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Soil organic matter and nitrogen cycling in response to harvesting, mechanical site preparation, and fertilization in a wetland with a mineral substrate

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Abstract

Forested wetlands are becoming an important timber resource in the Upper Great Lakes Region of the US. However, there is limited information on soil nutrient cycling responses to harvesting and post-harvest manipulations (site preparation and fertilization). The objective of this study was to examine cellulose decomposition, nitrogen mineralization, and soil solution chemistry four years after a forested, mineral soil wetland in Northern Michigan was whole-tree harvested, site prepared, and fertilized (N, P, N + P). Organic matter decomposition was greatest in the site preparation bedding treatment and lowest in whole-tree harvested with no mechanical site preparation treatment. Both N and P additions, alone and in combination resulted in increased cellulose decomposition regardless of site preparation treatment (15–38% for the harvest-only treatment, 20–40% for the bedded treatment, and 15–44% for the trenched treatment). However, based on dissolved organic carbon concentrations in the soil solution, organic matter decomposition was inhibited on an overall plot basis; that is, outside the area of cellulose strip placement. The site preparation bedding treatment resulted in a net mineralization of N (9.2 g-N m^{-2}) over a 10 week incubation period. The disc trench and harvest-only treatments resulted in a net immobilization of N (3.1 g-N m^{-2} and 1.5 g-N m^{-2}, respectively). Nitrogen, P, and N + P inhibited N mineralization in the bedded treatment by 10–25% over the control. There was a fertilizer-induced increase in N immobilization of 50–60% and 25–50% in the harvest-only and trenched treatments, respectively. It appears that soil microorganisms at this site are limited by soluble C more than N or P. By adding cellulose strips to the soil, the soluble C limitation was, in part, overcome. Once the soluble C limitation was alleviated, then the soil microorganisms responded positively to N and P additions. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Whole-tree harvest; Site preparation bedding; Site preparation trenching; Fertilization; Organic matter decomposition; Nitrogen mineralization; Solution chemistry

1. Introduction

Forested wetlands are recognized for their importance in maintaining environmental quality of a land-

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scape, yet they are an important economic timber base in the Upper Great Lakes Region of the US (National Wetlands Policy Forum, 1988). In Michigan alone, over 20% of the commercial forest lands have been classified as wetlands (Smith and Kahn, 1987). In the Upper Great Lakes Region, wetlands with a mineral subsoil have been heavily used as a timber resource because of their greater productive capacity and commercial operability during winter months compared to peatlands.

The common management technique for forested wetlands with a mineral subsoil in the Upper Great Lakes Region is whole-tree harvesting followed by intensive mechanical site preparation, such as bedding or disc trenching. We have shown that site preparation by bedding and trenching increased jack pine (*Pinus banksiana*, Lamb.) seedling growth compared to whole-tree harvesting only (Gale et al., 1998). Increased productivity is achieved through improvement in soil aeration and mixing of the forest floor with the mineral soil, thereby increasing nutrient mineralization from organic matter.

Because of the role of forested wetlands in the landscape, we need to develop a thorough understanding of silvicultural effects on nutrient cycling and long-term site productivity of that forest type. Many physical, chemical, and biological properties of forest ecosystems interact to determine the productivity of a given site. Soil organic matter is a critical component of site productivity because of its role in water relations, and nutrient storage and release (Burger and Pritchett, 1984; Fox et al., 1986). Nitrogen (N) is generally considered the most limiting element in temperate and boreal forests of North America (Kimmins and Feller, 1976; Krause, 1982; Vitousek and Matson, 1985; Binkley, 1986; Munson et al., 1993). A majority of the N in forest soils is bound to organic matter. Release of N through organic matter mineralization is critical for plant available N. Another element that is tied to the organic phase is phosphorus (P). It is also recognized as potentially limiting to forest productivity in temperate and boreal forests of North America (Fernandez et al., 1990; McLaughlin et al., 1994b, 1996b; Christ et al., 1997).

Whole-tree harvesting followed by site preparation bedding and disc trenching alters soil organic matter, and consequently N cycling (Burger and Pritchett, 1984; Vitousek and Matson, 1985; Fox et al., 1986; Trettin et al., 1995, 1996). Site preparation bedding and disc trenching have also shown to cause significant decreases in site productivity under certain conditions (Glass, 1976; Ballard, 1978). In forested wetlands with a mineral subsoil in the Upper Great Lakes Region, the majority of the soil nutrient reserves are in the forest floor. The mineral soil has little nutrient retention capacity and, therefore, any alterations to the forest floor can have adverse affects on soil productivity (Trettin et al., 1995).

Potential ameliorations of decreases in site productivity are N and P fertilization of forest stands. Forest fertilization has shown to be a potential mechanism for improving site productivity (Mahendrappa, 1978; Adams and Attiwill, 1984; Prescott and McDonald, 1994). Prescott and McDonald (1994) suggested that nutrient additions through fertilization appears to be the only practical means of alleviating nutrient supply problems in certain managed forests of British Columbia, Canada. However, the use of fertilizers to enhance site productivity has received mixed views in the north-central and north-eastern US. We have, however, shown that jack pine seedling growth on wetlands with a mineral subsoil was greater in response to N and P fertilization than with no fertilizer application, although seedling response was dependent upon the type of site preparation used (Gale et al., 1998).

We have been investigating whole-tree harvesting and site preparation effects on the structure and function of a forested wetland with a mineral subsoil in the Lake Michigan Drainage Basin for a number of years (Trettin, 1992; Trettin et al., 1992, 1995, 1996, 1997; McLaughlin et al., 1994a, 1996a; Gale et al., 1998). This is one of the only studies that have investigated high-yield forestry in northern forested wetlands without using some form of drainage (Trettin et al., 1995). Some of our findings to date have shown site preparation bedding and trenching have resulted in an initial increase in organic matter decomposition. These increases were positively related to site disturbance; greatest decomposition occurred on the bedded treatment, followed by trenched and whole-tree harvest only treatment (Trettin et al., 1996). In association with the greater organic matter decomposition, there was an initial loss of 38% of the mineral soil C within the first 18 months following harvesting and site preparation (Trettin et al., 1995). Five years after harvesting and site preparation, however, the bedded treatment appeared to have suffered the least amount of soil organic matter loss, with the organic matter content in the mineral soil of the bedded treatment being back to control stand levels (McLaughlin et al., 1996a). Although the mineral soil organic matter was back to control levels in the bedded treatment, organic matter in the forest floor of the bedded treatment was still only about one-third the organic matter content in the forest floor of the control stand (McLaughlin et al., 1996a).

We have also observed alterations in the chemistry of dissolved organic carbon (DOC) in both soil solution and groundwater five years following harvesting and site preparation. The harvest-only and bedded silvicultural prescriptions have resulted in more humic characteristic of DOC than that observed under reference conditions (McLaughlin et al., 1996a). We have also reported that elevated nitrate (NO_3^-), ammonium (NH_4^+), and dissolved organic N (DON) concentrations occurred in both the soil solution and groundwater in the bedded treatment and groundwater five years after installation (Trettin et al., 1997). In addition, there were changes in the N speciation, with 35% of the total N in soil solution occurring as NH_4^+ and NO_3^- in the treatments, but only 18% occurring as inorganic N in the control stand (Trettin et al., 1997). These results indicate that there were still alterations in organic matter decomposition and N mineralization at this site five years after whole-tree harvesting and mechanical site preparation.

Hydrology is also an important factor that influences the organic matter cycling of this site. Trettin et al. (1996) reported that in addition to disturbance, the hydrologic position within the wetland relative to the draining stream affected organic matter decomposition. McLaughlin et al. (1994a) reported that the hydrologic position within the wetland also had a significant impact on mineral soil C retention, with greater mineral soil C retention occurring in areas with a relatively deep water table than in areas where there were more shallow water table.

The objective of this current study was, therefore, to further improve our understanding of high-yield forest management on soil nutrient cycling of this forested wetland with a mineral subsoil. This objective was accomplished by superimposing N and P fertilization on the harvested and site preparation treatments four-years after their installation. We measured organic matter decomposition, N mineralization, and soil solution chemistry for one growing season following fertilization applications.

2. Materials and methods

2.1. Site description

The study was located in the Lake Michigan drainage basin in the central Upper Peninsula of Michigan (46°10′N, 86°43′W) on land owned by Mead Paper Corporation. The site is part of the Wetmore Outwash Plain, which is underlain by middle Ordovician limestone (Trenton Limestone). The drift thickness in the vicinity of the site ranges from 30 to 75 m. The elevation of the site is approximately 260 m above sea level.

Overstory vegetation primarily consists of black spruce (*Picea mariana*, (Miller) BSP), tamarack [*Larix laricina* (DuRoi) K. Koch.], and jack pine. The dominant species in the shrub layer are: *Vaccinium* spp., leatherleaf [*Chamaedaphne calyculata* (L.) Moench.], and labrador tea [*Ledum groenlandicum* (Oeder.)]. Surface vegetation is dominated by *Sphagnum* spp., with minor components of starflower [*Trientalis borealis* (Raf.)], and *Carex* spp. We have previously reported changes in the herbaceous and grass/sedge groups in response to harvesting and site preparation. For instance, relative coverage of herbaceous species is 0.4 in the uncut stand, whereas relative coverages are less then 0.1 in the whole-tree harvest only, disc trenched, and harvested and bedded treatments. The grass/sedge group has relative coverages ranging from 0.22 to 0.31 in the treated stand compared to 0.03 in the uncut stand (Gale et al., 1998). Percent coverage of bryophytes decreases with increasing disturbance intensity. Percent coverage of bryophytes in the uncut stand is 75% and decreases to 42% in the whole-tree harvest only, 21% in the disc trenched, and 17% in the bedded treatments.

The soil on the site has been mapped as a Kinross series (sandy, mixed, frigid, Typic Endoaquod). The Kinross series is poorly drained with a fine-sand solum overlain by a 5–15 cm organic horizon composed mainly of decomposed sphagnum. Forest floor organic matter contents however, are one-half to one-third the level in the harvested compared to the uncut stand

(McLaughlin et al., 1996a). The solum is uniform to a depth of 2.5 m, is acid throughout, and has a clay content generally less than 2%. Extractable iron (Fe) in the mineral soil ranges from 5.9 to 85 ug g^{-1} and aluminum (Al) ranges from 2.1 to 15.3 ug g^{-1} (McLaughlin et al., 1994a). Mineral soil Fe and Al are both lower than those reported for other Spodosols (McDowell and Wood, 1984; Moore et al., 1992). Soil total N and base cations are also extremely low in this forest ecosystem (Trettin, 1992). The water table is at or near the surface during most of the growing season (McLaughlin et al., 1994a).

2.2. Field design

The overall field layout was a randomized complete block design with three blocks located parallel to the West Branch of the Sturgeon River. Each block consisted of nine 32 m × 32 m plots with a 5 m buffer between each plot. Three blocks were also established in an uncut area adjacent to the cut area; each block in the uncut area contained only three plots. The uncut stand was not used as part of this current study.

Silvicultural prescriptions were applied in July, 1988. A 14.5 ha parcel of the study site was clearcut using feller bunchers. Tree bundles were skidded to a landing where trees were sorted into fiber and fuel product classes. Fuel wood was whole-tree chipped, while the fiber wood was delimbed, topped, and bucked into pulpwood bolts at the landing site. The effects of the harvest regime resulted in all trees approximately 5 cm and greater being removed from the site.

Three treatments were installed in three blocks in the harvested area along a gradient of geomorphic position and hydrology. Whole-tree harvesting (trees 5 cm dbh and larger were removed) and site preparation treatments were implemented in July 1988 and consisted of (1) harvest only, (2) harvested and bedding with chemical (Glyphosate) weed control (bedded treatment) and (3) harvest and disc trenching with chemical (Glyphosate) weed control (trenched treatment) (Fig. 1). The disc trenching disturbed about 45% of the soil surface area. The bedding treatment resulted in 100% disturbance of the soil surface.

Containerized 1–0 stock jack pine were planted at 2 m spacing in August, 1988 within each plot. To assess the effects of site preparation and fertilization

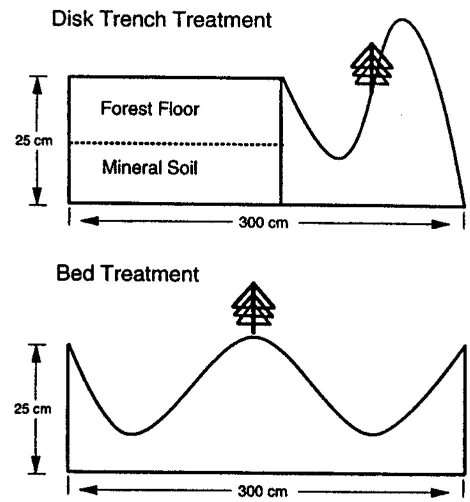

Fig. 1. Cross-sectional depiction of disc-trenched and bedded treatment and planting position of seedlings.

on soil nutrient cycling in the harvested area, three plots (representing each site preparation treatment) from each block in the harvested area were used. The total number of plots for each site preparation treatment was three. Within each plot, 10 m × 10 m subplots were established with a 3 m buffer strip left between each subplot. Four fertilization treatments were randomly assigned within each plot to one subplot. Fertilizers were applied in May, 1992 and included (1) N (100 kg ha^{-1} N as NH_4NO_3), (2) P (75 kg ha^{-1} P as super triple phosphate, (3) N + P, and (4) a control subplot with no fertilizer.

2.3. Incubation, sampling, and laboratory analyses

2.3.1. Cotton strip assay

The cotton strip assay was used as an index of organic matter decomposition (Latter and Howson, 1977; Harrison et al., 1988) using Shirley Soil Burial Cloth obtained from Shirley Institute, Manchester, England. The cloth was cut to 12 cm width and 30 cm length. One strip was inserted along a diagonal in the 10 m × 10 m fertilizer subplots, resulting in a total of 12 measurements per site preparation and nine measurements per fertilizer treatment. The strips were placed where the surface of the soil was uniform on the harvest-only treatment, between the trenches on the trenched treatment, and in the center of the planting bed on the bedded treatment.

Two consecutive five-week incubations were conducted during June through July (spring) and August through September (summer). These times were determined to be those required to achieve about a 50% loss in tensile strength (TS) based upon a pilot study (Trettin, 1992). At the end of the incubation periods, the cloth was carefully excavated from the soil, gently rinsed in water to remove adhering soil particles, and then air dried. Dried strips were stored in an air-tight container with desiccant until analyzed. Ten field blanks were used for each incubation period. These blanks were inserted into the soil and immediately removed. Sample strips, 4 cm wide, were prepared from each incubated cotton strip with the same, with the sample mid-point corresponding to 10 cm soil depth. TS was measured on a Monsanto 10 Tensiometer configured with rubber padded jaws 5 cm wide and 2.5 cm long, a gauge setting of 5 cm, and a speed of 5 cm min^{-1}. The cotton strips were tested at 100% moisture content, which was accomplished by soaking the cloth in water prior to testing. Cotton tensile strength loss (CTSL) was computed as

$$\mathrm{CTSL}\ (\%) = [\text{field blank TS}] - [\text{final TS}]$$

2.3.2. *Nitrogen mineralization*

Incubations for N mineralization were conducted using 7.6 cm diameter ABS plastic pipe. The core-ion exchange (IER) incubation was conducted as described by DiStefano and Gholz (1986). The method was applied by sampling an intact soil core, placing cation and anion exchange resins in the bottom of the core, and then inserting the entire core into a hole that was excavated with a 7.6 cm soil auger. Cores were incubated for 10 weeks, from June through September. The cores were placed where the surface was uniform on the harvest-only treatment, between the trenches for the trenched treatment, and in the center of the bed on the bedded treatment, similarly to the cotton strip assay placement.

The resins used were 11.5 g of BioRad AG 1-X4 anion exchange resin, 50–100 mesh size, and 8.0 g of BioRad AG 50-W-X4 cation exchange resin, 50–100 mesh. The two resins were added to separate nylon mesh bags. Another set of ion-exchange bags were made using 10 g of BioRad AG 501, 20–50 mesh resin, a mixed bed resin, was placed below the anion exchange resin at both the top and bottom of the core. Mixed bed resins at the top of the core were used to deionize precipitation as it entered the core. Placement of the mixed bag at the bottom of the core served as a deionizer of groundwater that could enter the core from the bottom. The resin discs were secured in the core and protected by nylon screening that was attached to the bottom of the core. There was one incubation conducted for each fertilizer treatment within a site preparation plot, for a total sample of 12 samples per site preparation and nine samples per fertilizer treatment.

Mineral soil samples were frozen until processed for inorganic N analyses. After thawing, soil samples were prepared by removing coarse roots and twigs and sieving through 2 mm sieve. Water content was determined on a 20 g subsample by drying at 105°C until constant mass was obtained. Inorganic N was measured on 5 g samples of mineral soil using 2 M KCl as described by Keeney and Nelson (1982). Soil and resin extracts were stored at 3°C until analyzed for NO_3^-–N and NH_4^+–N on a Bran and Luebbe TRAACS 800 (Bran and Luebbe, Industrial Method No. 794-86T). Net N mineralization was calculated as the quantity of accumulated NO_3^-–N and NH_4^+–N in the core plus the amount collected in the cation and anion exchange resins (mixed bed resins were not included in the calculations) subtracted from the inorganic N levels at the beginning the incubation.

2.3.3. *Soil Solution*

Soil solution was sampled at 30 cm depth using ceramic cup tension water samplers ('lysimeters') (Soil Moisture, Santa Barbara, CA). One lysimeter was placed in each of the four fertilizer treatments per site preparation. There was a total of 12 lysimeters per site preparation and nine lysimeters per fertilizer treatment. Solutions were filtered through Gelman 0.45 um filters and measured for pH, NH_4^+, NO_3^-, and DOC.

2.4. *Statistical analyses*

The experimental design was a randomized complete block design. The majority of the constituents in the soil solution, and the N mineralization and cotton strip assay data were not normally distributed ($p > 0.05$) based upon the Shapiro–Wilk test for normality (Conover, 1980). Levene's test for homogeneity of variances indicated that the variances were equal for all variables. However, because of the non-normal distributions of the data, nonparametric statistics were used for N mineralization and soil solution. The arcsine transformation was used for the organic matter decomposition data because the CTSL is in percent. All analyses were conducted using SAS (SAS Institute, 1992) and the 0.05 level of significance was used unless otherwise stated.

The treatment variables in the design were site preparation and fertilizer treatment. The Friedman test (using hydrologic position (square) within the wetland as a random effect) was used to test for treatment effects. If treatment differences occurred then nonparametric multiple comparisons were used to separate the ranks for N mineralization and soil solution. The Student–Newman–Keuls test was used for mean separation of the organic matter decomposition data.

3. Results

3.1. Organic matter decomposition

Average CTSL differed ($p < 0.05$) by both site preparation and fertilization. There was also a site preparation by fertilization interaction ($p < 0.05$), indicating that site preparation and fertilization were not independent.

Average CTSL was $68 \pm 14\%$ and $81 \pm 11\%$ in the bedded treatment, respectively, $61 \pm 13\%$ and $73 \pm 9\%$ in the trenched treatment, respectively, and $47 \pm 6\%$ and $55 \pm 10\%$ in the harvest-only treatment, respectively for both spring and summer incubations across all fertilizer treatments. The CTSL during both the spring and summer was different among all treatments ($p < 0.05$) with the bedded treatment highest followed by the trenched and harvest-only treatments.

Across site preparation treatments, CTSL during the spring and summer was $44 \pm 7\%$ and $58 \pm 9\%$, respectively in the no fertilizer treatment, $60 \pm 13\%$ and $70 \pm 11\%$, respectively for the N addition, $60 \pm 8\%$ and $74 \pm 9\%$, respectively for the P addition, and $71 \pm 17\%$ and $80 \pm 16\%$, respectively for the N + P addition. CTSL during both the spring and summer was greater ($p < 0.05$) in all fertilizer applications than that for the no fertilizer application. Cellulose decomposition in the N and P additions did not differ ($p > 0.05$) from each other. However, cellulose decomposition in the N + P addition was greater ($p < 0.05$) than that in either the N or P applications for both spring and summer incubations. The increase in CTSL during both incubations was similar in the bedded and trenched treatments (Fig. 2). However, in the harvest-only treatment, cellulose decomposition was greatest in the P addition for both incubation periods.

3.2. Nitrogen mineralization

Net N mineralization differed ($p < 0.05$) by both site preparation and fertilizer treatment. There was no site preparation by fertilizer interaction ($p > 0.05$), indicating that site preparation and fertilization were independent. The bedded site preparation was the only one that had a net N mineralization, across fertilizer treatments (7.8 ± 1.2 g N m^2). Both the harvest-only and trenched treatments resulted in a net immobilization of N. The rate of N immobilization in the trenched treatment (4.7 ± 1.3 g N m^2) was 40% greater than that of the harvest-only treatment (2.8 ± 1.2 g N m^2). Net N mineralization rates in all site preparation treatments were different ($p < 0.05$) from one another.

Across site preparation treatments, the no fertilizer application had the highest net N mineralization rate (1.6 ± 5.8 g N m^2). All fertilizer applications resulted in significant decreases ($p < 0.05$) in net N mineralization compared to the no fertilizer application. The P addition decreased the rate to 0.4 ± 5.9 g N m^2, N addition decreased N mineralization to -0.5 ± 5.7 g N m^2, and the N + P addition decreased N mineralization rates to -1.0 ± 6.0 g N m^2. The latter two fertilization applications did not differ ($p > 0.05$) from each other, but both were lower ($p < 0.05$) than the P addition. Net N mineralization in each of the site preparation treatments showed a similar response to fertilization (Fig. 3).

Nitrate–N accounted for <1% of the inorganic N in the harvest-only treatment, regardless of fertilizer application. However, NO_3^-–N accounted for 13 and 17% of the inorganic N for the trenched and bedded treatments in the no fertilizer application treatment. The proportion of NO_3^-–N decreased to 5–9% and 7–10% of the inorganic N in response to the

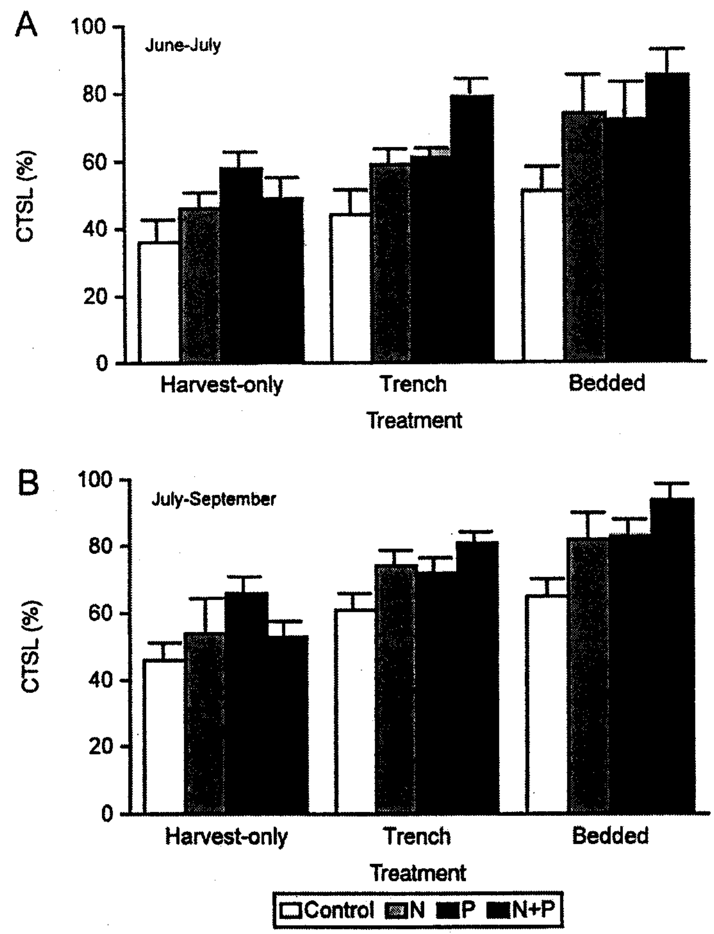

Fig. 2. Mean (+ standard deviation) percent CTSL for upper 10 cm of mineral soil in response to N and P fertilization four years following whole-tree harvesting and mechanical site preparation. (A) Spring (June–July) incubation, (B) summer (August–September) incubation.

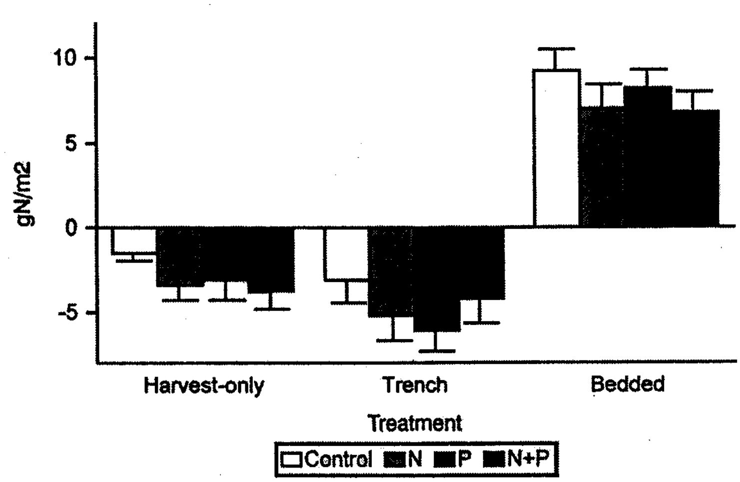

Fig. 3. Mean (+ standard deviation) N mineralization in upper 10 cm of mineral soil for a 10 week incubation (June–August) in response to N and P fertilization four years following whole-tree harvesting and mechanical site preparation.

fertilizer applications for the trenched and bedded treatments, respectively.

3.3. Soil solution

Soil solution pH differed ($p < 0.05$) by both site preparation and fertilization. There was also a site preparation by fertilizer interaction for soil solution pH ($p < 0.05$), indicating that site preparation and fertilization were not independent. Soil solution pH, across fertilizer treatments was 4.66 ± 0.42 in the harvest-only treatment, 4.55 ± 0.41 in the trenched, and 4.49 ± 0.33 in the bedded treatment. The solution pH in the harvest-only treatment was greater ($p < 0.05$) than that in the bedded and trenched treatments. However, there was no difference ($p > 0.05$) between the bedded and trenched treatment nor the harvest-only and trenched treatments for soil solution pH.

Across site preparation treatments, solution pH was 4.88 ± 0.31, 4.46 ± 0.44, 4.47 ± 0.32, and 4.48 ± 0.34 for the no fertilizer, N, P, and N + P additions, respectively. The controls in all three site preparation treatments had higher ($p < 0.05$) solution pH than did all three fertilization regimes (Fig. 4). The solution pH decrease lasted the entire growing season for all three fertilization regimes.

Concentration of NH_4^+ differed ($p < 0.05$) by site preparation and fertilization. There was no site preparation by fertilization interaction ($p > 0.05$). Mean NH_4^+ concentration was 1.34 ± 3.08 mg l^{-1}, 1.65 ± 2.06 mg l^{-1}, and 2.13 ± 2.86 mg l^{-1} for the harvest-only treatment, bedded, and trenched treatment, respectively, and differed ($p < 0.05$) by site preparation. There was no difference ($p > 0.05$) between the harvest-only and trenched treatments nor the trenched and bedded treatments. Ammonium concentration was, however, higher ($p < 0.05$) in the trenched compared to the harvest-only treatment. There was also a fertilizer effect on soil solution NH_4^+ concentration ($p < 0.05$), but no site preparation by fertilizer interaction ($p > 0.05$). Across site preparation treatments, NH_4^+ concentration in the no fertilizer (0.63 ± 0.65 mg l^{-1}) and P (1.15 ± 1.32 mg l^{-1}) did not differ ($p > 0.05$). However, NH_4^+ concentration in those two treatments were lower ($p<0.05$) than both the N (2.61 ± 2.35 mg l^{-1}) and N + P (3.93 ± 3.43 mg l^{-1}) fertilizer additions. There was no difference ($p > 0.05$) between the latter two fertilizer additions.

The NH_4^+ concentration in soil solution was quite variable during the sampling period for all site preparation treatments (Fig. 5). There was a general trend for decreased NH_4^+ concentration in the bedded and trenched treatments late in the growing season compared to early in the growing season. In all the harvest-only and bedded treatments, the NH_4^+ concentrations were similar in the fertilizer treatments to their respective control by the end of the growing season (Fig. 5). However, in the trenched treatment NH_4^+ concentrations were still 40 and 20% higher in the N and N + P additions, respectively then the no fertilizer addition treatment.

Soil solution NO_3^- concentration did not differ ($p > 0.05$) by site preparation, but did differ by fertilizer treatment ($p < 0.05$). There was no site preparation by fertilizer interaction ($p > 0.05$). Average soil solution NO_3^- concentration, across fertilizer treatments was 1.53 ± 2.38 mg l^{-1}, 1.72 ± 1.41 mg l^{-1}, and 1.35 ± 1.91 mg l^{-1} for the harvest-only, bedded, and trenched treatments, respectively. Across site preparation treatments, NO_3^- concentration in the no fertilizer application (0.50 ± 0.41 mg l^{-1}) and the P addition (0.55 ± 0.65 mg l^{-1}) did not differ ($p > 0.05$) from each other, but both were lower ($p < 0.05$) than both the N (2.61 ± 2.36 mg l^{-1}) and the N + P (2.47 ± 3.43 mg l^{-1}) additions. The latter two fertilizer treatments did not differ ($p > 0.05$) from each other. There was no site preparation by fertilizer interaction ($p > 0.05$).

As with NH_4^+, soil solution NO_3^- concentration tended to be higher during the early compared to late portion of the growing season (Fig. 6). In addition, NO_3^- concentration were near control levels by the end of the growing season for all fertilizer application for each of site preparations.

Soil solution DOC concentration did not differ ($p > 0.05$) by site preparation, but did differ ($p < 0.05$) by fertilizer application. There was no site preparation by fertilizer interaction ($p > 0.05$). Average soil solution DOC concentration was 27.5 ± 8.4 mg l^{-1}, 36.8 ± 10.4 mg l^{-1}, and 32.5 ± 9.9 mg l^{-1} for the harvest-only, bedded, and trenched treatments, respectively across fertilizer applications. Across site preparations, DOC concentrations were 22.1 ± 8.6 mg l^{-1}, 35.0 ± 10.5 mg l^{-1}, 36.1 ± 10.3 mg l^{-1},

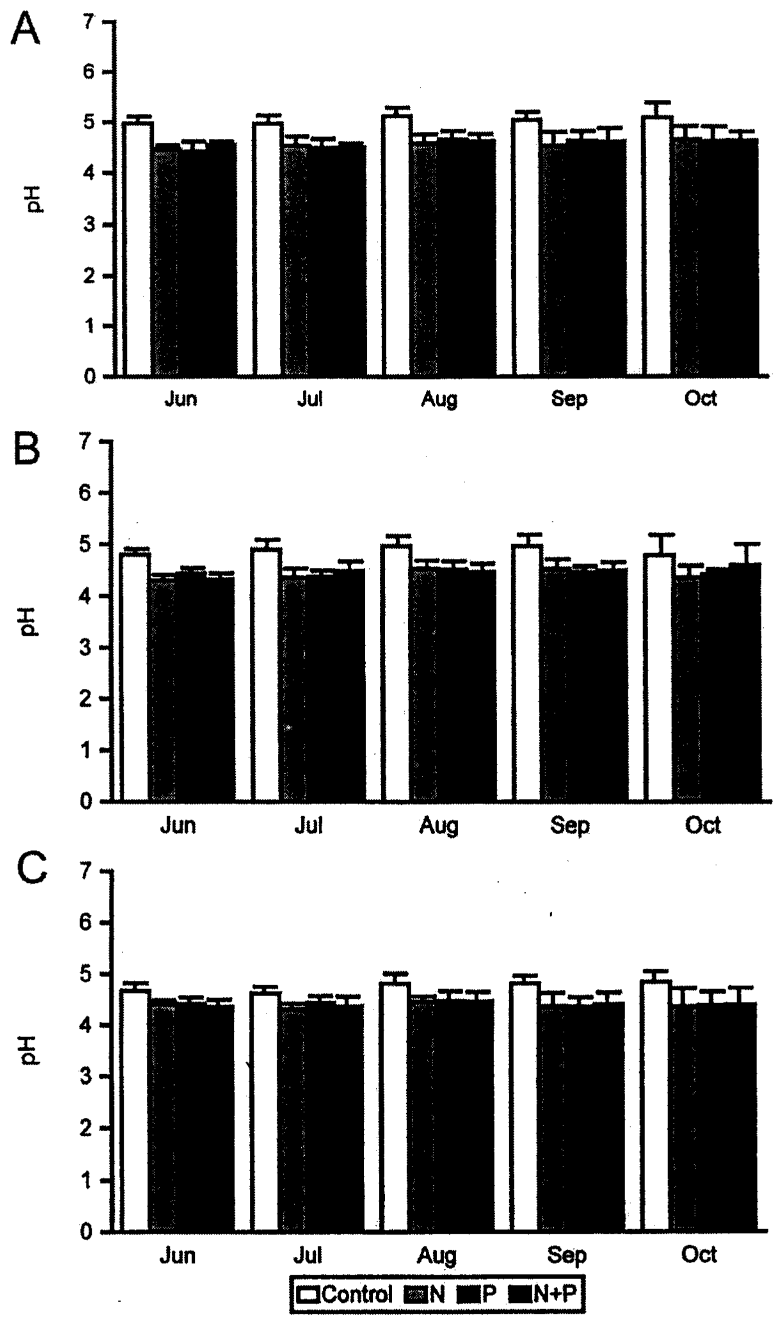

Fig. 4. Mean (+ standard deviation) soil solution pH collected at 30 cm depth in response to N and P fertilization four years following whole-tree harvesting and mechanical site preparation. (A) Whole-tree harvest only, (B) site preparation trenching, and (C) site preparation bedding.

and 35.9 ± 10.9 mg l^{-1} for the no fertilizer, N, P, and N + P additions, respectively. There were no DOC differences ($p > 0.05$) among the N, P, and N + P additions. All three fertilizer regimes resulted in higher ($p < 0.05$) DOC concentrations than the no application treatment. Dissolved organic C concentrations

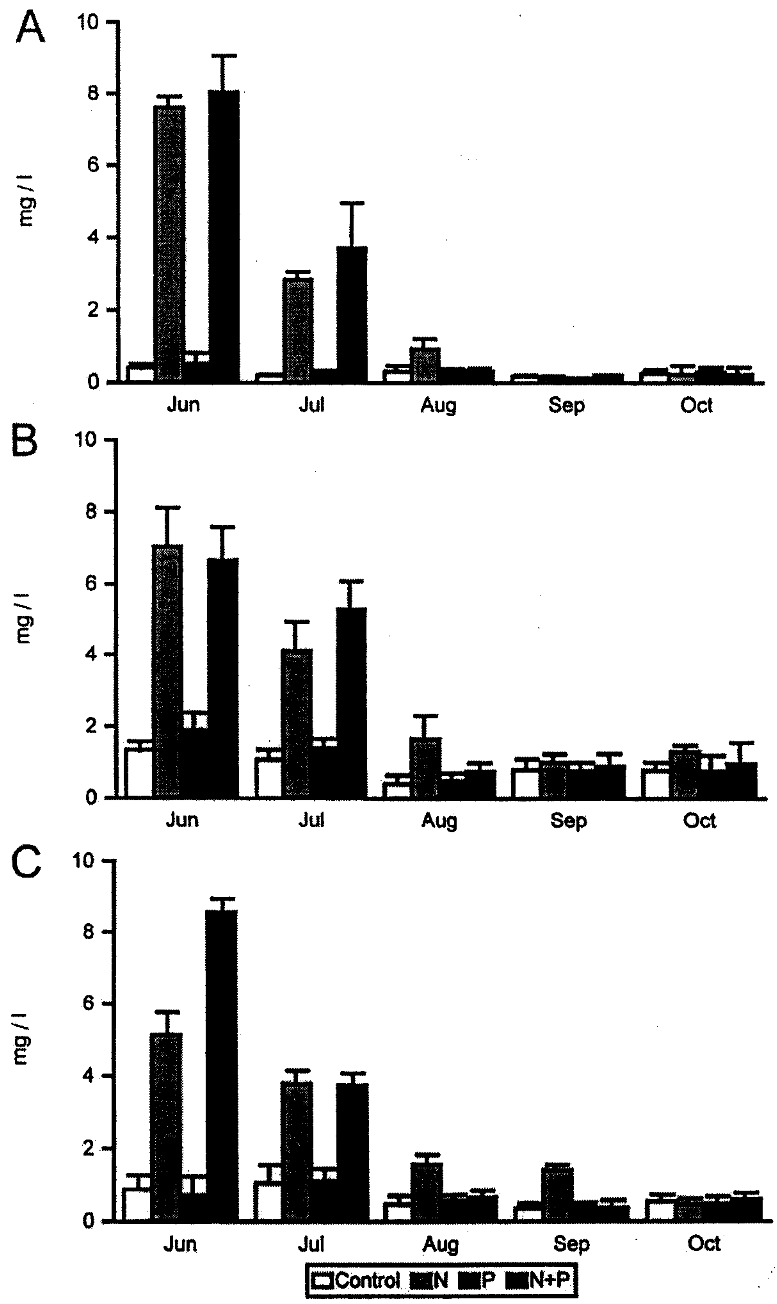

Fig. 5. Mean (+ standard deviation) soil solution NH_4^+ concentration collected at 30 cm depth in response to N and P fertilization four years following whole-tree harvesting and mechanical site preparation. (A) Whole-tree harvest only, (B) site preparation trenching, and (C) site preparation bedding.

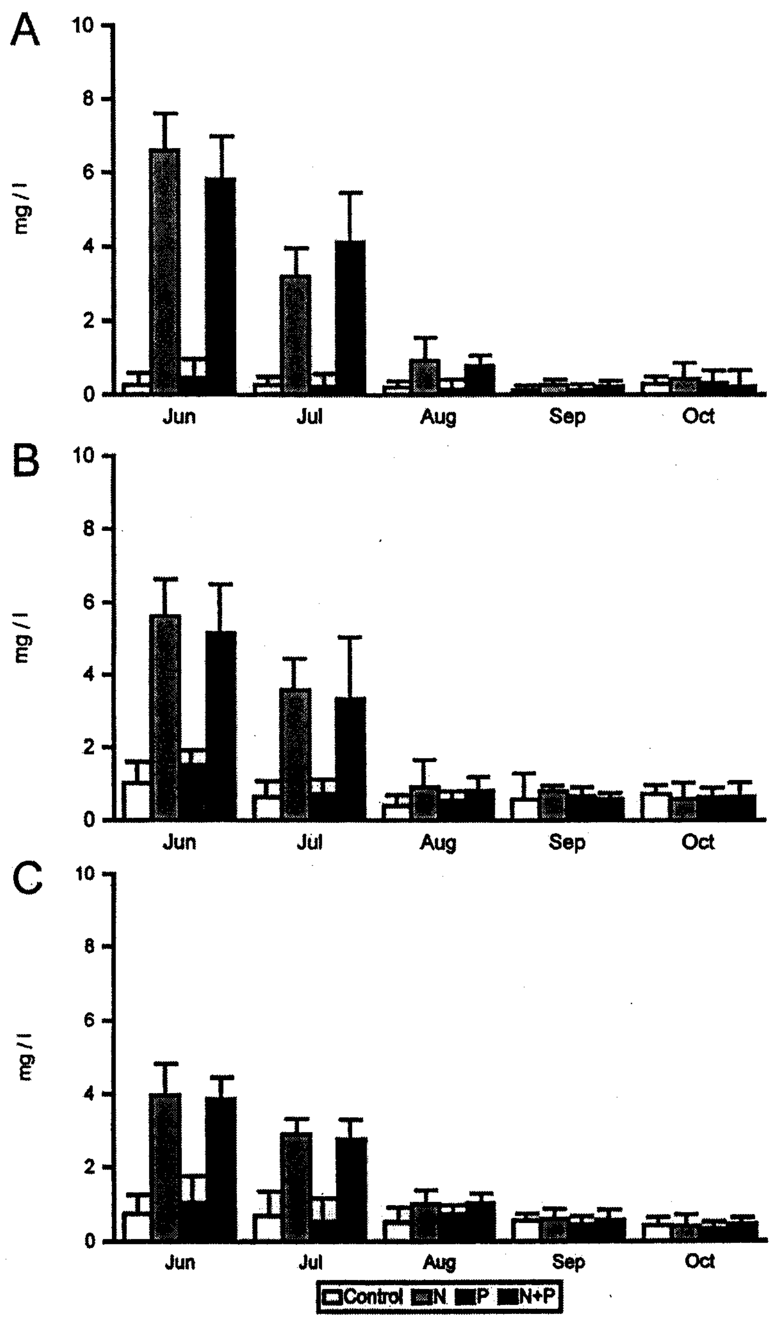

Fig. 6. Mean (+ standard deviation) soil solution NO_3^- concentration collected at 30 cm depth in response to N and P fertilization four years following whole-tree harvesting and mechanical site preparation. (A) Whole-tree harvest only, (B) site preparation trenching, and (C) site preparation bedding.

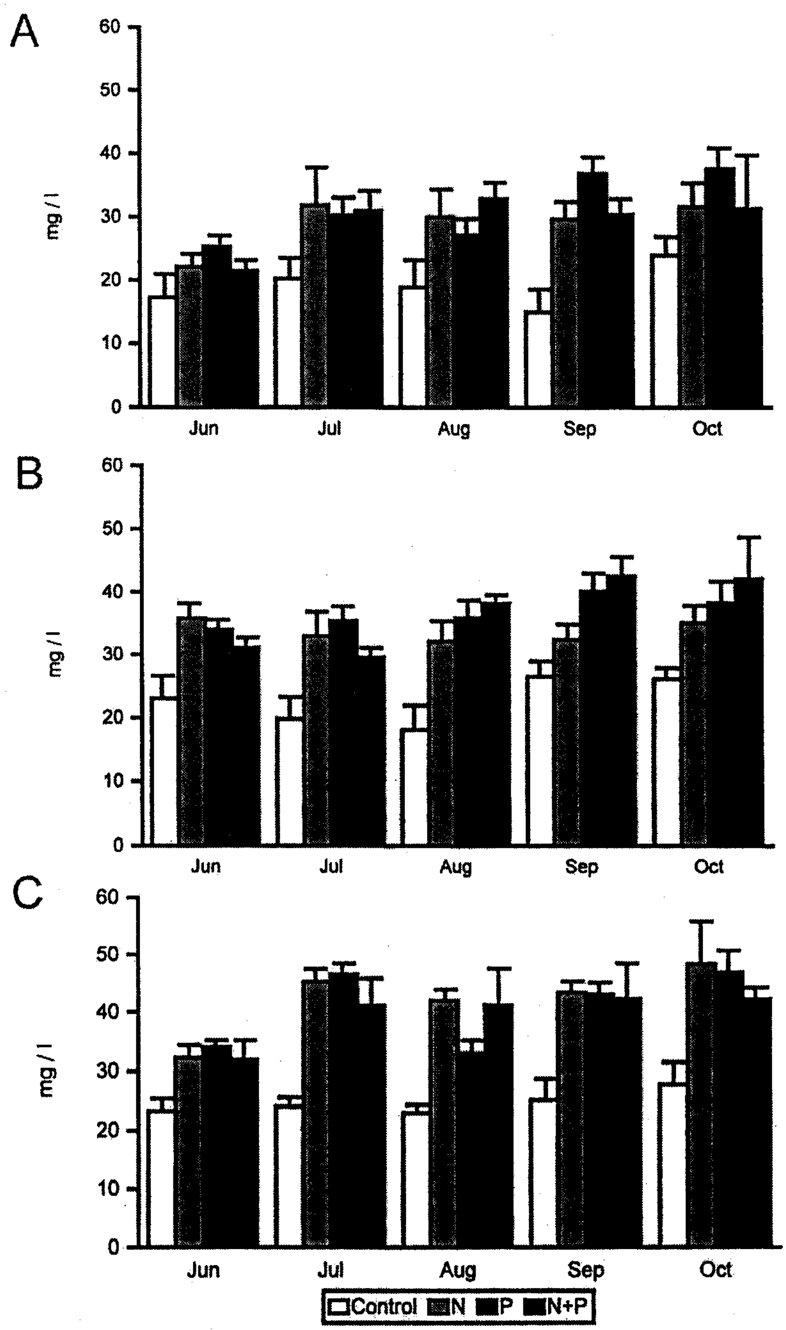

Fig. 7. Mean (+ standard deviation) soil solution DOC concentration collected at 30 cm depth in response to N and P fertilization four years following whole-tree harvesting and mechanical site preparation. (A) Whole-tree harvest only, (B) site preparation trenching, and (C) site preparation bedding.

remained elevated in the N, P, and N + P fertizer regimes over control levels for all site preparation treatments for the entire growing season (Fig. 7).

4. Discussion

4.1. Soil organic matter

The increase in CTSL in the bedded site preparation treatment over that in the trenched and harvest-only treatments was different to that which occurred within the first 18 months following harvesting (Trettin et al., 1996). Those authors reported no difference in CTSL between the bedded and trenched treatments for either the spring or summer incubations. However, the trenched treatment still shows elevated cellulose decomposition over that of the harvest-only treatment four-years following harvesting and site preparation for both the spring and summer incubations. Treatments that mix organic layers into mineral soils can lead to different microbial populations due to better soil aeration and improvement in substrate quality (Foster et al., 1980; Mallik and Hu, 1997). In addition, the site preparation bedding treatment reduces anoxic conditions, thereby shifting the microbial populations from more facultative, anaerobic, and fermentation organisms to more aerobic microbes. This would result in increased organic matter decomposition in the bedded treatment compared to the trenched or the harvest-only treatments.

McLaughlin et al. (1996a) reported higher hydrophilic acid component of the DOC in the bedded compared to the harvest-only treatment. They suggested this may be due to increased organic matter decomposition in the former than the latter treatment, as suggested by McKnight et al. (1985). McLaughlin et al. (1996a) also reported that C contents of the top 20 cm of mineral soil were 17.9 $Mg\ ha^{-1}$ in the bedded treatment compared to 11.3 $Mg\ ha^{-1}$ in the harvest-only treatment, and 12.7 and 8.9 $Mg\ ha^{-1}$ C in the forest floor of the bedded and harvest-only treatments, respectively. Startsev et al. (1998) reported that cellulose decomposition was positively related to air-filled porosity of the soil and soil organic matter content, indicating that those properties likely stimulate organic matter decomposition within the beds. Gale et al. (1998) reported significantly greater jack pine seedling diameter and height growth in the bedded than the trenched or the harvest-only treatment. They suggested that the growth increases were due to relieving the anoxic conditions in the elevated beds, thereby increasing biological activity, which the results from our study indicate.

In a study on organic matter decomposition of Norway spruce (*Picea abies* (L.) Karst.) Stand, Lundmark-Thelin and Johansson (1997) reported that needles decomposed faster in disc trench ridges than in an unprepared clearcut. After four years of decomposition, the remaining mass of litter was 26% of the original litter mass in a disc trenched treatment compared to 45% in the unprepared clearcut. They also reported that the microclimatic conditions inside the disc trench ridges promoted the activity of organic matter decomposing organisms. The greater organic matter decomposition in the disc trench treatment compared to the unprepared clearcut was similar to our results, even with different methodologies used in the two studies. For instance Lundmark-Thelin and Johansson (1997) measured litter decomposition, whereas we used cellulose decomposition as an index of decomposition. Lundmark-Thelin and Johansson (1997) also used an accumulated decomposition over a four-year period, where as we measured cellulose decomposition for the first 18-months following harvesting and site preparation, and again four years later.

Fertilization significantly increased cellulose decomposition during both the spring and summer incubations (Fig. 2). Most studies that have measured fertilization effects on organic matter decomposition have been conducted with litter decomposition or microbial activity, in general. Most of these studies have generally shown that inorganic N fertilization of forest soils reduces litter decomposition, whereas fertilization with urea increases decomposition. For instance, Nohrstedt et al. (1989) reported that the soil respiration rate, ATP content, and microbial biomass C decreased in response to 150 kg NH_4NO_3–N ha^{-1}fertilization in a scots pine (*Pinus sylvestris* L.) forest. Gill and Lavender (1983) reported that fertilization with 336 kg N ha^{-1} as urea and gypsum-coated urea both stimulated litter decomposition rates, but $Ca(NO_3)_2$ reduced decomposition for the first six months after application, and by 12 months had no effect on decomposition in a western hemlock (*Tsuga heterohylla* (Raf.) Sarg.) stand. Foster et al.

(1980) also reported inorganic N fertilization reduced microbial activity. They found that application of 200 kg-N as $(NH_4)_2SO_4$ depressed microbial activity, whereas the same N application rate as urea stimulated microbial activity in soils from a jack pine forest floor. Titus and Malcolm (1987) reported that fertilization of a cleared sitka spruce (*Picea sitchensis* (Bong. Carr) stand with 150 kg-N ha^{-1} urea-N, 50 kg-P ha^{-1} rock-P, and 100 kg-K ha^{-1} muriate potash significantly reduced litter decomposition. Mahendrappa (1978) reported an increase in organic matter decomposition in response to both urea-N and triple superphospate fertilization of a black spruce stand in New Brunswick, Canada. He, however, did not look at inorganic N fertilization. Ohtonen et al. (1992) reported that fertilization of coniferous plantations in Ontario, Canada significantly reduced microbial biomass C in both the forest floor and mineral soil using a slow release fertilizer composed of 9.1% NH_4^+–N and 17.9% NO_3^-–N. The decrease was greater when vegetation management with the herbicide Vision was superimposed on the fertilization treatment.

It is well accepted that organic matter decomposition is generally limited by soluble C as opposed to inorganic nutrients. For instance, Prescott and McDonald (1994) reported a stimulation of C mineralization upon the addition of glucose to a forest soil. Once the C deficiency is alleviated, organic matter decomposition may positively respond to N or P addition. Because our study used cellulose strips as an index of decomposition, we added a readily decomposable C source to the soil thereby, in part, alleviating soluble C deficiencies within the area of the cotton strips. That is likely the reason we saw a positive fertilization response to organic matter decomposition, whereas studies using litter decomposition have generally shown negative effects of inorganic N fertilization on organic matter decomposition.

Ohtonen et al. (1992) reported decreases of 11 and 35% in microbial biomass C in the forest floor and surface mineral soil, respectively after N and P fertilization four years after clearcut harvesting in Ontario. They, and other authors (e.g. Bååth et al., 1978; Söderström et al., 1983) suggested that the reduction in microbial biomass may be a direct result of increased NO_3^- concentrations on heterotrophic organisms. Ohtonen et al. (1992) also speculated that when fertilization is applied, the soil microbial biomass responds quickly, rapidly degrading the available organic C in the soil. Microbial biomass levels are then reduced due to low available soil C.

The higher DOC concentration in the fertilized versus non-fertilized treatments were similar to those reported by Currie et al. (1996) for a 70-year old red pine (*Pinus resinosa*, Ait.) plantation in Massachusetts. They reported a 35% increase in DOC concentration in A horizon leachates and a 44% increase in B horizon leachates in response to fertilization with 150 kg-N ha^{-1} $year^{-1}$ NH_4NO_3. Their reported increases in DOC were similar to ours, where we found a 35–40% increase in DOC concentration across site preparation treatments in response to addition of 100 kg-N ha^{-1} $year^{-1}$ NH_4NO_3, as well as 75 kg-P ha^{-1} $year^{-1}$. The high DOC concentration at 30 cm depth at our site is due to a low C retention capacity in the mineral soil (McLaughlin et al., 1994a).

The higher DOC concentration in the fertilized versus nonfertilized treatments contradicts the results of the cellulose decomposition. It would be expected that DOC concentration would decrease with increasing organic matter decomposition because of a more complete oxidation of organic matter to CO_2. Chemical differences of DOC can also indicate differences in organic matter decomposition (McKnight et al., 1985; McLaughlin et al., 1996a). Soluble humic substances can be produced by reactions among the products of incomplete decomposition (Stevenson, 1982; Liu et al., 1985). Cronan et al. (1992) reported an increase from <1% humic acid component of DOC in unfertilized control to 13.9% in response to N and P fertilization of a mature red pine forest in Maine. They also reported a 20% decrease (significant) in carboxyl content of DOC in the fertilized treatment.

Our results strongly indicate that on an area basis (beyond that of where the cellulose strips were incubated), there was an overall inhibition of organic matter decomposition induced by the fertilizer treatments. The inhibition was overcome by the addition of a readily decomposable C source; cellulose strips. This line of reasoning would support the general premise that microbial activity in forest soils, no matter if upland or wetland, is generally limited by easily decomposable C. Once the easily decomposable C limitation is overcome, soil microorganisms will respond to N and P additions.

4.2. Nitrogen dynamics

Nitrogen mineralization in the no fertilizer treatment was similar to those that occurred during the first 18-months following harvesting and site preparation (Trettin, 1992). The rates of N mineralization in the harvested and fertilized treatments were similar to those reported for other coniferous forests and forested wetlands in the northern regions of North America (Prescott and McDonald, 1994; Grigal and Homann, 1994; Ouyang, 1994). The bedded treatment was the only one to show a positive net N mineralization. As with cellulose decomposition, the net N mineralization in the bedded treatment was likely the result of creating more conducive conditions for microbial activity within the beds by decreasing anerobosis and increasing organic matter content.

Our study showed an increase in the net immobilization of N in response to fertilization. As with organic matter decomposition, the microorganisms responsible for converting organic N to inorganic N are often limited more by soluble C than by N or P (Ohtonen et al., 1992). However, there have been inconsistent results reported in the literature regarding the effects of fertilization on N mineralization. As with fertilizer effects on organic matter decomposition, the form, rate, and frequency of application, along with soil type affects the response of N mineralization. For instance, Adams and Attiwill (1984) reported that N fertilization increased N mineralization in a 23-year old radiata pine (*Pinus radiata* D. Don) plantation. There lowest application of N, however, was 500 kg-N ha^{-1}, which was five-fold greater than our application rate. Using a slow release fertilizer containing 9.1% N as NH_4^+ and 7.9% N as NO_3^- over a four-year period, Munson et al. (1993) showed no effect on N mineralization in a white spruce (*Picea glauca*, (Moench) Voss) plantation. Smolander et al. (1998) reported that net formation of mineral N was reduced by 50% in a Norway spruce forest four-years following clearcut harvesting, when the stand received a total of 860 kg-N ha^{-1} $year^{-1}$ N over a 34-year period prior to harvesting.

The increased nitrification in the bedded treatment over the harvest-only treatment resulted in an increase in soil solution acidity. This is similar to that which occurred within the first 18-months following harvesting (Trettin, 1992). The addition of N, P, and N + P increased the acidity of the soil solution for each of the site preparation treatments. Solution acidity differences invoked by the fertilization additions were likely due to increased organic acid concentrations in the fertilizer prescriptions over the controls as indicated by higher DOC concentrations in the fertilized versus nonfertilized treatments.

Nitrate concentrations in soil solution within each site preparation treatment were generally similar among the fertilizer treatments, with the exception of the first couple months after fertilization. However, DOC concentrations were about 40% higher in all fertilizations of the three site preparation treatments compared to their respective controls. It is widely accepted that organic acids can be a significant component of solution acidity in coniferous forests of the northern temperate and boreal regions (Cronan and Aiken, 1985; Vance and David, 1991; Dai et al., 1996; McLaughlin et al., 1996a). In further support of DOC being the cause of the increased acidity in response to fertilization, there was an inhibition of N mineralization in the fertilizer applications for all site preparations relative to their controls.

5. Conclusion

Cellulose decomposition and N mineralization were greater in the bedded compared to disc trenched or harvest only treatments, which was likely the result of lower anoxic conditions in the former compared to the latter two treatments. Relieving the anoxic conditions in the bedded treatment would contribute to stimulating microbial activity in that treatment, leading to greater cellulose decomposition and N mineralization rates. Whereas, anoxic conditions appear to still be prevalent in the disc trenched and whole-tree harvest treatments.

Cellulose decomposition and DOC both increased in response to N and P fertilization across site preparation treatments. These results are conflicting because high DOC concentrations can actually indicate reduced organic matter decomposition; high DOC concentrations indicate incomplete organic matter oxidation to CO_2. In contrast, increased cellulose decomposition is generally accepted as an index of higher organic matter decomposition rates. A possible explanation is that the placement of cellulose strips in the soil would lead to an increase of available C where the strips were placed. However, on a whole-plot basis; that is outside the areas of cellulose strip placement, organic matter decomposition was inhibited by N and P addition, as indicated by the high DOC concentrations. The lower N mineralization rates in response to N and P fertilization, across site preparation treatments also indicates that microbial activity was inhibited on a whole-plot basis by fertilizer application.

It may be that soil microorganisms at this site are limited more by available C than N or P, which is a generally accepted concept for upland forests. Addition of cellulose strips to the soil may have alleviated the available C limitation in the location of strip placement. Once the available C limitation was overcome, then soil microorganisms responded positively to N and P additions to the soil.

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