treatments, particularly in the case of bacteria (Figs. 4 and 6a)

4. Discussion

Decomposition of loblolly pine logging residues is a relatively slow process (Barber and Van Lear, 1984; Jorgensen and Wells, 1986). Thus, it was not surprising to find no significant differences in soil total C and total N between harvesting methods after 2–3 years unless residues were incorporated by bedding (Tables 3 and 5). The main effect of bedding on soil total C and N was significant at Tyler but not at St. Helena (Table 3), however, the interaction between site preparation and harvesting was significant at St. Helena (Fig. 1) but not at Tyler (Fig. 2). At both locations, there was considerably more logging residue on the HFBO plots than on the MWT plots (Table 2), but the tractor used to pull the bedding plow at Tyler had a front-mounted V-blade while the tractor used at St. Helena did not. The V-blade pushed much of the logging residue away from the path of the plow thus preventing its' incorporation into the beds. This could account for the lack of interaction between harvesting method and bedding on soil total C and N at Tyler.

Surface soil (0–15 cm) at St. Helena contained ~50% more total C than the soil at Tyler prior to harvesting but the losses in total C during the first year after harvesting and increases the second year were similar (8.2 and 7.6 kg ha^{-1} lost; 5.3 and 5.2 kg ha^{-1} gained, respectively). The losses could be attributed to soil respiration assuming the mean respiration rate at Tyler (~10 g m^{-2} per day or 3 Mg ha^{-1} per month, see Table 8) was representative of both locations and inputs from photosynthesis were reduced. Forest harvesting and herbicide treatment should reduce inputs from photosynthesis, at least for several months. Between year 1 and year 2, considerable regrowth occurred and soil total C increased (Table 3). Smethurst and Namibar (1990) reported that soil total C declined following harvesting a 37-year-old plantation of *Pinus radiata* and did not recovery completely for 4 years. However, they maintained weed-free conditions with repeated applications of herbicides.

Hendrickson et al. (1989) examined the effects of whole-tree harvesting on soil respiration rates and nutrient cycling in a mixed pine–hardwood stand in Ontario and found field respiration rates to be significantly higher in harvested than in uncut areas, which they attributed to increased soil temperatures in the harvested sites. They theorized that if elevated rates of soil respiration continued in the clear-cuts, it was possible that soil organic matter pools would stabilize at a lower level than in the original forest, thereby resulting in possible decreases in site productivity until the soil organic matter pool returned to pre-harvest levels. Knoepp and Swank (1997) reported soil total C declined during the first year after WTH harvesting but recovered to near pre-harvest levels within 4 years. After a commercial sawlog harvest, total C in the surface 10 cm doubled and remained at that level for 3 years (Knoepp and Swank, 1997). Both Hendrickson et al. (1989) and Knoepp and Swank (1997) worked at higher latitudes than our sites. Changes in soil temperature following overstory removal were probably greater and re-vegetation slower than we observed. Johnson (1992), after reviewing a number of studies, concluded that harvesting resulted in changes of <10% of pre-harvest soil C content. Our findings agree with this conclusion, although major fluctuations may extend over a period of months or years before soil C returns to pre-harvest levels.

There are conflicting reports of the effects of fertilization on soil C. Turner and Lambert (1988) reported a 22% increase in soil total C 30 years after application of phosphorus to a planting of *Pinus radiata* D. Don. growing on a P deficient site in Australia. In contrast, Harding and Jokela (1994) found no effect of fertilization on soil total C in a 25-year-old plantation of *Pinus elliottii* Englm. in Florida. Sixteen months after DAP application at our Tyler site, we measured 7.3 Mg ha^{-1} more total C in the surface 30 cm of fertilized plots than unfertilized plots (Table 5) but this difference was not significant ($P = 0.1407$). It seems improbable that fertilization could result in so large an increase in carbon sequestration in so short a time period although DAP significantly increased pine tree growth (unpublished data). At St. Helena, herbaceous weed control reduced herbaceous biomass >80% (unpublished data) and soil total C at 30–60 cm (Table 5).

Changes in soil total N (Tables 3–5) are more difficult to understand than the corresponding changes in total C. Total N in the surface 15 cm declined an average of 361 kg ha^{-1} at St. Helena and 381 at Tyler during the year following harvesting. Mineralization and leaching may be responsible for these declines in soil N, but the rate of mineral N flux during the first 9 months after harvesting would have to be several times that which we recorded between the 9th and 15th months at Tyler (Table 6). Earlier investigations of changes in soil total N after harvesting have produced conflicting results. Mroz et al. (1985) reported a loss of 1.3 Mg ha^{-1} of N from the top 1 m of soil following WTH in northern hardwoods, but Hendrickson et al. (1989) reported N leaching below the rooting zone was <2 kg ha^{-1} per year following WTH in northern mixed forests. Knoepp and Swank (1997) found that the N concentration in 0–10 cm of soil declined ~0.5 g kg^{-1} immediately following whole-tree harvesting (WTH). Assuming a BD of 1.0 g l^{-1}, the N loss would be ~500 kg ha^{-1} from the 0–10 cm layer on the WTH site. They found no change at 10–30 cm and suggested that the N remained in the profile below 30 cm. Binkley et al. (2000) reviewed other studies on the watersheds used by Knoepp and Swank (1997) and concluded that leaching and runoff could not account for the losses in soil N.

Equally puzzling is the rapid recovery of soil N during the second year. At St. Helena, surface soil total N increased 183 kg ha^{-1} or ~50% of the loss during the previous year. At Tyler, the increase between year 1 and year 2 was 370 kg ha^{-1} or 97% of the earlier decline. Knoepp and Swank (1997) found that it took ~5 years for surface soil total N to return to pre-harvest levels following WTH, but this translates to an accretion of 70–100 kg ha^{-1} per year, >10 times what could be expected from atmospheric deposition and non-symbiotic fixation (Binkley et al., 2000). Following a partial cutting—a commercial sawlog harvest (CSH) with tops left in place—Knoepp and Swank (1997) found that N increased ~1.0 g kg^{-1} or 1000 kg ha^{-1} in 0–10 cm the first year after harvesting and remained well above pre-harvest levels for 3 years. They attributed this increase to, "large amounts of logging residue left on site, root mortality, and a successional pattern that included N fixers". However, they had more fixers (*Robinia pseudoacacia* L. sprouts) on the WTH where N declined, than on the CSH where N increased.

Interannual variations in total soil C and N similar to those in the reference plots at St. Helena (Table 3) have been reported by other (Haines and Cleveland, 1981; Knoepp and Swank, 1997), but there is no documented processes that could explain such within or between year variations (Binkley et al., 2000). Richter et al. (2000) reported little long-term change in soil total N during 40 year of growth of a loblolly pine plantation in South Carolina. The increased level of soil total N that we observed following DAP application (Table 5) is in contrast to the work of Harding and Jokela (1994) who found no detectable long-term effects of N and P applications on soil total N to 90 cm.

Our findings and those from other studies (Mroz et al., 1985; Knoepp and Swank, 1997) suggest the possibility that, following clearcutting, mineral and soluble organic nitrogen is leached below the rooting zone where it remains until roots of regrowth capture it and return it to the surface soil. Further evidence for this theory is provided by the fact that Knoepp and Swank (1997) did not observe a decline in total N following CSH which left non-merchantable trees with living roots to capture any N mobilized following harvesting. However, there is no direct evidence that large fluxes of N do indeed occur and we cannot discount the possibility that the fluctuations in total N that we observed and those reported by others are artifacts resulting from natural variation or flawed sampling procedures.

A number of studies have reported increased N mineralization following harvesting and regeneration (Burger and Pritchett, 1984; Vitousek and Matson, 1985; Van Lear et al., 1990; Knoepp and Swank, 1993). However, in all of these studies harvesting was confounded with one or more mechanical site preparation treatments (Burger and Pritchett, 1984; Vitousek and Matson, 1985) or burning (Van Lear et al., 1990; Knoepp and Swank, 1993). The effect of tillage on "soil metabolism" is well known in agriculture (Richards, 1987). Tillage increases soil aeration and microbial activity leading to a decline in soil organic C, total N, and mineralizable N (Tisdale et al., 1985; Doran, 1987). Increased N mineralization after burning is also well documented (Schoch and Binkley, 1986; Covington et al., 1991).

We recorded higher net N mineralization post-harvest than pre-harvest (Table 6), but the pre-harvest measurements included the winter season when N mineralization would have been much lower than during the growing season (Vitousek and Matson, 1985; Knoepp and Swank, 1998; Piatek and Allen, 1999). Net N mineralization in unbedded soil during the 1 May to November period after harvesting was 61.6 kg ha^{-1}, slightly below the 67.6 kg ha^{-1} in the reference area during the 2nd May to November period (Table 6). Apparently, harvesting, per se, caused a shift from ammonification to nitrification (Fig. 3) but no increase in net N mineralization, at least for 2 years after harvesting. Bedding, which tilled the soil and incorporated surface organic matter, increased soil respiration, NO_3^- flux, and net N mineralization. Waide et al. (1988) reported an increase in nitrification but only a slight increase in net N mineralization after harvesting and site preparation consisting of felling all stems $\geq$2.5 cm but no other soil disturbance. Matson and Vitousek (1981) also found that clearcutting without site preparation resulted in increased nitrification but no significant change in net mineralization until the fourth year after harvesting when N mineralization was significantly higher in the harvested site than in the control.

We found that bedding increased nitrification and net N mineralization similar to that reported for chop-burn or shear-piled-disc site preparation (Vitousek and Matson, 1985). However, bedding differs from these other treatments in that the entire area is not treated uniformly. Bedding concentrates surface soil and organic matter into ridges or beds separated by scalped and undisturbed areas. Morris (1981) found that the concentration of mineral N within beds was ~50% higher than in the inter-bed areas during the first year after bedding. Since we did not monitor the inter-bed areas, our estimates for net N mineralization per hectare following bedding are probably too high. On a treated area basis, bedding may result in considerably less increase in net N mineralization than chop-burn or shear-pile-disc site preparation.

By the second growing season after harvesting at Tyler, net mineralization had declined and ammonification equaled or exceeded nitrification (Table 6; Fig. 3). Vitousek and Matson (1985) also reported a decline in NO_3^- flux the second year but nitrification and net N mineralization remained well above the reference plots, perhaps, due to greater incorporation of surface organic matter than we achieved with bedding. Neither of us detected significant differences in net N mineralization or NO_3^- flux between whole-tree and stem-only harvesting during the first 2 years following harvesting. Wilson (1994) also failed to detect differences in net N mineralization rate between different levels of organic matter removal 2 years after harvesting.

Piatek and Allen (1999) revisited the study site used by Vitousek and Matson (1985), 15 years after harvesting and regeneration, and found net N mineralization was significantly lower in whole-tree plots than in stem-only plots. But harvest intensity had no effect on pine growth or soil total N. As stated earlier, harvesting intensity in this study was followed by either chop-burn or shear-pile-disc site preparation which would accelerate nutrient cycling and/or increase nutrient removal, thus confounding differences due to harvesting intensity. In addition, half of each treatment plot received complete weed control for the first 5 years which significantly increased pine production irrespective of other treatments (NCSFNC, 1995). Interestingly, the site preparation treatment, chop-burn-no herbicide, which had the highest N mineralization rate at plantation age 15 years (Piatek and Allen, 1999), resulted in the greatest total biomass production at plantation age 6 years (Allen et al., 1991).

Apparently, southern pine logging residues have little effect on soil N mineralization for 2–3 years after harvesting unless they are incorporated into the soil or burned. Mechanical site preparation or slash burning increases net N mineralization but competing vegetation may benefit more than pine regeneration. Grogan et al. (2000) found that the species that benefitted the most from increased nutrient availability following wildfire were those originating as re-sprouts from established root systems.

The inverse relationship between N mineralization before harvesting and 2 years after harvesting (Table 7) was not expected. It suggests that the impact of intensive site disturbance may be greater and/or more enduring on sites with higher ambient net N mineralization rates, but this possibility needs further study before definitive conclusions are drawn.

Our rates of in situ soil respiration with treatment means ranging from about 8 to 13 g CO_2 m^{-2} per day, are within the range reported for other coniferous ecosystems. Cropper et al. (1985) found a mean soil respiration rate of 8.7 g CO_2 m^{-2} per day in a Florida slash pine (*Pinus elliottii*) stand. Carlyle and Than (1988) measured a mean rate of 12 g CO_2 m^{-2} per day in an Australian radiata pine (*Pinus radiata*) stand. Kaye and Hart (1998) found respiration rates to vary seasonally from about 1.0 to 11 g CO_2 m^{-2} per day in Arizona ponderosa pine (*Pinus ponderosa*)—bunch grass ecosystems.

Soil temperatures were slightly cooler in the winter and warmer in the summer after harvesting and site preparation than they were before, but these changes were not as great as those reported by Hendrickson et al. (1989). Soil respiration increased exponentially with soil temperature both before and after treatment, but the Q_{10} of soil temperature on soil respiration (Edwards, 1975) was 1.3 before treatment compared to 2.1 after treatment (Fig. 5). Both are at the lower end of the expected range of 1.3–3.3 (Reich and Schlesinger, 1992). Lloyd and Taylor (1994) found less sensitivity of soil respiration to fluctuations in soil temperature in biomes, such as ours, that have relatively high soil temperatures. The change in Q_{10} after harvesting may reflect the same changes in microbial metabolism that resulted in increased nitrification.

Since changes in soil C and N status result from the activity of the saprophytic organisms (Crossley, 1977; Coleman et al., 1988; Christiansen et al., 1989), they may be quantified by monitoring changes in saprophyte populations (Edwards, 1975; Edwards and Ross-Todd, 1983; Curry and Good, 1992; Mattson and Smith, 1993; Hoekstra et al., 1995). However, changes in microbial populations following harvesting and/or site preparation at Tyler were too rapid or too subtle to be detected by the methodology used. Our findings that harvesting and regeneration had only a transitory effect of soil microbial populations is compatible with the findings of Bird et al. (2000) that harvesting and regenerating the pine forest had little impact on the forest floor arthropod community except for increased abundance following application of DAP. Unfortunately, we were unable to continue monitoring microbial populations during the season following DAP applications. Such data may have provided an insight on the mechanism whereby the DAP affected the arthropod population.

5. Conclusions

We found that harvesting and regeneration of pine plantations in the US gulf coast region resulted in rapid and significant declines in soil total C and total N. However, both total C and N returned to near pre-harvest levels by the end of the second growing season. Harvesting, per se, caused a temporary increase in nitrification but little or no change in soil temperature, soil respiration, or net N mineralization during the 2 years following harvesting. Conversely, mechanical site preparation (bedding), which tilled the soil and incorporated surface organic matter, resulted in increased soil total C, total N, and net N mineralization. Increased net N mineralization, which did not persist beyond first growing season, may have benefitted competing vegetation more than pine regeneration.

Although harvesting and regeneration caused perturbation in soil processes, there was little indication of adverse long-term effects. However, the importance of soil C and N to forest productivity and our global environment suggests that further study is warranted of the spatial and temporal variations in soil C and N levels, not only following harvesting and regeneration but throughout the rotation in intensively managed plantations.

Acknowledgements

This research was supported in part by a Challenge Cost Share Grant from the USDA-FS Southern Research Station with participation by International Paper Company, Temple–Inland Forest Products Corporation and Willamette Forest Industries Inc. Special thanks are due Jim Barnett, Tom Cooksey, Darwin Foster, Dennis Gravatt, Van Maeger, Oktay Yildiz, and Allan Tiarks for their assistance with this study. We thank Dan Binkley for his review of the manuscript and constructive comments.

References

Allen, H.L., Dougherty, P.M., Campbell, R.G., 1990. Manipulation of water and nutrients—practice and opportunity in Southern US pine forest. For. Ecol. Manage. 30, 437–453.

Allen, H.L., Morris, L.A., Wentworth, T.T., 1991. Productivity comparisons between successive loblolly pine rotations in the North Carolina Piedmont. In: Dyck, W.J., Mees, C.A. (Eds.), Long-Term Field Trials to Assess Environmental Impacts of Harvesting. IEA/BE T6/A6 Report No. 5. FRI Bulletin No. 161. Forest Research Institute, Rotorua, NZ, pp. 125–136.

Baldwin Jr., V.C., 1987. Green and dry-weight equations for above-ground components of planted loblolly pine trees in the west gulf region. Soc. J. Appl. For. 11 (4), 212–218.

Barber, B.L., Van Lear, D.H., 1984. Weight loss and nutrient dynamics in decomposing woody loblolly pine logging slash. Soil Sci. Soc. Am. J. 48, 906–910.

Binkley, D., 1984. Ion exchange resin bags: factors affecting estimates of nitrogen availability. Soil Sci. Soc. Am. J. 48, 1181–1184.

Binkley, D., Matson, P.A., 1983. Ion exchange resin bag method for assessing forest soil nitrogen availability. Soil Sci. Soc. Am. J. 47, 1050–1052.

Binkley, D., Son, Y., Valentine, D.W., 2000. Do forest receive occult inputs of nitrogen? Ecosystems 3, 321–331.

Bird, S., Coulson, R.N., Crossley Jr., D.A., 2000. Impact of silvicultural practices on soil and litter arthropod diversity in a Texas pine plantation. For. Ecol. Manage. 131, 65–80.

Burger, J.A., Pritchett, W.L., 1984. Effects of clearfelling and site preparation on nitrogen mineralization in a southern pine stand. Soil Sci. Soc. Am. J. 48, 1432–1437.

Burger, J.A., Kelting, D.L., 1999. Using soil quality indicators to assess forest stand management. For. Ecol. Manage. 122, 155–166.

Byrnside Jr., D.S., Sturgis, M.B., 1958. Soil phosphorus and its fractions as related to response of sugar cane to fertilizer phosphorus, LAES Expt. Stn. Bull. 513.

Carlyle, J.C., Than, U.B., 1988. Abiotic controls of soil respiration beneath an 18-year-old *Pinus radiata* stand in south-eastern Australia. J. Ecol. 76, 654–662.

Christiansen, T.A., Lockwood, J.A., Powell, J., 1989. Litter decomposition by arthropods in undisturbed and intensively managed mountain brush habitats. Great Basin Nat. 49, 562–569.

Clark III, A., Phillips, D.R., Frederick, D.J., 1985. Weight, volume, and physical properties of major hardwood species in the Gulf and Atlantic Coastal plains. USDA-FS Research Paper SE-250. SEFES, Asheville, NC, p. 78.

Coleman, D.C., Crossley Jr., D.A., Beare, M.H., Hendrix, P.F., 1988. Interactions of organisms at root/soil and litter/soil interfaces in terrestrial ecosystems. Agric. Ecosyst. Environ. 24, 117–134.

Covington, W.W., DeBano, L.F., Huntsberger, T.G., 1991. Soil nitrogen changes associated with slash pile burning in pinyon-juniper woodlands. For. Sci. 37, 347–355.

Cropper Jr., W.P., Ewel, K.C., Raiche, J.W., 1985. The measurement of soil carbon dioxide respiration in situ. Pedobiologia 28, 35–40.

Crossley Jr., D. A., 1977. The roles of terrestrial saprophagous arthropods in forest soils: current status of concepts. In: Mattson, W.J. (Ed.), The Role of Arthropods in Forest Ecosystems. Springer, New York, pp. 49–56.

Curry, J.P., Good, J.A., 1992. Soil fauna degradation and restoration. Adv. Soil Sci. 17, 171–215.

Doran, J.W., 1987. Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. Biol. Fert. Soils 5, 68–75.

Edwards, N.T., 1975. Effects of temperature and moisture on carbon dioxide evolution in a mixed deciduous forest floor. Soil Sci. Soc. Am. Proc. 39, 361–365.

Edwards, N.T., 1982. The use of soda-lime for measuring respiration rates in terrestrial systems. Pedobiologia 23, 321–330.

Edwards, N.T., Ross-Todd, B.M., 1983. Soil carbon dynamics in a mixed deciduous forest following clearcutting with and without residue removal. Soil Sci. Soc. Am. J. 47 (5), 431–437.

Fisher, R.F., Binkley, D., 2000. Ecology and Management of Forest Soils, Wiley, New York, 489 pp.

Fox, T.R., Burger, J.A., Kreh, R.E., 1986. Effects of site preparation on nitrogen dynamics in the southern Piedmont. For. Ecol. Manage. 15, 241–256.

Gent, J.A., Allen, H.L., Campbell, R.G., Wells, C.G., 1986. Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and phosphorus fertilization. Soc. J. Appl. For. 10, 124–128.

Grigal, D.F., 2000. Effects of extensive forest management on soil productivity. For. Ecol. Manage. 138, 167–185.

Grogan, P., Bruns, T.D., Chapin III, F.S., 2000. Fire effects on ecosystem nitrogen cycling in a California bishop pine forest. Oecologia 122, 537–544.

Haines, S.G., Cleveland, G., 1981. Seasonal variation in properties of five forest soils in southwest Georgia. Soil Sci. Soc. Am. J. 45, 139–143.

Harding, R.B., Jokela, E.J., 1994. Long term effects of forest fertilization on site organic matter and nutrients. Soil Sci. Soc. Am. J. 58, 216–221.

Harmon, M.E., Ferrel, W.K., Franklin, J.F., 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247, 699–702.

Hart, S.C., Binkley, D., 1985. Correlations among indices of forest soil nutrient availability in fertilized and unfertilized loblolly pine plantations. Plant Soil 85, 11–21.

Hendrickson, O.Q., Chatarpaul, L., Burgess, D., 1989. Nutrient cycling following whole-tree and conventional harvest in northern mixed forest. Can. J. For. Res. 19, 725–735.

Hoekstra, J.M., Bell, R.T., Launer, A.E., Murphy, D.D., 1995. Soil arthropod abundance in coast redwood forest: effect of selective timber harvest. Environ. Entomol. 24, 246–252.

Huang, C.Y.L., Shulte, E.E., 1985. Digestion of plant tissue for analysis by ICP emission spectroscopy. Commun. Soil Sci. Plant Anal. 16, 943–958.

Johnson, D.W., 1992. Effects of forest management on soil carbon storage. Water Air Soil Pollut. 64, 83–120.

Jorgensen, J.R., Wells, C.G., 1986. Foresters' primer in nutrient cycling. A Loblolly Pine Management Guide. Gen. Tech. Rep. USDA-FS, SRS SE-37, 42 pp.

Kaye, J.P., Hart, S.C., 1998. Restoration and canopy-type effects on soil respiration in a ponderosa pine–bunch grass ecosystem. Soil Sci. Soc. Am. J. 62, 1062–1072.

Knoepp, J.D., Swank, W.T., 1993. Site preparation burning to improve southern Appalachian pine–hardwood stands: nitrogen responses in soil, soil water, and streams. Can. J. For. Res. 23, 2263–2270.

Knoepp, J.D., Swank, W.T., 1997. Forest management effects on surface soil carbon and nitrogen. Soil Sci. Soc. Am. J. 61 (3), :928–935.

Knoepp, J.D., Swank, W.T., 1998. Rates of nitrogen mineralization across an elevation and vegetation gradient in the southern Appalachians. Plant Soil 204, 235–241.

Landsberg, J.J., Gower, S.T., 1997. Applications of Physiological Ecology to Forest Management, Academic Press, New York, NY, 354 pp.

Lloyd, J., Taylor, J.A., 1994. On the temperature dependence of soil respiration. Funct. Ecol. 8, 315–323.

Matson, P.A., Vitousek, P.M., 1981. Nitrification potentials following clearcutting in the Hoosier National Forest. Indiana. For. Sci. 27, 781–791.

Mattson, K.G., Smith, H.C., 1993. Detrital organic matter and soil CO_2 efflux in forests regenerating from cutting in West Virginia. Soil. Biol. Biochem. 25, 1241–1248.

McKee Jr., W.H., Wilhite, L.P., 1986. Loblolly pine response to bedding and fertilization varies by drainage class on lower Atlantic Coastal plain sites. Soc. J. Appl. For. 10, 16–21.

Messina, M.G., Frederick, D.J., Clark III, A., 1986. Nutrient content and distribution in natural southern coastal plain hardwoods. Biomass 10, 59–79.

Morris, L.A., 1981. Redistribution and mobilization of nutrients as a result of harvest and site preparation of a pine flatwoods. Ph.D. Dissertations. University of Florida, Gainesville, FL, 190 pp.

Morris, L.A., Pritchett, W.L., Swindel, B.F., 1983. Displacement of nutrients into windrows during site preparation of a flatwoods forest. Soil Sci. Soc. Am. J. 47, 591–594.

Mroz, G.D., Jurgenson, M.F., Frederick, D.J., 1985. Soil nutrient changes following whole-tree harvesting on three northern sites. Soil Sci. Soc. Am. J. 49, 1552–1557.

NCSFNC, 1995. Fundamental Research in Forest Production. 24th Annual Report. North Carolina State Forest Nutrition Co-operative. Department of Forestry, North Carolina State University, Raleigh, 24 pp.

Olsen, S.R., Sommers, L.E., 1982. Phosphorus. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. 2nd Edition, Agronomy 9, 403–430.

Parkinson, D., 1994. Filamentous fungi. In: Methods of Soil Analysis. Part 2. Microbiological and Biochemical Properties. Soil Sci. Soc. Am. Madison, WI, 1121 pp.

Phillips, D.R., Messina, M.G., Clark III, A., Frederick, D.J., 1989. Nutrient content prediction equations for wetland trees in the US southern coastal plain. Biomass 19, 169–187.

Piatek, K.B., Allen, H.L., 1999. Nitrogen mineralization in a pine plantation 15 years after harvesting and site preparation. Soil Sci. Soc. Am. J. 63, 990–998.

Powers, R.F., Alban, D. H., Miller,R. E., Tiarks, A. E., Wells, C. G., Avers, P.E., Cline, R. G., Fitzgerald, R. O., Loftus Jr., N. S., 1990. Sustaining site productivity in North American forests: problems and prospects (pp. 49–79). In: Gessel, S.P, Lacate, D.S., Weetman, G.F., Powers, R.F. (Eds.), Proceedings of the 7th North American Forest Soils Conference on Sustained Productivity of Forest Soils, Vol. 525. University of British Columbia, BC, pp. 234–252.

Powers, R.F., Tiarks, A.E., Burger, J.A., Carter, M.C., 1996. Sustaining the productivity of planted forests (pp. 97–134). In: Carter, M.C. (Ed.), Proceedings of the 35th LSU Forestry Symposium on Growing Trees in a Greener World: Industrial Forestry in the 21st Century, p. 274.

Powers, R.F., 1999. If you build it will they come? Survival skills for silvicultural studies. For. Chronicle. 75 (3), 367–373.

Reich, J.W., Schlesinger, W.H., 1992. The global carbon dioxide flux in soil respiration and its relationship to climate. Tellus 44B, 81–99.

Reich, P.B., Grigal, D.F., Aber, J.D., Gower, S.T., 1997. Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse sites. Ecology 78 (2), 335–347.

Richards, B.N., 1987. The Microbiology of Terrestrial Ecosystems. Longman, New York, 399 pp.

Richter, D.D., Markewitz, D., Heine, P.R., Jin, V., Raikes, J., Tian, K., Wells, C.G., 2000. Legacies of agriculture and forest regrowth in the nitrogen of old-field soils. For. Ecol. Manage. 138, 233–248.

Schoch, P., Binkley, D., 1986. Prescribed burning icreased nitrogen availability in a mature loblolly pine stand. For. Ecol. Manage. 14, 13–22.

Smethurst, P.J., Namibar, E.K.S., 1990. Effects of slash and litter management on fluxes of nitrogen and tree growth in young *Pinus radiata* plantations. Can. J. For. Res. 20, 1498–1507.

Tew, D.T., Morris, L.A., Allen, H.L., Wells, C.G., 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. For. Ecol. Manage. 15, 257–267.

Thomas, G.W., 1982. Exchangeable cations. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. 2nd Edition. ASA and Soil Sci. Soc. Am. Madison, WI.

Tisdale, S.L., Nelson, W.E., Beaton, J.D., 1985. Soil Fertility and Fertilizers, 4th Edition. Macmillan, New York, 754 pp.

Turner, J., Lambert, M.J., 1988. Long term effect of phosphorus fertilization on forests. In: Cole, D.W., Gessel, S.P. (Eds.), Forest Site Evaluation and Long Term Productivity. University of Washington Press, Washington, pp. 125–133.

Van Lear, D.H., Kapeluck, P.R., Waide, J. B., 1990. Nitrogen pools and processes during natural regeneration of loblolly pine. In: Gessel, S.P., Lacate, D.D., Weetman, G.F., Powers, R.F. (Eds.), Proceedings of the 7th North American Forest Soils Conference on Sustained Productivity of Forest Soils, Vol. 525. University of British Columbia, BC, pp. 234–252.

Vitousek, P.F., Melillo, J.M., 1979. Nitrate losses from disturbed forest: patterns and mechanisms. For. Sci. 25, 605–619.

Vitousek, P.M., Matson, P.A., 1985. Disturbance, nitrogen availability, and nitrogen losses in an intensively managed loblolly pine plantation. Ecology 66, 1360–1376.

Waide, J.B., Caskey, W.H., Todd, R.L., Boring, L.R., 1988. Changes in soil nitrogen pools and transformations following forest clearcutting. In: Swank, W.T., Crossley Jr., D.A. (Eds.), Forest Hydrology and Ecology at Coweeta. Ecological Studies, Vol. 66. Springer, New York, pp. 221–232.

Wellington, E.M.H., Both, I.K., 1994. Actinomycetes. In: Methods of Soil Analysis. Part 2. Microbiological and Biochemical Properties, Soil Sci. Soc. Am. Madison, WI, 1121 pp.

Wells, C.G., Craig, J.R., Kane, M.B., Allen, H.L., 1986. Foliar and soil tests for the prediction of phosphorus response in loblolly pine. Soil Sci. Soc. Am. J. 50, 1330–1335.

Wilson, C.A., 1994. The effects of compaction and organic matter removal on nitrogen mineralization in a coastal plain soil of North Carolina. Master Thesis. North Carolina State University, Raleigh, NC, 31pp.

Zuberer, D.A., 1994. Recovery and enumeration of viable bacteria. In: Methods of Soil Analysis. Part 2. Microbiological and Biochemical Properties. Soil Sci. Soc. Am. Madison, WI, 1121 pp.