Carolyn L. Sanscrainte, College of Forest Resources, University of Washington, Box 352100, Seattle, Washington 98195-2100,

David L. Peterson,[1] and **Steven McKay,** USDA Forest Service, Pacific Northwest Research Station, 400 N. 34th Street, Suite 201, Seattle, Washington 98103

Carbon Storage and Soil Properties in Late-successional and Second-growth Subalpine Forests in the North Cascade Range, Washington

Abstract

We compared soil carbon (C) and soil chemical characteristics between late-successional subalpine forests and adjacent regenerating clearcuts (20-40 yr post harvest) that received different logging residue treatments (burned vs. unburned) at four sites in the North Cascade Range of Washington. Carbon storage in the O horizon and mineral soil, C concentration, and soil chemical properties in the mineral soil and spodic horizons were compared between forests and clearcuts, and between burned and unburned clearcuts. Mean carbon storage was 131.3 Mg ha^{-1} in clearcuts and 95.4 Mg ha^{-1} in forests. Mean C concentration was 55.3 g kg^{-1} in unburned clearcuts and 45.1 g kg^{-1} in burned clearcuts. Several soil chemical properties were correlated with C concentrations, although causation of patterns was difficult to infer. Calcium (Ca) concentration was significantly higher in mineral soils of clearcuts than in uncut forests, with unburned clearcuts having the highest Ca concentration. This is a potentially important change in chemical cycling, because subalpine soils have low cation content. Clearcut logging may affect post-harvest soil C storage and other soil properties on a temporary basis, but with the exception of Ca, no long-term effects were apparent at these sites. Post-harvest burning appeared to have a minimal effect 20-40 yr following logging.

Introduction

Soils underlying subalpine forests are important reservoirs of carbon (C) in the Pacific Northwest region of North America (Grier et al. 1981, Johnson et al. 1982, Prichard et al. 2000). Low temperatures slow the microbial breakdown of organic matter resulting in long residence times and relatively large quantities of belowground C, especially in Spodosols (Edmonds 1980, Powers and Van Cleve 1991, Kirschbaum 1995). Additionally, a consistent supply of soil water, from rainfall and snowmelt, may leach C into deeper horizons where it persists in more stable forms and is less subject to mineralization (Kuramoto and Bliss 1970, Vogt et al. 1989, Stone et al. 1993, Richter et al. 1995, Christensen et al. 1999).

Forest harvest can alter site conditions that influence decomposition rates and C stabilization mechanisms so that soils are converted from sinks to sources of atmospheric C (Powers 1980, Johnson et al. 1995, Rustad and Fernandez 1998, MacDonald et al. 1999). Even if total soil C quantities are not affected by tree harvest, redistribution of C within the soil profile is likely because of leaching and mechanical disturbance by logging equipment (Johnson et al. 1991, Ryan et al. 1992). Because soil organic matter provides most of the cation exchange capacity (CEC) of Spodosols (Federer and Hornbeck 1985), essential nutrients may be transported along with C deeper into the soil profile. Nutrients then may be initially less available for regrowing plants (Snyder and Harter 1984, Johnson et al. 1995, Johnson et al. 1997), thereby affecting forest productivity.

Little information exists on the effects of timber harvest on soil C in subalpine forest systems. The effects of harvest activities on temperate and tropical forest soils are extremely varied (Johnson 1992, Johnson and Curtis 2001). Most effects on soil C storage and distribution appear to be associated with one or more variables related to specific characteristics of (1) site (e.g., dominant vegetation, soils, climate) (Borchers and Perry 1992, Knoepp and Swank 1997), (2) harvest practices (Kraemer and Hermann 1979, Edwards and Ross-Todd 1983, Burger and Pritchett 1984, Miller and Sirois 1986, Mattson and Swank 1989, Johnson and Todd 1998, Piatek and Allen 1999, Bock and Van Rees 2002), and (3) study design (e.g., time since harvest, sampling depth) (Covington 1981, Black and Harden 1995, Johnson et al. 1995,

---

[1] Author to whom correspondence should be addressed.
E-mail: peterson@fs.fed.us

Knoepp and Swank 1997). Generally, there is a post-harvest pulse of C and nutrients to the soil. This pulse may be immediate when residues are burned (Adams and Boyle 1980), or occur more slowly when on-site residues are allowed to decompose (Entry and Emmingham 1998). The longevity of the period of higher C depends on environmental conditions that control decomposition, however, soil C content generally decreases over time after timber harvest (Alban and Perala 1992, Johnson 1992, Knoepp and Swank 1997, Johnson and Todd 1998).

Because decomposition rates are exceptionally slow in subalpine forest systems, the presence or absence of logging residues may affect soil C and chemical characteristics over a longer temporal scale than in low-elevation forests. In this study, we quantified soil C and other physical and chemical characteristics of the soil profile in late-successional subalpine forests and adjacent stands clearcut 20-40 yr ago in the North Cascade Range, Washington. Clearcut sites with and without post-harvest burning treatments were included in the analysis to evaluate the combined effects of logging and slash burning on subalpine soils.

Methods

Study Area

The study is in subalpine forests in a portion of the Mt. Baker-Snoqualmie National Forest that is northwest of Mt. Baker, the northernmost of the Cascade Range volcanoes (Figure 1). This portion of the North Cascades is steep, rugged, and composed of sedimentary and metamorphic formations that have been glacially modified. The resulting landscape is a mosaic of broad valleys, cirques, arêtes, and morainal and outwash deposits that is heavily dissected by many streams.

The North Cascades create an orographic barrier to weather systems moving inland from the Pacific Ocean, resulting in cool, wet winters (with high snowfall at higher elevations) and mild summers characterized by a period of low precipitation on the western slopes. Mean annual temperature is 5° C within the study area; January and July means are –2° and 14° C. Mean winter precipitation (November–February) at Wells Creek, the nearest Snotel weather station (elevation 1561 m) is 278 cm, the majority falling as snow and

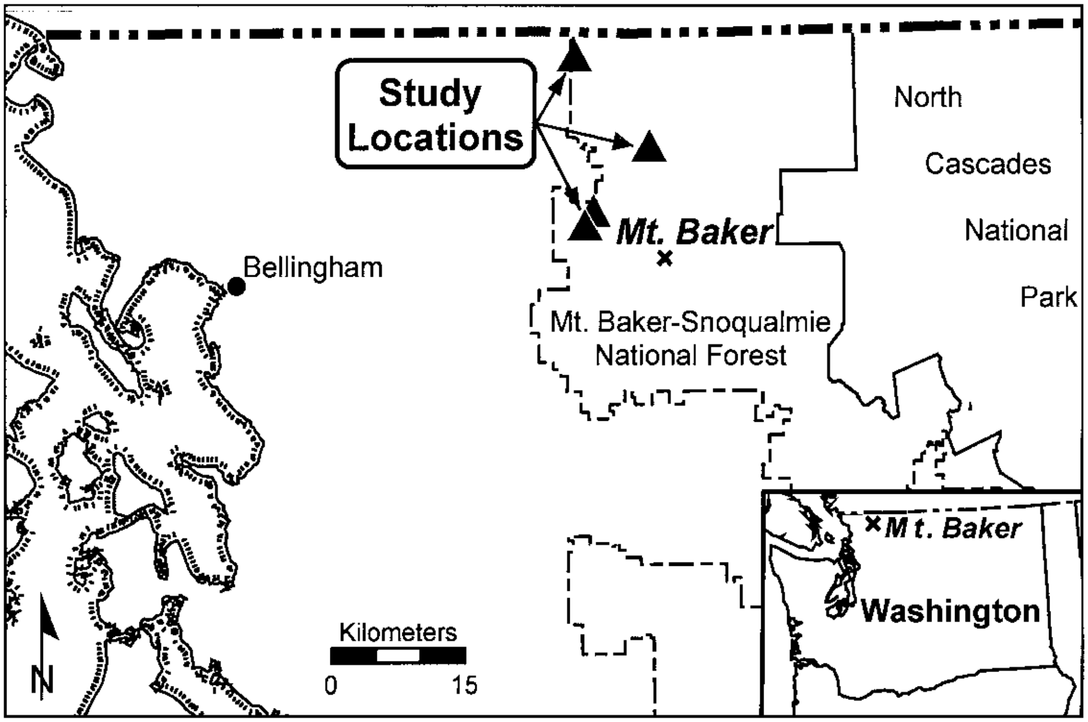

Figure 1. Location of the four study sites in the North Cascade Range.

accumulating in deep, persistent snowpacks. Mean summer precipitation (June–September) is 89 cm.

Spodosols, often skeletal, are common in the high-elevation forests of the study area. Soils have developed in hillslope sediments and tephra over sedimentary rock. Curved tree trunks and absence of A horizons are manifestations of soil creep on the steep slopes of the study area. Buried horizons in forests and clearcuts are evidence of mass wasting events. Soils are well-drained Typic Haplocryods and Typic Humicryods (Soil Survey Staff 1999).

Pacific silver fir (*Abies amabilis*) and mountain hemlock (*Tsuga mertensiana*) dominate forest overstories, while moss, woody debris, rustyleaf (*Menziesia ferruginea*), Alaska huckleberry (*Vaccinium alaskaense*), and Pacific silver fir seedlings are common in the understories. Subalpine fir (*Abies lasiocarpa*) and Alaska yellow cedar (*Chamaecyparis nootkatensis*) are occasionally present in smaller numbers. Dominant vegetation in clearcuts includes mountain hemlock, Pacific silver fir and Alaska-yellow cedar as regeneration, and big huckleberry (*Vaccinium membranaceum*), Alaska huckleberry, alpine ladyfern (*Athyrium filix-femina*), stink currant (*Ribes bracteosum*), and salmonberry (*Rubus spectabilis*).

Sampling Design

Soils were studied at four sites where undisturbed, late-successional forest stands abut clearcuts. All sites were selected to maintain similar topography, slope, and tree age class (Table 1). Post-harvest logging residues were previously yarded, piled, and burned at Sites 1 and 2, and only yarded and piled at Sites 3 and 4.

Within each forest and clearcut, three soil pits were excavated to allow sampling and description of the entire soil profile. Soil pits were at 50-m intervals at the same elevation across the slope. Soil pits in clearcuts were at least 50 m from the edge of the adjacent forest canopy. Soil pits were excavated to bedrock or to where rock fragments prohibited further digging. Within each soil profile, one sample was taken from each mineral horizon, and the Oi, Oe, and Oa horizons were composited as one sample, although depths were measured for each O sub-horizon. Additionally, 10 samples of the O horizon were collected at 10-m intervals along the sampling transect to obtain a larger spatial sample than the limited sampling at the soil pits allowed. Litter <2 cm in diameter was collected within a quadrat at each sample point.

Soil Analysis

Soil chemical analysis included %C, % nitrogen (N), pH, exchangeable cations, CEC, available

TABLE 1. Summary of site characteristics.

	Site 1	Site 2	Site 3	Site 4
Elevation (m)	1720	1553	1355	1240
Aspect	S-ESE	N	E-ESE	N-NNW
Landform	Valley sidewall	Glacial moraine	Valley sidewall	Valley sidewall
Slope (%)	37	48	45	46
Forest vegetation				
Overstory	Pacific silver fir	Pacific silver fir	Pacific silver fir	Mountain hemlock
Understory	Moss Rustyleaf	Strawberry-leaf huckleberry Alaska huckleberry	Woody debris Pacific silver fir	Woody debris Moss
Clearcut vegetation				
Regeneration	Alaska yellow cedar Pacific silver fir	Mountain hemlock Pacific silver fir	Pacific silver fir Alaska yellow cedar	Mountain hemlock Pacific silver fir
Understory	Big huckleberry	Salmonberry	Woody debris Ladyfern	Moss Ladyfern
Forest age (yr)	348	≥230	≥223	≥204
Clearcut year	1977	1964	1960	1962
Residue treatment	Yard, pile, and burn	Yard, pile, and burn	Yard and pile	Yard and pile
Soil subgroup	Typic Haplocryod	Typic Humicryod Typic Haplocryod	Typic Humicryod Typic Haplocryod	Typic Humicryod Typic Haplocryod

phosphorus (P), and extractable iron (F) and aluminum (Al). Prior to analysis, all soil samples were air dried and weighed, and mineral soil was sieved through a 2-mm screen.

Organic horizon samples were ground in a Wiley mill with a 20 mesh screen, then subsequently finely ground with a mortar and pestle to ensure homogenization for C and N analysis. Subsamples were analyzed for %C and %N with a CHN analyzer at the Forest Soils Laboratory, University of Washington.

Soluble extractions from the soil subsamples were required for the determination of both exchangeable cations and CEC. Extractions were prepared by saturating 2.5 g of air-dried, < 2-mm mineral soil subsamples with 60 ml of 1.0 M NH_4OAc. Samples were then placed in a mechanical extractor overnight to remove NH_4OAc from saturated exchange sites. The resulting solutions were collected and analyzed for exchangeable cation concentration by atomic absorption (Ca^{2+} and Mg^{2+}) or atomic emission (Na^+ and K^+) flame spectrophotometry at the Soil Characterization Laboratory, University of Missouri. Steam distillation and titration were then used to measure the adsorbed NH_4^+ and determine CEC (Soil Survey Staff 1992). Base saturation (BS) was calculated as the percent of CEC occupied by exchangeable cations.

Available P was extracted using the Bray 1 absorbed P method (Olsen and Sommers 1982, Soil Survey Staff 1992).

Samples from prospective Bs and Bhs horizons were analyzed for %Fe and %Al to verify spodic criteria (Soil Survey Staff 1992). Two grams of air-dried, < 2-mm soil were saturated with 200 ml of 0.2 M ammonium oxalate. These solutions were mixed on a mechanical shaker for 4 hr in the dark. The solutions were then filtered through a Whatman #42 filter. The resulting filtrates were analyzed for Fe and Al concentrations using inductively coupled argon plasma emission spectroscopy.

Soil pH for each horizon was determined with a pH meter. Deionized water was mixed with <2-mm mineral soil samples (2:1) prior to determination of pH.

Bulk density was determined by extracting an intact soil aggregate from each mineral horizon and measuring its volume displacement in water. Oven-dry mass of each sample soil aggregate was later measured in the laboratory. Bulk density of each horizon was calculated after accounting for the mass and volume of the >2-mm fraction.

Soil C mass (g kg^{-1}) for organic horizons was calculated by multiplying C concentration (g kg^{-1}) by organic layer mass (kg m^{-2}). Soil C mass for mineral soil was calculated as:

$$\begin{aligned} \text{C (kg m}^{-2}\text{)} = \Sigma\ [&\text{organic C concentrations of <2-mm material} \\ &\text{(g kg}^{-1}\text{)} \\ &\times \text{bulk density of <2-mm material} \\ &\times \text{horizon depth (m)} \\ &\times (1 - \text{rock volume [\%]/100\%}) \\ &\times 10^{4}\ \text{cm}^2\ \text{m}^{-2} \times 10^{-6}\ \text{kg}^2\ \text{g}^{-2}] \end{aligned}$$

where the summation is across the horizons within the soil profile (after Homann et al. 1995). All soil C is organic because carbonates (source of inorganic C) are not found in the parent materials of the study area, and soils are strongly acidic.

Statistical Analysis

Data were analyzed using an unbalanced, crossed two-factor mixed-effects ANOVA model with replication to detect differences between forests and burned and unburned clearcuts for the following variables: C storage (O horizon and mineral soil), soil chemical properties [pH, CEC, %BS, C, N available P, calcium (Ca), sodium (Na), magnesium (Mg), potassium (K) and C:N], depths in the mineral soil and specifically in spodic horizons, and mineral soil bulk density. Treatment is a fixed effect, and site and interaction are random effects. Correlation analyses were performed between C and all other soil chemical characteristics (N, pH, %B.S., CEC, N, available P and exchangeable cations) in forests, burned clearcuts, and unburned clearcuts. Because horizons varied among soil profiles, comparisons were made between means weighted for differences in horizon mass. Treatment effect differences were considered significant at $P < 0.05$.

Results

Soil Profile Characteristics

The cool, moist climate, dominance of coniferous vegetation, and glacial history were the primary influences on pedogenesis in the study area. Relatively shallow soils that have developed since glaciers carved and scoured the study area are on steep slopes prone to movement of hillslope sediments. Soils at Sites 1, 2, and 4 were primarily sandy loams, while soils at Site 3 were primarily coarse sandy loams (Table 2). An A horizon was absent in all but one clearcut soil profile. Spodosols with strongly expressed E horizons (determined by color) over one or more spodic

TABLE 2. Representative descriptions of forest and clearcut soil profiles at each site. Textures are as follows: C—crumb; CSL—coarse sandy loam; GSL—gravelly sandy loam; LS—loamy sand; SBK—subangular blocky; SL—sandy loam.

Horizon	Depth (cm)	Color (moist)	Texture	Structure	Rock Volume (%)	Roots
Site 1 Forest, Profile a—Typic Haplocryod						
O	1-0					
E	0-11	10YR 4/2.5	SL	SBK	20	Common medium and fine
Bs1	11-29	7.5YR 3/4	SL	SBK	10	Common medium and fine
Bs2	29-46	7.5YR 3/4	SL	SBK	25	Common medium and fine
CB	46-63	7.5YR 2.5/2	SL	SBK	40	Few fine and coarse
C	63+					
Site 1 Clearcut, Profile b—Typic Haplocryod						
O	6-0					
E	0-7	10YR 5/3	SL	SBK	10	Common fine
Bs1	7-19	7.5YR 4/6	CSL	SBK	20	Common fine; few medium
Bs2	19-39	7.5YR 4/6	SL	SBK	10	Common very fine; few fine
CB	39-62	10YR 3/6	SL	SBK	50	none
C	62+					
Site 2 Forest, Profile c—Typic Haplocryod						
O	13-0					
Eh	0-5	7.5YR 3/2	SL	SBK	10	Few very fine and fine
Bhs1	5-9	5YR 3/3	SL	SBK	10	Few fine and medium
Bs2	9-21	7.5 YR 3.5/5	SL	SBK	20	Few fine
Bs3	21-32	7.5YR 3/4	SL	SBK	30	Few fine and medium
BC	32-52	5YR 3/3	SL	C	80	Common fine and medium
CB	52+					
Site 2 Clearcut, Profile c—Typic Haplocryod						
O	2-0					
1Bs	0-11	7.5YR 4/4	SL	SBK	10	Common very fine and fine
2E	11-17	7.5YR 3/2.5	SL	SBK	5	Common fine; few medium
2Bs	17-37	7.5YR 3.5/5	SL	SBK	10	Common fine; few medium and coarse
2BC	37-52	10YR 3/3	GSL	SBK	20	Few very fine and fine
2CB	52-70	10YR 2/2	GSL	SBK	70	Few very fine
2C	70+					
Site 3 Forest, Profile a—Typic Humicryod						
O	2-0					
Eh	0-8	10YR 4/2	SL	SBK	30	Few fine and coarse
Bhs1	8-23	10YR3/8	CSL	SBK	50	Common coarse
Bs2	23-45	7.5 YR 4.5/6	SL	SBK	80	Few fine; common medium
BC	45-70	10YR 3.5/6	CSL	C	80	Few fine and medium
CB	70+					
Site 3 Clearcut, Profile a—Typic Haplocryod						
O	3-0					
E	0-7	10YR 2/2	SL	SBK	5	Common very fine and fine
1Bs	7-46	7.5YR 3/4	SL	C	40	Common very fine and fine; few medium
2Bs1	46-63	5YR 3/4	CSL	C	20	Few fine
2Bs2	63-77	5YR 3.5/5	CSL	SBK	40	Few fine
2BC	77-94	7.5YR 3/4	CSL	SBK	90	none
2CB	94+					

Continued on next page

TABLE 2. (Continued)

Horizon	Depth (cm)	Color (moist)	Texture	Structure	Rock Volume (%)	Roots
Site 4 Forest, Profile c—Typic Humicryod						
O	8-0					
Eh	0-13	10YR 2/1	LS	SBK	10	Common fine, medium and coarse
Bhs1	13-20	5YR 3/4	SL	SBK	10	Common fine and medium
Bs2	20-36	10YR 3/3	LS	SBK	10	Few fine and medium
Bs3	36-64	10YR 4/5	LS	SBK	10	Few fine and medium
Bs4	64+	10YR 4/6	LS	SBK	20	Few fine and medium
Site 4 Clearcut, Profile c – Typic Humicryod						
O	7-0					
1Bs1	0-10	10YR 4/6	SL	C	20	Common very fine; many fine; few medium
1Bs2	10-19	10YR 3/6	SL	SBK	30	Many fine; few medium
2E	19-22	10YR 3/3	LS	SBK	10	Common fine
2Bs	22-39	7.5YR 3.5/5	GSL	SBK	30	Common fine; few medium
2BC	39-67	10YR 3/6	GSL	SBK	50	Few fine and medium
2C	67+					

C—crumb; CSL—coarse sandy loam; GSL—gravelly sandy loam; LS—loamy sand; SBK—subangular blocky; SL—sandy loam

horizons (determined by color and Al and Fe content) were a dominant feature. Thick spodic horizons (up to 30 cm) frequently developed immediately above parent materials.

The O horizon was generally thicker in forests than in clearcuts (Table 3), although this difference was not statistically significant due to high variance among soil profiles. Mean proportion of the soil profile comprising spodic horizons was highest for forested sites, followed by clearcuts and burned clearcuts (Table 3), although these differences were not statistically significant. Rock content generally increased from 10% in upper horizons to 50-80% in deeper horizons. Exceptions occurred where movement of hillslope sediments had mixed the soil profile components. There were more buried horizons in clearcuts than forests, which suggests that forest harvest may have encouraged movement of hillslope sediments, although there were no data to confirm this.

Soil Carbon

Mean C storage in the O horizon was higher for forests than for clearcuts (Table 4), and mean C storage in the mineral soil was less for forests than for clearcuts. Neither difference was statistically significant due to high variance among soil profiles. Carbon storage and concentration in spodic horizons appeared mostly unaffected by tree harvest and burning. Although burned clearcuts had less C than unburned clearcuts, the difference was not significant.

As expected, C concentrations in the mineral soil generally were high (Table 4). Carbon concentrations were typically lowest in BC, CB, and

TABLE 3. Mean (± SE) bulk density, and horizon and soil profile depths for forests and clearcuts.

Site	Bulk density (g cm^{-3})	O (cm)	Horizon depth E (proportion of total)	Horizon depth Bs/Bhs (proportion of total)	Total depth (cm)
Forest	0.52 ± 0.07	10.2 ± 4.6	0.15 ± 0.02	0.67 ± 0.10	63.8 ± 16.8
All clearcuts	0.45 ± 0.02	5.5 ± 0.8	0.10 ± 0.02	0.53 ± 0.13	75.5 ± 11.1
Burned clearcut	0.46 ± 0.01	5.6 ± 5.9	0.09 ± 0.01	0.43 ± 0.09	67.0 ± 8.0
Unburned clearcut	0.44 ± 0.03	5.3 ± 1.2	0.11 ± 0.00	0.62 ± 0.04	84.0 ± 3.8

TABLE 4. Mean (± SE) C storage and concentration for forests and clearcuts.

		Mineral soil		
	O horizon	All horizons		Bs/Bhs horizons
Site	(Mg ha^{-1})	(Mg ha^{-1})	(g kg^{-1})	(g kg^{-1})
Forest	48.8 ± 16.1	95.4 ± 51.7	51.0 ± 19.3	49.5 ± 15.0
All clearcuts	30.0 ± 21.2	131.3 ± 46.0	50.2 ± 7.0	45.3 ± 8.7
Burned clearcut	29.5 ± 36.5	114.2 ± 29.8	45.1 ± 11.0	39.9 ± 5.2
Unburned clearcut	30.6 ± 4.5	148.4 ± 65.5	55.3 ± 2.6	50.7 ± 9.0

C horizons when those horizons were present, however, there was no consistent pattern in the spatial distribution of C in the overlying horizons.

Soil Chemical Characteristics

Post-harvest changes in soil chemical characteristics appeared to be at least partially controlled by logging residue treatment and were often correlated with C concentrations (Tables 5, 6). Calcium concentration was significantly higher in mineral soils of clearcuts than in uncut forests, with unburned clearcuts having the highest Ca concentration (Table 5). However, most other cations and soil chemical properties were similar between clearcuts and forests and between burned and unburned clearcuts. Nitrogen concentrations in the mineral soil were mostly unaffected by cutting and burning treatments.

Several soil chemical properties were correlated with C concentrations in this study (Table 6), although correlations were not consistent among forest vs. clearcut and burned vs. unburned clearcuts. One of the strongest correlations we discovered between C and N concentrations was significant for burned clearcuts only. There was also a significant correlation between C and CEC and between C and BS, but only for the two clearcut treatments.

TABLE 5. Mean (± SE) chemical properties of mineral soil for forests and clearcuts.

Site	pH (H_2O)	CEC (cmol kg^{-1})	B.S. (%)	N (g kg^{-1})	Avail. P (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	K (mg kg^{-1})	C:N
All horizons										
Forest	–	35.1 ± 10.7	2.0 ± 0.7	1.7 ± 0.6	4.1 ± 3.0	61 ± 37	1.1 ± 0.6	19.4 ± 2.0	29.5 ± 2.7	30.1 ± 4.9
All clearcuts	–	31.6 ± 6.2	5.1 ± 3.0	1.5 ± 0.6	6.0 ± 4.1	271 ± 177	1.2 ± 1.0	17.7 ± 2.2	28.4 ± 7.9	37.5 ± 13.1
Burned clearcut	–	30.6 ± 5.9	2.6 ± 0.7	1.1 ± 0.6	6.6 ± 6.4	128 ± 57	0.5 ± 0.3	16.2 ± 1.8	24.7 ± 6.5	46.1 ± 16.0
Unburned clearcut	–	32.4 ± 8.9	7.6 ± 0.4	1.9 ± 0.3	5.5 ± 2.7	415 ± 94	1.9 ± 1.1	19.5 ± 0.4	32.2 ± 9.4	29.0 ± 5.5
Bs/Bhs horizons										
Forest	4.4 ± 0.3	39.3 ± 7.3	1.9 ± 0.8	1.7 ± 0.6	3.9 ± 2.7	45 ± 22	0.9 ± 0.7	18.5 ± 2.1	29.6 ± 6.8	30.6 ± 7.9
All clearcuts	4.9 ± 0.2	33.2 ± 7.2	5.4 ± 3.3	1.4 ± 0.5	2.6 ± 0.7	183 ± 102	1.8 ± 1.8	19.1 ± 3.2	28.4 ± 7.4	36.3 ± 12.7
Burned clearcut	4.4 ± 0.6	33.4 ± 9.7	3.5 ± 3.2	0.9 ± 0.1	2.3 ± 0.9	108 ± 91	2.1 ± 3.0	18.2 ± 4.7	29.7 ± 12.1	44.9 ± 12.2
Unburned clearcut	4.6 ± 0.2	33.1 ± 7.8	7.3 ± 2.8	1.8 ± 0.0	3.0 ± 0.1	257 ± 25	1.6 ± 1.1	20.0 ± 2.1	27.1 ± 3.7	27.7 ± 6.4

TABLE 6. Significant correlation coefficients (r^2) between C concentration and soil chemical properties in forests, burned clearcuts, and unburned clearcuts. No correlations were significant for pH, Na, and K.

	CEC (cmol kg^{-1})	B.S. (%)	N (g kg^{-1})	Available P (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})
Forest	—	—	—	0.20	—	0.31
Burned clearcut	0.80	0.22	0.80	0.27	—	—
Unburned clearcut	0.23	0.25	—	—	0.33	0.24

Discussion

We identified a possible trend toward decreased O-horizon depth after timber harvest (Table 3). Previous studies have attributed decreases in O-horizon accumulations after harvest (without burning) to: (1) redistribution of residues into the mineral soil at the time of clearcutting, (2) ensuing decomposition (Johnson et al. 1991, Ryan et al. 1992, Black and Harden 1995, Parker et al. 2001) and (3) the post-harvest dominance of herbaceous and deciduous litter that decomposes more easily than coniferous litter (Edmonds 1980).

The amount of the soil profile comprising spodic horizons was not significantly different in clearcuts than in uncut forests (Table 3). In a study of Spodosols in deciduous hardwood clearcuts in New Hampshire, thicker Bs1 horizons observed 3 yr after timber harvest were due to increased solubility and mobility of soil organic matter (Johnson et al. 1991). However, it is also possible that in coniferous forests spodic characteristics break down after tree harvest due to the loss of organic acids from overstory trees (R. David Hammer, University of Missouri, personal communication).

Although forests may be more productive and have slower decomposition rates than young regeneration in clearcuts (Covington 1981), logging residues in cool coniferous ecosystems persist for long periods of time (Harmon et al. 1990, Johnson and Curtis 2001) and probably contribute to the similar quantities of O-horizon C in forests and clearcuts in this study. A large portion of the soil C in late-successional forests is stored as lignin (Entry and Emmingham 1998), which reduces organic matter decomposition and C turnover rates and facilitates high C concentrations. Much of the primary source of soil C (surficial organic matter and logging residues) was oxidized when burning was conducted following clearcut logging. Consequently, easily decomposed herbaceous litter (relative to the forest) has been the primary source of soil C since harvest in burned clearcuts.

Immediately after harvest, C storage in the O horizon may change depending upon how the severity of the disturbance at the time of harvest affects the quality and quantity of logging residues (Johnson 1992, Piatek and Allen 1999, Harmon and Marks 2002). Eventually a period is reached when organic matter degrades as wood and leaf litterfall are reduced by tree removal, and residues left on site decompose (Covington 1981, Parker et al. 2001). The degradation phase may be augmented by higher decomposition rates (Marra and Edmonds 1996, MacDonald et al. 1999) and the prevalence of herbaceous and shrub litter that decomposes relatively quickly. The degradation phase gradually shifts to an aggradation phase as vegetation recovers and the quantity and size of wood litterfall increases (Covington 1981).

The clearcuts in this study appear to be in the degradation phase. O-horizon C storage was likely greater in clearcuts than in forests immediately after harvest due to logging inputs (Johnson et al. 1991, Simard et al. 2001, Bock and Van Rees 2002). Although there may be some release of C from decomposing logging residues, the similarity in O-horizon C between forests and clearcuts indicates that C inputs from decomposing logging residues are probably decreasing. The translocation of C from decomposing logging residues and accelerated decomposition of litter from early successional plants can increase soil C pools in unburned clearcuts (Covington 1981, Johnson et al. 1991, Entry and Emmingham 1998, Bock and Van Rees 2002).

The similar C concentrations between forests and clearcuts in this study, however, indicate another mechanism may be at work. For example, total C storage can be affected simply by differences in soil volume among soil profiles. In addition, movement of hillslope sediments can transport C deeper into the soil profile and result in large reserves of long-term C storage (Richter et al. 1995, Christensen et al. 1999), especially in mountain landscapes.

Effects of timber harvest on mineral-soil C pools tend to be relatively small in most forests, with net gains or losses affected mostly by the type of residue management (Johnson 1992). No difference was found in the top 10 cm of burned and unburned mineral soils 32-36 yr after broadcast burn in the western Cascade Range in Oregon and Washington (Kraemer and Hermann 1979). In a study evaluating the effects of post-harvest residue removal, no detectable differences were found in mineral soil C storage 5 mo after tree harvests in a southern mixed deciduous forest (Edwards and Ross-Todd 1983). No change in mineral soil C pools were found in northern hardwood forests 3 yr after harvest, although there was evidence of redistribution of organic matter in the solum (Johnson et al. 1991).

With the notable exception of Ca, we found minimal changes in other soil chemical properties that might have been affected by cutting and burning. At 20-40 yr after harvest and burning, any nutrients that were initially released have likely been removed through leaching in this high-precipitation environment. A variety of effects on soil chemistry have been observed at different temporal scales in other forests. Soil pH, N, CEC, Ca, and Mg increased, and K decreased after clearcutting a boreal mixed-wood forest (Bock and Van Rees 2002). Large post-harvest (without burning) changes in exchangeable cations in forest soils in the southeastern U.S. have been attributed to plant uptake and leaching (Johnson and Todd 1990, Knoepp and Swank 1994, Richter et al. 1995). Studies of mineral soils in forests within 2 yr after burning found increases in soil nutrients, which, except for N, were largely retained in the soil (Adams and Boyle 1980).

High post-harvest Ca concentrations in the mineral component of subalpine soils may have been related to the stability of Ca cations. Soil organic matter typically selects for divalent over monovalent cations, and Ca moves through the soil with anions released as organic matter mineralizes (Snyder and Harter 1984). This is a potentially important change in chemical cycling, because these subalpine soils have very low cation content. Increased residence time of Ca may be particularly important in Spodosols in which Ca tends to accumulate in spodic horizons after tree harvest (Snyder and Harter 1984; Johnson et al. 1991, 1995, 1997). Calcium in the mineral soil may eventually return to pre-harvest levels as it is accumulated by recovering forest vegetation (Knoepp and Swank 1994, Richter et al. 1995). Positive correlations between C and CEC and between C and exchangeable cations found in this study are typical in Spodosols with low clay contents (Federer 1984, Federer and Hornbeck 1985, Johnson et al. 1995).

At 20-40 yr after harvest, similar O-horizon C pools and mineral soil C concentrations in forests and clearcuts indicate that a mechanism other than logging residue decomposition and mixing into the mineral soil may be responsible for current patterns. Buried horizons in clearcuts indicate that deeper soils may be the result of harvest-induced movement of hillslope sediments. Consequently C storage likely varies spatially within the clearcuts. Organic matter is an important source of exchange sites for soil nutrients in these low-clay Spodosols, and logging slash continues to be a source of soil nutrients, particularly Ca, up to 40 yr after clearcutting. The soil environment should be a strong consideration in management of subalpine forests of the Cascade Range, particularly with respect to treatment of logging residues, because post-harvest effects may require decades to be fully manifested.

Acknowledgements

We thank David Hammer, Darlene Zabowski, Kermit Cromack, and Chris Swanston for reviewing previous drafts of the manuscript. Nate Ennen, Amy Hessl, Tara Hudiburg, Jeremiah Nelson, Peter Noonan, Susan Prichard, and Marnie Tyler assisted with the fieldwork. Duane Emmons, Dan Potts, Sarah Schrock, Peter Springs and Dongsen Xue contributed laboratory assistance at the University of Washington. Russ Dresbach of the Soil Characterization Lab at the University of Missouri also provided laboratory assistance. Robert Norheim prepared the map in Figure 1. Research was funded by the U.S. Geological Survey Global Change Research Program and the USDA Forest Service Pacific Northwest Research Station.

Literature Cited

Adams, P. W., and J. R. Boyle. 1980. Effects of forest fire on soil nutrients in clearcut and whole-tree harvest sites in central Michigan. Soil Science Society of America Journal 44:847-850.

Alban, D. H., and D. A. Perala. 1992. Carbon storage in Lake States aspen ecosystems. Canadian Journal of Forest Research 22:1107-1110.

Black, T. A., and J. W. Harden. 1995. Effect of timber harvest on soil carbon storage at Blodgett Experimental Forest, California. Canadian Journal of Forest Research 25:1385-1396.

Bock, M. D., and K. C. J. Van Rees. 2002. Forest harvesting impacts on soil properties and vegetation communities in the Northwest Territories. Canadian Journal of Forest Research 32:713-724.

Borchers, J. G., and D. A. Perry. 1992. The influence of soil texture and aggregation on carbon and nitrogen dynamics in southwest Oregon forests and clearcuts. Canadian Journal of Forest Research 22:298-305.

Burger, J. A., and W. L. Pritchett. 1984. Effects of clearfelling and site preparation on nitrogen mineralization in a southern pine stand. Soil Science Society of America Journal 48:1432-1437.

Christensen, T. R., S. Johnson, T. V. Callaghan, and M. Havstrom. 1999. On the potential CO_2 release from tundra soils in a changing climate. Applied Soil Ecology 11: 127-134.

Covington, W. W. 1981. Changes in forest floor organic matter and nutrient content following clear cutting in northern hardwoods. Ecology 62:41-48.

Edmonds, R. L. 1980. Litter decomposition and nutrient release in Douglas-fir, red alder, western hemlock and Pacific silver fir ecosystems in western Washington. Canadian Journal of Forest Research 10: 327-337.

Edwards, N. T., and B. M. Ross-Todd. 1983. Soil carbon dynamics in a mixed deciduous forest following clearcutting with and without residue removal. Soil Science Society of America Journal 47:1014-1021.

Entry, J. A., and W. H. Emmingham. 1998. Influence of forest age on forms of carbon in Douglas-fir soils in the Oregon Coast Range. Canadian Journal of Forest Research 28:390-395.

Federer, C. A. 1984. Organic matter and nitrogen content of the forest floor in even-aged northern hardwoods. Canadian Journal of Forest Research 14:763-767.

Federer, C. A., and J. W. Hornbeck. 1985. The buffer capacity of forest soils in New England. Water Air Soil Pollution 26:163-173.

Grier, C. C., K. A. Vogt, M. R. Keyes, and R. L. Edmonds. 1981. Biomass distribution and above- and belowground production in young and mature *Abies amabilis* zone ecosystems of the Washington Cascades. Canadian Journal of Forest Research 11: 155-167.

Harmon, M. E., and B. Marks. 2002. Effects of silvicultural practices on carbon stores in Douglas-fir – western hemlock forests in the Pacific Northwest, U.S.A.: results from a simulation model. Canadian Journal of Forest Research 32:863-877.

Harmon M. E., W. K. Ferrell, and J. F. Franklin. 1990. Effects of carbon storage of conversion of old-growth forests to young forests. Science 247:699-702.

Homann, P. S., P. Sollins, H. N. Chappell, and A. G. Stangenberger. 1995. Soil organic carbon in a mountainous, forested region: relation to site characteristics. Soil Science Society of America Journal 59: 1468-1475.

Johnson, C. E., A. H. Johnson, T. G. Huntington, and T. G. Siccama. 1991. Whole-tree clear-cutting effects on soil horizons and organic-matter pools. Soil Science Society of America Journal 55:497-502.

Johnson, C. E., C. T. Driscoll, T. J. Fahey, T. G. Siccama, and J. W. Hughes. 1995. Carbon dynamics following clearcutting of a northern hardwood forest. Pages 463-486 *In* W. W. McFee and J. M. Kelly (editors), Carbon Forms and Functions in Forest Soils. Soil Science Society of America, Madison, Wisconsin.

Johnson, C. E., R. B. Romanowicz, and T. G. Siccama. 1997. Conservation of exchangeable cations after clear-cutting of a northern hardwood forest. Canadian Journal of Forest Research 27:859-868.

Johnson, D. W. 1992. Effects of forest management on soil carbon storage. Water, Air, and Soil Pollution 64:83-120.

Johnson, D. W., and P. S. Curtis. 2001. Effects of forest management on soil C and N: storage meta analysis. Forest Ecology and Management 40:227-238.

Johnson, D. W., D. W. Cole, C. S. Bledsoe, K. Cromack, Jr., R. L. Edmonds, S. P. Gessel, C. C. Grier, B. N. Richards, and K. A. Vogt. 1982. Nutrient cycling in forests of the Pacific Northwest. Pages 186-232 *In* R. L. Edmonds (editor), Analysis of Coniferous Forest Ecosystems in the Western United States. Hutchinson Ross, Stroudsberg, Pennsylvania.

Johnson, D. W., and D. E. Todd. 1990. Nutrient cycling in forests of Walker Branch Watershed, Tennessee: roles of uptake and leaching in causing soil changes. Journal of Environmental Quality 19:97-104.

Johnson. D. W., and D. E. Todd. 1998. Effects of harvesting intensity on forest productivity and soil carbon storage in a mixed oak forest. Pages 351-363 *In* R. Lal, J. M. Kimble, R. F. Follett, and B. A. Stewart (editors), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, Florida.

Kirschbaum, M. U. F. 1995. The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biology and Biochemistry 27:753-760.

Knoepp, J. D., and W. T. Swank. 1994. Long term soil chemistry changes in aggrading forest ecosystems. Soil Science Society of America Journal 58:325-331.

Knoepp, J. D., and W.T. Swank. 1997. Forest management effects on surface soil carbon and nitrogen. Soil Science Society of America Journal 61:928-935.

Kraemer, J. F., and R. K. Hermann. 1979. Broadcast burning prescribed fire: 25-year effects on forest soils in the western flanks of the Cascade Mountains. Forest Science 25:427-439.

Kuramoto, R. T., and L. C. Bliss. 1970. Ecology of subalpine meadows in the Olympic Mountains, Washington. Ecological Monographs 40:317-347.

MacDonald, N. W., D. L. Randlett, and D. R. Zak. 1999. Soil warming and carbon loss from a lake states spodosol. Soil Science Society of America Journal 63:211-218.

Marra, J. L., and R. L. Edmonds. 1996. Coarse woody debris and soil respiration in a clearcut on the Olympic Peninsula, Washington, U.S.A.. Canadian Journal of Forest Research 26:1337-1345.

Mattson, K. G., and W. T. Swank. 1989. Soil and detrital carbon dynamics following forest cutting in the Southern Appalachians. Biology and Fertility of Soils 7:247-253.

Miller, J. H., and D. L. Sirois. 1986. Soil disturbance by skyline yarding vs. skidding in a loamy hill forest. Soil Science Society of America Journal 50:1579-15°3.

Olsen, S. R., and L. E. Sommers. 1982. Phosphorus. Pages 403-430 *In* A. L. Page, R. H. Miller, and D.R, Keeney (editors), Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties. American Society of Agronomy, Madison, Wisconsin.

Parker, J. L., I. J. Fernandez, L. E. Rustad, and S. A. Norton. 2001. Effects of nitrogen enrichment, wildfire, and harvesting on forest-soil carbon and nitrogen. Soil Science Society of America Journal 65:1248-1255.

Piatek, K. B., and H. L. Allen. 1999. Nitrogen mineralization in a pine plantation fifteen years after harvesting and site preparation. Soil Science Society of America Journal 63:990-998.

Powers, R. F. 1980. Mineralizable soil nitrogen as an index of nitrogen availability to forest trees. Soil Science Society of America Journal 44:1314-1320.

Powers, R. F., and K. Van Cleve. 1991. Long-term ecological research in temperate and boreal forest ecosystems. Agronomy Journal 83:11-24.

Prichard, S. J., D. L. Peterson, and R. D. Hammer. 2000. Carbon distribution in subalpine forests and meadows of the Olympic Mountains, Washington. Soil Science Society of America Journal 64:1834-1845.

Richter, D. D., D. Markewitz, C. G. Wells, H. L. Allen, J. K. Dunscombe, K. Harrison, P. R. Heine, A. Stuanes, B. Urrego, and G. Bonan. 1995. Carbon cycling in a loblolly pine forest: implications for the missing carbon sink and for the concept of soil. Pages 233-252 *In* W.W. McFee and J.M. Kelly (editors), Carbon Forms and Functions in Forest Soils, Soil Science Society of America, Madison, Wisconsin.

Rustad, L. E., and I. J. Fernandez. 1998. Soil warming: consequences for foliar litter decay in a spruce-fir forest in Maine, USA. Soil Science Society of America Journal 62:1072-1080.

Ryan, D. F., T. G. Huntington, and C. W. Martin. 1992. Redistribution of soil nitrogen, carbon and organic matter by mechanical disturbance during whole-tree harvesting in northern hardwoods. Forest Ecology and Management 49:87-99.

Simard, D. G., J. W. Fyles, D. Paré, and T. Nguyen. 2001. Impacts of clearcut harvesting and wildfire on soil nutrient status in the Quebec boreal forest. Canadian Journal of Soil Science 81:229-237.

Snyder, K. E., and R. D. Harter. 1984. Changes in solum chemistry following clearcutting of northern hardwood stands. Soil Science Society of America Journal 49:223-228.

Soil Survey Staff. 1992. Soil Survey Lab Methods Manual. Soil survey investigations report 42. USDA Soil Conservation Service, Lincoln, Nebraska.

Soil Survey Staff. 1999. Keys to Soil Taxonomy, 9th edition. Pocahontas Press, Blacksburg, Virginia.

Stone, E. L., W. G. Harris, R. B. Brown, and R. J. Kuehl. 1993. Carbon storage in Florida spodosols. Soil Science Society of America Journal 57: 179-182.

Vogt, K. A., E, Moore, S. Gower, D. Vogt, D. Sprugel, and C. Grier. 1989. Productivity of upper slope forests in the Pacific Northwest. Pages 137-163 *In* D. Perry (editor), Maintaining the Long-term Productivity of Pacific Northwest Ecosystems. Timber Press, Portland, Oregon.

Received 4 October 2002
Accepted for publication 29 June 2003