

Mineral soil carbon and nitrogen still low three decades following clearcut harvesting in a typical Acadian Forest stand



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ABSTRACT

Intensive forest management practices can alter forest soil organic matter (SOM) storage (kg C ha^{-1}) due to changes in the environmental variables that control SOM cycling and stability. Here we investigate whether SOM losses are observed three decades following clearcut harvesting in a temperate forest ecosystem that includes the deep mineral soil (to a depth of 50 cm). We compared SOM stored as carbon (C) and nitrogen (N) in paired (35-year-old; 110-year-old reference) Acadian Forest sites that differed only in their time since harvest. We found lower mineral soil carbon (C) and nitrogen (N) storage (27% and 26% respectively), and lower C and N concentrations at the 35-year-old site compared with the 110-year-old reference site. Isotopic compositions of C and N through the soil profile did not provide insight into the dominant mechanisms driving SOM losses at the 35-year-old site in this study. This is the second study to document decreases in mineral soil C and N storage in a red spruce forest within the Acadian Forest Region three decades following clearcut harvesting.

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1. Introduction

Soil organic matter (SOM) held in forest soils represents an important global carbon (C) reservoir (Bajtes, 1996; Jobbágy and Jackson, 2000; Schlesinger, 1997; Wäldchen et al., 2013), and an important source of mineralizable nitrogen (N) (Aber et al., 1993; Auchmoody and Filip, 1973; Lea et al., 1980; Nadelhoffer and Fry, 1988; Vitousek and Howarth, 1991). The majority of research investigating SOM cycling and storage (mass per unit area of soil) in forest soils has focused upon the organic and shallow mineral soil horizons, often at the expense of the deeper mineral horizons which hold a significant proportion of the total SOM (Jobbágy and Jackson, 2000). This has been justified in part by the fact that the deeper mineral SOM has been assumed to be stable, and that it cycles over much longer timescales than that held within the upper soil horizons (Davidson and Janssens, 2006).

The chemical nature of SOM and the environmental factors that control SOM stability, retention and mineral interactions (e.g. Ågren and Bosatta, 2002) are complex and represent an area of active research and debate (Davidson and Janssens, 2006; Kleber et al., 2010; Schmidt et al., 2011). As the amount of SOM in the mineral soil represents a balance between organic matter inputs (litter and rhizodeposition) and outputs (decomposition and leaching), approaches that study these

relationships from a mechanistic perspective through the study of individual element cycles, such as C and N, have also been able to successfully identify key processes controlling SOM dynamics. Emphasis has been placed in such studies upon the environmental controls such as temperature (e.g. Kirschbaum, 2000) and moisture (e.g. Reichstein et al., 2005) that regulate decomposition rates, transport mechanics, and organo-mineral interactions (Conant et al., 2008), as well as the role labile organic matter transported to depth in a soil profile may play in priming the decomposition of deep mineral SOM (Blagodatskaya and Kuzyakov, 2008; Fontaine et al., 2007). While such studies provide invaluable mechanistic insight, when applied to the field, the relationships may become more complex, (e.g. Risk et al., 2008), making it less clear where the balance may lie in terms of longer term SOM storage and stability under specific scenarios of environmental change.

Harvesting represents a major land-use disturbance in forest soils, creating a step change in multiple environmental factors that control SOM cycling and stability (Risk et al., 2008). The majority of studies measuring post-harvest soil SOM have focused on the forest floor and shallow mineral soil (Nave et al., 2010), most within a decade after harvesting (Laiho et al., 2003), resulting in a lack of conclusive evidence that intensive disturbances to forest soil systems, such as clearcut harvesting, alter SOM stores (Johnson and Curtis, 2001; Nave et al., 2010; Stinson et al., 2011; Taylor et al., 2007, 2008). When an approach is used that includes sampling of deeper mineral soils (>20 cm depth) and makes use of reference sites that have not experienced a disturbance for at least 110 years, however, studies have detected differences in C and N stored in temperate forest soils of northeastern North America (Diochon and Kellman, 2009; Zummo and Friedland, 2011). The

Abbreviations: DOC, dissolved organic carbon; GHG, greenhouse gas; SOM, soil organic matter.

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discrepancies among the various studies, while perhaps due primarily to sampling depth, may also be attributed to the high spatial variability of SOM, a lack of consistent sampling design and methodology between studies, and the difficulty in selecting appropriate reference sites. The lack of consistency in reported findings has led to calls for a more complete evaluation of mineral SOM stores of C in establishing policies, for example those related to forest management, C accounting efforts, and bioenergy production (e.g. Buchholz et al., 2013; Friedland and Gillingham, 2010).

Studies examining specific environmental controls upon C, and N cycles in harvested forest soils provide evidence that an immediate pulse of C (Johnson et al., 1995; Kreutzweiser et al., 2008) and N (Holmes and Zak, 1999; Likens et al., 1970; Vitousek and Matson, 1985) arising from the decomposition and destabilization of harvest residues and SOM occurs in these forest soils (Yanai et al., 2003; Zummo and Friedland, 2011). Mineralized N (nitrate and ammonium) leached from soils represents a loss of N from a system that normally cycles N very efficiently, and can occur simultaneously with increased uptake of N from a single regenerating cohort of fast-growing trees in the decades following clearcut harvesting (Vitousek, 1977). Given the lack of consensus about what the longer term (i.e. decadal scale) effects of harvesting are upon SOM storage and stability, the specific mechanisms driving deep SOM losses, and the complexity of the interactions among controlling environmental variables, field evaluation of decadal scale changes to SOM stores following harvesting should play a critical role in clarifying these relationships.

Evaluation of SOM changes on the time scale of a forest cycle (spanning decades) often relies upon the use of a space for time substitution (or chronosequence) approach (Pickett, 1989), although such data require careful interpretation (Clark and Johnson, 2011; Diochon et al., 2009). This allows for net changes related to forest age alone to be evaluated. Along with changes in bulk soil profile C and N, additional indicators of process changes, such as C to N ratios (C:N), the compound specific nature of SOM (Schmidt et al., 2011), and analysis of soil conceptual pools through isolation of physical fractions (Sohi et al., 2001) have been used to successfully identify mechanisms driving longer term SOM changes. Natural abundances of stable isotopes are also increasingly used to provide insight into the longer term processes that cycle SOM within the mineral soil (Billings and Richter, 2006; Diochon and Kellman, 2008; Diochon et al., 2009; Zummo and Friedland, 2011).

Soil C age (Trumbore, 2000) and $\delta^{13}\text{C}$ signatures (Ehleringer et al., 2000; Nadelhoffer and Fry, 1988; Risk et al., 2009) typically increase with depth through the soil profile, reflecting a process (or processes) leading to SOM formation (Billings and Richter, 2006). Measuring $\delta^{13}\text{C}$ through the soil profile and how it changes through time following disturbance can provide insight into changes in mineral soil C following forest harvesting that would not be apparent from C concentrations and storage alone. For example, Diochon and Kellman (2008) showed that $\delta^{13}\text{C}$ enrichment patterns observed through space and time at a red spruce (*Picea rubens* Sarg.) chronosequence in central Nova Scotia were consistent with a kinetic fractionation due to increased decomposition rather than due to mixing of C from different sources. This supported the hypothesis that increased decomposition following clearcut harvesting was the mechanism through which C storage decreased in the decades following clearcut harvesting. Similarly, Zummo and Friedland (2011) found a lighter $\delta^{13}\text{C}$ signature at depth, indicative of increased mixing of plant-derived material likely due to mechanical disturbance, that could explain observed C depletion at shallower depths.

Likewise, $\delta^{15}\text{N}$ also generally increases with depth in forest soils (Nadelhoffer and Fry, 1988). Hobbie and Quimette (2009) identify leaf litter, root litter, and fungal material as three potentially important organic matter sources that influence soil $\delta^{15}\text{N}$ profiles. However, due to the high turnover of ammonium, nitrate, and amino acids in soils (Jones and Keilland, 2002; Schimel and Bennett, 2004), measuring

$\delta^{15}\text{N}$ enrichment in soils at any given time may be of limited utility in determining how N is cycling through forest soils (Hobbie and Quimette, 2009). Nevertheless, $\delta^{15}\text{N}$ trends in forest soils do reflect the myriad of processes that cycle N through forest soils, which could provide insights into decadal scale soil N and SOM cycling following disturbance.

Forest soils of the Acadian Forest Region provide useful model systems for understanding SOM dynamics in moist temperate forest soils subjected to routine clearcut harvesting disturbances (Mosseler et al., 2003; National Forestry Database, 2008; Wilson and Colman, 2001). Research within the soils of this region has provided insight into the mechanisms regulating C and N fluxes (e.g. Lavoie et al., 2013), allowing for a better understanding of the consequences clearcut harvesting has upon SOM storage and stability. Using a chronosequence approach, previous research in this region (Diochon et al., 2009) reported bulk soil C and N storage losses that were predicted to reach a minimum approximately three decades following clearcut harvesting. However, these findings require additional field verification. Investigations of specific conceptual SOM pools and soil profile stable isotopic patterns (Diochon et al., 2009) suggested that the observed post-harvesting SOM losses were likely driven by increased mineralization of the apparently stable organo-mineral fraction in the deep soil (Diochon and Kellman, 2008, 2009).

The objective of this study is to conduct a comparative field analysis of mineral soil C and N storage within paired red spruce sites in central Nova Scotia that represent the minimum (three decades) and maximum (>110 years) C and N stores predicted in the previous regional studies outlined above. We hypothesized that C and N storage will be lower within soils of the most recently harvested site as a result of increased decomposition of SOM, increased leaching of dissolved C and N within the mineral soil components, and reduced inputs of organic material to the rhizosphere through litter and root sources. By comparing the concentrations (g kg^{-1} soil) and storage (Mg ha^{-1}) of C and N, along with their stable isotope trends ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), this study should assist in developing, in these model forest systems, a better understanding of the consequences of clearcut harvesting on SOM three decades after harvest.

2. Materials and methods

2.1. Study sites

Two sites were used for this study, characterized by forests aged 35 and 110 years respectively. These ages were selected as they correspond to the greatest soil C harvest cycle differences predicted by another regional study (Diochon et al., 2009; located approximately 60 km away from this paired site), conducted within similar forest type, and characterized by similar topography and soil series. Both sites in this study are located east of the village of Mooseland, Nova Scotia along the Tangier River in Halifax Regional Municipality (44°56'42.51"N, 62°47'39.53"W). The site containing the 110-year-old reference forest is located within the Otter Ponds Demonstration Forest, operated by four non-governmental organizations on publicly owned Crown land. The second site (35-year-old forest) is located 2.5 km to the north on a parcel of private land owned by Ecofor Management of Mooseland.

Both sites are within the Eastern Ecoregion in the Eastern Drumlins Ecodistrict of the Nova Scotia site classification system (Neily et al., 2003). They are located on soils of the Halifax soil series, which are characterized by a strong Ae horizon, a brown sandy loam top-soil, and a yellowish-brown sandy loam subsoil that are from an olive- to yellow-brown stony sandy loam till parent material derived from quartzite (MacDougall et al., 1963). Organic horizons average 11.9 cm within the 35-year-old site and 13.3 cm in the 110-year-old site. Mineral soil pH averages 4.5 within these soils. Both are well-drained sites dominated by red spruce with some balsam fir

(*Abies balsamea* (L.) Mill.), and a small component of eastern white pine (*Pinus strobus* L.), yellow birch (*Betula alleghaniensis* Britt.), and red maple (*Acer rubrum* L.). These forests are typical of the Acadian Forest Region, a typical forest of the northern temperate zone (Mosser et al., 2003). Mean annual air temperature is 5.8 °C, with mean January and July temperatures −5.8 °C and 16.9 °C, respectively. The region receives 1300 mm of precipitation annually. Both sites are between 90 and 110 m above sea level.

Both study sites were clearcut harvested in 1900. Sites were harvested for lumber using axes and horses. As logging operations at that time happened exclusively in winter, little physical disturbance to the forest floor and mineral soil was likely. Limbs, large diameter tops, and any tree boles unsuitable for lumber (rotten, crooked, small, etc.) would have been left on site. It is unlikely that this was the first major harvest at both sites. At the 110-year-old reference site a second-growth stand of red spruce currently dominates the canopy. Evidence exists that balsam fir once grew among the red spruce. Windthrow in the red spruce has begun to create holes in the ≥20-m canopy, allowing for the establishment of an understory of red spruce, balsam fir, and some yellow birch, ranging from 1 to 4 m in height. The 35-year-old site was clearcut harvested again in 1974. The recent 1974 harvest was a summer mechanical harvest operation involving the use of chainsaws and skidders. Limbs and small-diameter tops would have been left as detritus. This forest is currently thick, undergoing self thinning, and is dominated by red spruce, balsam fir, and a small proportion of red maple, yellow birch, and white pine. Almost no ground vegetation is present, with the exception of some mosses. The only difference in forest management practices and general site and soil characteristics between the two sites is the clearcut harvesting that took place at the 35-year-old site in 1974, as both sites were harvested by the same company to the same standards circa 1900.

2.2. Field sampling methods

The methods described by Huntington et al. (1988) were used to calculate bulk density due to the rocky nature of soils in the region. Three bulk density sampling pits were established randomly within a representative area of each forest site; within 7 m of each bulk density pit, two other pits were dug and used for additional soil collection. Therefore, soil samples (for SOM analysis) were collected from a total of nine soil pits within each site, and bulk density was measured at three of these nine soil pits within each site.

Sampling of each bulk density pit was preceded by removal of the organic layer from the top of the mineral soil, exposing the Ae horizon. Soil in the pits was excavated by stratum at the following mineral soil depths; 0–10 cm, 10–20 cm, 20–35 cm, and 35–50 cm. Large rocks and small boulders were removed from the stratum and weighed. Rock volume was calculated using a rock density of 2.65 Mg m⁻³. Soil was sieved to 12 mm in the field, and fractions greater and less than 12 mm were weighed in the field. Approximately 1 L of soil from the <12 mm fraction was bagged and taken to the lab for analysis. Samples were stored in a cooler while being transported to storage at 4 °C. The exact depth of each stratum was calculated by using a 25-cell grid. Depth measurements were taken from the corner of each cell and averaged to get total strata volume. Depth of each stratum was defined as the average distance from the corner of each cell to the bottom of the stratum where no rocks were encountered. Where rocks were encountered (i.e., where a rock protruded up from the stratum below), the thickness of the protruding rocks was measured, summed, and averaged across all cell corners in that stratum to give an average rock thickness. The same was done for roots extending into a stratum from below. Root volume was calculated by measuring all roots >2 cm in diameter wholly within a given stratum using total length and diameter every 10 cm. Soil sample pits were excavated, sieved to <12 mm in the field, and the same strata sampled. All pits were backfilled following sampling.

2.3. Laboratory analysis methods

Moisture content, bulk density, and percentage coarse fragments were determined in the lab using samples of each strata in each bulk density pit. To determine bulk density, samples were dried at 105 °C until they reached a constant weight. For each strata, bulk density was calculated using the following equation (Huntington et al., 1988):

$$BD = S / (V_t - V_1 - V_2)$$

where BD is bulk density (g m⁻³), S is oven-dried mass of soil <2 mm in that particular strata, V_t is the total strata volume, V₁ is the grid coarse fragment volume, and V₂ is the weighed coarse fragment volume, including all rocks >2 mm weighed and converted to a volume using a standard density of 2.65 Mg m⁻³.

The <2 mm fraction was homogenized and ground using a roller mill. Samples prepared for each stratum were analyzed for % C, % N, δ¹³C, and δ¹⁵N using an elemental analyzer (Eurovector EA-3028-HT, Manchester, UK) coupled to a CF-IRMS (Nu-Horizon Isotope Ratio Mass Spectrometer, Wrexham, UK; GV Isoprime Mass Spectrometer, Manchester, UK). Isotopic contents were expressed as the relative difference (parts per thousand) between the sample collected and the Pee Dee Belemnite (PDB) standard in the case of C, and atmospheric N₂ gas in the case of N, where:

$$\delta^{13}\text{C} \text{ or } \delta^{15}\text{N} (\text{‰}) = \left[\left(\frac{R_{\text{sample}}}{R_{\text{standard}}} \right) - 1 \right] * 1000$$

where R is the ratio of the heavy/light isotopes (¹³C/¹²C; ¹⁵N/¹⁴N). All sample preparation and analysis were completed at the Department of Earth Sciences, St. Francis Xavier University, Antigonish, NS, Canada.

2.4. Statistical analysis

All reported site means represent averages from nine samples. In calculations requiring bulk density, average site bulk density was applied to the C and N concentrations determined from each of the nine within-site strata samples.

Minitab 16 Statistical Software was used for statistical analysis of C and N concentrations (g kg⁻¹ soil), storage (Mg ha⁻¹), C:N ratios, stable isotopic compositions (δ¹³C and δ¹⁵N) and bulk density (g cm⁻³) throughout the soil profile. Data that did not fit a normal distribution were subjected to either an arcsine-square root or log base 10 transformation to achieve normal distribution. A general linear model of regression allowing for unbalanced data analysis was used to test differences between sites and strata as well as the interaction site and strata had on observed differences. Significance was assessed at α = 0.05.

3. Results

3.1. Bulk density

Soil bulk density was found to differ significantly both between sites ($p = 0.002$) and between strata ($p < 0.001$), with site and strata interacting significantly ($p = 0.039$, Table 1). Bulk density increased through depth at both sites (Fig. 1(a)). However bulk density only differed between sites below 20 cm, with the 35-year-old site having 0.18 and 0.23 more g cm⁻³ soil (<2 mm) than the 110-year-old site at the 20–35 cm and 35–50 cm depth intervals, respectively.

3.2. Soil C and N concentrations

The C concentrations (g C kg⁻¹ soil) of the soils decreased through depth at both sites (Fig. 1(c)). Overall, C concentrations found at the 110-year-old site were determined to be significantly greater than those at the 35-year-old site ($p = 0.010$; Table 1), with significant

Table 1

Average soil C, N, and bulk density (BD) data for each site by depth strata (\pm SE). Concentrations of C and N are measured in g/kg soil, stable isotopes are measured in ‰ relative to the standard, and bulk density is measured in g soil >2 mm/cm³. x denotes statistically significant differences between sites, y denotes statistically significant differences between strata, and z denotes statistically significant interaction between site and strata. Statistical significance was assessed at $\alpha = 0.05$.

Soil strata	Stand age (years)	BD ^{xyz} (g cm ⁻³)	C ^y (Mg C ha ⁻¹)	N ^y (Mg N ha ⁻¹)	[C] ^{xy} (g kg ⁻¹ soil)	[N] ^{xy} (g kg ⁻¹ soil)	$\delta^{13}\text{C}^y$ (‰)	$\delta^{15}\text{N}^y$ (‰)	C:N ^{xyz}
Organic	35	0.05 (0.01)	25.05 (2.05)	0.74 (0.04)	424.43 (34.78)	12.50 (0.60)	-25.43 (0.03)	2.82 (0.18)	33.92 (1.91)
	110	0.03 (0.00)	17.34 (0.68)	0.45 (0.02)	441.08 (17.27)	11.48 (0.58)	-25.89 (0.12)	2.09 (0.24)	38.74 (2.48)
0–10	35	0.72 (0.06)	29.57 (4.11)	1.07 (0.12)	41.36 (5.75)	1.50 (0.17)	-26.00 (0.16)	5.98 (0.20)	27.41 (0.95)
	110	0.72 (0.05)	38.34 (5.42)	1.49 (0.22)	53.52 (7.57)	2.12 (0.31)	-25.41 (0.15)	7.36 (0.56)	25.91 (0.84)
10–20	35	0.66 (0.01)	24.74 (3.07)	1.03 (0.12)	37.63 (4.66)	1.56 (0.19)	-25.23 (0.28)	7.21 (0.43)	24.34 (0.80)
	110	0.67 (0.04)	35.29 (4.17)	1.52 (0.17)	52.38 (6.19)	2.21 (0.25)	-24.74 (0.17)	7.70 (0.17)	23.25 (0.55)
20–35	35	0.92 (0.06)	40.98 (4.17)	1.82 (0.17)	29.59 (3.01)	1.31 (0.12)	-24.90 (0.26)	7.93 (0.44)	22.27 (0.57)
	110	0.74 (0.01)	47.12 (9.25)	2.17 (0.40)	42.58 (8.35)	1.72 (0.33)	-24.59 (0.16)	8.44 (0.26)	21.26 (0.48)
35–50	35	1.16 (0.09)	42.95 (7.46)	1.97 (0.43)	24.64 (4.28)	1.13 (0.22)	-24.20 (0.19)	7.94 (0.30)	22.00 (0.57)
	110	0.94 (0.01)	54.86 (10.21)	2.26 (0.43)	39.16 (7.29)	1.55 (0.28)	-24.31 (0.16)	8.16 (0.25)	24.16 (1.86)

differences observed between strata ($p < 0.001$). The 110-year-old site contains approximately 71 g C more per kg soil than the 35-year-old site.

Similar to C concentrations, N concentrations also decreased through depth at both sites (Fig. 1(d)). Nitrogen concentrations were significantly greater throughout the whole profile at the 110-year-old site ($p = 0.031$, Table 1). Significant differences were also found between strata at both sites ($p < 0.001$).

3.3. Soil C and N storage

Carbon storage (Mg C ha⁻¹), calculated from the combined measures of bulk density and C content, was found to be statistically different between the two sites through the soil profile when the organic layer was removed from the analysis ($p = 0.044$; Table 1, Figs. 1(e), 2). This represents a difference of over 37 Mg C ha⁻¹ in the mineral soil C content between the sites, or 27% greater C storage in the mineral soil of the 110-year-old reference site (Fig. 2). This difference exists despite the greater bulk density of the deeper mineral soil at the 35-year-old site (Fig. 1(a)). Overall, it was determined that there were statistically significant differences between the strata at both sites at $\alpha = 0.05$ (Table 1). Variability of C storage was greater deeper in the soil profile (Table 1, Fig. 1(e)).

Similar to the C observations, mineral soil N stores were significantly greater in the 110-year-old site ($p = 0.022$; Table 1, Figs. 1(f), 3). This represents a 26% greater (1.55 Mg N ha⁻¹) N store in this older reference site (Fig. 3). Again, this observation is made despite the greater mineral soil bulk density at the 35-year-old site. Variability of N storage was greater at lower depths in the soil profile at both sites (Table 1, Fig. 1(f)).

3.4. Soil C:N ratios

The ratios of C to N (C:N) were not found to be significantly different at the two sites ($p = 0.592$; Table 1), with significant differences between strata ($p < 0.001$). Interaction between site and strata was not found to be significant ($p = 0.151$). Ratios generally decreased with depth through the soil profile (Fig. 1(b)).

3.5. Soil $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ contents

No statistically significant differences were found between the $\delta^{13}\text{C}$ isotopic signatures of the two sites, with profile signatures ranging from -26.0 to -24.2‰ and -25.9 to -24.3‰ at the 35-year-old and 110-year-old sites respectively (Table 1). However, it was determined

that, within each site, isotopic signatures differed between strata, with $\delta^{13}\text{C}$ increasing through depth (Table 1; Fig. 4(a)).

Delta-¹⁵N values were also found to be significantly different between strata within sites ($p < 0.001$) but not different between sites ($p = 0.710$). Organic layer $\delta^{15}\text{N}$ values (2.82 and 2.09‰ for the 35-year-old and 110-year-old sites respectively), became heavier with depth until the 20–35 cm strata (7.93 and 8.44‰ for the 35-year-old and 110-year-old sites respectively), below which $\delta^{15}\text{N}$ values did not change.

4. Discussion

4.1. Trends in soil carbon

Carbon storage and concentration were found to be within the range of those determined by Diochon et al. (2009) in the same forest type in central NS. However, amounts of total C stored (Mg C ha⁻¹) observed at the two sites analyzed here are higher than those reported by Diochon et al. (2009), particularly below 35 cm in the soil profile. For example, the 110-year-old reference site in this study contained approximately 30 Mg C ha⁻¹ more than the ≥ 125 -year-old reference site of Diochon et al. (2009), 25 Mg C ha⁻¹ of which came from differences between the 35 and 50 cm strata from these two studies. Carbon concentrations are also higher than those reported by Diochon et al. (2009). Although the forest, geological, soil, and climatic conditions are similar between these two studies, there is a geographical separation between the two sets of sites of approximately 60 km, suggesting differences between reference sites are likely indicative of natural regional variability. This perhaps highlights the importance of selecting sites for SOM studies employing a space for time substitution approach within close geographical proximity to each other, as was done in this and the Diochon et al. (2009) study.

The largest difference in C storage between strata at the 35- and 110-year-old sites was found in the top two strata between 0 cm and 20 cm. Variability within sites was also found to be the lowest (Fig. 1(e)) in these two strata. This is in contrast to Diochon et al. (2009), who found the greatest differences below 20 cm mineral soil depth.

It is interesting to note that despite a higher bulk density (and thus more soil in the <2 mm fraction in which to store C) below 20 cm at the 35-year-old site, the 110-year-old site still contains significantly more C in the mineral soil. This suggests that, regardless of any bulk density differences that may exist between the two sites, mineral soil differences in C concentrations are still great enough to drive observed C storage trends. Bulk density differs most greatly between the sites

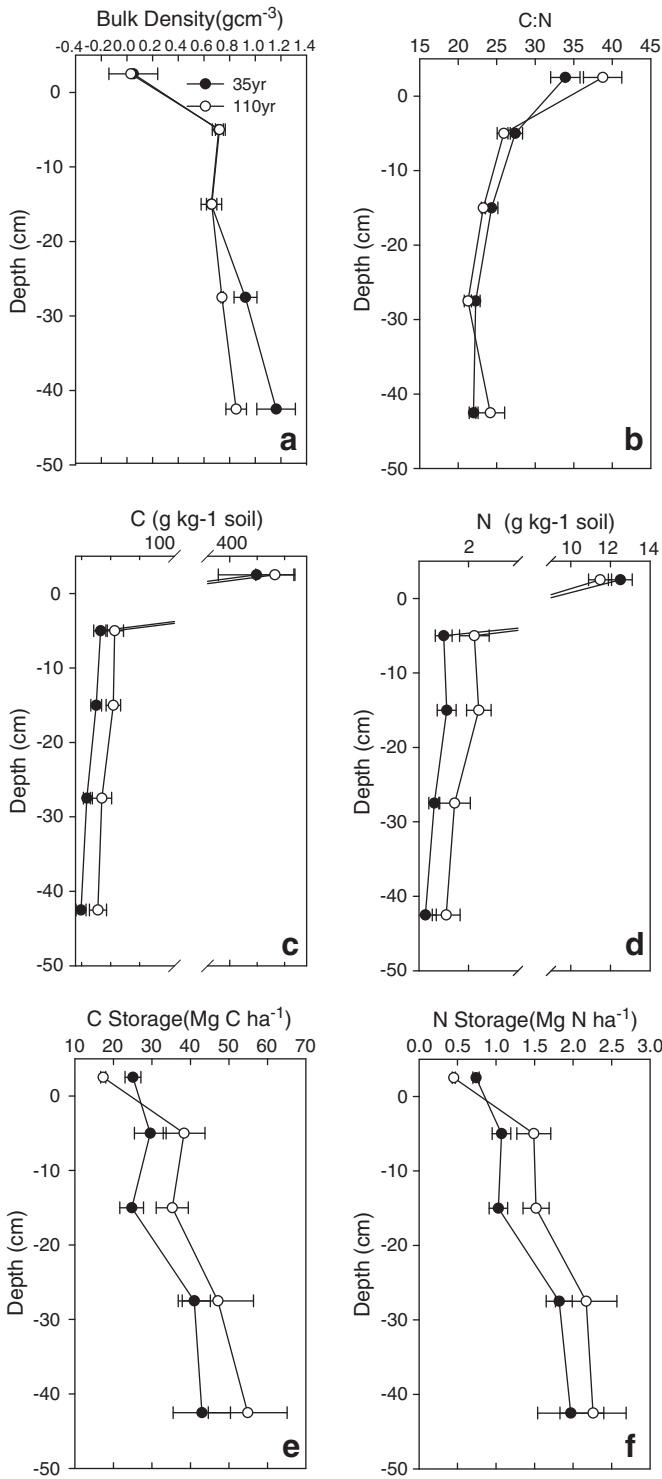


Fig. 1. (a) Bulk density, (b) C:N, (c) C storage, (d) N storage, (e) [C], and (f) [N] soil profiles. Sites are represented separately according to the key found in (a). Error bars represent 95% confidence intervals. For specific strata means and standard errors see Table 1.

below 20 cm in the soil profile, which is also where the greatest variability in within-site C stores is found at both sites.

A statistically significant difference in C between the 35- and 110-year-old sites was found within the mineral soil (excluding the organic layer (OL)). Had this study focused exclusively on the OL, or OL plus shallow mineral soil (0–20 cm), C storage differences between sites might have been obscured. This suggests that incorporating the deeper mineral soil measurements increases the likelihood of detecting

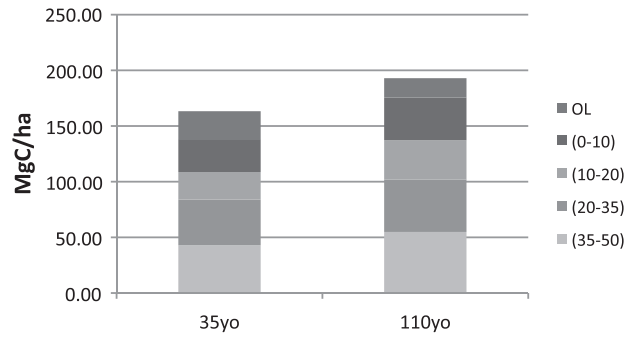


Fig. 2. Soil C storage (in Mg C ha⁻¹) at the 35- and 110-year-old sites. Carbon storage per depth strata, including the organic layer (OL), and mineral soil (0–10 cm; 10–20 cm; 20–35 cm, and 35–50 cm) are shown. Each site shows the mean soil C storage value for soil samples taken from nine soil pits. For specific strata means and standard errors see Table 1.

decadal-scale differences in soil C stores. Not incorporating lower mineral soil strata and focusing primarily on the OL could generate misleading conclusions about the effect of human disturbances on forest soil C storage.

This is the second study demonstrating lower stores of forest soil C in a red spruce forest within the Acadian Forest Region approximately three decades following clearcut harvest relative to a mature reference site. Incorporating mineral soil strata below 20 cm in the soil profile has been particularly useful in determining C storage trends following clearcut harvesting at these two sites. By incorporating these strata, this study was able to demonstrate a strong statistically significant difference in C within the mineral soil between these two sites.

Delta-¹³C isotopic enrichment through depth observed by [Diochon et al. \(2009\)](#) and [Zummo and Friedland \(2011\)](#) was also observed in this study (Fig. 4(a)) and was investigated as a potential tool for identifying processes controlling SOM cycling within the soil profiles of these sites. The 35-year-old site showed a somewhat greater isotopic enrichment through depth within the mineral soil than the 110-year-old site, a pattern observed by [Diochon and Kellman \(2008\)](#) in similarly aged forest soils of a forest chronosequence. While overall, significant differences between the paired sites in this study were not observed, consistent with the observed C:N ratios, it is instructive to consider how isotopic patterns between the two sites might differ as a function of changes anticipated in the C cycling processes. Patterns of $\delta^{13}\text{C}$ enrichment are expected within forest profiles through depth, as a consequence of the Suess Effect, mixing of different organic matter sources and decomposition ([Diochon et al., 2009](#); [Wynn et al., 2006](#)). Root biomass is typically enriched in $\delta^{13}\text{C}$ relative to aboveground

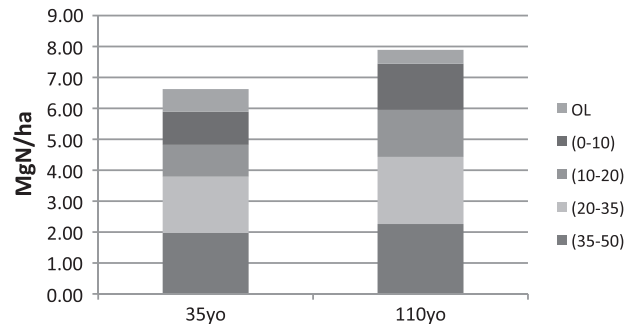


Fig. 3. Soil N storage (in Mg N ha⁻¹) at the 35- and 110-year-old sites. Nitrogen storage per depth strata, including the organic layer (OL), and mineral soil (0–10 cm; 10–20 cm; 20–35 cm, and 35–50 cm) are shown. Each site shows the mean soil N storage value for soil samples taken from nine soil pits. For specific strata means and standard errors see Table 1.

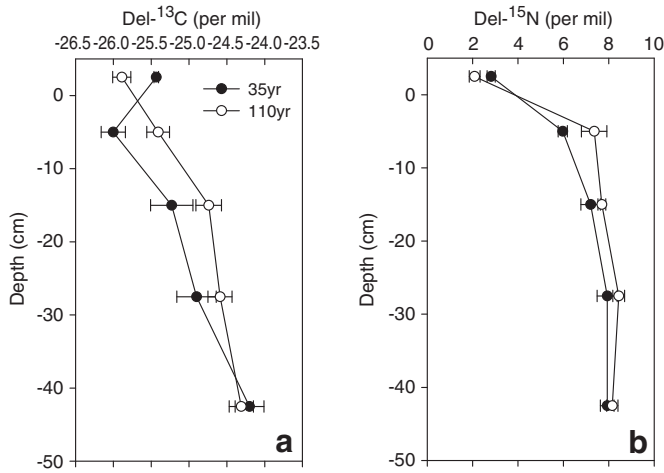


Fig. 4. Delta¹³C (a) and delta¹⁵N (b) signatures through the soil profiles. Sites are represented separately according to the key found in (a). Error bars represent 95% confidence intervals. For specific strata means and standard errors see Table 1.

biomass by 1.5% to 2.5% (Risk et al., 2009; Wedin et al., 1995). There may be some legacy effects in the delta¹³C soil profile signatures from the early post-harvest period when root inputs were reduced, although litter inputs would have been reduced during this period as well. A lighter signature could also be explained by mechanical mixing processes as observed by Zummo and Friedland (2011), although this would be expected to occur only within the upper soil profile. In contrast, increased decomposition of SOM, coupled with reduced inputs, should result in a heavier delta¹³C signature with depth at the 35-year-old site, consistent with a kinetic fractionation driven by decomposition (Wynn et al., 2006). If operating simultaneously, however, source input and decomposition processes might effectively cancel each other out, obscuring any efforts to link delta¹³C patterns to specific SOM cycling processes. In this study, we targeted sites, based upon the results of Diochon et al. (2009) that showed minimal C stores, rather than based upon the greatest expected differences in delta¹³C signatures. The isotopic analysis of Diochon and Kellman (2008) showed that the maximum isotopic enrichments (expected under elevated rates of decomposition) occurred at their 15-year-old chronosequence site, although they were still evident at their 45-year-old site. Furthermore, the greatest SOM losses observed by Diochon et al. (2009) were also most evident in the deeper mineral soil profile, in contrast to this study, which identified the upper mineral soil as also playing an important role. This suggests that harvesting-driven SOM loss mechanisms may occur within different parts of the mineral soil profile, depending upon localized conditions. Additional study sites comprising a greater range of forest ages within close proximity to this paired site (i.e. a full chronosequence) would be required to determine whether isotopic trends within individual depth strata changed in a manner similar to those observed following harvesting by Diochon and Kellman (2008) and Diochon et al. (2009).

4.2. Trends in soil nitrogen

Nitrogen results presented a clear trend of greater mineral soil storage and concentration at the 110-year-old site relative to the 35-year-old site. Similar to C storage trends, N storage and concentration is greater in all mineral strata at the 110-year-old site, with the most significant differences found above 20 cm (Fig. 1(f)). Coincidentally, these strata are also where between-site bulk density variability is the least (Fig. 1(a)). Considering the role that SOM plays in maintaining and increasing the amount of N in forest soils, it is not surprising that N storage is similar to C storage, with 26% and 27% more MgN ha⁻¹ and MgC ha⁻¹ found at the 110-year-old site. These findings

are consistent with an expected direct relationship between soil C and N through SOM quantity. Significant changes in SOM quality between sites would be expected to alter C:N ratios, and hence relative changes in storage.

Differences in N storage at these two sites are driven by greater N concentrations at the 110-year-old site, despite the greater soil bulk density at depth at the 35-year-old site.

One would expect nutrient availability in these N poor soils to be primarily dependent on SOM mineralization as a N source. The fact that C storage is greater at the 110-year-old site would suggest that the ability of that soil to hold onto and fix more N would be greater, thus leading to higher N concentrations and stores.

The findings reported here are consistent with Diochon et al. (2009), who found lower N concentrations below 20cm at their 45-year-old site relative to their ≥125-year-old reference site. Likewise, Zummo and Friedland (2011) found higher N concentrations in all strata at their mature reference site relative to their high disturbance site.

The profile patterns in delta¹⁵N observed at the two sites, which show enrichment through depth (Fig. 4(b)), are similar to patterns observed in other forest soils (Hobbie and Quimette, 2009). The profiles are consistent with the conceptual model proposed by Hobbie and Quimette (2009) which attributes ¹⁵N enrichment through depth to fractionation when N is transferred to host plants by mycorrhizal fungi, along with stabilization and decomposition of SOM. Although these patterns provide insight into general characteristics of these sites with respect to N availability, the lack of difference in delta¹⁵N between the two sites provides no immediate insight into how SOM cycles and changes 35 years following clearcut harvesting. As with delta¹³C patterns, shallow mineral soil delta¹⁵N differences may be a function of mixing of younger organic matter into the mineral soil following the harvesting disturbance.

4.3. Insights from C:N ratios

Ratios of C:N are similar to those reported by both Diochon et al. (2009) and Zummo and Friedland (2011). No significant differences in C:N ratios between the 35- and 110-year-old sites indicate that C and N are present in the same proportion at both sites despite observed reductions in C and N at the younger site. This could be explained by losses of SOM in the mineral soil, which caused proportional C and N losses 35 years following clearcut harvesting; however, the exact mechanism for this proportional change is unclear.

4.4. Observed patterns of bulk density

It has been widely reported that bulk density can be influenced by anthropogenic activities, particularly forest harvesting. However, it is unlikely that the differences in bulk density observed here below 20 cm are a result of past management practices. Zummo and Friedland (2011) found no effect of site disturbance on bulk density below their 20–30 cm strata. As well, Rab (2004) and Hartmann et al. (2008) show that increases in bulk density as a result of compaction during harvesting extend only 11 years after harvest. This suggests that the observed differences in bulk density are a result of natural geophysical differences between the sites and not a result of past management activities.

4.5. Implications for forest management practices

This study provides further evidence that clearcut harvesting decreases mineral soil C and N storage in forest soils, and that these losses are evident 35 years following harvesting. Along with Diochon et al. (2009) and Zummo and Friedland (2011), it is shown here that, by including deeper mineral strata and not restricting the focus to the organic layer and shallow mineral strata, we are able to detect statistically significant trends in C and N storage between sites.

Likewise, the selection of appropriately aged reference sites is imperative for detecting changes in soil C and N storage. For example, Nave et al. (2010) qualified reference stands in studies they analyzed as stands that have not been harvested for at least 30 years. Data presented here and in both Diochon et al. (2009) and Zummo and Friedland (2011) suggest that soil C losses do not recover for more than three decades following clearcut harvest, and could stay below pre-harvest levels for 75 years (Diochon et al., 2009). Therefore, selecting reference stands that have yet to recover lost C and N as a result of past management practices could further confound trends in soil C and N cycling following clearcut harvesting. Conclusions drawn as a result of this confusion have the potential to be misleading and both economically and ecologically costly.

The detailed analysis of N found here is of particular interest to forest owners and managers. If forest harvesting and management goals are to ensure a long-term sustainable wood supply, the impact various forest management activities have on long-term soil N levels must be understood. The results presented here suggest that the effect of clearcut harvesting on soil N is evident 35 years after clearcut harvest and that a direct relationship exists between soil C and N following clearcut harvesting. As SOM plays an important role in maintaining N levels within forest soil systems, observed SOM losses would be expected to limit the ability of mineral soils to store and fix N. If clearcut harvesting further exacerbates the N limitation of forests through SOM losses (as evidenced by lower soil C at recently clearcut sites), clearcut harvesting has the potential to compromise the long-term productivity and sustainability of the forestry industry. Given the prevalence of clearcut harvesting in the Acadian and other forest regions, the impact of clearcut harvesting on soil C and N storage, and in turn forest productivity, needs to be further investigated in a deliberate and methodical way.

5. Conclusions

Clearcut harvesting of forest systems alters organic matter inputs, outputs, and shifts environmental conditions in a manner that has the potential to reduce SOM stored within mineral soils in the decades following this disturbance. This study documents significantly lower mineral soil C and N storage and concentrations at a 35-year-old red spruce site than at a 110-year-old reference site. It is the second study to document a SOM loss in the decades following clearcut harvesting within the Acadian Forest Region, and does so by including analysis of the deep mineral soil. Differences between the two sites are found within the soil profile despite differences in bulk density that would suggest a greater capacity of the 35-year-old site to hold greater C and N stores. Observed $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ enrichment with depth in the soil profile was consistent with soil isotopic enrichment patterns observed in other similar studies, but differences between the paired sites were not sufficiently clear to allow for a delineation of processes driving the observed site differences. Further efforts should focus upon replication of this type of field study, in addition to investigation of the specific physical, biological and chemical mechanisms responsible for destabilizing SOM within harvested forest soil profiles.

The importance of sample designs that allow potential differences between forest sites to be identified is also illustrated in this study. Of particular importance is the inclusion of deeper mineral soil strata, as well as the selection of appropriately aged reference sites that have had a sufficient amount of time since their most recent disturbance to accumulate any potential soil C and N lost as a result of that disturbance. Efforts to replicate these studies across landscapes are logistically challenging, but are ultimately also required if we are to make conclusive observations on an ecosystem level.

Fully understanding SOM cycling in forest soils and the mechanisms driving this cycling is important for ensuring the sustainability of forest resource activities, as well as in developing a complete understanding of what role managed forests can play in the global greenhouse gas

exchange system. More research must be undertaken to see if these observed trends in forest soil C and N following clearcut harvesting are prevalent in other forest ecosystems.

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