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Effects of harvesting intensity, vegetation control and fertilization on 5–20 year post-harvest N availability in boreal jack pine and black spruce forest soils in northern Ontario, Canada

Paul W. Hazlett[a,*], Caroline E. Emilson[a], Dave M. Morris[b], Robert L. Fleming[a], Laura A. Hawdon[a], Jean-Denis Leblanc[a], Mark J. Primavera[a], Tom P. Weldon[a], Martin M. Kwiaton[b], Michael K. Hoepting[c]

[a] Natural Resources Canada–Canadian Forest Service, 1219 Queen St. E., Sault Ste. Marie, Ontario P6A 2E5, Canada
[b] Ontario Ministry of Natural Resources and Forestry, Centre for Northern Forest Ecosystem, Research, 421 James Street South, Thunder Bay, Ontario P7E 2V6, Canada
[c] Natural Resources Canada–Canadian Wood Fibre Centre, 1219 Queen St. E., Sault Ste. Marie, Ontario P6A 2E5, Canada

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ABSTRACT

The impact of harvesting intensity, vegetation control and fertilization on soil N availability 5–20 years post-harvest was determined at 18 jack pine and black spruce forests in northern Ontario, Canada. The study sites are affiliated with the North American long-term soil productivity (LTSP) study. Boreal forest growth is commonly N limited and young stands approaching crown closure acquire most of their N from the soil. The study sites represented a range of soil types and were harvested with three levels of organic matter removal (stem-only harvest, full-tree harvest and full-tree harvest with organic horizon removal by blading). Three study sites had multiple applications of glyphosate to control competing vegetation and one site included a trial with two applications of N, P, K fertilizer to the full-tree harvest treatment. We used short-term anaerobic laboratory incubations and *in-situ* closed top tube growing season incubations to determine mineralizable N and net N mineralization, respectively. Profile (organic plus mineral horizons) mineralizable N pools were higher in operational clearcut (stem-only and full-tree harvesting) treatments compared to the uncut reference forest 10–14 years post harvest. Full-tree harvesting with blading significantly reduced profile mineralizable N pools at this time compared to operational harvesting, while the same treatment at one upland site also reduced net N mineralization pools. Profile mineralizable N pools and microbial biomass C and N were lower in full-tree compared to stem-only harvesting treatments, suggesting that increased slash retention with stem-only harvesting was playing a role in enhanced soil N availability at a time when plantations were approaching a period of greater N demand. Fertilization and vegetation control treatments had few effects on N indices, although net N mineralization pools for the stem-only and full-tree harvest that also had the repeated herbicide treatment were consistently, but not significantly, lower than non-herbicided treatments. Soil N indices were useful predictors of dominant height growth for jack pine to a greater degree than for black spruce, and soil N concentrations were as effective at predicting height growth as more resource intensive measurements. Our results point to the importance of continued monitoring of soil and stand conditions at these LTSP sites as treatment effects on soil N cycling and site productivity will likely continue to evolve. At this stage of stand development, full-tree harvesting plus organic horizon removal, followed by operational harvesting has led to lower soil N availability than operational tree-length harvesting, and stands with understory vegetation control are now showing indications of reduced N availability.

1. Introduction

Nitrogen (N) is an essential macronutrient that is an important constituent in several plant compounds. In many cases, the health and growth of natural and plantation forests, particularly northern conifer-dominated forests are limited by N supply (Prescott et al. 2000;

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* Corresponding author.
E-mail address: paul.hazlett@canada.ca (P.W. Hazlett).

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Binkley and Fisher 2020). Fertilization trials conducted in semi-mature boreal forests of northern Ontario in the 1960s and 1970s demonstrated positive forest growth responses to N-based fertilizer applications (Morrison et al. 1981; Foster et al. 1986) confirming N limitations in this region. In a meta-analytical review of these trials and others across Canada's boreal forest, Newton and Amponsah (2006) reported that jack pine and black spruce growth was enhanced with inorganic N fertilizer applications across a range of site quality classes.

In terms of forest management, a better understanding of soil N supply would be helpful in determining the effects of on-site management practices on forest ecosystem services, including site productivity as expressed by forest growth. The overarching goal would be incorporation of this improved scientific understanding of soil N dynamics and availability into forest management policies and guidelines through an adaptive management framework to enable continuous improvement in the sustainability of forest management practices (Puddister et al. 2011; Morris et al. 2020). As the majority of plant-available N in forest soils is derived by the mineralization of organic-N locked up in organic matter, the degree of biomass and organic residue removal/retention during forest harvesting can effect N supply, turnover and availability. Removal of competing tree and herbaceous plants by herbicide application can also modify the quantity and quality of soil organic matter inputs and as a result affect decomposition and soil N availability.

Many studies assessing N availability utilize soil incubation approaches (Binkley and Hart 1989; Hart et al. 1994). Soils are incubated in the laboratory or field for defined time periods at various temperatures and moisture contents, while at the same time eliminating N uptake by plants and potential leaching losses. The net change in inorganic-N concentrations over the incubation period is a measure of the balance between mineralization and immobilization and provides an index of soil N availability. Anaerobic methods assess only net changes in ammonium (NH_4^+-N), primarily from the flush of N from microbial biomass, whereas aerobic methods can be used to measure changes in both NH_4^+-N and nitrate (NO_3^--N) pools, from the turnover of microbial biomass and labile soil organic matter. Laboratory methods, whether anaerobic or aerobic, are conducted under controlled conditions and therefore address only substrate quality as a factor controlling potential N availability. Field incubations provide an index of net N mineralization which incorporates substrate quality in addition to temperature and moisture changes resulting from forest management.

Even though changes in soil temperature and moisture after forest harvesting would seem to favour increased organic matter decomposition and mineralization, a review of North American boreal forest N incubation experiments by Kreutzweiser et al. (2008) reported that most studies showed no increase in inorganic-N production. Where increases did occur, it was more often in the forest floor than the mineral soil, and while some studies showed increased N production during the first few years after harvest, others indicated that logging effects on N cycling could be delayed by more than a decade (e.g., Hazlett et al. 2007). The importance of dissolved organic N (DON) as a plant nutrient has also been demonstrated in boreal forests (Näsholm et al. 1998), with ectomycorrhizal fungi retaining N and playing a key role in soil N cycling (Högberg et al. 2017).

In previous papers we have reported on the effects of increased biomass removals on the amounts of carbon (C) and nutrients removed and retained on site (Hazlett et al. 2014), and the effects on soil reserves 20 years post-harvest (Morris et al. 2019) for upland boreal jack pine and black spruce sites in northern Ontario, Canada associated with the North American long-term soil productivity (LTSP) study. Using on-site, post-harvest estimates of harvesting residues, we found that N removals from stem-only and full-tree harvesting were more similar than those estimated using pre-harvest stand biomass calculations and theoretical harvest scenarios (i.e., average removal was ~5% of pre-harvest total site N reserves). In contrast, full-tree harvest plus stump, coarse root and forest floor removal removed on average ~50% of pre-harvest total site N reserves. Twenty years post-harvest, we found no significant differences in total soil N reserves between pre-harvest levels and the stem-only and full-tree treatments. However, the soil reserves of the full-tree harvest with stump, coarse root and forest floor removal treatment remained significantly lower than the pre-harvest levels.

Here we report on N-related soil incubation results 10–14 years post-harvest at 18 LTSP affiliate sites in northern Ontario, Canada, and on repeated measurements 5, 10, 14 and 20 years post-harvest at one site. We explore the effects of biomass removal intensity, vegetation control and fertilization on organic horizon and upper mineral soil mineralizable N, net N mineralization and microbial biomass measurements by posing five specific questions: 1) What were the effects of operational stem-only harvest and full-tree harvest compared to the uncut/pre-harvest forest? 2) What were the effects of stem-only harvest (coarse and fine slash left on site) compared to full-tree harvest (coarse slash only left on site)? 3) What were the effects of full-tree harvest with organic horizon removal compared to stem-only and full-tree harvest without organic horizon removal? 4) What were the effects of vegetation control through herbicide application compared to no vegetation control? 5) What were the effects of fertilization with N and NPK on full-tree harvest sites compared to full-tree harvest without fertilization? We also examine the relationships between soil N indices and stand productivity with question six: 6) What were the relationships between mineralizable N, net N mineralization, microbial biomass, soil N, soil C:N and stand productivity?

2. Materials and methods

2.1. Study sites, experimental design and treatments

The 18 sites in this study make up the Ontario affiliate component of the North American wide LTSP network (Powers 2006) and span 81° to 89°W longitude and 46° to 50°N latitude (Fig. 1). The sites selected were considered the most susceptible to increased biomass removal levels in this region. The pre-harvest forests at the sites were fire-origin boreal conifer stands ranging in age from 57 to 125 years, with sites in northeast Ontario (NE) comprised pre-dominantly of an overstory of jack pine (Pinus banksiana Lamb.) and those in northwest Ontario (NW) by black spruce (Picea mariana) (Table S1). Understory vegetation was variable across the sites, ranging from shrub and herb rich to extremely poor. There were no Alnus species (N_2 fixing) at any of the sites. The study sites experience cold continental climates, with annual precipitation ranging from 688 to 1009 mm yr^{-1} and annual mean temperatures of −0.7 to 4.4 °C. Sites in the NW generally receive lower annual precipitation and have lower annual mean temperature than those in the NE. At the 14 upland sites, soil profile development varied from weakly developed Dystric Brunisols (Inceptisols) to well-developed Humo-Ferric Podzols (Spodosols) (Soil Classification Working Group (SCWG), 1998). The sites represent a gradient in texture (20–87% sand content) ranging from silt loam (5 sites) to silty sand (6 sites) to loamy sand (3 sites), with Fibrimor or Humifibrimor forest floors (3–14 cm depth) (Heck et al. 2017). Two sites had wet mineral soils with Humic Gleysol (Inceptisol) profiles, and two sites were located in peatlands with soil profiles classified as Fibrisols (Histosols). Hereafter these four sites will be referred to as wetland sites. Organic horizons at the four wetland sites were thicker (34–100 + cm) than at the upland sites, with forest humus forms classified as Fibrihumimors and Fibric Peatymors.

From 1993 to 1995, an area of approximately 10 ha was clearcut (i.e., no residual trees left standing) at each site. A series of harvest treatments were applied in the clearcut at each site using a randomized block design, with each treatment replicated three times on 30 m × 30 m plots separated by 20 m buffers (Tenhagen et al. 1996; Duckert and Morris 2001). Three 30 m × 30 m control plots were also established in an uncut reference forest (UC) adjacent to the clearcut at each site. The core treatments implemented at each site included: stem only harvest (SO – delimbed at the stump with only the merchantable bole being removed to roadside), full-tree harvest (FT – the entire tree with bole

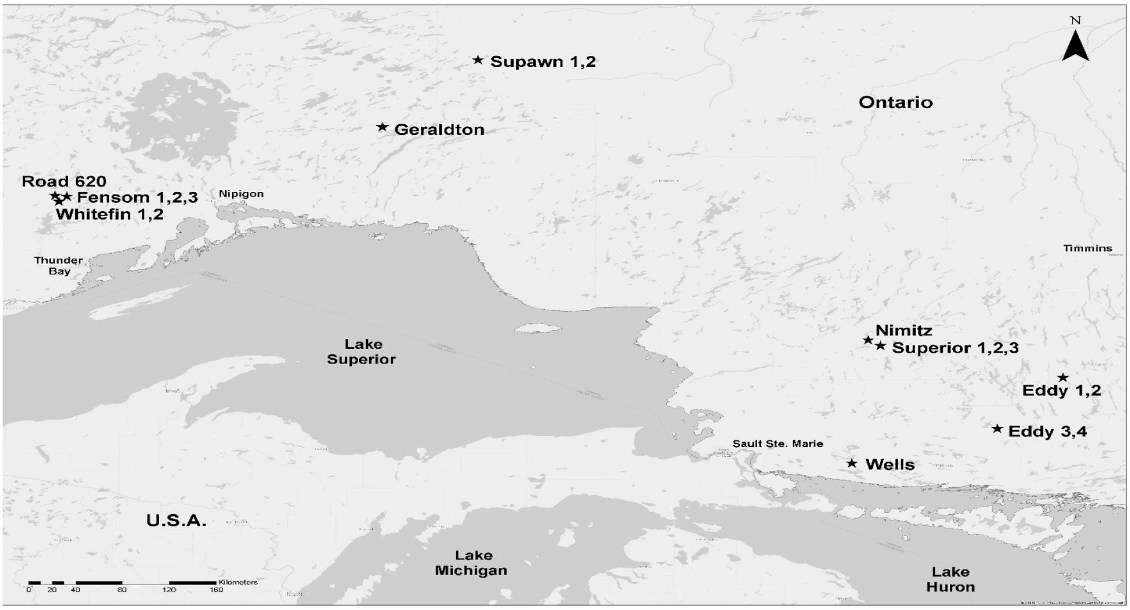


Fig. 1. Location of affiliate LTSP study sites in northern Ontario.

and branches removed to roadside), and full-tree harvest plus organic horizon removal (FTB). The SO and FT treatments followed a modified LTSP protocol in that they were applied operationally (i.e., no additional effort was made to completely remove all tops, branches, breakage and non-merchantable trees in the FT treatment, or to retain all these components in the SO treatment). Depending on the harvesting equipment used at each site, SO delimbing was done at the stump manually or by a mechanical delimber. At some sites, the delimber operated over the SO plot to distribute branches and tops while at other sites, it operated outside the treatment plot and slash was distributed by hand on to the plots. The SO treatment retained, on average, 15 Mg ha^{-1} dry weight mass more slash than the FT treatments largely in the form of live branches and tree tops (Hazlett et al. 2014). At the upland sites, the FTB treatment was accomplished using a bulldozer to remove all slash, folic (i.e., upland forest or non-wetland vegetation) surface organic horizons, stumps and coarse roots. A portion of the upper mineral soil (up to 5 cm) was also removed, usually in a discontinuous manner across the plot areas. For the wetland sites, the FTB treatment removed 20–25 cm of the surface organic material, including stumps and the low ericaceous shrub layer. All material was piled in windrows 10 m from plot edges to not influence tree measurements and soil sampling. Hereafter the FTB treatment will describe the blading across all sites as organic horizon removal. The FTB treatment at our sites was a more severe organic matter removal than was implemented at other LTSP network installations where only the organic horizon was removed. Blading in this manner reflects the operational practice used in this region at the time of study establishment and therefore this treatment has practical implications for forest management. Plots were planted with either jack pine (NE) or black spruce (NW) at 2 × 2 m spacing (2500 seedlings ha^{-1}) the spring after harvest. Buffer areas between plots were also planted to reduce edge effects as the stands developed. A split-plot vegetation control treatment was added to the SO, FT and FTB plots at three of the NE sites (Wells, Eddy 3, Superior 3). One half of each 30 × 30 m plot had no vegetation control (NH) while the other half had complete vegetation control (H) with three manual applications of glyphosate (Vision 5 L ha^{-1}) applied over a seven year period from year 2 to 11 after plantation establishment (Wells 1995, 1999, 2002; Eddy 3 1996, 2000, 2003; Superior 3 1997, 2001, 2004). The understory vegetation at the three coarse soil, jack pine ecosites utilized for the vegetation control experiment was predominately herbs and low shrubs that generally presented limited competition for regeneration. The remaining NE sites had operational herbicide applications, a single treatment of glyphosate applied aerially 2–7 years after planting. No herbicide was applied at the NW sites. At Nimitz, a second experiment with a fertilizer trial was established. Fertilizer was applied in the spring of 2002 and 2005, 8 and 11 growing seasons after the site was planted with FT (full-tree harvest, no fertilizer), FTN (full-tree harvest, 100 kg N ha^{-1} as $(NH_4)_2SO_4$) and FTNPK (full-tree harvest, 100 kg N ha^{-1} as $(NH_4)_2SO4$, 50 kg P ha^{-1} as $Ca(H_2PO_4)_2$, 50 kg K ha^{-1} as KCl) treatments. Each treatment was replicated five times on 40 m × 40 m plots. The experimental area was aerially herbicide treated 3 years after plantation establishment and half of each plot had an additional manual application of glyphosate at year 8 when the fertilizer experiment was established.

2.2. *Laboratory and field incubations*

Soil sampling for anaerobic laboratory incubations and microbial biomass determinations was conducted in fall 2003 (NW sites) and fall 2007 (NE sites), 10 and 14 growing seasons after plantation establishment, respectively. Samples were taken from harvest treatment and uncut reference forest plots. For the anaerobic laboratory incubations conducted with samples collected at the upland NW sites, organic horizon (LFH) samples were collected at three locations (offset by 120°) within the rooting zone in the mid-crown area of nine planted trees on each treatment plot (i.e., 27 sampling locations per treatment plot). Organic horizon depths were measured at these locations and averaged. An upper (20 cm) mineral soil sample was also collected at each location. For the four wetland sites with thicker organic horizons (Whitefin 1, Whitefin 2, Supawn 2, Road 620) upper (0–10 cm) and lower organic samples (10–20 cm) were taken. For purposes of comparison with the upland soil sampling depths, throughout this paper at the wetland sites, the upper organic horizon was categorized as organic, and the lower organic horizon was categorized as mineral. The organic and mineral soil samples were bulked for each tree giving nine samples for each soil horizon per treatment for the anaerobic incubation. Additional samples were collected at four locations within each treatment plot for microbial biomass determinations. For the NE sites 2″ diameter plastic pipe 30 cm in length was used to extract core samples from four locations on each treatment plot at each site. In the laboratory each core was extruded and separated into organic horizon (LFH), mineral 0–10 cm and mineral 10–20 cm depth subsamples, and these common sample depths were bulked together to achieve a single sample for each site/treatment/plot combination.

Soils (NE, field moist; NW air-dried) were sieved (organic, 6.3 mm; mineral, 2 mm) to remove woody material, roots and coarse fragments, hand ground (NW, organic) and then homogenized. Samples were anaerobically incubated to determine an index of potential mineralizable N (Powers 1980). Subsamples of organic (NE, 5 g oven-dried equivalent; NW, 2 g air-dried) and mineral soil (NE, 20 g oven-dried equivalent; NW, 10 g air-dried) were weighed into vials. For the NW soils, 50 mL of deionized water (DW) was added to each sample and samples were placed in an incubator for 14 days at 30° C. After the incubation period, 50 mL of a 4 M KCl solution was added to the samples (which yielded a 2 M extraction solution with the DW) and agitated for one hour at 180 rpm. NE samples were shaken for one hour with 80 mL (organic) and 60 mL (mineral) of 2 M KCl solution. A second sample was weighed into a vial and incubated for 14 days at 30 °C after addition of 40 mL (organic) and 30 mL (mineral) DW. At the conclusion of the incubation period, the samples were shaken for 1 h with 40 mL (organic) and 30 mL (mineral) of 4 M KCl solution. All samples were filtered, and extract solutions were analysed for NH_4^+-N using the sodium nitroprusside method on a Technicon autoanalyzer IIC. Mineralizable N was estimated as the incubated sample NH_4^+-N concentration for NW soils (NW site unincubated soil NH_4^+-N concentrations were negligible) and the difference between unincubated and incubated NH_4^+-N concentration for NE soils. Microbial biomass C (C_{mic}) and N (N_{mic}) were determined on field moist samples by the chloroform fumigation-extraction method (Voroney et al. 1993). Unfumigated and fumigated subsamples (5 g organic, 20 g mineral) were shaken for one hour with 50 mL (organic) and 60 mL (mineral) 0.5 M K_2SO_4 followed by filtration. Inorganic–N (NH_4^+-N and NO_3^--N), total N and dissolved organic carbon were determined by Technicon autoanalyzer IIC using sodium nitroprusside, cadmium reduction, autoclave digestion/cadmium reduction and acid/potassium persulphate methods, respectively.

At the Wells site, soil N mineralization was also measured using a field *in-situ* core incubation method (Raison et al. 1987). *In-situ* field incubations were conducted for 90 days from June to September in 1998, 2003, 2007 and 2013; 5, 10, 14 and 20 growing seasons after plantation establishment. At seven locations in each treatment plot, two PVC soil incubation tubes (5 cm diameter and 30 cm length) were hammered vertically into the soil until the tubes were flush with the soil surface. One tube was covered and remained in the soil for 90 days. The second tube was removed immediately and refrigerated at 4 °C (hereafter T1). After 90 days (T90), the remaining *in-situ* tube was removed and refrigerated (4 °C). The soil from each tube was extruded and separated into organic (LFH), mineral 0–10 cm and mineral 10–20 cm depth subsamples. Samples were processed using the same approach as for the laboratory incubation and extracted with 2 M KCl (organic, 5 g ODW + 50 mL; mineral, 10 g ODW + 30 mL). Extract solutions were filtered and analysed for NH_4^+-N and NO_3^--N using the same methods as for microbial biomass N. Net N mineralization of NO_3^--N and NH_4^+-N during the 90-day incubation were calculated by subtracting initial from final concentration.

Subsamples of each laboratory and field *in-situ* incubation soil sampled were dried (organic 70° C; mineral air-dried) and ground in a Wiley mill (organic) or passed through a 2 mm sieve (mineral) prior to C and N analysis. Total organic C (TC) for the organic horizons was determined by loss-on-ignition or dry combustion and total N (TN) concentrations were determined by the semi-micro-Kjeldahl procedure or dry combustion. Mineralizable N, net N mineralization and soil C and N concentration data were combined with soil mass data to calculate plot level pools for organic and mineral horizons and organic + mineral horizons (profile). Soil mass estimates were calculated using combinations of plot and site quantitative quadrat and pit sampling, and horizon depth, bulk density and coarse fragment content measurements (Morris et al. 2019).

Jack pine (NE) and black spruce (NW) tree height was measured 5, 10, 15 and 20 growing seasons after plantation establishment on 25 (NE) or 45 (NW) trees in each treatment plot.

2.3. Statistical analysis

To address our questions we compiled and analyzed five different datasets: datasets 1–3 included laboratory incubation soil mineralizable N and microbial biomass data. Datasets 4 and 5 included *in-situ* field incubation net mineralization measurements at the Wells site. Specifically, dataset 1 included data from all of the 18 LTSP sites collected at 10 (NW) or 14 (NE) years post-harvest (Q1-3), dataset 2 included data from three NE LTSP sites (Wells, Eddy 3, Superior 3) with vegetation control treatments applied, collected at 14 years post-harvest (Q4), and dataset 3 included data from Nimitz with fertilization treatments applied, collected 14 years post-harvest (Q5), dataset 4 included data from Wells 5, 10, 14, and 20 years post-harvest where no vegetation control was applied (Q1-Q3), and dataset 5 included data from Wells both with and without vegetation control treatments 14 and 20 years post-harvest (Q4).

Shapiro tests and visual investigations of histograms were used to determine appropriate transformations. Data were transformed when required using log10 or square root transformations. In the case of datasets 4 and 5 where there were negative values for net mineralization, the data were zero-adjusted based on the most negative value prior to normality transformation. Mixed model ANOVA's were run to assess the impacts of biomass removal intensity, vegetation control and fertilization treatment while accounting for the random effect of site where datasets included multiple sites. The Wells site data was analyzed for each year separately rather than using repeated measures ANOVA because organic horizons were not sampled on the FTB treatment in early years, and the vegetation control treatment was only measured at 14 and 20 years post-harvest. Orthogonal contrasts were applied to address questions 1–3, and where interactions between explanatory variables were significant, the data and results were displayed as a subset of the interaction variable of interest. All data handling and analyses were performed in R version 4.0.3 using the lme4 package (Bates et al. 2015) for mixed model ANOVAs. Contrasts were created using the ginv function in the MASS package (Venables and Ripley 2002).

Using the tree height data, dominant 5-year height increments were calculated (Alban 1972) using the upper quartile of measured trees for each plot. Selection of the upper quartile avoided the inclusion of trees with insect damage to terminal shoots. Spearman correlation coefficients and regression analysis were performed in SigmaPlot Version 14.0 (Systat Software, San Jose, CA) to determine relationships between soil N indices and tree growth (Q6). Datasets 1–3 (mineralizable N and microbial biomass data above) and soil TN and C:N were used with dominant height increment to evaluate relationships for jack pine and black spruce at the 18 LTSP sites. For Wells, stand level aboveground biomass increment and foliar N content were calculated according to the methods of Fleming et al. (2018). Datasets 4 and 5 (N mineralization) and soil TN and C:N were used with dominant height increment, aboveground biomass increment and foliar N content to evaluate relationships for jack pine at specific times post-harvest. Soil N indices measured at earlier stages of plantation growth at Wells were also correlated with year 15–20 dominant height increment to determine if they could be used to predict future stand productivity.

3. Results

3.1. Laboratory incubations: Mineralizable N and microbial biomass

There were significant interactions between biomass removal treatments and soil type for several, but not all mineralizable N and microbial biomass measurements across the 18 LTSP sites (Table S2). Operational clearcutting using SO and FT treatments had significantly lower organic horizon mineralizable N concentrations and lower N pools when compared to UC for loamy sand and silt loam soil types, respectively, at

10–14 years post-harvest (Fig. 2a and 2h, linear contrast L_1). Mineral horizon mineralizable N concentrations and pools were significantly lower in SO and FT treatments compared to UC for the wet mineral soil type (Fig. 3d and 3i, linear contrast L_1), but higher for SiS and SiL soil types (Fig. 3d, 3g, 3h, linear contrast L_1). The effect of additive changes in organic and mineral horizon pools resulted in a significant increase in the overall profile mineralizable N pool for the clearcut treatments compared to the uncut reference forest (Fig. 4a, linear contrast L_1). The organic horizons of the SO treatment had significantly higher mineralizable N concentrations than FT for the SiS soil type (Fig. 2b, linear contrast L_2), and a higher mineralizable N pool for the course textured LS sites (Fig. 2f, linear contrast L_2). While we observed no significant differences between SO and FT mineral horizon mineralizable N concentrations or pools for any individual soil types (Fig. 3a-3j, linear contrast L_2), the profile mineralizable N pool was significantly higher across all 18 sites (Fig. 4a, linear contrast L_2). Removal of logging slash, LFH at upland sites and upper organic horizons at wet mineral and peatland sites, resulted in a significant decrease in FTB mineralizable N pools when compared to SO and FT treatments (Fig. 4a, linear contrast L_3). Differences in mineral horizon mineralizable N pools between the FTB treatment and non-bladed treatments were inconsistent, with FTB pools significantly higher pools for LS (Fig. 3f, linear contrast L_3), lower pools for SiS (Fig. 3g, linear contrast L_3), and no differences for other soil types (Fig. 3h-3j, linear contrast L_3). There were no significant effects of biomass removal treatment or soil type on organic and mineral horizon C_{mic}:N_{mic} (Table S2). There were no significant differences between organic horizon C_{mic} and N_{mic} when comparing SO and FT to UC (Fig. 4b and 4c, linear contrast L_1). Mineral horizon C_{mic} and N_{mic} were significantly higher for SO/FT compared to UC on SiS (Fig. 5b and 5g, linear contrast L_1), but were significantly lower for both wet mineral (Fig. 5d and 5i, linear contrast L_1) and peatland (N_{mic} only) soil types (Fig. 5j, linear contrast L_1). Greater slash retention with SO did result in significantly higher organic horizon C_{mic} and N_{mic} compared to FT (Fig. 4a and 4c, linear contrast L_2), but showed no effect on mineral horizon C_{mic} and N_{mic} for any soil type (Fig. 5a-5j, linear contrast L_2). Even though a gradient from high to low mineral horizon C_{mic} and N_{mic} from SO to FT to FTB treatments was evident for SiS, SiL and wet mineral soil types (Fig. 5b-5d, 5g-5i), FTB was only significantly lower than SO/FT for the SiS soil type (Fig. 5b and 5g, linear contrast L_3).

Soil mineralizable N concentrations and pools were not significantly

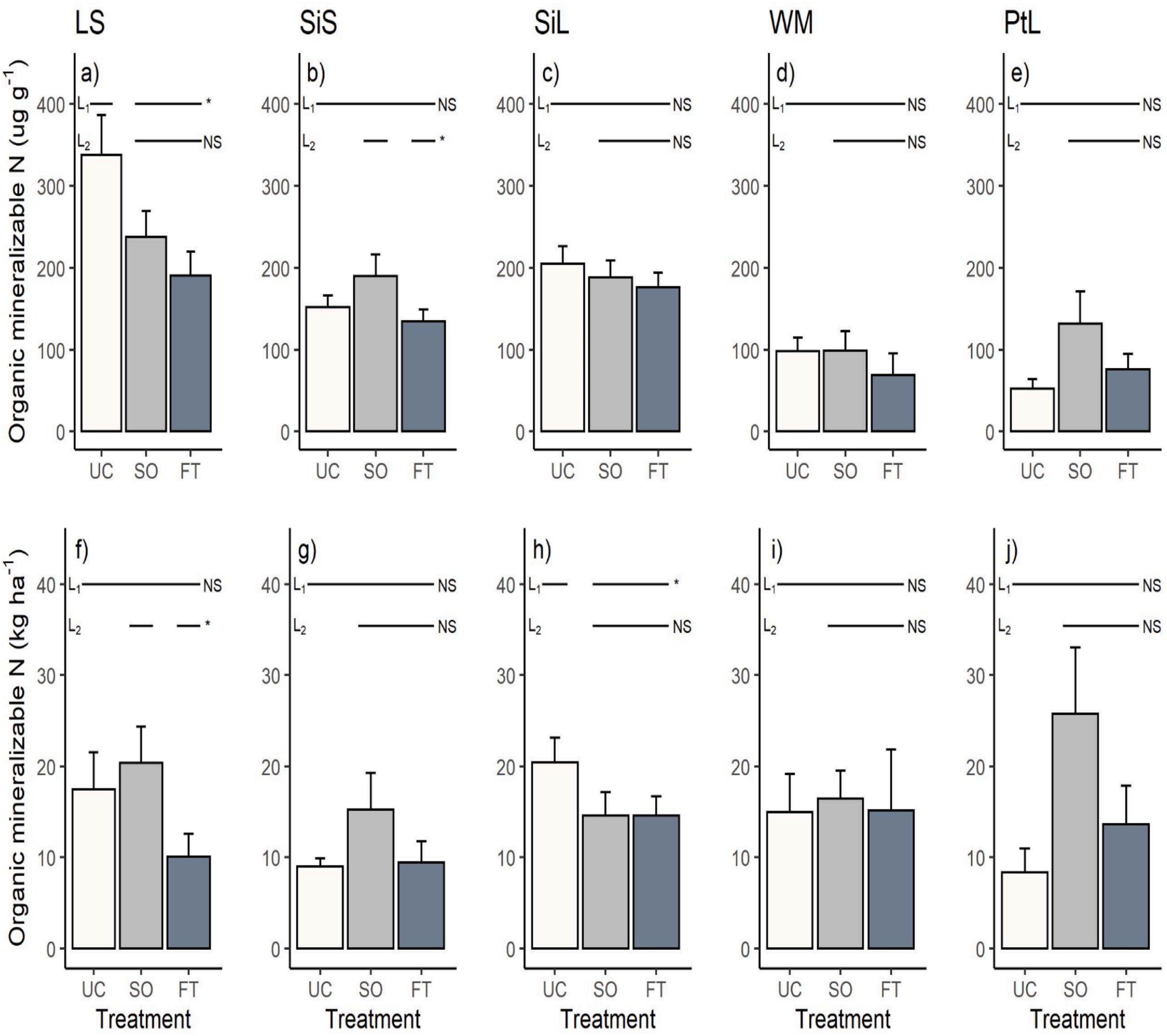


Fig. 2. Anaerobic laboratory organic horizon mineralizable N concentrations and pools measured 10 and 14 years post-harvest for uncut reference forest (UC) and biomass removal treatments (SO = stem-only harvest; FT = full-tree harvest) for contrasting soil types at 18 Ontario LTSP sites. LS = loamy sand, SiS = silty sand, SiL = silt loam, WM = wet mineral, PtL = peatland. Vertical bars represent standard errors. Horizontal lines that overlap treatment bars were not significantly different for orthogonal contrasts ($p < 0.05$; NS $p \geq 0.05$). L_1 = UC vs. SO/FT, L_2 = SO vs. FT, L_3 = FTB vs. SO/FT.

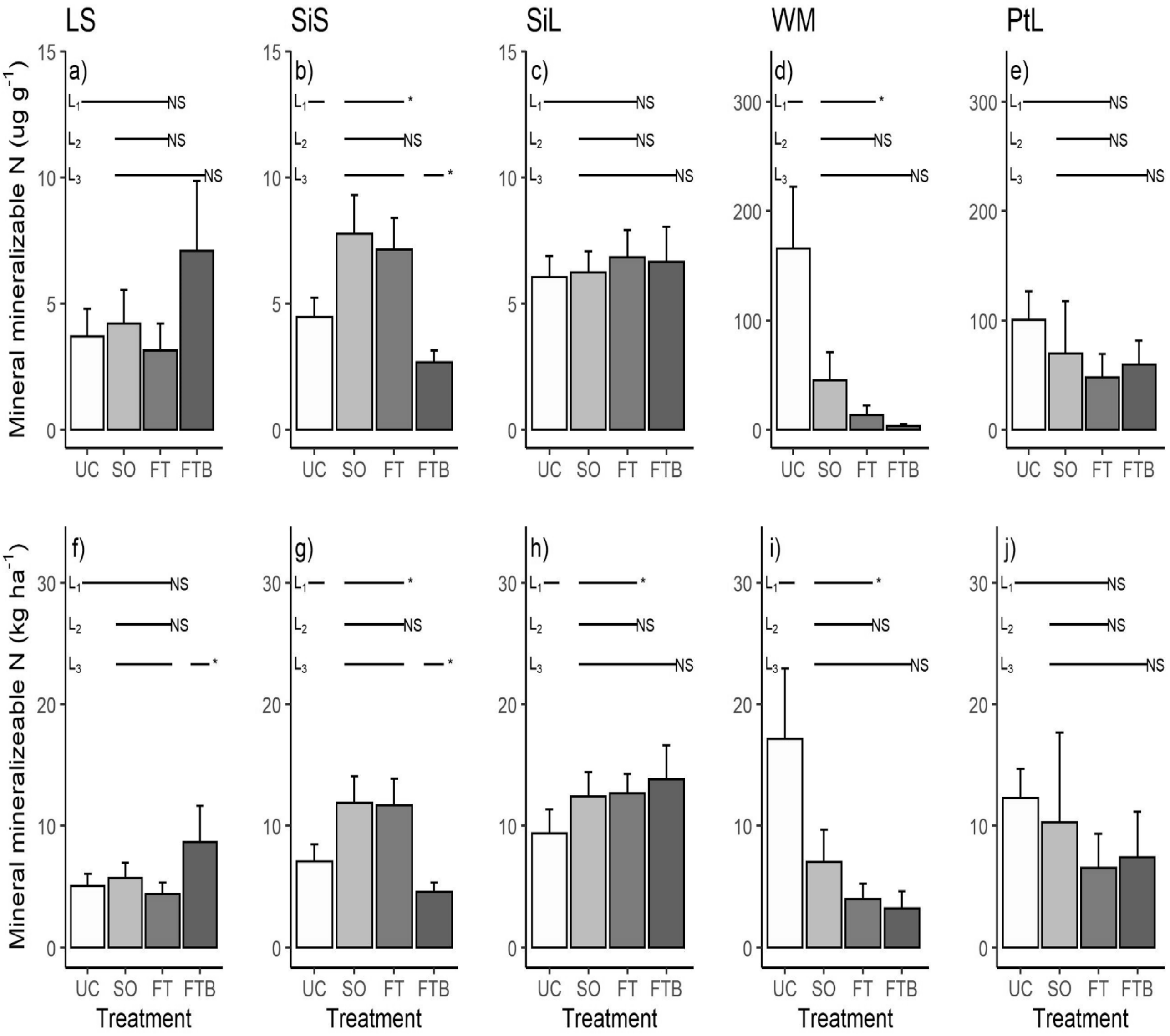


Fig. 3. Anaerobic laboratory mineral horizon mineralizable N concentrations and pools measured 10 and 14 years post-harvest for uncut reference forest (UC) and biomass removal treatments (SO = stem-only harvest; FT = full-tree harvest; FTB = full-tree harvest plus organic horizon removal) for contrasting soil types at 18 Ontario LTSP sites. LS = loamy sand, SiS = silty sand, SiL = silt loam, WM = wet mineral, PtL = peatland. Vertical bars represent standard errors. Horizontal lines that overlap treatment bars were not significantly different for orthogonal contrasts (* $p < 0.05$; NS $p \geq 0.05$). L_1 = UC vs. SO/FT, L_2 = SO vs. FT, L_3 = FTB vs. SO/FT.

changed by vegetation control (Tables S3, S4) or fertilization (Tables S5, S6). For the three NE sites with herbicide applications, non-significant increases and decreases in C_{mic} and N_{mic}, respectively, did result in significant higher C_{mic}:N_{mic} in the organic horizons for non-herbicided plots in both SO and FT (Table S4). Mineral horizon C_{mic}:N_{mic} for non-herbicided plots were also significantly higher than herbicided plots for the SO treatment (Table S4). At the Nimitz fertilization trial, the only significant change was a decrease in organic horizon N_{mic} for FTNPK compared to the FT and FTN treatments, but only on the vegetation control plots (Table S6).

3.2. *Field incubations: N mineralization*

Based on the *in-situ* N mineralization incubations conducted at Wells (5, 10, 14 and 20 years post-harvest), there were no significant differences between SO and FT treatment NH_4^+-N, NO_3^--N and inorganic-N mineralization concentrations and pools for organic and mineral horizons, or the total soil profile for any of the sampled years (Table S7, Fig. 6a-6d, linear contrast L_2; Tables S8-S11, linear contrast L_2). The only exception was the 20-year post-harvest organic horizon NH_4^+-N and inorganic-N pools when the FT treatment had higher values than the SO (Table S11, linear contrast L_2). As the incubations were only performed on one of the UC replicate plots we were unable to statistically compare the UC treatment to the SO/FT treatments. There was a tendency towards higher 0–10 cm mineral horizon NH_4^+-N and inorganic-N mineralization concentrations and pools for SO and FT when contrasted with UC at 5 years post-harvest, less differences at 10 and 14 years, and higher levels in the clearcut treatments again at 20 years (Fig. 6a-6d, Tables S8-S11). As expected, removal of logging slash and the organic horizon resulted in lower total profile NH_4^+-N and inorganic-N mineralization concentrations and pools for FTB compared to SO/FT where the organic horizon was left on site (Fig. 6c and 6d, linear contrast L_3; Tables S10 and S11, linear contrast L_3). While this difference was largely due to the removal of the organic horizon, 0–10 cm mineral horizon NH_4^+-N and inorganic-N mineralization concentrations and pools showed a tendency to be lower at 14 and 20 (significantly lower) years post-harvest in the FTB compared to SO/FT (Fig. 6c and 6d; Tables S10 and S11, linear contrast L_3). In contrast to the these later sampling dates,

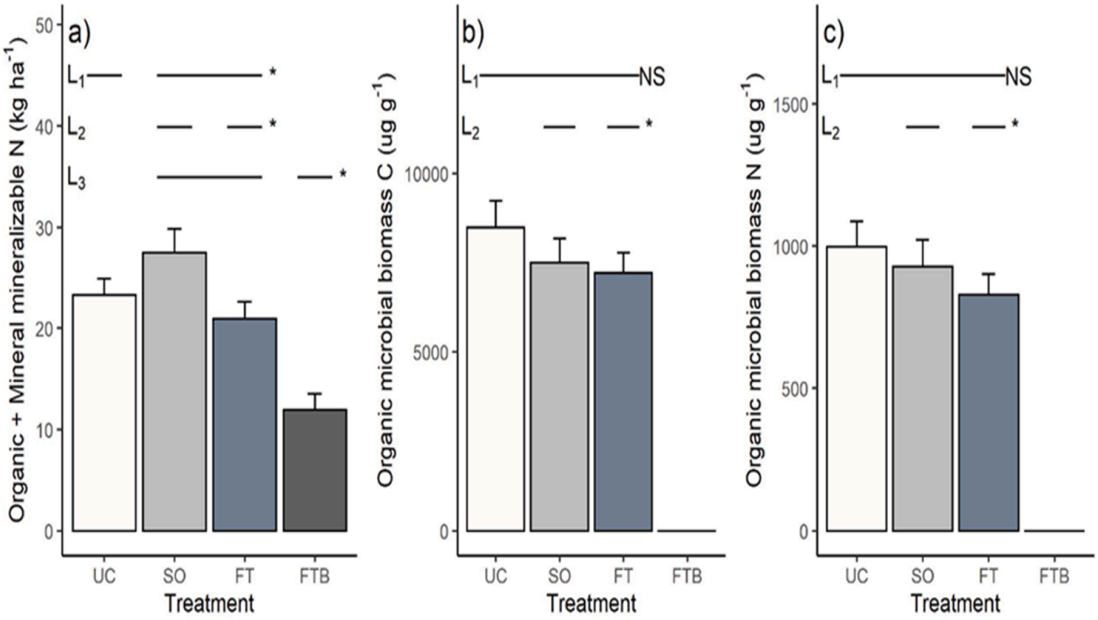


Fig. 4. Anaerobic laboratory profile mineralizable N pools and microbial biomass C and N measured 10–14 years post-harvest for uncut reference forest (UC) and biomass removal treatments (SO = stem-only harvest; FT = full-tree harvest; FTB = full-tree harvest plus organic horizon removal) at 18 Ontario LTSP sites. Vertical bars represent standard errors. Horizontal lines that overlap treatment bars were not significantly different for orthogonal contrasts ($p < 0.05$; NS $p \geq 0.05$). L_1 = UC vs. SO/FT, L_2 = SO vs. FT, L_3 = FTB vs. SO/FT.

higher mineral horizon N mineralization for FTB at 5 years post-harvest, and lower N mineralization in the mineral horizon of SO/FT at 10 years post-harvest resulted in no significant differences in profile N mineralization between SO/FT and FTB (Fig. 6a and 6b, linear contrast L_3; Table S8 and S9, linear contrast L_3). Nitrification was negligible in UC for all soil horizons and incubation years. Non-significant increases in NO_3^--N concentrations and pools were particularly evident at 5 and 10 years post-harvest, in the organic and 0–10 cm mineral soil horizons of the SO, FT and FTB treatments (Tables S8 and S9).

At 14 and 20 years post-harvest, total profile NH_4^+-N and inorganic-N mineralization pools tended to be higher in the SO and FT no vegetation control compared to vegetation control treatments, but the differences were not statistically significant (Table S12, Fig. 7a and 7b, Tables S13 and S14). The organic horizons on the no vegetation control SO and FT plots had the highest NH_4^+-N and inorganic-N mineralization concentrations, and, by 20 years post-harvest, FT-NH values were significantly greater than the FT-H treatment (Table S14). There were no significant differences between FTB no vegetation control and vegetation control treatments for N mineralization concentrations and pools at 14 and 20 years post-harvest.

3.3. *N indices and plantation productivity*

Relationships between mineralizable N, microbial biomass, soil TN, soil C:N and year 10–15 dominant height increments for the biomass removal treatments at the 18 LTSP sites are reported in Table 1. Sites were grouped by soil type (LS and SiS combined to represent sandy soils, ≤ 50% silt) and tree species. In general, upland jack pine plantation height growth showed stronger relationships to N indices than upland black spruce. Jack pine growth was significantly correlated to several N indices, including mineralizable N, microbial biomass and soil TN and C:N measurements. In contrast, on the wet mineral and peatland soil types, black spruce height growth was more often significantly correlated with microbial biomass indices, however the strongest relationship was with mineral horizon C:N. For the Wells site *in-situ* field incubations, correlations were generated for N mineralization, soil TN and soil C:N measurements at 5, 10, 14 and 20 years post-harvest with the corresponding jack pine dominant height increments for each sample period (Table 2). Statistically significant relationships were more prevalent at 20 years post-harvest than at earlier stages of plantation development (Table 2, Fig. 8a-8f). Correlations between soil N indices and two other plantation productivity measurements (aboveground tree biomass increment, foliar biomass N pools) yielded less frequent significant relationships than dominant height increment, with the exception of aboveground tree biomass increment at 14 year post-harvest (Table S15). With only a few exceptions (i.e., 10 year total profile TN, 14 year mineral horizon and total profile net mineralization), soil N indices measured at earlier stages of plantation development were not significantly correlated to future jack pine dominant height increments, measured at 15–20 years post-harvest (Table S16).

4. Discussion

4.1. *Treatment effects on soil N dynamics*

Most studies that assess forest soil N availability report soil concentration data. However, combining concentration data with measurements of soil mass can account for the effect of harvest management practices on both litter/soil quality and litterfall/decomposition rates that influence overall vegetation N supply. We report both N concentrations (mass N per mass soil, i.e., μg g^{-1}) and pools (mass N per unit area for given soil horizons/depths, i.e., kg ha^{-1}), and we include organic horizon soil N which is not routinely assessed in many studies. The organic horizons at our sites represent a substantive store of organic matter and N.

4.1.1. *Question 1: What were the effects of operational stem-only harvest and full-tree harvest compared to the uncut/pre-harvest forest?*

Anaerobic incubation mineralizable N results for the total profile showed increased pools for the operationally harvested treatments when compared with the uncut forest for the 18 sites 10–14 years post-harvest. While there was no significant interaction between biomass removal treatment and soil type for the profile pool, 6 of the 9 sites that showed SO/FT greater than UC also had greater organic horizon mineralizable N

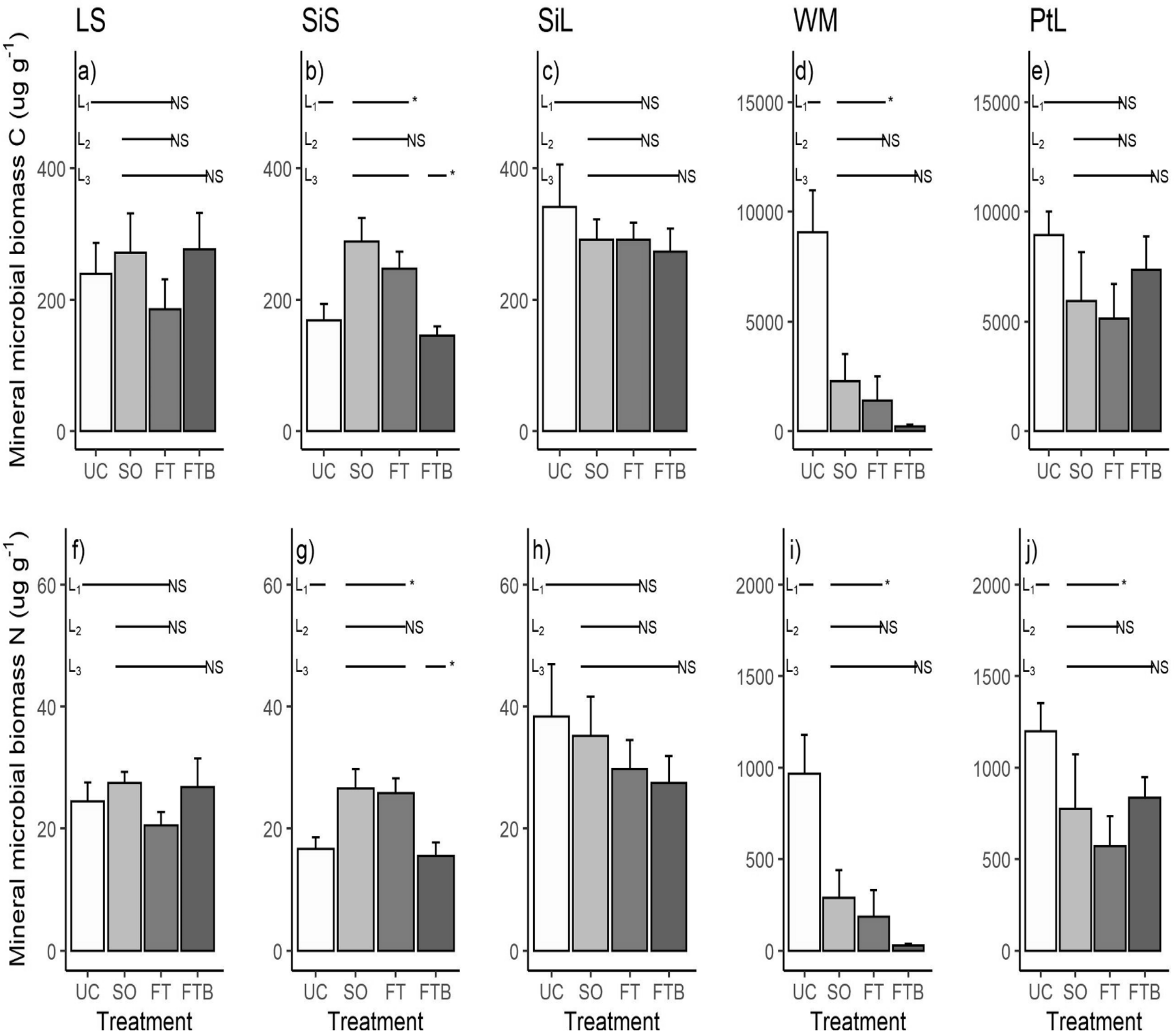


Fig. 5. Anaerobic laboratory mineral horizon microbial biomass C and N measured 10 and 14 years post-harvest for uncut reference forest (UC) and biomass removal treatments (SO = stem-only harvest; FT = full-tree harvest; FTB = full-tree harvest plus organic horizon removal) for contrasting soil types at 18 Ontario LTSP sites. LS = loamy sand, SiS = silty sand, SiL = silt loam, WM = wet mineral, PtL = peatland. Vertical bars represent standard errors. Horizontal lines that overlap treatment bars were not significantly different for orthogonal contrasts (* $p < 0.05$; NS $p \geq 0.05$). L_1 = UC vs. SO/FT, L_2 = SO vs. FT, L_3 = FTB vs. SO/FT.

pools. At this stage of plantation development, these sites have passed through the commonly reported, post-harvest assart nutrient flush (Kimmins, 2004) and with the building of the tree canopy have begun to develop a litterfall flux to the soil surface (i.e., a recoupling of some nutrient cycling pathways).

Studies reporting boreal forest harvesting effects on organic horizon N availability at similar times post-harvest have been variable. The decrease in organic horizon mineralizable N concentration at the LS sites in our study after harvesting was also reported using a field incubation approach for a boreal forest stand in Quebec 15 years post-harvest (Brais et al. 2002). Using laboratory incubations Paré and Van Cleve (1993) and Simard et al. (2001) reported increases and no change in net N mineralization, respectively, for boreal stands 11–16 years after logging. In another study examining N availability in coniferous ecosystems in British Columbia, Grenon et al. (2004) classified a range of sites from responsive to unresponsive to clearcutting for measured N variables. Factors that were identified as controlling site inorganic-N production and consumption included soil temperature, moisture and pH, chemical inhibitors, site vegetation recovery, soil faunal communities, and soil C and N status. There is a recognition that forest harvesting and subsequent soil disturbance by site preparation equipment would differentially (e.g., soil type dependent) alter these factors, both initially, as well as over time, thereby affecting soil N dynamics. These differences in harvesting response across our sites were highlighted by the significant increases in mineral soil horizon mineralizable N pools after clearcutting at the finer textured (SiS, SiL) upland sites, decreases for the lower organic layers at wet mineral sites and no significant changes for coarse textured upland sites (LS) or peatlands. The increase in mineral horizon mineralizable N at the SiS sites, and decrease at the wet mineral sites were matched by similar changes in mineral horizon C_{mic} and N_{mic} on those soil types.

4.1.2. *Question 2: What were the effects of stem-only harvest compared to full-tree harvest?*

For the *in-situ* aerobic incubations at the Wells site, measurements at four different times post-harvest showed no differences in net N mineralization pools between stem-only and full-tree harvesting. However, the anaerobic incubation results including all 18 sites (10–14 years post-harvest) showed higher profile mineralizable N pools on the stem-only compared to the full-tree treatment due to the additive effect of

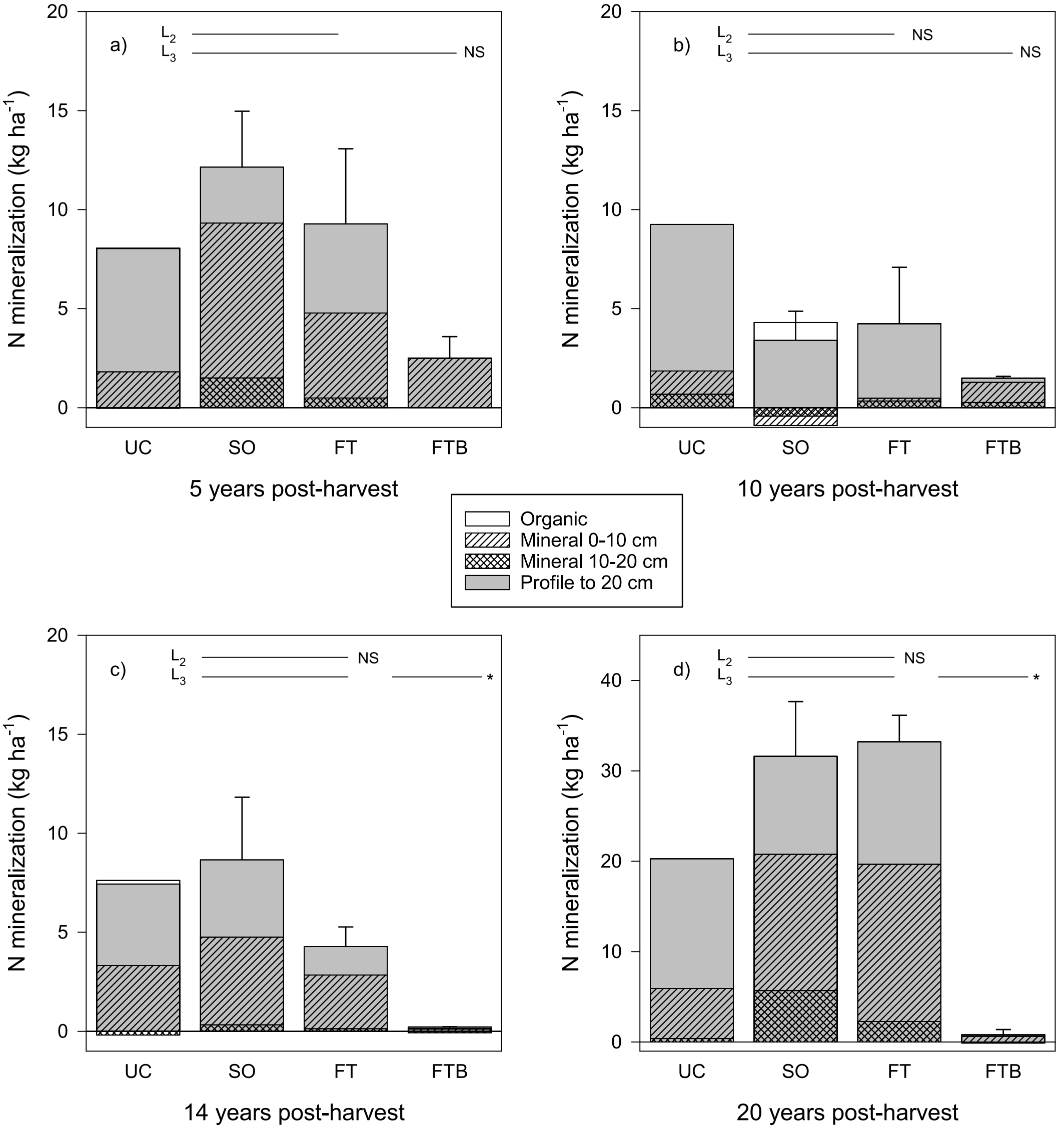
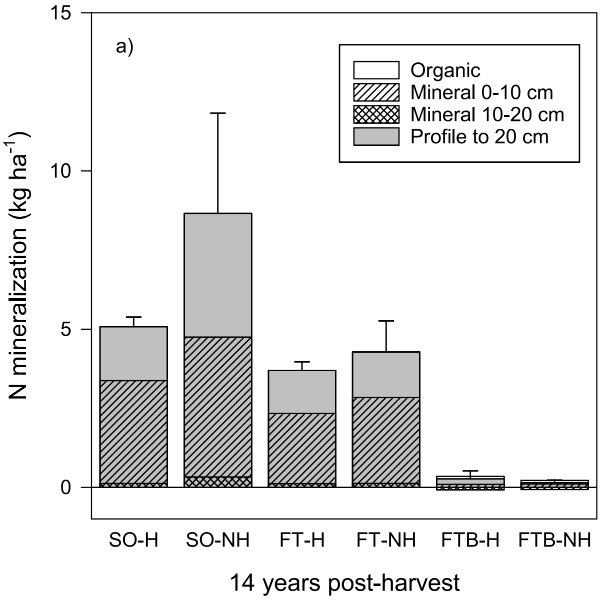


Fig. 6. *In-situ* field incubation N mineralization for uncut reference forest (UC) and biomass removal treatments (SO = stem-only harvest; FT = full-tree harvest; FTB = full-tree harvest plus organic horizon removal) at Wells LTSP site 5, 10, 14 and 20 growing seasons post-harvest. For years and treatments when N immobilization (negative net N mineralization) was occurring for mineral horizons, the shaded bar represents the profile pool. Vertical bars represent standard errors. Horizontal lines that overlap treatment bars were not significantly different for orthogonal contrasts (* $p < 0.05$; NS $p \geq 0.05$). L_2 = SO vs. FT, L_3 = FTB vs. SO/FT.

non-significant increases in both organic and mineral horizon pools. The increased slash loading on the stem-only harvested plots also increased C_{mic} and N_{mic} compared to full-tree harvesting.

As with harvesting in general, studies examining the effects of increased forest residue removals (SO vs FT) on N dynamics have yielded varied results. O'Connell et al. (2004) examined N dynamics for five years after harvest using zero, single and double slash loading plots in Eucalyptus plantations in Australia. They found that mineralizable soil N concentrations and net mineralization increased with increasing slash retention, and concluded that N mineralized from harvest residues will contribute to future plantation N requirements. Smolander et al. (2013) reported a steady but non-significant increase in net N mineralization concentrations for the humus horizon, 4 years after a gradient in fresh logging residue (0, 10, 20 and 40 Mg ha^{-1}) was distributed in a thinned Scots pine stand in Finland. In a loblolly pine stand in North Carolina, USA, Piatek and Allen (1999) used the *in-situ* aerobic core incubation method to evaluate differences in net N mineralization pools between stem-only and full-tree harvested plots. They reported significantly higher mineralization for the upper 15 cm of mineral soil on stem-only plots 15 years post-harvest. In contrast, Smaill et al. (2010) found no significant differences in mineralizable N concentrations and N_{mic} between stem-only and full-tree treatments at four *Pinus radiata* plantations in New Zealand. These researchers used the anaerobic incubation method that we used in our study and measured mineralizable N in the organic horizon (FH) and upper mineral soil (0–2.5 cm depth).

While the stem-only harvest at our sites left, on average, approximately two and one-half times more C and N on site than the full-tree harvest we previously reported that at 20 years post-harvest there were no differences between upper profile total C and N reserves (Morris et al. 2019). Stem-only and full-tree slash was distributed 42, 45 and 13% as coarse (>7 cm diameter) and fine (<7 cm diameter) woody debris and foliage, respectively. In contrast, N loadings in slash were primarily as foliage (60%) with both coarse and fine woody debris contributing 20%. While we would expect the foliage and fine woody debris from logging to decompose quickly providing labile sources of C and N to the soil surface immediately after harvest (Piirainen et al. 2002;



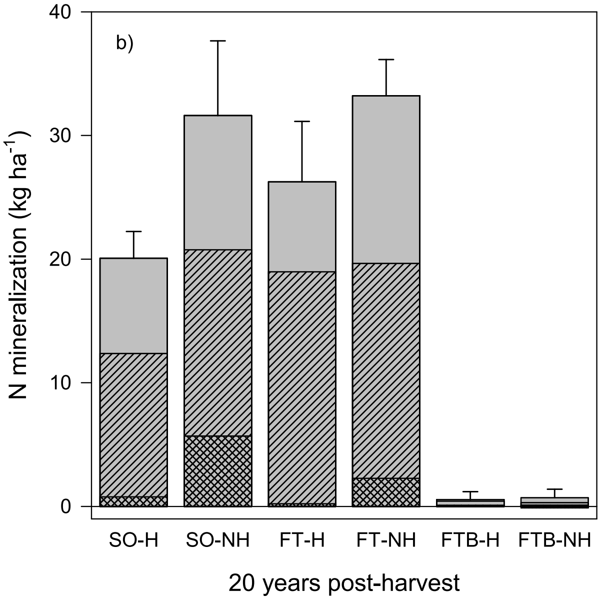


Fig. 7. *In-situ* field incubation N mineralization for vegetation control/no vegetation control (H/NH) biomass removal treatments (SO = stem-only harvest; FT = full-tree harvest; FTB = full-tree harvest plus organic horizon removal) at Wells LTSP site, 14 and 20 growing seasons post-harvest. For years and treatments when N immobilization (negative net N mineralization) was occurring for mineral horizons, the shaded bar represents the profile pool. Vertical bars represent standard errors; H/NH means comparisons for each treatment are not significantly different at $p < 0.05$.

Fahey et al. 1991; Rosén and Lundmark-Thelin 1987), our mineralizable N results demonstrate that the effects of greater slash retention on soil N dynamics can be present several years post-harvest. In a previous study examining litter decomposition at our NW affiliate LTSP study sites, Symonds et al. (2013) found that decomposition rates were the same for both black spruce and jack pine needles, and for stem-only and full-tree harvested plots. Further, while they reported needle and twig (<0.6 mm diameter) N mass losses from 20 to 30% after the first 6 months on the forest floor, N mass in needle litter increased to 20% above initial content and was maintained there for up to 4 years, when the experiment was ended. In relation to the slash decomposition at our sites, we have observed that needle abscission from logging residues takes place primarily in the second and third year after harvesting. It therefore seems likely that when this immobilized N was released through further decomposition, the effect would be greater on the stem-only treatment due to the higher slash loadings.

Coarse slash at our sites could also be playing a role in N cycling processes as it decomposes more slowly, over longer time periods after harvest. While coarse slash only contributed 20% of the total N loading in slash for both clearcut treatments, the content of N in coarse slash at the NE sites was two times greater on the stem-only plots when compared to the full-tree plots (~2 kg ha^{-1} difference on average). Total N loadings for fine slash and foliage were only 1.4 times greater on the stem-only treatment. A separate experiment examining coarse woody debris (CWD) dynamics at several of the NW coarse textured upland sites used in this study showed a loss of N from CWD between years 4–14 post-harvest after an initial stage of N immobilization (Wiebe et al., 2012). They found that the CWD N loss represented 80% of the soil available N pool 14 years post-harvest, in spite of its small contribution to the total N pool.

4.1.3. *Question 3: What were the effects of full-tree harvest with organic horizon removal compared to stem-only and full-tree harvest without organic horizon removal?*

The removal of the folic forest floor at the upland sites and the upper organic horizons at wet mineral and peatland sites was the most important factor that led to lower profile mineralizable N pools on the bladed treatment when compared to stem-only and full-tree harvesting. These surface organic horizons contributed on average, approximately 60% (14.5 kg ha^{-1}) of the profile mineralizable N pool when they were left in place. The importance of the organic horizon to overall site N availability was also confirmed by the *in-situ* incubations at the Wells site. With the exception of the 10-year post-harvest incubation, the organic horizon removal treatment had lower profile net N mineralization pools, with values ranging from 23% of the stem-only and full-tree harvest pools at 5 years post-harvest to 2% at 20 years. The impact of organic horizon removal was also evident in the mineral soil at the Wells site with lower mineralized NH_4^+-N concentrations and pools at years 5, 14 and 20 post-harvest in comparison to the non-organic horizon removal treatments.

Wilhelm et al. (2017) reported results from 18 core and affiliate LTSP sites across North America that showed that although this severe treatment increased stress-tolerant bacteria and fungi populations 11–17 years after harvest compared to the less intensive treatments, the microbial community was largely resilient with little impact on the overall community composition. The study included six upland sites from the current study that had stumps and coarse roots removed during the blading treatment while the other LTSP sites removed only slash and the organic horizon. At our study sites the removal of the organic horizon, harvesting residues, stumps and coarse roots appears to have rapidly exhausted the supply of labile organic matter, which has reduced available C, becoming a limit to microbial growth and soil N availability. The removal also affected the amount of residues and tree litter that could be incorporated into the soil as substrate for N mineralization. In these slow growing forests, the litterfall flux is slow to develop, decomposition rates are slow, and even at 20 years post-harvest the organic horizon consists only of a thin litter horizon. One additional complicating factor in our experiment that is likely influencing these results is the removal of up to 5 cm of the upper mineral soil in the organic horizon removal treatment. As noted by Morris et al. (2019), this removal led to a lower total mineral soil N reserve, when compared to non-organic horizon removal treatments, essentially due to the surface exposure of lower N content soil horizons that were deeper in the profile prior to blading. It is also possible that the surface exposure of the mineral soil following blading could have contributed to changing soil N dynamics through changes in water and gas exchange.

The Wells site is one of the six SiS sites that also showed a lower

Table 1

Spearman rank correlation results for relationships between soil N indices and dominant height increments from years 10 to 15 for the northeastern jack pine (NE-Pj) and northwestern black spruce (NW-Sb) study sites for stem-only harvest (SO), full-tree harvest (FT) and full-tree harvest plus organic horizon removal (FTB) treatments. (p values in parentheses. Bolded values indicate significance at $p < 0.05$.)

Soil type[1]	Species	Organic Min N (μg g^{-1})	Mineral Min N (μg g^{-1})	Organic + Mineral Min N (kg ha^{-1})	Organic N_{mic} (μg g^{-1})	Organic C_{mic}: N_{mic}	Mineral N_{mic} (kg ha^{-1})	Mineral C_{mic}: N_{mic}	Organic Soil TN (g kg^{-1})	Organic Soil C:N	Mineral Soil TN (g kg^{-1})	Mineral Soil C:N	Organic + Mineral Soil TN (kg ha^{-1})
LS SiS	NE-Pj	0.158	0.144	**0.353**	0.103	−0.028	**0.357**	**−0.348**	**0.360**	−0.201	0.136	0.073	**0.495**
		(0.262)	(0.176)	**(<0.001)**	(0.512)	(0.859)	**(0.001)**	**(0.002)**	**(0.001)**	(0.077)	(0.206)	(0.497)	**(<0.001)**
	n=	52	90	90	42	42	80	80	78	78	88	88	88
	NW-Sb	−0.076	−0.140	0.093	−0.071	0.156	0.128	−0.032	−0.024	0.199	−0.091	0.050	0.089
		(0.732)	(0.481)	(0.642)	(0.751)	(0.482)	(0.520)	(0.871)	(0.908)	(0.336)	(0.651)	(0.802)	(0.655)
	n=	22	27	27	22	22	27	27	25	25	27	27	27
SiL	NE-Pj	**0.354**	**0.389**	**0.446**	−0.141	**−0.334**	0.127	**−0.343**	0.187	−0.089	−0.148	**0.488**	0.053
		(0.011)	**(<0.001)**	**(<0.001)**	(0.336)	**(0.020)**	(0.282)	**(0.003)**	(0.142)	(0.487)	(0.208)	**(<0.001)**	(0.652)
	n=	51	75	75	48	48	73	73	63	63	74	74	74
	NW-Sb	0.379	0.340	0.410	−0.086	−0.005	−0.001	−0.002	**0.720**	**−0.622**	0.383	0.320	0.172
		(0.118)	(0.164)	(0.089)	(0.729)	(0.980)	(0.993)	(0.987)	**(<0.001)**	**(0.006)**	(0.114)	(0.189)	(0.487)
	n=	18	18	18	18	18	18	18	18	18	18	18	18
Wet mineral/ peatland	NW-Sb	0.255	**−0.368**	0.276	−0.171	**−0.414**	**−0.555**	**−0.464**	0.094	−0.175	−0.325	**−0.778**	0.325
		(0.151)	**(0.035)**	(0.119)	(0.364)	**(0.023)**	**(<0.001)**	**(0.007)**	(0.601)	(0.328)	(0.065)	**(<0.001)**	(0.065)
	n=	33	33	33	30	30	33	33	33	33	33	33	33

[1] LS = loamy sand, SiS = silty sand, ≤ 50% silt; SiL = silt loam, > 50% silt.

Table 2

Spearman rank correlation results for relationship between soil N indices and jack pine dominant height increments measured at the same number of years post-harvest at the Wells study site for tree-length harvesting (TL), full-tree harvesting (FT), and full-tree harvesting plus organic horizon removal (FTB) treatments. (p values in parentheses. Bolded values indicate significance at $p < 0.05$.)

Years post-harvest	Organic N min (μg g^{-1})	Mineral N min (μg g^{-1})	Organic + Mineral N min (kg ha^{-1})	Organic Soil TN (g kg^{-1})	Organic Soil C:N	Mineral TN (g kg^{-1})	Mineral C:N	Organic + Mineral TN (kg ha^{-1})
5	−0.200	**−0.817**	**−0.733**					
	(0.714)	**(0.004)**	**(0.020)**					
n=	6	9	9					
10	−0.383	**0.783**	0.433			−0.102	−0.200	−0.462
	(0.285)	**(0.009)**	(0.223)			(0.733)	(0.513)	(0.123)
n=	9	9	9			12	12	12
14	−0.187	0.296	0.152	−0.463	0.172	0.253	0.251	**0.480**
	(0.451)	(0.227)	(0.541)	(0.052)	(0.487)	(0.305)	(0.309)	**(0.043)**
n=	18	18	18	18	18	18	18	18
20	**0.577**	0.475	**0.624**	**0.523**	**−0.626**	**0.581**	−0.073	**0.748**
	(0.012)	(0.052)	**(0.006)**	**(0.026)**	**(0.005)**	**(0.011)**	(0.767)	**(<0.001)**
n=	18	17	18	18	18	18	18	18

anaerobic incubation mineralizable N pool and N_{mic} for the mineral soil of the organic horizon treatment compared to the stem-only and full-tree treatments. We are uncertain as to why the organic horizon treatment had a higher mineralizable N pool for the LS soil types in our study. Elevated soil temperatures were used to explain increased mineral soil net N mineralization with forest floor removal at a boreal spruce LTSP installation in northeastern British Columbia (Tan et al. 2005). The authors used an *in-situ* buried bag method during the growing season seven years after harvest to determine N mineralization but also found that forest floor removal resulted in lower mineral soil N_{mic} and soil enzyme activities related to N cycling when compared to stem-only harvesting where the forest floor was left intact (Tan et al. 2008). Our use of the laboratory anaerobic incubation method discounts the field effects of changing moisture and temperature conditions that could affect mineralizable N rates at specific times.

4.1.4. Questions 4 and 5: What were the effects of vegetation control and fertilization?

Our study was unable to demonstrate any strong effects of vegetation control or fertilization on anerobic incubation mineralizable N or *in-situ* N mineralization. Intra and inter species related differences in litter quantity and quality have the potential to affect N dynamics in soil (Knoepp and Swank 1998; Ste-Marie and Paré 1999), and as such, vegetation control treatments that change plant communities could indirectly feedback to alter N availability. As a result, herbicide applications could lead to two possible scenarios, short-term effects of increased fresh organic matter inputs that increase N immobilization, decreasing N mineralization, and longer-term effects where higher quality litter modifies soil properties and increases N mineralization. The three NE sites where we assessed vegetation control were jack pine-coarse sand ecosites (56–85% sand), classified as shrub and herb poor due to low nutrient and moisture regimes. This site type would be expected to show less impact by vegetation control on N cycling in comparison to richer sites with more prolific, diverse vegetation communities.

In our study, glyphosate was applied three times to treated plots, whereas operational herbicide application to this site type would only occur once, two to four years after plantation establishment. While vegetation control increased planted tree growth (Fleming et al. 2018), three years after application total vegetation coverage was not different between herbicided and non-herbicided plots. The herbicide treatment did alter the abundance of some species groups promoting grasses over

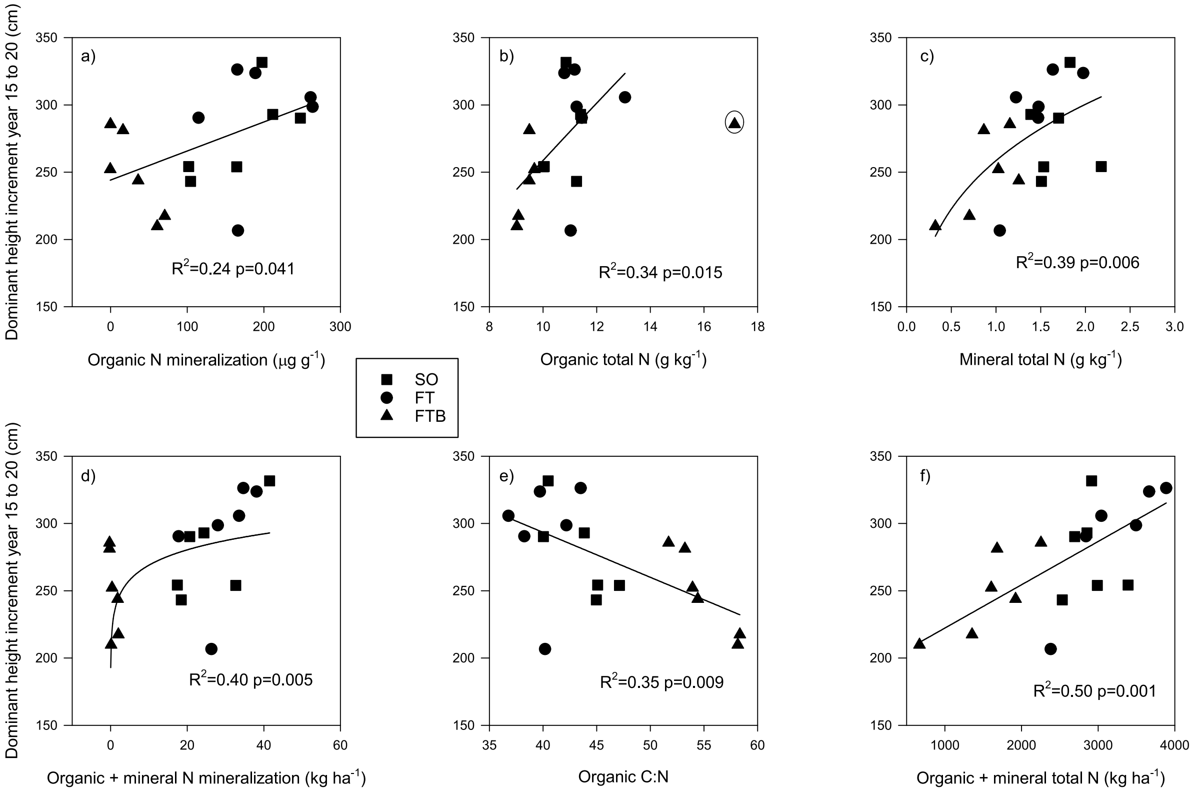


Fig. 8. Regression relationships with fitted curves between soil N indices measured 20 growing seasons post-harvest and dominant height increments from years 15–20 measured at Wells LTSP site for stem-only harvest (SO), full-tree harvest (FT) and full-tree harvest plus organic horizon removal (FTB) treatments. Circled outlier FTB point in Fig. 7b was not included in the regression.

shrubs as the repeated vegetation control virtually eliminated herbs and shrubs in subsequent years (Tiveau 2000). Higher full-tree non-herbicided organic horizon net mineralization 20 years post-harvest and decreases in organic horizon C_{mic}:N_{mic} indicate that effects of vegetation control may still occur on these sites as the influence of treatment differences in litterfall quantity and composition transfer into the soil profile.

Fertilizer additions in our study at the Nimitz site added N directly onto the forest floor and should contribute N in litterfall for several years after application. An earlier fertilization trial in a 45-year-old jack pine stand at this site (Morrison and Foster 1977), estimated the distribution of N in ecosystem components three years after a 300 kg N ha^{-1} urea application. They estimated that the N applied was distributed 23% in the trees, 1% in ground vegetation, 26% in the forest floor, 10% in the mineral soil, with 30% lost through volatilization and 10% remained unaccounted for. Approximately three and fourfold increases over the unfertilized control in aboveground and foliage dry matter, respectively, were realized with the fertilizer treatment.

The lack of a fertilization response in mineralizable N concentrations and pools at our site may have resulted from the low absolute amount of N added to the soil. We added two applications of 100 kg N ha^{-1} separated by three years, in comparison to total N reserves of ~2000 kg ha^{-1} in slash, the forest floor and upper 20 cm of mineral soil after full-tree harvesting at the site (Morris et al. 2019). In contrast, net N mineralization rates increased from two to ten times at three Norway spruce sites in Sweden fertilized with $(NH_4)_2SO4$ (Andersson et al. 2002; Demoling et al. 2008). Fertilizer had been added continuously (daily, weekly or annually) for 9–30 years prior to the mineralization measurements, with cumulative N additions ranging from 780 to 1060 kg N ha^{-1}. Similarly, Adams and Attiwill (1984) added up to 1000 kg N ha^{-1} over a period of 4 months to a 23-year old *Pinus radiata* plantation in southern Australia. Fertilization increased rates of N mineralization immediately after application, but rates returned to control plot levels within two and a half years. Given the results of these other experiments, if there was an effect at the Nimitz trial, fertilization at the levels we used would likely have had a small, short-lived impact on N availability that was not detectable when we did our sampling three years after the last fertilizer application. It remains to be seen if annual elevated N additions in litterfall will have a future impact on soil N cycling.

4.2. *Tree growth and soil N indices*

In earlier research at the Ontario affiliate LTSP sites, we found positive relationships between 10 and 15 year jack pine dominant height increments and immediate post-harvest C and nutrient reserves on sandy (≤50% silt) sites (Hazlett et al. 2014). We reasoned that metrics that assessed post-harvest soil nutrient quantities and availability would be more robust indicators of long-term productivity than nutrient budget derived metrics (e.g. stability ratios, nutrient replacement times). This study extends that work by evaluating the relationships between soil-based N indices and plantation tree growth several years after establishment, across a gradient of site productivity (upland sites Pj SI50 14.1–20.7 m; wetland sites Sb SI50 10.2–14.5 m) and biomass harvesting removals in these N limited boreal forests. By considering several indices that included both concentration and pool measurements, we also hoped to evaluate the value of different metrics in relation to the data required to calculate them.

4.2.1. *Question 6: What were the relationships between soil N indices and stand productivity?*

We observed that a number of N indices were significantly related to 10–15 year dominant height increments when we considered the 18 LTSP sites in our study. For upland sites, jack pine showed a greater number of significant relationships between soil N indices and tree growth than black spruce. At this stand biological age, the jack pine plantations were approaching crown closure (tree heights at age 15–6.5 m), a great canopy nutrient demand, and therefore the role of profile soil mineralizable N and total N pools were seemingly more important factors for tree growth than at the black spruce sites (Fleming et al. 2021). Black spruce is a slower growing species (tree heights on upland sites at age 15–4.5 m) and it appears that factors other than inorganic N availability are controlling growth on our sites at this stand stage.

Profile mineralizable N pools seem to be a more broadly applicable N index for predicting jack pine growth, showing a significant relationship with jack pine dominant height increment for all soil types, while the profile total soil N pool was only significantly related to height at the coarser textured sites. Foster et al. (1995) reported a positive relationship between soil total N content and aboveground phytomass for mid- to late-rotation jack pine stands developed on sandy soils. Mineral soil C_{mic}:N_{mic} was also consistently negatively related to height for jack pine across all soil types and black spruce growing on wet mineral and peatland soil types. C_{mic}:N_{mic} showed a wide range (3.6–21.6 [mean 11.3] for upland sites; 2.3–17.7 [mean 8.5] for wet mineral/peatland sites) and these results suggest that site and biomass removal treatment combinations with more fungal-dominated microbial biomass were associated with plantations exhibiting lower growth rates. Kranabetter et al. (2007) identified a similar relationship between stand height and forest floor C_{mic}:N_{mic} (but not mineral soil C_{mic}:N_{mic}) across a boreal site productivity gradient in southern British Columbia, over a narrower C_{mic}:N_{mic} range (~2.5–8) than we found in our study.

The effectiveness of N indices in predicting jack pine dominant height increments at the Wells site was greater 20 years post-harvest than at earlier stages of stand development, but at best, still only accounted for half of the variability in height increment. At 20 years, the profile net N mineralization pool determined using the field incubation approach showed a positive relationship to jack pine growth, which was also present for the LS/SiS soil type when mineralizable N was measured using the laboratory incubation. Negative relationships between mineral horizon and profile net N mineralization pools with growth at 5 years post-harvest were due to higher tree growth on the full-tree bladed treatment despite the smaller N mineralization pools. Increased tree growth on the bladed treatment compared to non-bladed treatments was attributed to favourable changes in physical soil characteristics (e.g., soil temperature and moisture conditions) in the first years after plantation establishment (Fleming et al. 2006; Fleming et al. 2021; Ponder et al. 2012).

In general, we found jack pine dominant height increment showed a greater number of significant relationships with soil N indices compared to stand level biomass increment and foliar N content. Soil N indices were poorly related with foliar N content across all years and showed most significant relationships with stand level biomass increment 14 years post-harvest. Being able to link soil N availability indices to dominant height increment to a greater degree than other stand measurements supports the supposition that it is a good measure of soil quality in these young, even-aged stands. Dominant height increments are not strongly influenced by stand density, which can vary among treatments and sites and affect stand biomass estimates. (Bontemps et al. 2009). Our attempt to predict future stand productivity using N indices measured earlier in stand development, did however, have limited success. The factors that primarily limit tree growth are changing as stand development proceeds (Fleming et al. 2021) and nutrient cycling processes between trees and the soil are likely just now becoming reestablished.

In summary, while we found no one soil N index that could be used to predict jack pine and black spruce growth universally across all of our sites, soil types and treatments, there were several that were more effective than others in specific situations. Our results suggest that soil inorganic N availability was more critical for jack pine than black spruce in the first 15 years after planting, and that jack pine growth was becoming more strongly linked to N availability at 20 years post-harvest. Generally, our results indicate that measurements of organic and mineral horizon total N concentrations are as effective at predicting dominant height increment as more resource intensive measurements that require either incubation techniques and/or estimates of soil mass. A limitation in our evaluation of N indices as a predictor of stand productivity was that we considered only measurements of inorganic N in our incubation experiments. While Kranabetter et al. (2007) also reported significant relationships between soil total N and C:N with stand height, they found stronger relationships with N indices that included both inorganic and organic N availability measurements.

5. Conclusions

Our evaluation of soil N indices at Ontario jack pine and black spruce affiliate LTSP study sites demonstrated that biomass removal treatments, vegetation control and fertilization had varying effects on N availability across both treatment types and stages of initial stand development. Profile mineralizable N pools determined using anaerobic incubations were higher in operational clearcut (stem-only and full-tree harvesting) treatments than in uncut reference forest. Full-tree harvesting with removal of logging slash, stumps, coarse roots, the folic forest floor and 5 cm of mineral soil on upland sites or the upper 10 cm of organic horizon on wet sites significantly reduced profile mineralizable N pools compared to operational harvesting. The same treatment at one upland site also reduced net N mineralization pools determined using an *in-situ* field incubation. Our previous work at these sites (Morris et al. 2019) had shown no statistically significant difference in soil total N reserves between stem-only and full-tree harvesting 20 years post-harvest. Of particular note in the current study were lower profile mineralizable N pools and lower organic horizon microbial biomass C and N in full-tree compared to stem-only harvesting treatments, suggesting that increased slash retention with stem-only harvesting was enhancing soil N availability at a time when plantations were approaching a period of greater N demand. Fertilization and vegetation control treatments had few effects on N indices, although net N mineralization pools for the stem-only and full-tree harvest that also had the repeated herbicide treatment were consistently (but not significantly) lower than their non-herbicided counterparts at the one site where this was measured.

At 10–15 years post-harvest, soil N indices were positively correlated with jack pine, and to a lesser degree, black spruce dominant height growth. While our study results suggest that more intensive biomass removals lead to changes in soil N dynamics that may result in decreased tree growth at our sites, to date we have not found significant declines in full-tree harvest compared to stem-only harvest stand productivity with either species (Fleming et al. 2014; Morris et al. 2014). A prudent approach at this time is the continued monitoring of soil and stand conditions at these sites to determine if decreased N availability with full-tree harvesting now is an early warning of future decreases in productivity. Further, since the full-tree harvesting treatment in our study was applied operationally (i.e., harvesting for traditional wood products only), we suggest a cautionary approach to higher levels of biomass removals for these soil/site types. More intensive harvesting where removals include nonmerchantable and poor quality trees to provide feedstock for bioenergy or other bioproducts would remove potential site downed woody debris reserves. The loss of this stand “biological legacy” (Morris et al. 2020), these large stores of organic matter that contribute to soil C and nutrient reserves, could reduce future site N availability and forest growth. The effect of vegetation control should also be further evaluated to determine if decreases in N mineralization on herbicide treated plots become significant in the as these stands develop. On the other hand, the complete removal of logging slash, stumps, coarse roots and the organic horizon had a negative effect on soil N availability and the detrimental effect of this treatment on stand growth has increased as these plantations approach crown closure (Fleming et al. 2018). Blading should not be used for site preparation on these boreal forest site types. Treatment effects on N cycling processes at this stage have the potential to impact stands development and soil productivity into the future. Only through knowledge of the long-term effects will we be able to develop truly sustainable forest management practices.

CRediT authorship contribution statement

Paul W. Hazlett: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Funding acquisition. **Caroline E. Emilson:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **Dave M. Morris:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - review & editing, Funding acquisition. **Robert L. Fleming:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - review & editing, Funding acquisition. **Laura A. Hawdon:** Investigation. **Jean-Denis Leblanc:** Investigation. **Mark J. Primavera:** Investigation. **Tom P. Weldon:** Investigation. **Martin M. Kwiaton:** Investigation. **Michael K. Hoepting:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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