Effects of Forest Harvest on Soil Carbon and Related Variables in Canadian Spodosols

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Knowledge about soil organic carbon (SOC) response to forest harvest in conifer stands is limited. The objective of this study was to determine the short- to medium-term effects of bole-only clearcut harvest on SOC and related variables in a Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco]-dominated forest of southwestern British Columbia. We collected soil samples from control (mature forest), cleared (harvested 1–5 yr before sampling), and regenerating (harvested 8–15 yr before sampling) stands and measured SOC, pH, texture, moisture, total N, loss-on-ignition, effective cation exchange capacity (CEC_e), and pyrophosphate-extractable Fe and Al. We found that SOC stocks in the forest floor were higher in cleared and regenerating plots than in control. The mineral subsoil played an important role in the overall response of SOC storage after harvest. In mineral horizons, SOC concentration was higher in cleared plots and similar to control levels in regenerating plots. Treatment effects were restricted to SOC associated with the sand size fractions. This suggests that clearcutting resulted in additional soil organic matter (SOM) inputs to the mineral soil, but that these inputs were not stabilized or retained in regenerating plots. Harvest also affected bulk organic matter composition. The C/N and C/SOM ratios were lower in regenerating plots while the CEC_e/C ratio was higher, suggesting an increase in organic matter maturity and oxidation.

Abbreviations: Al_p, pyrophosphate-extractable aluminum; CEC_e, effective cation exchange capacity; Fe_p, pyrophosphate-extractable iron; PC, principal component; SEM, standard error of the mean; SOC, soil organic carbon; SOM, soil organic matter.

Disturbances that alter the SOM cycle have wide effects because SOM influences many biogeochemical processes. Knowledge about SOC stocks and the effects of forest management on the forest floor and mineral soil C is generally limited (Kurz et al., 2002; Nalder and Merriam, 1995). While a relatively large number of studies have investigated C dynamics in northern hardwoods (Covington, 1981; Federer, 1984; Londo et al., 1999; Zummo and Friedland, 2011), coniferous forests have received less attention. There are indications that soils of coniferous forests generally show a good retention of C and N stocks after harvest (Johnson, 1992; Johnson and Curtis, 2001; Nave et al., 2010). This could be due to slower decomposition due to litter recalcitrance and low temperatures (Johnson, 1995), and to the rapid resumption of C accumulation and limited nutrient loss after disturbance (Gholz and Fisher, 1982).Information on soil C dynamics is especially scarce below the top 10 to 20 cm of the soil profile.

Recently, several authors have emphasized the need to consider subsoil layers when evaluating C stocks and dynamics (Harrison et al., 2011; Johnson et al., 2011; Rumpel and Kögel-Knabner, 2011). Studies that investigate the entire soil profile

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generally report no effect of harvest in the soil parent material or C horizon (Snyder and Harter, 1985), but any part of the solum may show treatment effects. Diochon and Kellman (2009) proposed that concentrations of C below 20 cm may be driving the temporal response of soil C storage after harvest. Indeed, even moderate changes in SOC distribution and dynamics in deeper horizons have the potential to influence the overall SOC balance due to the large quantities of SOC at stake. Collecting data on C stocks in the entire soil profile is also essential to differentiate between net changes of soil C and translocation (Federer, 1984; Yanai et al., 2003), as redistribution may be an important mechanism by which SOC is conserved in forest soil after disturbance (Hendrickson et al., 1989; Rubino et al., 2010).

Forest harvesting is generally thought to lead to a reduction of soil C stocks for a few decades, followed by a partial or complete recovery period during which soil C stocks increase (Aber et al., 1979; Covington, 1981; Jiang et al., 2002). In some models, harvesting is associated with a short-lived increase in soil C stocks as a result of increased inputs of aboveground and belowground biomass (Bengtsson and Wikstrom, 1993; Johnson et al., 2010).

Notwithstanding the usefulness of such models for the generation of present and future regional estimates, empirical data that confirm these models is relatively scarce (Yanai et al., 2003). Local effects such as logging type, harvest technology, site history, forest type, and climate greatly influence ecosystem response to disturbance. Soil characteristics such as pH (Nierop and Verstraten, 2003), moisture (Londo et al., 1999), N content (Moran et al., 2005), texture (Oades, 1988), and organo-metallic and organo-mineral interactions (Mikutta et al., 2005; Rasmussen et al., 2005) also have the potential to influence soil C retention.

Particle-size fractionation is a useful indicator of SOM dynamics (Borchers and Perry, 1992; Gartzia-Bengoetxea et al., 2009; Norris et al., 2011; Parker et al., 2002). Soil organic matter associated with the clay fraction is considered to be the most stable fraction, with physical occlusion and the formation of complexes with mineral elements contributing to its stabilization (Eusterhues et al., 2003; Paul, 1984; Sollins et al., 1996). In contrast, silt and sand-sized SOM fractions are considered to be more reactive due to weaker interactions with minerals (Six et al., 2002; Tiessen and Stewart, 1983).

Bulk SOM composition is another useful indicator of SOC cycling. The most common indicator of SOM composition is the C/N ratio, which reflects differences in C and N net accumulation rates. Coniferous forests shed litter with a high and relatively constant C/N ratio (McGroddy et al., 2004). The bulk of logging slash typically consists of coarse woody material that also has a low N concentration. During the initial decomposition stage, the C/N ratio of fresh organic inputs decreases as C is lost to the atmosphere (Baldock and Skjemstad, 2000; Johnson, 1995) and N immobilization dominates over mineralization (Keeney, 1980). Under the broad assumption that N inputs do not vary significantly, narrowing C/N ratios can be thought of as an indicator of SOM maturity and humification (John et al., 2005).

Another common indicator of SOM composition is the C concentration of organic matter (C/SOM ratio). A high C/SOM ratio suggests a predominance of C-rich, potentially hydrophobic compounds. Oxygen is the second most abundant element in SOM after C, such that a narrow C/SOM ratio should indicate a higher degree of oxidation and a higher O content (Ussiri and Johnson, 2003). Oxygen-bearing groups include functional groups such as carboxyl and phenolic groups (Johnson, 1995) and confer a general hydrophilic tendency to organic compounds.

In coarse-textured, acid soils, a large portion of the CEC_e is provided by organic functional groups (Federer and Hornbeck, 1985). The ratio between CEC_e and SOC (CEC_e/C ratio) provides an indicator of organic matter functional group density. A high CEC_e/C ratio denotes SOM of high maturity and sorptive capacity (Miralles et al., 2009), which may help reduce nutrient loss after logging, minimize environmental impacts, and improve forest regeneration (Johnson et al., 1997).

The aim of this study is to assess the effects of forest harvest on SOC distribution and characteristics in a conifer forest of coastal British Columbia. We hypothesize that these forest soils are relatively resilient to SOC losses following harvest and that the mineral subsoil plays a large role in C retention after harvest.

MATERIALS AND METHODS

Sampling Sites

This study was conducted in the Roberts Creek study forest (49°27′ N, 123°41′ W) on the Sunshine Coast of southwestern British Columbia. The area lies within the Coastal Western Hemlock [*Tsuga heterophylla* (Raf.) Sarg.] biogeoclimatic zone and experiences a mean annual temperature of 10.2°C and mean annual precipitation of 1369 mm (Environment Canada, 2011). Elevation ranges from 350 to 590 m above sea level with a gentle (~ 15%) southerly slope. The dominant overstory species is Douglas fir, although western hemlock and western red cedar (*Thuja plicata* Donn ex D. Don) are also found among the tallest trees. Western hemlock and western red cedar are also found in the understory together with abundant salal (*Gaultheria shallon* Pursh), western sword fern [*Polystichum munitum* (Kaulf.) C. Presl], and bracken fern [*Pteridium aquilinum* (L.) Kuhn]. Charcoal on standing and fallen snags indicates that the current forest (~ 145-yr old) initiated following wildfires (D'Anjou, 2002). The soil type is Aquentic Haplorthods (Soil Survey Staff, 2006) of sandy loam to loamy sand texture. The following sequence of horizon was observed: Oi, Oe, Oa, E, Bs1, Bs2, BCg, and Cg. Profile morphology and SOM distribution are reported in Grand and Lavkulich (2011).

Harvest Treatment and Sampling

We sampled 27 soil pits by morphological horizon. Each sample was collected to represent the entire horizon around a ~ 90 cm diam. soil profile. The forest floor was separated into two parts: (i) fresh litter (Oi) and (ii) hemic and sapric layer (Oe+Oa). The litter layer was thin and patchy in many plots and often dominated by coarse woody debris. Only the hemic and sapric layer was sampled.

Nine soil pits were located on undisturbed forested plots (control), 11 were located on cleared stands (harvested 2–5 yr before sampling) and 7 in regenerating stands (harvested 8–15 yr before sampling). Vegetation in cleared stands was dominated by the herb layer (particularly fireweed, *Epilobium angustifolium* L.) while regenerating plots were dominated by young Douglas firs. The harvest method was a a clearcut with bole-only removal and slash left untreated on site. Variable retention occurred in some of the harvested plots; in this case, we only sampled clearcut portions of the plot, maintaining a minimum distance of at least 12 m to the nearest retained tree. Samples from harvested stands spanned seven harvest clusters distributed throughout the experimental forest (Fig. 1). Control locations were interspersed in the areas between and around harvested plots and at a distance of at least 30 m from the edge of the disturbance.

When sampling harvested plots, our objective was to gain insight about the in situ effects of vegetation removal over time, rather than the extent of mechanical disturbance caused by logging equipment. Large differences can arise between harvested plots due to changes over time in logging technology (Yanai et al., 2003) as well as the skill and commitment of logging crew to minimize soil disturbance. We sampled morphologically undisturbed soil profiles with no signs of mechanical disturbance or water erosion. We avoided old logging roads, equipment tracks, and preferential flow channels. Overall, the area of harvested plots showing signs of disturbance was visually estimated 10 to 25% of stand area.

Soil Analyses

Soil pH and moisture were measured on field-moist samples before sieving. Soil pH was determined potentiometrically in a 0.01 M $CaCl_2$ solution (Schofield and Taylor, 1955; Van Lierop, 1990). Gravimetric moisture content was determined by oven-drying at 70°C (organic horizons) or 105°C (mineral horizons) to constant weight. Because it is a one-point measurement (in late summer), the gravimetric moisture content had no absolute meaning, but gave an indication of possible moisture regime differences between plots.

Other analyses were performed on the <2 mm fraction (mineral soil) or on material ground to pass through a 2-mm sieve (forest floor). Soil organic matter concentration was determined by loss on ignition in a muffle furnace (Kalra and Maynard, 1991). Total C and N concentrations were measured by dry combustion using an induction furnace (LECO model CN-2000). Texture was estimated after dispersion in Na hexametaphosphate by a combination of sieving and sedimentation steps (Kettler et al., 2001). Organic matter concentration in the sand, silt, and clay fractions was estimated by loss-on-ignition. Soil organic C and N stocks were calculated using SOC and N concentration, horizon thickness, bulk density, and adjusted for coarse fragment content. Bulk density was not directly measured but was estimated based on SOC concentration and sampling depth using the equations of Heuscher et al. (2005) and Federer et al. (1993) (Grand and Lavkulich, 2011). Estimated bulk density averaged 0.15 g cm^{-3} in the forest floor and ranged from 1.25 g cm^{-3} (Bs1) to 1.42 g cm^{-3} (BCg) in mineral horizons. Organically complexed Al and Fe (pyrophosphate-extractable aluminum [Al_p] and pyrophosphate-extractable iron [Fe_p]) were extracted with sodium pyrophosphate (Bascomb, 1968). The cation exchange capacity was estimated as the sum of base cations displaced by a 0.5 M $(NH_4)_2SO_4$ solution and of exchangeable acidity extracted with 1 M KCl (McLean, 1965).

Statistical Analyses

Statistical analyses were performed using SAS version 9.2 software (SAS Institute, 2008) and statistical tests were performed with an α level of 0.05. Means are given ± standard error of the mean (SEM).

The effects of harvest treatment were investigated using a mixed statistical model. Treatment effects (control/cleared/regenerating plots), horizon effects and the treatment × horizon interaction were included as fixed effects. Observations were blocked by harvest operation using a random group effect (G-side). To avoid pseudo-replication with respect to horizon effect, we included the horizon effect as a repeated measure (R-side random effect). This sets a common correlation among all observations of the same soil profile. We used the Toepliz covariance structure to model the correlation between horizons (Littell et al., 2006).

Degrees of freedom were calculated using the Satterthwaite adjustment. Model diagnostics (normality, homoskedasticity, goodness of fit) were run on the conditional residuals (Haslett and Haslett, 2007). Variables with non-normal residual distribution were transformed according to results of the Box–Cox procedure (Box and Cox, 1964) to achieve approximate normality. Treatment means were compared using a *t* test with no provision for multiple inferences (Webster, 2007). If the interaction term was significant, treatment means were compared separately for each horizon. In this case, the analysis reduced to a single-factor experiment in which there are no repeated measures.

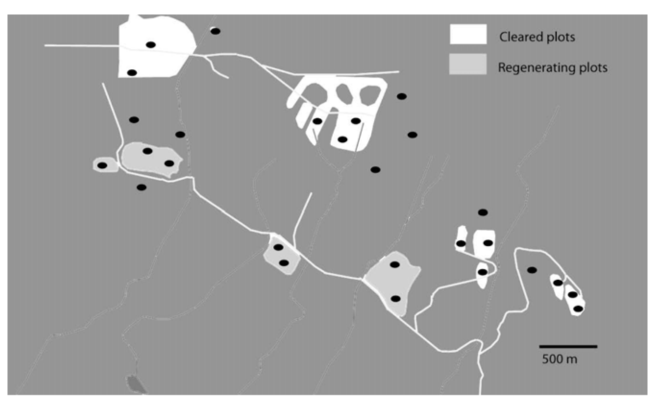

Fig. 1. Approximate sampling locations in Roberts Creek Study Forest

Finally, we used a principle component (PC) analysis to represent treatment effects in an integrative way. Input variables for the PC analysis were SOC, C/N, C/SOM, Al_p, Fe_p, moisture, and CEC_e/C. Eigenvectors and results of the PC analysis are presented in the next section.

RESULTS

Differences in mean soil characteristics between treatments are summarized in Table 1. Differences in variance were also observed. In the forest floor and illuvial horizons of cleared plots, the variables SOC, SOM, C/SOM, N/SOM, and C/N all had a significantly higher variance than in control plots as evaluated by Levene's test for homogeneity of variance (test results not shown).

Soil Organic Carbon

Treatment effects on SOC concentration were different in the forest floor and in the mineral soil. No significant difference between treatments was observed in the forest floor while in illuvial (Bs-BCg) horizons, SOC concentration was 40% higher in cleared than in control and regenerating plots (Table 1, Fig. 2). Silt and clay-associated SOM was similar in all treatments. Sand-sized SOM in illuvial horizons showed significant treatment effects that followed the general pattern observed for total SOC (Table 1).

The C stock of the forest floor was significantly higher in regenerating plots than in control (Fig. 3), despite the small decrease in C concentration (Table 1). This higher C stock corresponded to a higher forest floor thickness (70% on average, Table 1). The thickness of mineral horizons was not affected by treatment. Consequently, C stocks followed the same general pattern as SOC concentration (Table 1). Total profile stocks were 25% higher in cleared than in control plots (Fig. 3), but this difference was not statistically significant. The proportion of total profile SOC present in the forest floor was significantly higher (*p* value = 0.01) in regenerating plots (45%) when compared to control sites (25%) (Fig. 3).

Total Nitrogen

Treatment effects on N concentration were similar to patterns observed for SOC, but were not statistically significant in any horizon (Table 1). Nitrogen stocks followed the same general trend as SOC stocks. In regenerating stands, forest floor N stocks were 2.5 times higher than in control stands (Table 1). Nitrogen stocks in the E horizon were relatively constant. In illuvial horizons, soil N stocks were significantly lower in regenerating than in cleared stands.

Indicators of Bulk Organic Matter Composition

Measured indicators of bulk SOM composition included the C/SOM, N/SOM, CEC_e/C, and C/N ratios. The C/SOM ratio of organic and illuvial horizons was significantly lower in regenerating than in control or cleared plots. The N/SOM ratio showed no significant treatment trends in mineral horizons. In the forest floor, the N/SOM ratio was higher in regenerating plots than in control or cleared plots. The CEC_e/C ratio was significantly higher in illuvial horizons of regenerating plots when compared to control or cleared plots (Table 1).

The forest floor of regenerating stands had a lower C/N ratio than control or cleared plots. In the eluvial horizon, both cleared and regenerating plots had a lower C/N ratio than control (Table 1). Treatment also affected the depth profile of the C/N ratio (Fig. 4). In control plots, the C/N ratio narrowed rather smoothly with depth. In cleared plots, the C/N ratio was lower in the E horizon while lower horizons were largely unaffected, causing the Bs1 horizon to have a higher C/N ratio than the overlying E. In regenerating plots, this trend was smoothed as C/N was slightly lower (although not significantly so) in illuvial horizons. The relationship between SOC concentration and the C/N ratio was also different between treatments (Fig. 5). In control plots, there was no correlation between SOC and C/N, while a positive relationship was observed in cleared and regenerating plots.

Pyrophosphate-Extractable Metals

Table 1 shows the effects of treatment on the sum of Al_p and Fe_p. Similar trends were observed for Al_p and Fe_p individually (not shown). No significant changes were observed in the forest floor. In the E horizon of regenerating stands, Al_p and Fe_p were lower and the $C/(Al+Fe)_p$ ratio was higher than in control or cleared plots. In the illuvial horizons, Al_p and Fe_p concentrations were higher in cleared plots than in control or regenerating plots. This trend matched the changes in SOC so that the $C/(Al+Fe)_p$ ratio remained essentially constant at ~5.

Principal Component Analysis

Treatment effects were summarized by plotting samples along PC axes. Table 2 shows the eigenvector coefficients of the first 3 PCs for mineral horizons. Eigenvector coefficients are the values used to linearly combine the original variables into orthogonal PCs. A high eigenvector coefficient signals that the associated original variable is an important part of the PC considered, and that the original variable correlates highly with the PC.

The first 3 PC accounted for 77% of the total variance. The first PC (PC1) is an index of organic matter content, as shown by its correlation with SOC, moisture, and organically-complexed Al and Fe. The third PC (PC3) is an index of organic matter "freshness" or "immaturity" and correlated positively with C/N and C/SOM ratios, and negatively with the CEC_e/C ratio. The interpretation of the second PC (PC2) is less obvious. PC2 correlated positively with the C/N ratio and the CEC_e/C ratio, but negatively with the C/SOM ratio. PC2 thus probably reflects the fact that some of the processes controlling the C/N and C/SOM ratios are different. The C/SOM ratio is likely to be mostly influenced by the oxidation state of the organic matter, while the C/N ratio depends both on the extent of organic matter decomposition and on the fate of the mineralized N. The PC2 and PC3 represent similar amounts of variance (15 and 14%, respectively), indicating that either are equally valid representations of the

Table 1. Mean ± standard error of the mean (SEM) of selected soil variables by soil layer and treatment. *P* values at the end of each row document the statistical significance of treatment effect. Within each row, means followed by different letters are significantly different at the α = 0.05 level.

Soil property	Soil layer	Treatment			*p* value
		Control *n* = 9	Cleared *n* = 11	Regenerating *n* = 7	
Thickness†, cm	Oe+Oa	6.3±0.7a	10.7±2.3b	11.7±1.6b	**0.02**
	Mineral	87.3±6.3	74.5±5.8	80.3±10.9	0.41
SOC‡, %	Oe+Oa	38.1±2.1	30.7±4.7	29.2±3.6	0.12
	E	1.6±0.2	1.7±0.3	1.3±0.2	0.46
	Bs-BCg	1.7±0.1a	2.3±0.2b	1.6±0.2a	**0.03**
N‡, %	Oe+Oa	1.06±0.07	0.82±0.12	1.03±0.14	0.13
	E	0.06±0.01	0.08±0.01	0.06±0.01	0.20
	Bs-BCg	0.08±0.01	0.10±0.01	0.07±0.01	0.18
Clay-sized SOM§, %	E	0.80±0.07	0.81±0.13	0.60±0.08	0.16
	Bs-BCg	1.31±0.21	1.47±0.15	1.14±0.14	0.65
Silt-sized SOM§, %	E	0.44±0.03	0.53±0.05	0.51±0.09	0.29
	Bs-BCg	0.65±0.05	0.86±0.06	0.59±0.07	0.06
Sand-sized SOM§, %	E	1.47±0.11	1.34±0.17	1.11±1.07	0.18
	Bs-BCg	1.96±0.13a	2.47±0.18b	1.56±0.17c	**0.004**
C stock¶, kg m^{-2}	Oe+Oa	3.6±0.5a	5.9±1.2ab	7.6±1.7b	**0.05**
	E	1.1±0.2	1.0±0.2	1.1±0.3	0.89
	Bs-BCg	11.1±1.2ab	13.1±1.1a	8.5±0.7b	**0.01**
	profile	15.9±1.3	20.0±1.5	17.2±1.8	0.21
N stock¶, kg m^{-2}	Oe+Oa	0.10±0.01a	0.16±0.03a	0.25±0.04b	**0.02**
	E	0.04±0.01	0.05±0.01	0.05±0.01	0.71
	Bs-BCg	0.51±0.06ab	0.61±0.07a	0.42±0.04b	**0.05**
	profile	0.66±0.06	0.83±0.08	0.73±0.06	0.29
C/N#	Oe+Oa	36.2±1.1a	37.8±4.5a	29.0±2.6b	**0.05**
	E	29.3±2.4a	21.3±1.5b	21.7±2.3b	**0.02**
	Bs-BCg	24.2±1.2	23.2±1.0	21.2±1.1	0.58
C/SOM, %††	Oe+Oa	53.0±1.2a	54.1±2.5a	47.9±1.6b	**0.05**
	E	60.3±4.4	64.9±4.8	59.1±2.7	0.60
	Bs-BCg	49.8±2.0a	50.6±1.8a	41.1±1.8b	**0.02**
N/SOM††, %	Oe+Oa	1.48±0.05a	1.53±0.13a	1.81±0.10b	**0.05**
	E	2.33±0.30	3.28±0.40	2.87±0.26	0.19
	Bs-BCg	2.27±0.15	2.25±0.12	2.03±0.12	0.67
CEC_e/C‡‡	Oe+Oa	1.10±0.11	1.05±0.17	1.42±0.23	0.35
	E	2.57±0.38	3.12±0.45	2.68±0.17	0.72
	Bs-BCg	0.92±0.05a	0.90±0.09a	1.30±0.09b	**0.005**
Moisture§§	Oe+Oa	0.87±0.29a	1.21±0.33b	1.39±0.16b	**0.01**
	E	0.10±0.05a	0.16±0.07b	0.13±0.03ab	**0.05**
	Bs-BCg	0.13±0.01	0.19±0.01	0.13±0.01	0.09
$(Al+Fe)_p$¶¶, g kg^{-1}	Oe+Oa	3.0±1.5	3.4±0.8	4.6±2.2	0.54
	E	1.1±0.3a	1.0±0.2a	0.5±0.1b	**0.03**
	Bs-BCg	3.8±0.4a	5.0±0.4b	3.5±0.5a	**0.02**
$C/(Al+Fe)_p$##	Oe+Oa	253.9±44.7	162.8±50.1	142.0±57.2	0.35
	E	18.8±2.9a	18.5±2.3a	26.6±1.9b	**0.05**
	Bs-BCg	5.0±0.3	5.1±0.3	4.6±0.3	0.90

† Thickness of the organic (Oe+Oa) and mineral soil layers (E-BCg).

‡ Soil organic carbon and nitrogen concentration expressed as mass % in the organic (Oe+Oa), eluvial (E) and illuvial (Bs-BCg) horizons. Concentration in the illuvial horizon represents the arithmetic mean of Bs1, Bs2, and BCg horizons.

§ Clay, silt, and sand-sized organic matter concentration, expressed as mass percentage.

¶ Carbon and nitrogen stocks in different horizons and entire profile (to 1-m depth) expressed in kg m^{-2}.

\# Carbon to nitrogen mass ratio.

†† Carbon and nitrogen concentration of soil organic matter, expressed as mass percentage.

‡‡ Ratio of sum of exchangeable cations (cmolc) to soil organic carbon (kg).

§§ Gravimetric moisture content expressed on oven-dried soil basis.

¶¶ Sum of organically-complexed (pyrophosphate extractable) iron and aluminum concentration (g kg^{-1}).

\## Mass ratio of carbon to organically-complexed iron and aluminum.

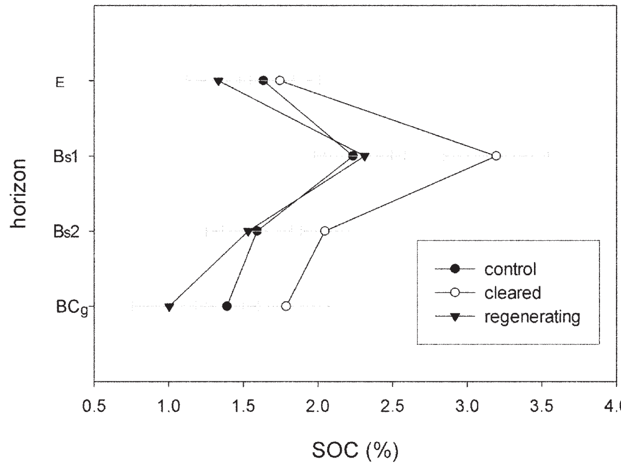

Fig. 2. Soil organic carbon (SOC) depth profile in mineral horizons of control, cleared, and regenerating plots. Points represent SOC means ± standard error of the mean (SEM).

range of the original variables. We chose to represent PC1 and PC3 as the *x* and *y* axes in the bivariate graph (Fig. 6). PC3 was preferred to PC2 on the *y* axis because PC3 is a more straightforward representation of the illustrated processes.

Samples from the Bs1 horizon were moderately clustered according to treatment (Fig. 6). We found similar results for the Bs2 and BCg horizons (not shown). Samples from cleared plots tended to score higher than control on PC1, an index of SOM content. Samples from regenerating plots were characterized by a low score on PC3, indicating low C/N and C/SOM ratios and a high CEC_e/C ratio.

DISCUSSION

The Chronosequence Approach

This study investigated forest harvest effects using the disturbance chronosequence approach, where disturbed sites are compared to spatially distinct control sites. The basic assumption of disturbance chronosequences is that the only difference between sites should be their disturbance regime, and that all other site properties should be similar (Dyck and Cole, 1994). In Roberts Creek we observed no altitudinal, longitudinal, or latitudinal gradients in any of the soil properties measured (test results not shown). Since all sampling sites exhibited reasonable similarity in properties that are likely to affect the response variables, the chronosequence is expected to yield valid results (Pennock and van Kessel, 1997).

The statistical power of chronosequence methods is limited by the error term introduced in the experiment by spatial variability (Yanai et al., 2003). In Roberts Creek, within-plot variability was particularly high in the forest floor. The degree of replication was also low due to limitations in sampling and analytical resources as well as in the number of suitable study sites. This resulted in a high probability for Type II error (false negative) (Eberhardt and Thomas, 1991). This means that only large

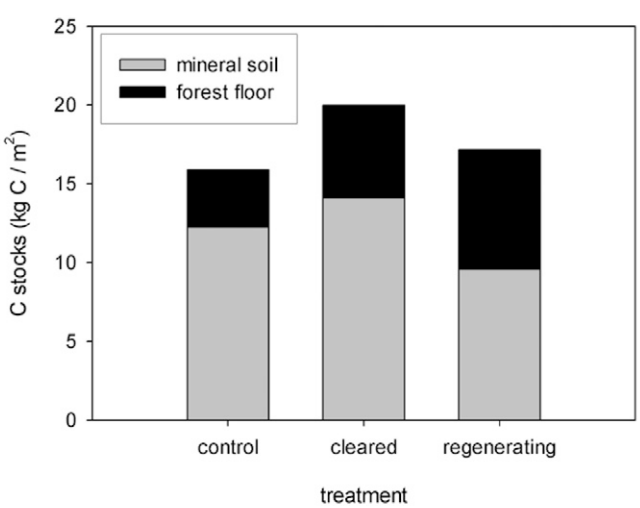

Fig. 3. Average C stock in the soil profiles of control, cleared, and regenerating plots.

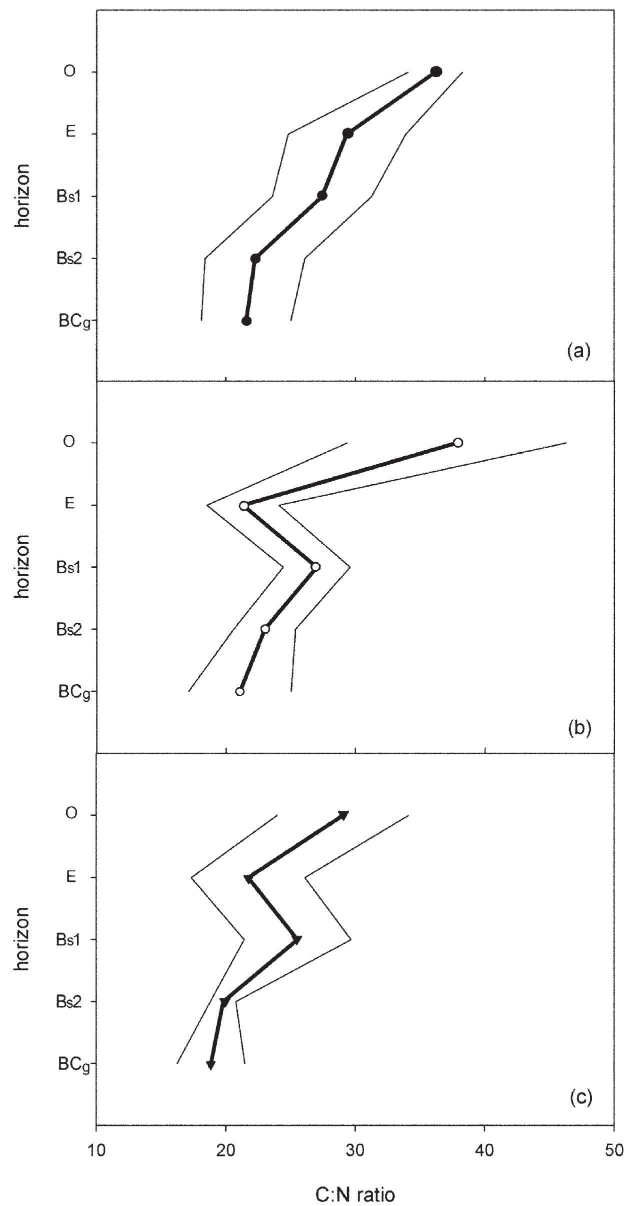

Fig. 4. The C/N variation in profiles of (a) control plots, (b) cleared plots, and (c) regenerating plots. Mean (thicker line) is shown with 90% confidence limits.

treatement effects could be detected, commonly in the range of 35 to 150% change.

Soil Organic Carbon

Soil organic C concentration in the mineral subsoil was significantly higher in cleared plots relative to control. This increase was not likely due to mechanical mixing since physical profile disturbance was minimal. Mineral horizon boundaries showed no evidence of disruption and the C content of the overlying E horizon was constant. A more likely explanation involves a temporary intensification of organic matter illuviation immediately after harvest (Kalbitz et al., 2004; Morris, 2009; Snyder and Harter, 1985). The importance of dissolved C transport was supported by the high correlation between SOC and $Al_p + Fe_p$ ($r^2 = 0.69$, $p < 0.0001$) (Rasse et al., 2006). Decomposing roots may also contribute SOM to the subsoil.

The SOC concentration was similar in control and regenerating plots throughout the soil profile, suggesting that SOC gains were not retained or that older C was metabolized. This is a surprising finding since spodic horizons are known to stabilize C by interaction with minerals and metals (Eusterhues et al., 2005; Kleber et al., 2005; Mikutta et al., 2006; Rasmussen et al., 2006; Scheel et al., 2007; Schmidt et al., 2000). Parfitt (2009) noted that SOM generally interacts rather slowly with minerals while Buurman et al. (2007) suggested that mineral protection did not act on primary organic matter, so that fresh inputs of organic matter to the illuvial horizons are not necessarily stabilized.

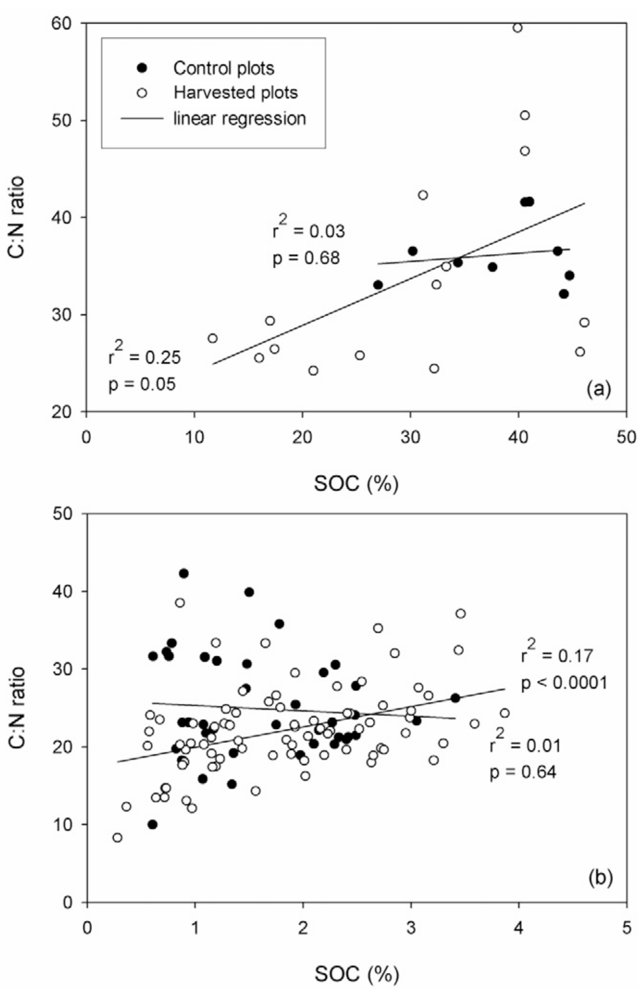

Fig. 5. The C/N ratio as a function of soil organic carbon (SOC) in (a) the organic layer and (b) the mineral soil. The relationship between SOC and C/N ratio was similar in both cleared and regenerating plots (grouped under "harvested" for clarity).

Table 2. Eigenvectors of the first 3 principal components (PC1–PC3) for mineral horizon analysis. The last line shows the percentage variance explained by each factor. The highest coefficients are in bold font.

Variables	PC1	PC2	PC3
	SOM content		SOM immaturity
SOC†	**0.50**	0.01	0.07
C/N‡	0.09	**0.63**	0.76
C/SOM‡	0.25	**–0.48**	**0.30**
Al_p§	**0.49**	0.17	–0.18
Fe_p§	**0.47**	0.14	–0.22
Moisture¶	**0.41**	0.08	–0.19
CEC_e:C#	–0.21	**0.57**	**–0.45**
Variance explained	48%	15%	14%

† Soil organic carbon concentration.
‡ Carbon to nitrogen and carbon to soil organic matter ratios.
§ Pyrophosphate-extractable aluminum and iron.
¶ Gravimetric moisture content.
# Effective cation exchange capacity to carbon ratio.

In the mineral soil, most changes occurred in SOM associated with the sand fraction. This confirms that sand-sized SOM is the most sensitive to changes in land management (Gregorich et al., 2006). Sand-sized SOM is not protected by interaction with minerals (Zinn et al., 2007) and is susceptible to decomposition. In contrast, SOM associated with the silt and clay fraction was comparatively constant across treatments, suggesting that it contains mostly mineralogically, chemically, and biochemically stabilized SOC (von Lützow et al., 2007). Organic matter associated with the clay fraction showed the least relative variation, supporting the hypothesis that the clay fraction was saturated with SOM (Gulde et al., 2008; Six et al., 2002). This is expected in soils with low clay content and few complexation sites

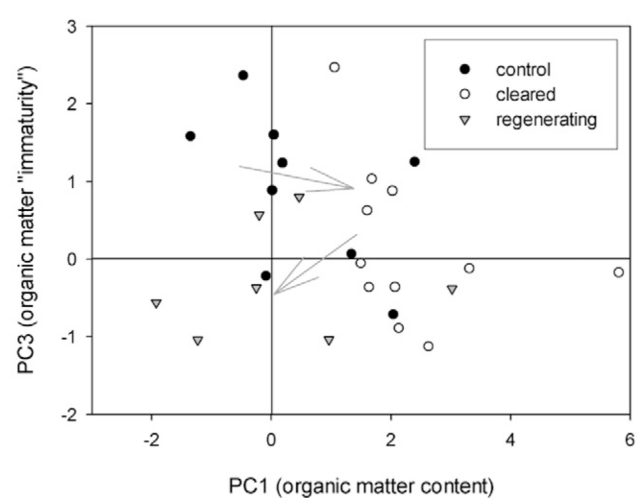

Fig. 6. Distribution of control, cleared and regenerating samples along the first (PC1) and third principal components (PC3) for the first spodic horizon (Bs1).

(Borchers and Perry, 1992). The $C/(Al+Fe)_p$ ratio also remained essentially constant at ~5. This constant and relatively narrow C/metal ratio suggests that in the subsoil, metals are present in sufficient amounts for humus to reach its maximum metal sorptive capacity, and probably the maximum protection that can be afforded by metal complexation.

Variations in total profile C stock were not statistically significant, due in part to the different behavior of organic and mineral layers. Forest floors of regenerating plots had a higher C stock than control plots, suggesting that the gradual conversion of living biomass into detrital pools and subsequent incorporation into the forest floor outweighed decomposition, leaching, and translocation losses. In control plots, the forest floor only accounted for a quarter of profile SOC, suggesting tight nutrient cycling with rates of loss through decay and transfer approximately equal to those of gain from biomass (Simonson, 1959). In regenerating stands, the forest floor accounted for almost half of profile SOC. Organic matter in the forest floor is more susceptible to degradation or mobilization due to the lack of protection by interaction with the mineral phase, and is more vulnerable to C losses following harvest than the mineral soil (Nave et al., 2010).

Total Nitrogen

Nitrogen stocks in the overall profiles of cleared and regenerating plots were not significantly different than in control. This contrasts with many studies of hardwood forests, which reported a significant decrease in soil N content for 5 to 15 yr after clearcutting (Federer, 1984; Hendrickson et al., 1989). In the forest floor of regenerating plots, N stocks were higher than in control, likely due to inputs of detrital organic matter. In the mineral soil, retention of dissolved N by reactive mineral phases such as ferrihydrite and imogolite-type material, which are abundant in the subsoil (Grand and Lavkulich, 2008), may have prevented more significant losses. Even though N stocks were largely conserved over the timeframe of the study (15 yr), subsoil N stocks were significantly lower in regenerating than in cleared plots. This trend could extend into the future, which could exacerbate N limitation for regenerating forests (Hendrickson et al., 1989).

Since bulk density was estimated from depth and SOM concentration rather than being directly measured, the C and N stocks reported here are subject to some error. De Vos et al. (2005) reviewed the predictive quality of 12 models for bulk density estimation, and found that all models produced underestimates of field bulk density. Underestimation error was up to 9 to 36% (Boucneau et al., 1998; De Vos et al., 2005). The uncertainty introduced by bulk density estimates is, however, expected to be moderate compared to the variability in coarse fragment content and C concentration (Holmes et al., 2012). Skid trails, tracks, and landings sites were avoided and soil compaction was not likely to be an important factor at sampled sites. Another source of uncertainty are coarse fragments, which were not analyzed for C content but have been shown to contain between <1 and 25% of SOC (Zabowski et al., 2011). This suggests that the C and N stocks presented here may be conservative estimates. Carbon and N stock comparisons with other sites should therefore be considered with caution.

Organic Matter Composition Indicators of Decomposition

Organic matter in regenerating plots generally had lower C/N and C/SOM ratios relative to control. This suggests increased organic matter decomposition and maturation after harvest (Dai et al., 2001; Hannam et al., 2005; Kalbitz et al., 2004), with the C/N and C/SOM ratios decreasing as C is preferentially lost from SOM (Johnson, 1995). In the forest floor, the N/SOM ratio was significantly higher in regenerating than in cleared and control stands, which may indicate intense oxidation.

Several factors are likely to enhance organic matter decomposition after disturbance (Spielvogel et al., 2006). The alleviation of summer drought may contribute to higher decomposition rates (Niinistö et al., 2011). In Roberts Creek, we observed a higher soil moisture content in the topsoil of cleared plots relative to control during sampling in late summer, possibly due to a decrease in canopy interception and vegetation uptake (Bekele et al., 2007). In regenerating plots, forest floor moisture content remained higher than in control, perhaps reflecting incomplete canopy closure. It should, however, be noted that these moisture measurements only represent one point in time and are not likely to be representative of year-round conditions. Soil temperature is also likely to increase after harvest as a result of increased solar irradiation (Johnson et al., 1985). Finally, fresh needles and early successional litter may have higher N content and be less recalcitrant than mature forest litter (Covington, 1981). In Roberts Creek, we observed active growth of fireweed in cleared plots and a few N_2-fixing alders (*Alnus rubra* Bong.) in regenerating plots, which may contribute easily degradable organic matter to the soil (Bradley et al., 2001) and exert a priming effect on existing soil organic matter (Crow et al., 2009; Fontaine et al., 2007). These conditions can stimulate microbial activity (Gabriel and Kellman, 2011). On the other hand, Prescott et al. (2000) reported that forest floor material lost mass at similar rates in forests and clearcuts, but pointed out that the response of decomposition to clear-cutting is highly variable and cannot be generalized.

Carbon and Nitrogen Relations

The C/N depth profile differed markedly between treatments. The C/N ratio decreased rather constantly with depth in control plots but showed sharp differences between horizons in cleared plots. This suggests that forest harvest disrupted a preexisting steady state of organic matter maturation. In the forest floor, the mean C/N value of cleared plots remained similar to control values while the variance was significantly higher (p = 0.02 by Levene's test for homoskedasticity). We propose that this higher variance but constant mean could result from varying proportions of fresh organic matter inputs from logging slash and increased maturation of existing organic matter. In the E horizon, the C/N ratio was lower in cleared plots than in control, suggesting that SOM in the top part of the profile was rapidly affected by disturbance.

Treatment also affected the relationship between SOC concentration and the C/N ratio. In control plots, there was no relation between SOC and C/N, in accordance with the observation of Waksman (1924), who noted that soils tend to achieve a relatively stable C/N ratio over time. In cleared and regenerating plots however, there was a positive relationship. This corresponds to a "nutrient dilution effect" (McGroddy et al., 2004), with SOC concentration increasing more rapidly than N concentration in organic-rich samples. On the other hand, samples low in SOM also had a low C/N ratio, consistently with the idea that decomposition reduces both the amount of organic matter and the C/N ratio. This suggests that forest harvest disrupted the steady-state relations observed in undisturbed plots (Chaer et al., 2009).

Implications

The soil C/N ratio generally shows an inverse relationship with net nitrification, with a C/N ratio of 25 to 30 in the topsoil generally considered to be a threshold below which net nitrification and nitrate leaching may take place (Gundersen and Rasmussen, 1990; Gundersen et al., 1998). In control sites, the C/N ratio in the uppermost layers (Oe+Oa and E horizons) was high, suggesting that these soils were not actively nitrifying. In cleared and regenerating plots however, the C/N ratio in the E horizon averaged 21 (range 14–28). In the forest floor, regenerating plots had a significantly lower C/N ratio than control, averaging 29 on average (range 24–42). This suggests that at least some of the profiles from cleared and regenerating plots may release nitrate (Hazlett et al., 2007). Acid soils generally have high N release rates because the N requirement of fungi tends to be lower than that of bacteria (Kooijman and Martinez-Hernandez, 2009).

The CEC_e/C ratio is an indicator of organic exchange site density, and was significantly higher in illuvial horizons of regenerating plots compared to cleared and control stands. The pH was constant or slightly lower in cleared and regenerating plots than in control (data not shown), implying that much of the increase in the CEC_e/C ratio was due to actual changes in the character of SOM. Changes may include increased oxidation and increased density of oxygen-bearing functional groups such as carboxl and phenolic groups (Johnson, 1995). A high CEC_e/C ratio denotes SOM of high maturity and sorptive capacity (Miralles et al., 2009) that may help retain nutrients on-site.

Integrated Effects of Forest Harvest

The principal component analysis showed that the main difference between control and cleared plots was the amount of SOC, while regenerating plots were characterized by a change in bulk organic matter composition. This suggests that the response to harvest includes two stages. The first stage was characterized by SOM gains, probably resulting from the gradual assimilation of logging slash (Lee et al., 2002), increased translocation of dissolved C to mineral horizons (Rubino et al., 2010) and root decay. The second stage was characterized by SOM losses from the mineral soil and changes in bulk organic matter quality suggesting the prevalence of mature SOM that is more oxidized and bears a larger number of functional groups.

Podzolization and Soil Organic Matter Dynamics

Because SOM translocation is one of the main soil-forming factors in Spodosols (Lundström et al., 2000; Petersen, 1976), observed changes in SOM dynamics were likely a product of the interaction between the land disturbance and podzolization processes. The increase in SOC concentration in Bs-BCg horizons of cleared plots and concomittant increase in pyrophosphate-extractable metals suggests that illuvial accumulation of SOM in the subsoil may have temporarity increased after harvest. Possible causes include an increase in effective precipitation and resulting increase in soil moisture, and the effect of large additions of fresh SOM to the litter layer as logging slash. Decomposition of the litter layer generates mobile low-molecular weight organic compounds involved in SOC and metal translocation to the subsoil (Buurman and Van Reeuwijk, 1984; De Coninck, 1980; Petersen, 1976).

The increased illuviation of SOC to the mineral subsoil after harvest may improve soil resilience to the biochemical effects of forest harvest (Strahm et al., 2009). In Roberts Creek, the translocation of dissolved C, Al, and Fe species to the subsoil and their subsequent precipitation is likely to have made a significant contribution to the retention of SOM and associated nutrient retention capacity in profiles of cleared plots.

The abundance of logging slash thus appeared to be one of the key to the conservation of SOC stocks both in the forest floor and in the subsoil after harvest. Whole-tree harvesting is currently not a widespread forestry practice in British Columbia, but may receive growing consideration in the future as the demand for biomass to produce bioenergy increases. By reducing the amounts of logging slash inputs, whole-tree harvesting is likely to decrease ecosystem resilience to the effects of logging.

CONCLUSIONS

We found that clearcut harvesting of coastal British Columbia Douglas fir stands influenced SOM content, distribution, and bulk composition in underlying Spodosols. Our results suggest that the soils' response to harvest included two stages. The first stage was characterized by an increase in C stock in the forest floor and an increase in SOC concentration in the mineral subsoil, likely resulting from the gradual assimilation of logging slash, SOC illuviation, and root decay. The second stage was characterized by SOM losses from the mineral soil and changes in bulk organic matter quality suggesting an increased degree of decomposition. The sand-sized fraction recorded the largest variations in SOC concentration between treatments, while the clay fraction had a comparatively constant SOC concentration, suggesting that there was no net formation of new organo-mineral complexes and that new SOM inputs were not stabilized. The majority of the C stock was located in the mineral subsoil and the overall variations of SOC storage between treatments followed changes in illuvial horizons. Studies of C dynamics in spodic soils should therefore take into account the entire thickness of illuvial horizons. When considering the entire solum, forest harvesting was not accompanied by a significant variation of SOC stocks up to 15 yr after cutting. Changes in the C/N depth profile, correlation between SOC and C/N and partition of SOC between the forest floor and mineral soil however provided indications that the preexisting steady state between SOM inputs and decomposition had been disrupted. A study on the evolution of SOM amount and composition in plots harvested 15+ yr before sampling is needed to ascertain long-term effects of forest harvesting in these soils.

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