Looking deeper: An investigation of soil carbon losses following harvesting from a managed northeastern red spruce (*Picea rubens* Sarg.) forest chronosequence

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1. Introduction

Intensive forest management practices (e.g. assisted regeneration and fertilization) are seen as a means to increase forest productivity, thereby increasing a forest’s potential to sequester and store carbon (C). Though these activities increase the rate of C accumulation in biomass and shorten the forest cycle, the effects of current management practices on stores of soil C are not well documented. Studies of soil C storage have typically focused only on the organic layer (e.g. Covington, 1991; Wallace and Freedman, 1996; Yanai et al., 2003b) and the top 10–20 cm of mineral soil (e.g. Black and Harden, 1995; Olsson et al., 1996; Taylor et al., 2007; Teklay and Chang, 2008), ignoring the deeper mineral soil, despite the fact that it typically stores 50% of total soil C (Jobbagy and Jackson, 2000). While the deeper mineral soil is assumed to be stable and largely insensitive to the effects of management activities, including deeper soil C in studies of soil C storage provides us with a more complete picture of soil C dynamics and the response of the whole soil to management activities.

Forest C storage represents a balance of C inputs and losses, and because soil is the largest terrestrial reservoir of C (Schlesinger, 1997), small changes in its pool size have the potential to significantly alter atmospheric CO2 concentrations. Dixon et al. (1994) estimate that, globally, over 69% (787 Pg) of the total C pool in forest ecosystems is stored in the soil and Houghton (2003) has indicated that substantial losses of C from the soil can be caused by forest harvesting, particularly in the years immediately following harvest. Following harvest, rates of microbial respiration often exceed inputs causing a net loss of C. As the stand regenerates, C inputs increase and exceed outputs, and storage accrues. Whether storage returns to pre-disturbance conditions is a function of time. Time since harvest is a factor that was identified but not considered in the meta-analysis of Johnson and Curtis (2001) that examined the effects of forest management on soil C storage. Johnson and Curtis (2001) concluded that forest harvesting had little or no effect on soil C stores but acknowledged that temporal trends in storage were apparent in long-term and chronosequence studies. In the studies included in the analysis, time since treatment ranged from 1 month to 83 years, potentially masking significant temporal changes in storage. Identifying periods of loss...
and gain, and the processes that are driving the change could therefore assist us in mitigating losses and maximizing gains, thereby more effectively managing soil C stores.

Unfortunately, evaluating the effects of forest management on soil C storage is methodologically challenging. There are few remaining reference forest stands that are free of legacy effects. In northeastern North America, several hundred years of land clearing for agriculture and forest harvesting have eliminated the majority of coniferous old growth forest reference systems (Mosseler et al., 2003) making inferences regarding the effects of forest harvesting on soil C stores difficult. Today’s intact or virgin old growth forests are typically located as relics populations, in ravines or on steep slopes, or as tiny forest fragments with large edge to interior ratios. While these populations have intrinsic value, they may not be appropriate for comparison because between site differences in physical factors potentially obscure any management-induced differences in storage. Without a reference stand, it becomes difficult to define a stable equilibrium condition and true potential for storage. Furthermore, the rocky nature of many soils in post-glacial environments makes soil sampling using conventional methods (e.g. push probe) problematic and prone to bias (Harrison et al., 2003). For this reason, it is often necessary to hand excavate larger soil pits, which is, on the scales necessary to detect small changes in pool size with statistical significance (Trumbore, 2000). Conant et al., (2003), extremely labor intensive (Kulmatiski et al., 2003). The high spatial variability in soil C storage and the intensive resource requirements for sampling are further compounded when examining vertical changes in a comprehensive manner alongside temporal changes that occur on the time scale of decades. Researchers are often forced to substitute space for time and take a chronosequence approach (Pickett, 1989) to examining the effects of management on soil C storage since forest succession spans decades. Replication of forest stands included in chronosequences is often not possible because comparable stands are not always available (e.g. Zak et al., 1990; Idol et al., 2002; Howard et al., 2004; Teklay and Chang, 2008), particularly old growth reference stands. While the findings of unreplicated chronosequences are often approached with caution, confidence that observed patterns are in fact real can be increased by other indicators, such as stable isotopes, that support observed patterns in C storage.

Increasingly, investigations of changes in soil stores of C during ecosystem development and secondary succession are employing stable isotopes. Stable isotopic signatures have been used to highlight influential processes guiding the biological and physical dynamics in a soil system (e.g. Nadelhoffer and Fry, 1988; Ehleringer et al., 2000) but have rarely been used on the time scales of secondary succession (Billings and Richter, 2006). Stable isotopes exhibit less spatial variability than elemental concentrations (Balesdent et al., 1993; Garten et al., 2000) and the incorporation of stable isotopes in studies examining soil organic matter dynamics in response to disturbance may help elucidate key processes driving changes in stores, complement storage estimates (Billings and Richter, 2006) and increase our confidence in the findings from chronosequence studies.

In a stable profile, δ13C typically becomes more enriched with depth, coincident with a decrease in elemental concentration and age of soil organic matter (Trumbore, 2000). Studies have often attributed this trend to microbial processing under the assumption that microbes respire isotopically depleted compounds and incorporate enriched compounds into their biomass (e.g. Nadelhoffer and Fry, 1988; Ehleringer et al., 2000). As the soil organic matter pool decomposes, the concentration of C decreases and the residual pool becomes isotopically enriched with a mixture of residual substrate, microbial products and metabolites. This trend of decreasing C concentration and δ13C enrichment with depth, resulting from the isotopic fractionation associated with C mineralization, is often described using the Rayleigh equation (Mariotti et al., 1981; Balesdent and Mariotti, 1996). When examined alongside %C, changes in δ13C throughout post-harvest succession may therefore provide complementary evidence for increased rates of decomposition that have occurred within the profile. In the case of soil C loss due to mineralization, there should exist an inverse relationship between the ln %C and the δ13C for a specific depth interval across the age sequence.

The objective of this study was to investigate, using the largest old growth red spruce forest in northeastern North America as a reference condition, age-related patterns of change in C storage, C concentration and δ13C to determine whether clearcut harvesting affects stores of deeper (> 20 cm) soil C in a red spruce forest. We also examine the association between C concentration and δ13C within depth strata across the chronosequence to investigate whether the patterns indicate increased mineralization of soil C post-harvest.

2. Methods

2.1. Description of study area

The study area is located in the Abrahams Lake area of the Liscomb Game Sanctuary, Nova Scotia, Canada (45°10′- N 62°38′-W). The soils in the study area are Halifax series sandy loam textured orthic hummo-ferric podzols derived from quartzite. Mean annual air temperature is 5.8 °C and mean January and July temperatures are ~5.8 °C, and 16.9 °C, respectively. The region receives 1300 mm of precipitation annually. The area is 185–200 m a.s.l. and the topography is rolling (< 10°). The average growing season lasts 196 days from May to October. The vegetation cover is typical of red spruce (Picea rubens Sarg.) forests in the Acadian Forest Region (AFR) and the AFR is typical of forests in the temperate zone (Mosseler et al., 2003).

The area was selected for study because of the existence of one of the last remaining virgin old growth red spruce forests in the AFR. Since ca. 1940, the typical forest harvest practice for red spruce stands is clear-cutting with branches and foliage left on site. No scarification, planting or fertilizing follows harvesting. Thinning has been practised in the last 20 years but was not at the sites included in this study. Currently, the forest in the study area is managed with rotations of about 60 years.

In 2005 we established a chronosequence of five sites representing important stages of forest development (Mosseler et al., 2003). The sites are within 5 km of each other and have the same elevation, parent material, soil texture, and topography to minimize between site variability (Cole and Van Miegroet, 1989; Yanai et al., 2003a). The sites were described by Neily et al. (2001) and, based on aerial photographs and early accounts of forest conditions in Nova Scotia (Fernow, 1912), prior to harvest the sites were intact mature red spruce stands that originated naturally. The sites were identified based on harvesting history and by the age of the overstory in 2005 (dbh ring counts, five trees per stand). The intact, mature old growth red spruce stand is 125+ years and the last date of intervention, either through natural or anthropogenic causes, is unknown but trees within the stand are in excess of 200 years (Mosseler et al., 2003). As is typical with other soil C studies using experimental chronosequences (e.g. Idol et al., 2002; Howard et al., 2004; Peichl and Arain, 2006; Gough et al., 2007; Teklay and Chang, 2008), stand age was unreplicated because comparable replicates could not be located.

Stand characteristics are provided in Table 1. The groundcover was dominated by mosses in the 15- (32%), 45- (80%), 80- (46%),
and 125- (65%) year stands. Bazzania tribolata dominated the 80-
(47%) and 125+ -year stands and Pleurozium schreberi dominated
the 15- and 45-year stands. Living groundcover was sparse in
the recent clearcut with trace amounts of seedlings (< 1 m
2) and herbaceous species (< 1%). Forbs and shrubs common
among the sites included lambkill (Kalmia angustifolia), creeping
snowberry (Gaultheria hispidula), bunchberry (Cornus canadensis),
blue-bead lily (Clintonia borealis), Canada mayflower (Maianthemum canadense),
and wood sorrel (Oxalis acetosella).

2.2. Field and laboratory methods

Because of the rocky nature of the soils, soil bulk density could
not be accurately determined using standard soil core or clod
methods. Instead, the method of Huntington et al. (1988) was
used at all sites. In 2005, three soil pits (71 cm × 71 cm × 50 cm deep)
for each site were hand excavated and measured in a 400 m
2 area representative of the stand. Pit location was randomly
determined. The organic horizons were removed, sieved through a 6.25-mm
sieve in the field, and weighed. The mineral soil was excavated
by depth, rather than genetic horizon, using the following sampling
depths: 0–5, 5–10, 10–15, 15–20, 20–35, and 35–50 cm. The depth
interval 0–5 cm was generally coincident with the E horizon, while
the remaining intervals were representative of the B horizon. The A
horizon was typically < 1 cm or absent. Volume of the excavated
strata was determined using a 25 cell grid that was centered over
the pit. At the corners of each cell, the distance perpendicularly
downward was measured and averaged to calculate total strata
volume (V). Rocks were weighed and volume was calculated by
dividing the weight using an average rock density 2.65 Mg m
3. The volume of rocks or roots that crossed strata boundaries was partitioned between
strata. Strata boundary was defined as the average depth of all grid
points that did not intersect rocks. Rock protruding up from the
bottom of the pit into the lowermost excavated horizon was
treated as part of the rock volume with that strata.

The < 2 mm fraction of the soil was homogenized by grinding
the sample on a roller mill and then analyzed for %C, %N, and 13C
using an elemental analyzer (Eurovector EA-3028-HT, Manchester,
UK) coupled to a CF-IRMS (CV Isoprobe Mass Spectrometer,
Manchester, UK). Isotopic contents are expressed as the relative difference (in parts per thousand) between the sample and the
standard (Pee Dee Belemnite (PDB)), according to

\[ \delta^{13}C = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000. \]

where R is the ratio of the heavy/light isotope content of the
element. Sample preparation and analysis were completed at the
Environmental Sciences Research Centre, Antigonish, NS.

2.3. Calculations and analysis

The total quantity of C in each pit was calculated by summing
the quantity of the C in each strata, determined by multiplying bulk
density by the soil volume < 2 mm and C concentration. We
calculated total storage of C at each site by taking the average
quantity of C from each pit. To examine trends with stand age, we
used regression analysis. Data were fit to a linear function:

\[ Y = A(t) + B, \]

which is the total strata volume, \( V_1 \) is the grid measured coarse fragment
volume, and \( V_2 \) is the weighed coarse fragment volume, which
includes all rock > 2 mm removed from the pit, weighed and
converted to a volume using 2.65 Mg m
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points that did not intersect rocks. Rock protruding up from the
bottom of the pit into the lowermost excavated horizon was
treated as part of the rock volume with that strata.

We used the Rayleigh equation to examine the relationship
between the observed C concentrations and their corresponding

\[ R = \frac{V_r}{V_t} = \frac{1}{\sqrt{V_t}} \left( \frac{V_c}{V_t} \right)^{1/2}, \]

where BD is the bulk density (g m
3), S is the soil mass < 2 mm, V
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volume, and V
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standard (Pee Dee Belemnite (PDB)), according to

\[ \delta^{13}C = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000. \]
isotopic signatures across the chronosequence. The Rayleigh equation:

$$\delta = \delta_0 + \epsilon \ln \frac{C}{C_0}.$$ 

describes enrichment ($\epsilon$) resulting from isotopic fractionation associated with mineralization, where $\delta_0$, $C_0$ represents the $\delta^{13}C$ signatures and C concentrations of the old growth reference system. If $\epsilon < 0$ then we interpret this to mean that enrichment has occurred as a result of loss (increased mineralization). Theoretically, the Rayleigh equation is only applicable in the case of a simple monodirectional closed system. Therefore, the value of $\epsilon$ should be interpreted as the apparent enrichment factor.

Statistical analyses were not performed to examine changes in soil C storage, bulk density, C concentration, $\delta^{13}C$, or the ratio of C-to-N relative to stand age because there is no replication of stand age. This precludes the use of inferential statistics (Hurlbert, 1984). All values presented are means $\pm$ 1 S.E. We interpret the standard errors to be representative of the spatial variability of the site (Richter et al., 1999). All analyses were completed in Sigmaplot 8.0 (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1. Total soil carbon storage

Total soil C storage (Fig. 1) was highest in the old growth stand (161.5 $\pm$ 6.5 Mg C ha$^{-1}$) and lowest in the 45-year-old clearcut (76.0 $\pm$ 19.3 Mg C ha$^{-1}$). The gamma function produced the best fit for soil C storage. Based on the gamma function, C storage reaches a minimum (71.4 Mg C ha$^{-1}$) 32 years post-clearcut with the rate of accumulation increasing to a maximum at age 70 (1.8 Mg C ha$^{-1}$ year$^{-1}$), after which the rate of accumulation begins to decrease. Storage approaches the old growth forest at approximately 100 years.

Soil C storage in each of the depth strata across the chronosequence is presented in Fig. 2. Storage is low and relatively constant (~12 Mg C ha$^{-1}$) in the organic layer in the 1-, 15-, and 45-year stands and is considerably higher in the 80- (29 Mg C ha$^{-1}$) and 125+- (38 Mg C ha$^{-1}$) year stands. In the 0–5 cm strata, storage is relatively consistent in the 15-, 45- and 80-year sites (~10 Mg C ha$^{-1}$) and is approximately half of the carbon stored in the 0–5 cm strata in the recent clearcut (29 Mg C ha$^{-1}$) and the 125+-year site (26 Mg C ha$^{-1}$). No age-related variation is apparent in the 5–10 cm strata. Storage increases slightly across the chronosequence in the 10–15 and 15–20 cm depth strata from minimums of 7 and 6 Mg C ha$^{-1}$ in the recent clearcut to 8 and 12 Mg C ha$^{-1}$ in the old growth. Age-related variations in storage in the 20–35 and 35–50 cm depth strata are characterized by the shape of the gamma function in Fig. 1. Storage is greatest in the 125+-year stand (37 and 28 Mg C ha$^{-1}$) and lowest in the 45-year stand (13 Mg C ha$^{-1}$) in the 20–35 cm depth strata and similarly low between the 15- and 45-year stands (~17 Mg C ha$^{-1}$) in the 35–50 cm depth strata.

3.2. Bulk density and carbon concentration

In all depth strata except 35–50 cm, bulk density was variable with no clear pattern with stand age (Table 2). In the 35–50 cm depth strata, bulk density increased slightly with age across the chronosequence. Carbon concentrations in the organic, 0–5, 5–10 and 10–15 cm were variable across the chronosequence (Table 2). In the 15–20 cm strata, concentrations increased with stand age and in the 20–35 and 35–50 cm depth strata, C concentrations exhibited a pattern characteristic of the gamma function (Fig. 1).

3.3. C-to-N ratios

C-to-N ratios increased with depth at all sites but were variable across the chronosequence (Table 2). In the organic layer, C-to-N ratios were noticeably higher in the 45- and 80-year stands relative to the other sites and can be attributed to lower nitrogen (N) concentrations in the organic layer at these sites (Table 2). In the 0–5 cm strata, ratios were similar among the 1-, 15-, and 45-year stands but higher in the 80- and 125+- (highest) year forests. Carbon concentrations were variable among the 1-, 15-, and 45-year stands (Table 2), which means that N concentration patterns are similar to those of C. Age-related variations were similar among the 5–10, 10–15, 15–20, and 35–50 cm depth strata with the C-to-N ratio of the soil being higher in the 80-year stand and similar among the other sites. In the 20–35 cm strata,
C-to-N ratios decline from year 1 post-clearcut to 45 years and then increase in the 80-year stand.

3.4. \( ^{13}C \) and enrichment factors

The \( ^{13}C \) ratios were variable in the organic, 0–5, 5–10, and 10–15 cm depth strata but exhibited the inverse pattern of the C concentration for the 15–20, 20–35 and 35–50 cm depth strata (Table 2). Across the chronosequence, Rayleigh equations were significant only for the 20–35 cm \( (r^2 = 0.66, P = 0.09) \) and 35–50 cm \( (r^2 = 0.88, P = 0.02) \) depth strata. The enrichment factors (\( \epsilon \)) for these strata were \(-0.67 \pm 0.28 \) permil and \(-0.36 \pm 0.08 \) permil, respectively. It is, however, worth noting that \( \epsilon \) and \( r^2 \) increased and \( P \)-values decreased with increasing depth (Table 3).

### 4. Discussion

4.1. Soil carbon storage

Clearing and harvesting of the forests of northeastern North America has been occurring for centuries and the effects of these activities on soil C storage are poorly known. While the between site variability in our study was high and the sites are not replicated, the temporal pattern of soil C storage in this study suggests there is about a 30 year period of loss during which storage and elemental concentrations at these sites are depleted by approximately 50%. After this period, stores re-accumulate and are within the range of the reference stand by about 100 years.

Changes in storage across the chronosequence do not appear to be attributable to changes in the bulk density; instead, changes in storage are consistent with changes in C concentrations. Carbon concentrations were variable across the chronosequence in the organic and top 20 cm of mineral soil but below 20 cm, the pattern of C concentrations were consistent with the trends observed in the whole soil. Storage in these strata is a significant portion (average 56%, range 39–66%) of total soil C storage at all sites and the age-related variations in storage below 20 cm suggest alteration of biogeochemical processes deeper in the mineral soil.
4.1.1. A local phenomenon?

Forest floor and mineral soil C pools in the 80-year and reference old-growth forest stands are in the range of other mature coniferous forests in North America (30–60 and 60–180 Mg C ha⁻¹, 1, respectively) (Freedman et al., 1986; Hendrickson et al., 1989; Fernandez et al., 1993; Simmons et al., 1996; Tremblay et al., 2002; McLaughlin and Phillips, 2006; Van Miegroet et al., 2007). Post-harvest estimates of C storage in the forest floor documented by other studies are highly variable both with geography and time since harvest. The values reported in our study for the recent clearcut are much lower (10 Mg C ha⁻¹ vs. 30–40 Mg C ha⁻¹) than similar forests in Eastern North America (e.g. Hendrickson et al., 1989; McLaughlin and Phillips, 2006). A more negative isotopic value and lower C concentration for the forest floor in the recent clearcut relative to the older clearcuts is consistent with mixing between the organic layer and mineral soil, which likely reflects the degree of mechanical disturbance by harvesting activities in this region. Forest floor estimates for the 15-year and 45-year sites are within the range reported in the literature (Freedman et al., 1986; Fleming and Freedman, 1998).

Comparisons with other studies for mineral soil storage are more difficult, owing to the differences between studies in both the cumulative depth sampled and the sampling intervals. However, when we account for these differences our estimates compare favorably with those reported in the literature for stands of similar age (Tremblay et al., 2002; Parker et al., 2001; McLaughlin and Phillips, 2006) and with our modeled values for C storage (Freedman et al., 1986; Hendrickson et al., 1989), suggesting that our observation of a period of substantial loss (~50%) followed by accumulation is not a localized phenomenon.

4.2. Soil organic carbon dynamics

4.2.1. C-to-N ratios

In northern temperate forests, Compton et al. (1998) and Goodale and Aber (2001) have reported contrasting patterns of soil C-to-N ratios with succession that have been attributed to differences in N inputs, more specifically, deposition. Compton et al. (1998), in a region with moderate N deposition, reported that C accumulation outpaced N accumulation in the first several decades of succession resulting in higher C-to-N ratios with time. In an area of high N deposition, Goodale and Aber (2001) reported a narrowing of C-to-N ratios as N accumulation (via deposition) outpaced carbon accumulation.

In this study, the temporal pattern of C-to-N ratios were found to be highly variable. In the organic layer, C-to-N ratios increased with time since harvest and can be related to more rapid accumulation of C relative to N (Table 2). Atmospheric deposition of N in Nova Scotia is low to moderate (~0.33 g m⁻² year⁻¹) (Turunen et al., 2004) and the C-to-N ratios are much wider (40+, Table 2) than those reported for comparable forests in regions of higher N deposition (20–30) (Parker et al., 2001; McLaughlin and Phillips, 2006). Therefore, it may take several hundred years for C-to-N ratios to approach the undisturbed condition in the organic layer (Table 2). In the mineral soil, the 80-year stand typically had the widest C-to-N ratios and is consistent with lower N accumulation relative to C accumulation. During the stem exclusion stage of stand development, inputs of organic matter to the soil increase, potentially outpacing the rate of N accumulation. Similar to the organic layer, it may take several hundred years for N to accumulate to approach pre-disturbance levels.

4.2.2. δ¹³C and enrichment factors

In climatically similar forests, approximately 50% of soil C is stored in the top 20 cm of mineral soil (Jobbagy and Jackson, 2000) and the responsiveness of the deeper 50% to environmental perturbations is a hotly debated topic (e.g. Knorr et al., 2005; Giardina and Ryan, 2000). Forest harvesting removes the forest canopy thereby altering the soil's thermal environment (Bekele et al., 2007), mechanically mixes and redistributes C in the soil (Yanai et al., 2003a) and affects nutrient dynamics (Likens et al., 1970; Qualls et al., 2000). These changes have the potential to alter microbial community dynamics and accelerate mineralization in the deeper mineral soil.

If higher rates of mineralization ensue then we would expect to see a decrease in C concentration and a concomitant increase in δ¹³C values (Nadelhoffer and Fry, 1988). While the Rayleigh equations were only significant for the deeper mineral soil, it is worth noting that, with increasing depth, the values of e and r² increased and the P-values decreased for C. The Rayleigh equation assumes the system is closed and the reactions are in one direction. In this system, however, microbial biomass is cycling alongside soil organic matter and inputs from roots and dissolved organic carbon (DOC) are continuously being added. As with most conifers, red spruce sap is shallow rooted (Blum, 1990) so it is reasonable to expect large annual inputs in the shallow mineral soil from fine roots and DOC. In the deeper mineral soil, where inputs of carbon are assumed to be small both from roots and DOC, the relationships are significant and greater isotopic fractionation is consistent with higher rates of mineralization as a consequence of harvesting.

Based on the higher C concentration and lighter δ¹³C ratios in the deeper (>20 cm) mineral soil in the 1-year clearcut (Table 2), we hypothesize that a fraction of the C chemically mixed into the 0–5 cm depth interval of the mineral soil from the organic layer was transported deeper into the mineral soil in the year(s) after harvesting. We speculate that the availability of a labile pool of C primed the older, biologically protected organic matter and resulted in increased mineralization of this stable pool of C (Fontaine et al., 2004, 2007).

4.3. Implications for management

While we can not conclusively identify the catalyst(s) of the loss observed here, the findings of our study suggest that, in the short term, losses of C below 20 cm in the mineral soil have the potential to lower the sink potential of coniferous forests if sufficient time is not allotted to allow stores of soil C to accrue to pre-disturbance levels. In Nova Scotia there is no minimum age requirement for harvesting and while red spruce is a long-lived species, harvesting is initiated as young as 60 years old, and sometimes even younger depending on site conditions and land ownership. Relative to the reference condition, harvesting at age 60 is equated with a loss of 42% of total carbon (62 Mg C ha⁻¹) in the top 50 cm of soil and a loss of 26% (33 Mg C ha⁻¹) relative to the 80-year stand, with >50% occurring below 20 cm in the mineral soil. For comparison, proximate red spruce forests in the 41–60 and 61–80 year age classes have only sequestered 85 Mg C ha⁻¹ and 90 Mg C ha⁻¹, respectively in tree biomass (Taylor, 2005). If we consider the C lost from the soil, the total C actually sequestered per hectare is reduced by 67% and 23% in the 41–60 and 61–80 year age classes, respectively.

Based on an annual average gain of 1.5 Mg C ha⁻¹ in the soil, increasing the rotation length from 60 to 100 years would increase storage of both C and N to within the range of the estimate for the reference condition. This rate of increase would also offset provincial annual greenhouse gas emissions (Hughes et al., 2005) by 11% (2.3 Tg year⁻¹) based on the most recent forest inventory (Townsend, 2004). Using an 80-year rotation cycle, Taylor (2005) showed that in proximate red spruce forests total carbon storage declined by 75 Mg ha⁻¹ after three harvests with no
losses attributable to tree biomass. This estimate is essentially equivalent to the C sequestered in biomass for one rotation. While Taylor’s estimates were derived using a simulation model CBM-CFS 3 (Canadian Forest Service, Northern Forestry Centre, Edmonton, Alta., Canada), all losses were identified as occurring in the medium and slow cycling dead organic matter pools. By allowing these pools to regenerate, we provide the potential to complement gains in biomass rather than undermine them.

5. Conclusions

In this study we documented a period of decline in soil C storage post-clearcutting, approximately 30 years after which stores begin to increase and approach equilibrium by 100 years after harvest. Storage, elemental concentrations and C isotope ratios suggest the deeper mineral soil is driving the observed changes and losses in the deeper soil are consistent with increased rates of mineralization post-harvest. While the findings of unreplicated chronosequence studies are often interpreted with caution, they may reveal important information about general patterns that may be important to consider in the design of future studies examining management-induced changes in soil C storage, as well as possible drivers of the observed changes. When increased emphasis is placed upon intensive vertical rather than spatial sampling, and the location of appropriate replicates may not be feasible, these factors may be partially offset by the inclusion of process indicators that can confirm observed patterns. In this study, observed losses of soil C below 20 cm in the mineral soil were reinforced by patterns of C stable isotopes that pointed to increased mineralization of soil C as a dominant process across these sites. As C storage decreased in the 20–35 and 35–50 cm depth intervals post-harvest, residual C became isotopically enriched. Further investigation is required to establish whether these patterns are observed in other systems but this study does point to the importance of considering the whole soil, rather than just the organic layer and shallow (0–20 cm) mineral soil when documenting soil C changes.

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