Long-Term Soil Changes from Forest Harvesting and Residue Management in the Northern Rocky Mountains

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Soil changes associated with forest harvesting, differing utilization levels, and post-harvest prescribed burning were determined using an empirical study to investigate the long-term impacts on soil physical and chemical properties at Coram Experimental Forest in northwestern Montana. In 1974, two replications of three regeneration cuttings (shelterwood, group selection, and clearcut) were installed. In addition, four residue management regimes (high utilization with no burning, medium with no burning, medium with broadcast burning, and low with broadcast burning) were implemented (~74, 63, 65, and 54% wood removal, respectively). Thirty-eight years after harvesting, changes were evaluated in mineral soil and forest floor physical and chemical properties (organic matter [OM], C, N, Ca, K, and Mg pools, soil bulk density, and pH) and in coarse woody debris levels. There were no differences in soil pH and bulk density across all regeneration cuttings and residue treatments, probably due to the minimal soil effects associated with the forest harvesting operations that were used (hand felling and cable yarding). Comparisons between harvest and burning and the control indicate no statistical differences in OM, C, and N contents. Minor differences in extractable cation pools were noted in several comparisons among the treatments; these may be attributed to litter inputs from the differing vegetation compositions of overstory and shrub layers rather than nutrient changes within the mineral soil itself. At this moist-cool forest, intensive biomass utilization, with or without broadcast burning, had few long-term impacts on soil properties of soil C, OM, and nutrients.

Abbreviations: ANOVA, analysis of variance; CEF, Coram Experimental Forest; NMS, nonmetric multidimensional scaling; OM, organic matter.

Core Ideas

- **Long-term (38 yr) soil changes after woody residue management were evaluated.**
- **There were no differences in soil physical and chemical properties.**
- **Differences in extractable cation pools may be due to different vegetation litter inputs.**

Increased extraction of woody biomass materials as an alternative energy feedstock is a concern in many forest ecosystems because of the possibility of adverse impacts on soil productivity (Janowiak and Webster, 2010). Recent legislative efforts in the United States such as the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 promote the active use of forest woody biomass as a substitute for fossil fuel. Currently, many sites are already whole-tree harvested, and it is likely that future logging will transition to also using more of the tree for wood chips or bioenergy. Therefore, it is imperative to assess the long-term impacts of intensive biomass harvesting on site productivity and determine compliance with sustainable forest management objectives.

Woody residues such as coarse and fine woody debris, unusable tops and branches, and cull trees that fall after logging operations are commonly left on site due to their low commercial value (Farve and Napper, 2009). These residues decompose and release nutrients into the soil or the atmosphere, serving an integral role in nutrient cycling (Fontaine et al., 2003). Organic matter derived from woody resides can directly affect a site's soil productivity by becoming a primary

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source of nutrients for vegetation growth. In addition, OM can improve soil productivity by supporting C cycling and sequestration, N availability, gas exchange, water availability, and biological diversity (Jurgensen et al., 1997). Finally, OM increases aeration, cation exchange capacity (Shepherd et al., 2002), and soil aggregation (Jastrow, 1996); buffers soil pH changes (Jurgensen et al., 1997); and provides food and habitat for soil meso- and microfauna (Harvey et al., 1980).

Research investigating the ecological consequences of intensive harvesting parallels studies that have compared the relative impacts of whole-tree and conventional harvesting. Simulation studies and nutrient budget analyses in the 1970s (e.g., Weetman and Webber, 1972; White, 1974; Kimmins, 1976) warned that increased OM utilization would risk site nutrient depletion; however, those studies were criticized because they lacked knowledge of several key processes (e.g., weathering, biological fixation, and leaching). Thus, previous research has yielded uncertainty about intensifying biomass removal from forest sites (Mann et al., 1988; Egnell and Valinger, 2003). The shortcomings of such prior studies have demonstrated the importance of long-term field experiments to address this issue (Dyck and Mees, 1990; Farve and Napper, 2009).

Because most plant nutrients are located in the branches and foliage, whole-tree harvesting can remove as much as three times the nutrients as conventional bole-only harvesting where tops are left on site (Alban et al., 1978; Johnson et al., 1982; Phillips and Van Lear, 1984; Powers et al., 2005). Some empirical studies have reported negative impacts of whole-tree harvesting on soil productivity and aboveground vegetation growth. For example, in a meta-analysis by Johnson and Curtis (2001), whole-tree harvesting decreased soil C and N by 6%, whereas conventional harvesting (leaving tops and limbs) increased soil C and N by 18%. A risk analysis concluded that soil pH, P, K, Ca, and Mg were the primary indicators of the adverse impacts of whole-tree harvesting on soil productivity (Wall, 2012).

In contrast, a recent meta-analysis reported no adverse effects of harvesting intensity on soil C storage (Nave et al., 2010), and a review by Thiffault et al. (2011) argued that there is no unequivocal conclusion about the effects of whole-tree harvesting on soil productivity. In many cases, the majority of site nutrients (including C) are contained in the forest floor and mineral soil (Powers et al., 2005; Page-Dumroese and Jurgensen, 2006; Sanchez et al., 2006; Clarke et al., 2015). Often the impact of harvest operations on C stocks has focused on aboveground biomass, but a large portion of total C and N stocks in many western North American forests is found belowground (Page-Dumroese and Jurgensen, 2006). Additionally, the amount of material removed during harvesting influences site conditions (such as soil temperature and moisture) and alters soil properties (pH, nutrients, and water holding capacity; Jandl et al., 2007).

Understanding the long-term impacts of residue removal coupled with various site preparation techniques is also critical for understanding the processes leading to soil changes and site resilience. One advantage of residue utilization is that it can help advance the goal of fuel reduction through biomass removal (Root and Betts, 2016). Fuel reduction treatments are widely applied across the West for the purpose of restoring fire-resilient forests, with harvesting and prescribed burning regarded as the most effective methods for achieving this goal (Agee and Skinner, 2005). Intensive biomass harvesting (often combined with prescribed fire) is likely to be increasingly highlighted as a tool to help meet this objective. However, even prescribed burning alone has been shown to produce varying impacts to long-term site productivity (Lindeburgh, 1990). To our knowledge, research that specifically addresses the interaction between intensive biomass removal and prescribed burning is rare, and a void exists in our understanding of such compound treatment effects on productivity.

Thiffault et al. (2011) noted a discrepancy in the results between European and North American productivity trials. European studies have reported negative impacts in general, but in North America the Long-term Soil Productivity (LTSP) study detected no soil productivity decline 10 yr after intensive OM harvesting where the forest floor is retained (Powers et al., 2005). Many of the LTSP stands have not yet reached canopy closure and thus maximum nutrient stress, and other empirical studies are not mature enough to draw a conclusion about the long-term impacts (Wall, 2012). Thus, the consequences of intensifying harvest operations should be assessed at different spatial and/or temporal scales.

Although harvesting intuitively seems likely to negatively impact site OM and nutrient pools, there is scant long-term evidence of this. Therefore, the objective of this study was to investigate the long-term impact of intensive biomass utilization and broadcast burning on woody residue, forest floor, and mineral soil C, OM, and nutrient pools 38 yr after biomass harvesting and broadcast burning in a moist-cool forest of the northern Rocky Mountains. We tested two hypotheses. First, if there is a long-term adverse impact of intensive biomass extraction on soil pools, then substantial differences in soil characteristics between various biomass utilization treatment units and the untreated control should be expressed. Second, if differences in soil characteristics between treatment and control are detected, then increased biomass utilization intensity will exhibit detrimental consequences to soil quality. To examine these hypotheses, we tested for differences—in both the forest floor and the mineral soil layer—in OM, C, N, and extractable cation (K, Mg, and Ca) contents, plus soil bulk density and soil pH.

METHODS

Study Site

The study site was located at northwestern Montana's Coram Experimental Forest (CEF), approximately 20 km east of Columbia Falls and 9 km south of Glacier National Park. The experimental units were established on east-facing slopes in Upper Abbot Creek Basin (48°25′ N, 113°59′ W). The elevation and slope of the study site ranged from 1195 to 1615 m and from 30 to 80%, respectively (Shearer and Schmidt, 1999).

The climate of CEF is the modified Pacific maritime type (Adams et al., 2008). Average annual precipitation is 1076 mm, ranging from 890 to 1270 mm (Farnes et al., 1995); precipitation occurs predominantly during winter as snow. Average temperatures in summer and winter are 6 and −7°C, respectively (Adams et al., 2008), and the average annual temperature is 2 to 7°C (Hungerford and Schlieter, 1984). The mean length of the growing season as estimated by the frost-free days near the study site is approximately 81 d (Shearer and Kempf, 1999).

The soils at CEF primarily consist of a mixture of Precambrian sedimentary rocks and glacial till, with a thin, fine-textured volcanic ash surface (Shearer and Kempf, 1999). This soil mixture forms a rich, loamy soil in the study area with high rock-fragment content (∼45%). Soils of the study area are classified as loamy-skeletal isotic Andic Haplocryalfs (Soil Survey Staff, 2006).

The original experiment was conducted in an old-growth forest (>200 yr old) without any harvesting history. Western larch (*Larix occidentalis* Nutt.) is the dominant forest cover type (Society of American Foresters Cover Type 212; Eyre, 1980) of the study site. Major overstory tree species are western larch, Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], subalpine fir [*Abies lasiocarpa* (Hook.) Nutt.], and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.). Western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] and western redcedar (*Thuja plicata* Donn ex D. Don) are distributed sporadically. Paper birch (*Betula papyrifera* Marshall), black cottonwood [*Populus balsamifera* L. ssp. *trichocarpa* (Torr. & A. Gray ex Hook.) Brayshaw], and quaking aspen (*Populus tremuloides* Michx.) are the primary broadleaf species. Rocky Mountain maple (*Acer glabrum* Torr.), Saskatoon serviceberry [*Amelanchier alnifolia* (Nutt.) Nutt. ex M. Roem.], Sitka alder [*Alnus viridis* (Chaix) DC. ssp. *sinuata* (Regel) Á. Löve & D. Löve], mallow ninebark [*Physocarpus malvaceus* (Greene) Kuntze], dwarf rose (*Rosa gymnocarpa* Nutt.), huckleberry (*Vaccinium membranaceum* Douglas ex Torr., *Vaccinium myrtilloides* Michx.), and white spirea (*Spiraea betulifolia* Pall.) are the dominant species in the shrub community. The study site is within the subalpine fir–queencup beadlily [*Clintonia uniflora* (Menzies ex Schult. & Schult. f.) Kunth] habitat type (Pfister et al., 1977).

Experimental Design

The original experimental design consisted of a combination of regeneration cutting treatments and biomass utilization treatments with and without broadcast burning (Newman and Schmidt, 1980; Fig. 1). The woody debris treatments were nested in each regeneration cutting treatment, forming a split-plot experimental design. In this design, there were two replicates of three regeneration cutting treatment units (shelterwood, group selection, and clearcut) situated at upper slope and lower slope locations. Two control (uncut) units were sampled at the same upper and lower slope locations. The treatment units consisted of:

1. Two shelterwood units (14.2 and 8.9 ha in size), where approximately half of the standing timber (based on merchantable volume) was cut and the remainder retained as reserves. The retained trees were mostly old-growth larch, mature Douglas-fir, and other species to help new stand establishment (Shearer and Kempf, 1999).
2. Two group selection cutting units, each consisting of eight groups (patch cuts) averaging 0.3 ha in size (range: 0.1–0.4 ha). All timber within each group was cut; the intervening timber between groups was left uncut.
3. Two clearcuts of 5.7 and 6.9 ha in size, where all standing timber was cut.

Four woody debris treatments were applied. These were comprised of three levels of biomass utilization intensity (low, medium, and high) followed by a broadcast burning treatment (burned vs. unburned). Specifically, these combinations were: medium, unburned (M_U); high, unburned (H_U); low, burned (L_B); and medium, burned (M_B) (the woody residue treatments are summarized in Table 1). The original experimental design did not have a full-factorial design because the low biomass utilization intensity contained an excessive fuel load for an unburned treatment, whereas the high utilization treatment lacked sufficient fuels to implement a burning treatment.

Logging was conducted in the fall of 1974. All trees were hand felled, and logs were removed from the site using a running skyline yarding system, which minimized soil disturbance and erosion. All woody materials (live and dead, down and standing) with larger sizes than utilization standards (Table 1) were removed. Dead woody materials more than 1/3 sound were removed. Fine woody materials such as branches and tops were bundled and removed manually. The mean preharvest volume of woody material was 512 m^3 ha^{-1}. The mean preharvest tree densities for trees >7.62 and 17.8 cm diameter at breast height were 519 and 45 trees ha^{-1}, respectively (Benson and Schlieter, 1980). On average, 36.5, 83.8, and 71.0% of the total woody biomass was removed in the shelterwood, group selection, and clearcut units, respectively. Broadcast burning was conducted in early September 1975. However, burning conditions were unfavorable (cool and wet) and as a result, none of the designated areas were severely burned (based on observed loss of surface OM and color change in the mineral soil; Artley et al., 1978).

The experimental units were conserved intact without any additional subsequent entry or disturbance. Thirty-eight years later, the regeneration biomass was 56.1, 34.5, and 19.7 Mg ha^{-1} for clearcut, group selection, and shelterwood, respectively (Jang, 2015; Jang et al., 2015a). For shelterwood units, the mean biomass of retained trees was 116.5 Mg ha^{-1}. The tree-layer biomass for the control was 194.6 Mg ha^{-1} (data not shown).

Soil Sampling

For each clearcut and shelterwood unit, 10 soil sampling points were allocated on two parallel transects (five cores per transect) within each subplot unit (woody debris treatment unit), for a total of 40 sampling points per unit. The transects were juxtaposed with the original permanent sampling points to

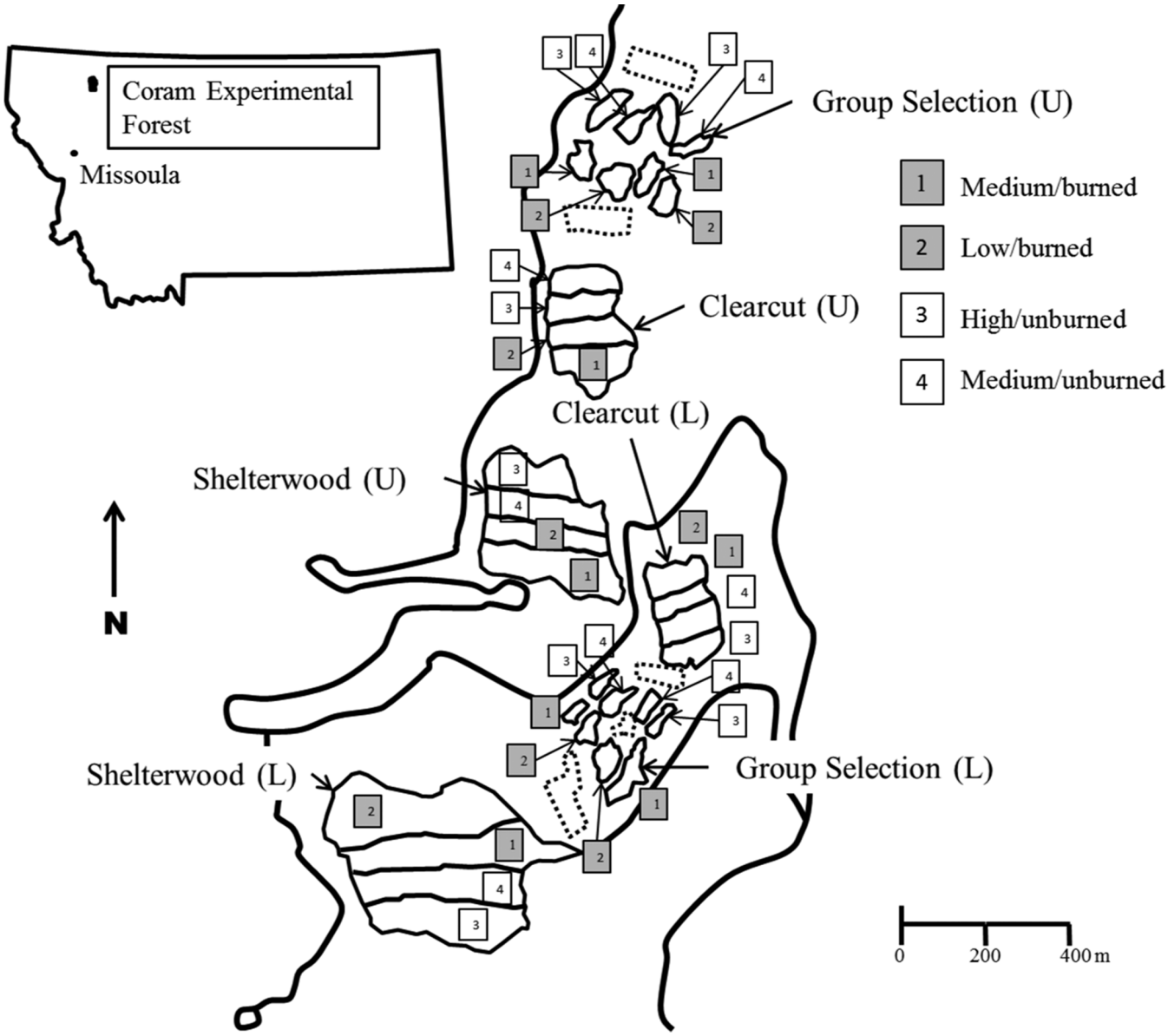

Fig. 1. Study site and the experimental units. Letters following regeneration cutting designate the upper (U) and lower (L) replicates. Dotted polygons represent the uncut controls.

avoid edge effects (≥50 m). For each group selection unit, three sampling points were positioned approximately 30 m apart within each cut group approximately 15 m inside the cut boundary, for a total of 24 sampling points per unit. Due to small patch sizes, many sampling points in group selection units were located close (approximately <15 m) to the uncut forest. Additionally, a total of 37 points (three to six points per unit) were sampled in the uncut patches adjacent to the group selection units. Soil samples were collected from 20 sampling points in the upper control unit, where the locations were not influenced by the edg-

Table 1. Description of residue management treatments within regeneration cutting units (from Benson and Schlieter, 1980; Shearer and Schmidt, 1999; Shearer and Kempf, 1999).

Utilization treatment	Abbreviation	Cut trees†	Max. size of retained woody materials‡	Removed woody materials	Fire treatment
			cm by m	% (v/v)	
Medium, unburned	M_U	>17.8 cm dbh§	7.6 by 2.4	62.9	unburned
High, unburned	H_U	all trees	2.5 by 2.4	72.3	unburned
Low, burned¶	L_B	all trees	14.0 by 2.4	54.2	burned
Medium, burned	M_B	all trees	7.6 by 2.4	65.6	burned

† Except designated overstory shelterwood trees.

‡ Live and dead, standing and down logs (small-end diameter by length); for dead down logs, they were removed if 1/3 sound.

§ Diameter at breast height.

¶ 1974 US Forest Service standards.

es of other regeneration cutting (i.e., clearcut). Because the uncut patches adjacent to the group selection units and the uncut control units are located proximately (Fig. 1) and had consistent vegetation and soil properties, they were combined and treated as a control to reduce variance.

The entire forest floor (Oi, Oe, and Oa horizons combined) and material <0.6 cm in diameter (e.g., twigs) were collected from within a 30-cm-diameter hoop, and the depth was recorded as the average of four points around the edge. After the forest floor material was removed, we sampled the mineral soil using a 10-cm-diameter core sampler to a depth of 30 cm (Jurgensen et al., 1977) and divided the soil core into two sample depths (0–10 and 10–30 cm). Each soil sampling depth was stored in a zip-type bag and kept cool until it was processed in the laboratory. In each cutting and utilization treatment, 10 15.2-m line-intercept transects were established to estimate the biomass of woody residue 0.6- to 7- and >7-cm sound, rotten, and buried wood. We followed the wood-classification categories and specific gravity values outlined by Brown (1974) to estimate mass. Woody residue <0.6 cm in diameter was sampled as part of the forest floor.

Laboratory Analyses

Before sieving, the total soil bulk density was calculated from the large core samples after they were dried to 80°C and weighed. After drying, the mineral soil was sieved through a >2-mm mesh screen to remove coarse fragments, which were then weighed so that the fine-fraction bulk density could be estimated. All live roots were separated by hand from the forest floor and mineral soil samples and were weighed. Forest floor and mineral soil samples were ground to pass a 0.04-mm mesh sieve and analyzed for total C and N with a Leco-600 analyzer (Leco Corp.). Mineral soil K, Ca, and Mg were extracted with pH-neutral NH_4OAc and measured through a PerkinElmer atomic absorption spectrometer (Model 5100PC). Forest floor samples were ashed, dissolved in 6 mol L^{-1} HNO_3, and analyzed for K, Ca, and Mg on the PerkinElmer atomic absorption spectrometer. Mineral soil pH was measured on a 1:2 (v/v) soil/deionized water slurry. Total OM contents were measured by weight loss after 8 h of combustion at 375°C (Ball 1964). Mineral soil nutrients, C, and OM pools were calculated using the fine-fraction bulk density (Cromack et al., 1999). We did not analyze the coarse-fragment (>2-mm) component for nutrients; however, other researchers have found them to contain appreciable amounts of C and N (Harrison et al., 2003; Whitney and Zabowski, 2004).

Data Analysis

Relationships among the measured soil properties were visualized by non-metric multidimensional scaling (NMS), which reduces the dimensionality of the original data, facilitating the display of multivariate data points. Bray–Curtis distance was used for distance matrix calculation. The analysis was conducted using the *vegan* package (Oksanen et al., 2013) in R (R Development Core Team, 2008).

Because the experimental design was a split-plot design, mixed effects models were utilized. The basic model was constructed as

$$y_{ijkl} = \mu + \alpha_i + B_k + \varepsilon_{(1)ik} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{(2)ijk} + \varepsilon_{ijkl} \quad [1]$$

where y_{ijkl} is the response variable, μ is the grand mean, α_i is the effect of the ith regeneration cutting treatment (whole-plot effect), B_k is the kth block effect (random effect), β_j is the jth woody residue treatment effect (subplot effect), $\alpha\beta_{ij}$ is the interaction between whole-plot and subplot effects, and $\varepsilon_{(1)ik}$, $\varepsilon_{(2)ijk}$, and ε_{ijkl} are the whole-plot and subplot error terms and the variation among sampling points in a subplot, respectively. If the effect of the woody residue treatment was statistically significant (with $\alpha = 0.05$ level), then linear contrasts were tested to examine the difference (i) between the treated vs. the control, and (ii) among the treatments. Because the untreated control had only one level on both whole plot and subplot, computation was infeasible. Thus, response variables were subtracted from the mean of the control to test the first hypothesis, and the controls were excluded for testing the second hypothesis. The *multcomp* package (Hothorn et al., 2014) was used for testing the linear contrasts.

RESULTS

Woody Residue

Woody residue distributions were distinctly different between the harvested treatments and the uncut control (Fig. 2a; Supplemental Table S1). In the shelterwood and clearcut units, total woody debris 38 yr after harvesting was less than in the uncut control for all utilization treatments. However, the group selection harvest unit with M_U, H_U, and L_B utilization treatments had a greater amount of woody residue than the controls. A majority of the total mass in the treatment units including the control was comprised of sound, rotten, and buried wood >7.5 cm in diameter.

Total amounts of woody residue for the shelterwood, group selection, clearcut, and control were 54 Mg ha^{-1} (SE: 7), 134 Mg ha^{-1} (SE: 21), 73 Mg ha^{-1} (SE: 9), and 200 Mg ha^{-1} (SE: 35), respectively (Fig. 2a; Supplemental Table S1). After 38 yr, the L_B treatment had the greatest mass of woody residues (102 Mg ha^{-1}, SE: 17), followed by the M_U (88 Mg ha^{-1}, SE: 16), M_B (74 Mg ha^{-1}, SE: 10), and H_U (59 Mg ha^{-1}, SE: 11) treatments (data not shown).

Woody residue (including all size and decay classes) OM content was higher in the uncut control than any harvest treatment except the group selection M_U treatment, where OM contents were slightly higher (213 Mg ha^{-1}, SE: 40; Fig. 2a). The woody residue OM pools generally followed utilization intensity, with the H_U and M_B treatments in all three regeneration cuttings having the lowest OM amounts.

As expected, C contents in the woody residue followed OM content. The control and M_U treatments in the group selection units had the highest C pool sizes compared with all other cutting and utilization intensity treatment combinations. The C

content in the woody residues of the L_B treatment across all regeneration cuttings was 49 Mg ha^{-1} (SE: 8), and the M_U, M_B, and H_U treatments were 42 Mg ha^{-1} (SE: 7), 36 Mg ha^{-1} (SE: 5), and 28 Mg ha^{-1} (SE: 5), respectively. Likewise, N contents for those woody residue treatments were 246 kg ha^{-1} (SE: 35 kg ha^{-1}), 217 kg ha^{-1} (SE: 34 kg ha^{-1}), 194 kg ha^{-1} (SE: 25 kg ha^{-1}), and 153 kg ha^{-1} (SE: 27 kg ha^{-1}), respectively (for details, see Supplemental Table S2). The N contents of the woody residues were relatively low and accounted for only a small percentage of the total woody residue–mineral soil (0–30-cm) pool (Supplemental Table S2). Not unexpectedly, woody residue contained only 2 to 10% of the total ecosystem N pool. In the group selection M_U treatment, the woody residue component contained 10% of that treatment's N (Supplemental Table S2), which was 3% higher than the control stands. Woody residue C and N contents for the control were 96 Mg ha^{-1} (SE: 17) and 482 kg ha^{-1} (SE: 89) (Supplemental Table S2).

There were several significant differences in OM, C, and N contents among the woody residue treatments and the control. Regeneration cutting, woody residue treatment, and their interactions significantly influenced the woody residue mass and C and N contents (Table 2). However, the significant differences were the result of (i) the difference between the treatments and the control, and (ii) the OM distribution in the L_B and M_U treatments, especially in the group selection unit. As Table 3 indicates, the differences were statistically significant only in the contrasts between those biomass utilization treatments in the group selection cutting units.

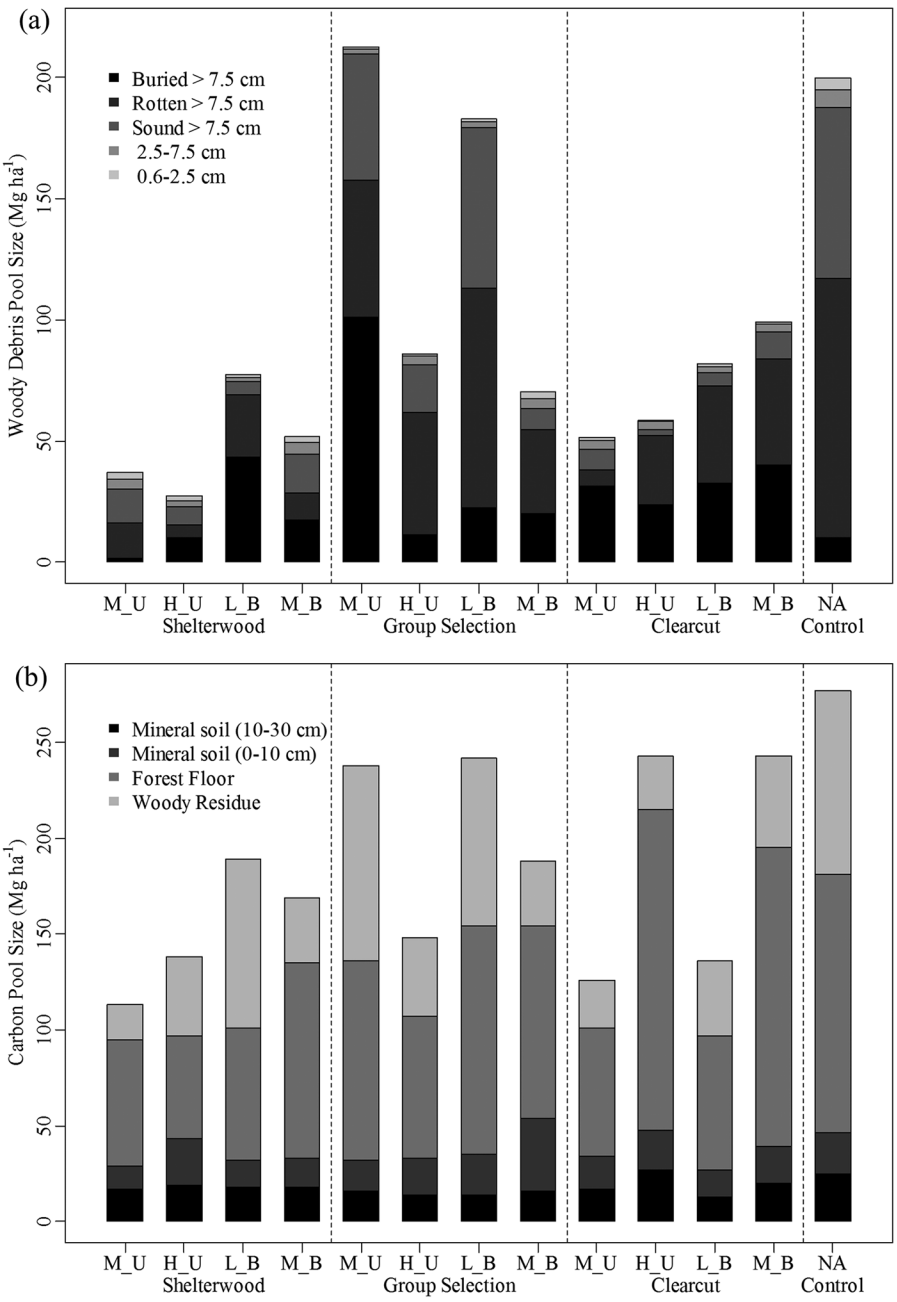

Fig. 2. Distribution of (a) woody debris mass by size class and (b) C in woody residue, forest floor, and mineral soil 38 yr after cutting and utilization treatments at Coram Experimental Forest (M_U: medium, unburned; H_U: high, unburned; L_B: low, burned; and M_B: medium, burned; for details, see Table 1).

Forest Floor

The C pool size in the forest floor ranged from 54 (shelterwood H_U treatment) to 167 (clearcut H_U treatment) Mg ha^{-1} and mirrored the forest floor OM pool size (Fig. 2b; Supplemental Table S2). In all three regeneration cuttings, C pool size was the largest in the forest floor and woody residues, with at least 50% of the C in these organic materials. Utilization treatments alter the distribution of N in the forest floor and woody residues, which ranged from 11 to 34% of the total ecosystem N pool. Similarly, Ca and Mg distributions were high in the forest floor: 56 to 75% of the Ca and 57 to 72% of the Mg (Fig. 3; Supplemental Table S3). The Ca pool was highest in the control (mean: 10881 mg kg^{-1}; SE: 504), however, Mg pools were greatest in the group selection L_B and M_B utilization treatments, while K pools were greatest in the clearcut with H_U (801 mg kg^{-1}; SE: 60) (Fig. 3; Supplemental Table S3). Pool size also reflected the distribution of cations in the forest floor and mineral soil but did not follow the same trends as the OM, C, and N pools. For example, C pools were often highest in the forest floor, and this was also the case for Ca and Mg, but K pools were variable. In the group selection cuttings, the K pool was highest in the upper mineral soil depth (0–10 cm) in the M_U and H_U utilization treatments but highest in the forest floor after broadcast

Table 2. Test result summary of ANOVA for soil properties.

Dependent variable	Regeneration cutting (R)		Woody residue treatment (W)		R × W	
	F value	*p* value	*F* value	*p* value	*F* value	*p* value
			Woody debris			
Organic matter (Mg ha^{-1})	12.29	<0.001***	2.87	0.038*	3.61	0.002**
C (Mg ha^{-1})	12.33	<0.001***	2.86	0.039*	3.61	0.002**
N (kg ha^{-1})	11.09	<0.001***	2.58	0.055	3.15	0.006**
			Forest floor			
Organic matter (Mg ha^{-1})	6.37	0.136	0.60	0.616	2.31	0.036*
C (Mg ha^{-1})	6.80	0.128	0.43	0.734	2.72	0.015*
N (kg ha^{-1})	7.29	0.121	0.44	0.728	2.84	0.012*
Extractable Ca (mg kg^{-1})	0.87	0.534	1.71	0.167	2.26	0.040*
Extractable Mg (mg kg^{-1})	0.72	0.581	0.69	0.557	3.22	0.005**
Extractable K (mg kg^{-1})	3.87	0.206	1.84	0.142	4.38	<0.001***
			Mineral soil layer (0–10 cm)			
Soil bulk density (Mg m^{-3})	3.44	0.225	1.72	0.165	2.08	0.059
pH	0.27	0.789	0.78	0.505	0.65	0.693
Organic matter (Mg ha^{-1})	0.22	0.819	0.96	0.413	1.34	0.244
C (Mg ha^{-1})	1.28	0.439	3.19	0.026*	2.25	0.042*
N (kg ha^{-1})	0.82	0.550	2.68	0.049*	3.96	0.001**
Extractable Ca (mg kg^{-1})	0.44	0.697	0.59	0.626	0.46	0.834
Extractable Mg (mg kg^{-1})	0.08	0.929	0.81	0.491	0.65	0.694
Extractable K (mg kg^{-1})	3.34	0.231	3.11	0.028*	1.28	0.272
			Mineral soil layer (10–30 cm)			
Soil bulk density (Mg m^{-3})	0.718	0.582	0.76	0.516	0.66	0.679
pH	0.630	0.614	0.19	0.906	1.15	0.339
Organic matter (Mg ha^{-1})	0.577	0.634	0.95	0.420	0.62	0.717
C (Mg ha^{-1})	3.067	0.246	0.24	0.871	1.93	0.079
N (kg ha^{-1})	2.026	0.330	0.22	0.882	0.65	0.693
Extractable Ca (mg kg^{-1})	1.289	0.437	0.41	0.744	0.73	0.629
Extractable Mg (mg kg^{-1})	0.087	0.920	1.94	0.125	1.11	0.358
Extractable K (mg kg^{-1})	0.529	0.654	2.38	0.072	3.58	0.003**

* Significant at the <0.05 level.

** Significant at the <0.01 level.

*** Significant at the <0.001 level.

Table 3. The *p* values for the linear contrasts testing the difference of soil properties between the high and medium utilization unburned, medium and low burned, and medium burned and unburned treatments.

Property	Shelterwood			Group selection			Clearcut		
	High vs. medium	Medium vs. low	Burn vs. unburn	High vs. medium	Medium vs. low	Burn vs. unburn	High vs. medium	Medium vs. low	Burn vs. unburn
				Woody debris					
Organic matter (Mg ha^{-1})	1.000	0.959	1.000	0.005**	0.014*	0.001**	1.000	0.997	0.458
C (Mg ha^{-1})	1.000	0.965	1.000	0.005**	0.013*	0.001**	1.000	0.997	0.462
N (kg ha^{-1})	1.000	0.980	1.000	0.008**	0.055	0.003**	1.000	0.996	0.430
				Forest floor					
Organic matter (Mg ha^{-1})	0.991	0.989	0.987	0.980	1.000	0.998	0.026*	0.709	0.048*
C (Mg ha^{-1})	0.998	0.989	0.994	0.938	1.000	1.000	0.007**	0.763	0.021*
N (kg ha^{-1})	0.987	1.000	0.999	0.894	1.000	1.000	0.009**	0.378	0.113
Extractable Ca (mg kg^{-1})	0.883	0.353	0.543	0.974	0.938	0.954	0.866	0.811	1.000
Extractable Mg (mg kg^{-1})	0.996	0.831	0.996	0.028*	1.000	<0.001***	0.998	1.000	1.000
Extractable K (mg kg^{-1})	0.993	0.193	0.515	0.654	0.311	0.005**	0.165	0.184	0.163
				Mineral soil layer (0–10 cm)					
C (Mg ha^{-1})	0.023*	1.000	0.965	0.998	0.614	0.991	0.927	0.894	0.994
N (kg ha^{-1})	0.048*	1.000	0.947	1.000	0.220	0.834	0.972	0.655	0.997
Extractable K (mg kg^{-1})	0.485	0.280	0.792	1.000	1.000	1.000	0.631	0.937	0.419
				Mineral soil layer (10–30 cm)					
Extractable K (mg kg^{-1})	0.998	0.536	0.979	1.000	1.000	1.000	<0.001***	1.000	<0.001***

* Significant at the <0.05 level.

** Significant at the <0.01 level.

*** Significant at the <0.001 level.

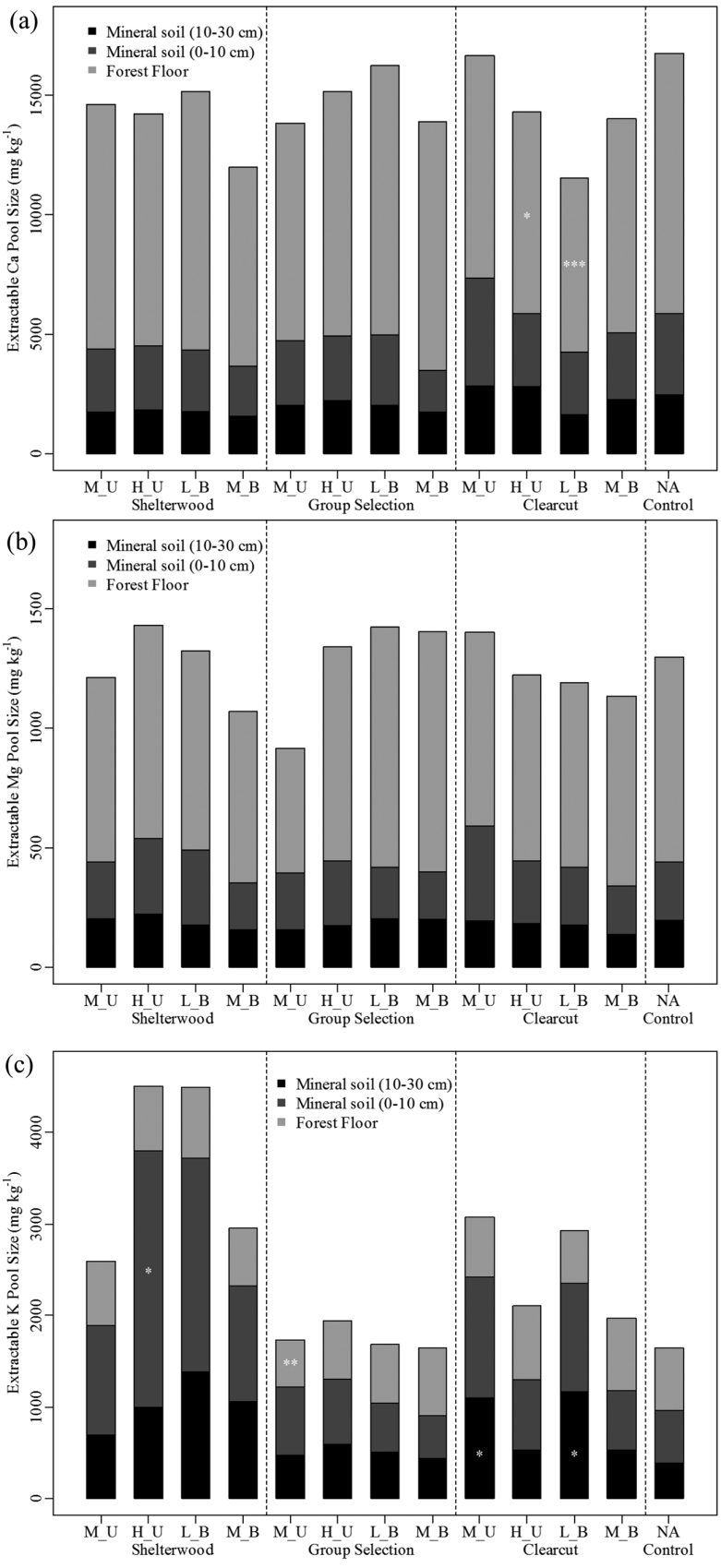

Fig. 3. Content of (a) Ca, (b) Mg, and (c) K in the forest floor (total in tissue) and mineral soil (extractable) 38 yr after cutting and utilization treatments at Coram Experimental Forest (M_U: medium, unburned; H_U: high, unburned; L_B: low, burned; and M_B: medium, burned; for details, see Table 1). Statistical difference from the uncut control at the corresponding layers: * <0.05 level; ** <0.01 level; * <0.001 level.**

burning in both the low and moderate utilization intensity units. In the shelterwood cutting units, all utilization treatments had the highest K distribution in the surface mineral soil, with very low values (<21% of the soil K pools). The distribution of K in the clearcut H_U and M_B utilization treatments was highest in the forest floor; the M_U and L_B units had greater soil K in the mineral soil.

The NMS approach provides an overview of the differences in all combined soil characteristics in all of the regeneration cutting units by woody residue treatment, displaying the integration of all measured variables. As shown in Fig. 4a, all utilization treatments overlap in the NMS-projected two-dimensional space compared with the control. Thus, soil properties were comparable among the biomass harvesting treatments in the forest floor (and mineral soil). The projected area of forest floor for each utilization treatment is considerably larger than that of the control.

Except for woody residues, regeneration cutting proved not to be a significant factor for describing changes in forest floor pools (Table 2). The analysis of variance (ANOVA) test results detail changes in forest floor properties. For the regeneration cutting × woody residue interaction term, all chemical properties in the forest floor were statistically significant (OM, $p = 0.036$; C, $p = 0.015$; and N, $p = 0.012$; Table 2). However, differences in OM, C, and N in the forest floor were significant only for the clearcut treatment (Table 3). Organic matter, C, and N were significantly higher in the H_U treatment compared with the M_U treatment (p = 0.026, 0.007, and 0.009, respectively). In addition, in the medium utilization treatments of the clearcut units, broadcast burning (M_B treatment) resulted in larger long-term changes in forest floor OM ($p = 0.048$) and C ($p = 0.021$) than the unburned (M_U) treatment. Significant Mg differences were noted only in the group selection units where the contrast of high and medium utilization levels was significant ($p = 0.028$). Furthermore, in the group selection units, the M_B treatment increased Mg (418 mg kg^{-1}) and K (232 mg kg^{-1}) pools over the M_U treatment ($p < 0.001$ and 0.005, respectively). Although the interaction term for the forest floor soil chemical properties was significant in all cases (Table 2), only Ca in the H_U ($p = 0.027$) and L_B ($p < 0.001$) treatments of the clearcut units and K in the M_U treatment of the group selection units ($p = 0.007$) were statistically different from the control (data not shown). Contrasts with the greatest magnitude were Ca (−2793 and −3681 mg kg^{-1} in clearcut H_U and L_B treatments, respectively) and K (−162 mg kg^{-1} in the group selection units).

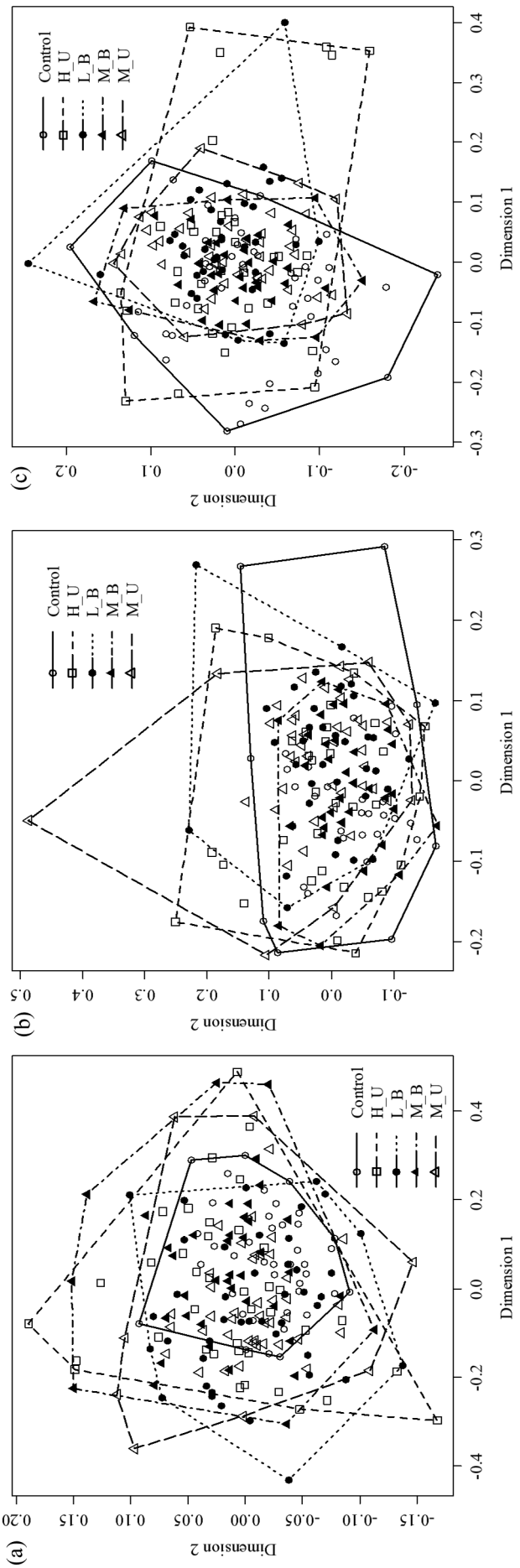

Fig. 4. The non-metric multidimensional scaling points distribution for soil properties by the woody residue treatments at the (a) forest floor, (b) 0- to 10-cm mineral soil layer, and (c) 10- to 30-cm mineral soil layer 38 yr after harvesting at Coram Experimental Forest of Montana. Each line indicates the convex hull for the woody residue treatment (M_U: medium, unburned; H_U: high, unburned; L_B: low, burned; and M_B: medium, burned; for details, see Table 1).

Mineral Soil

Probably because of the use of a skyline logging system, there were no significant differences in soil bulk density among the regeneration cutting and woody residue treatments (data not shown). There were also no long-term significant treatment impacts on soil pH. At these sites, the fine-fraction bulk density was 1.3 Mg m^{-3} and was fairly consistent among mineral soil depths.

In the mineral soil (0–30 cm), the total OM pool size ranged from 15 to 40% of the total soil profile OM content (inclusive of the forest floor and woody residue (Supplemental Table S2). Only the group selection with M_U utilization and the clearcut with M_B utilization had lower OM pools in the mineral soil than the control stands. The shelterwood with H_U utilization had the greatest OM pools in the mineral soil (0–30 cm), at 40% of the profile. Organic matter content was variable within the same regeneration cutting treatment. However, among the utilization treatments there was no consistent pattern of OM accumulation (Supplemental Table S2). There was also no clear pattern of C accumulation in the mineral soil. For example, C in the surface mineral soil (0–10 cm) of the control was 21 Mg ha^{-1} (SE: 2). However, the group selection with M_B utilization resulted in the largest C pools (38 Mg ha^{-1}) within the 0- to 10-cm soil depth, while the clearcut with H_U utilization had the highest C (27 Mg ha^{-1}) within the 10- to 30-cm soil depth. Those differences in C pools at the 0- to 10-cm depth were exhibited by statistical significance for the interaction term between the woody residue treatment and regeneration cutting (p = 0.042, Table 2). The linear contrast tests showed that the significant difference between high vs. medium utilization levels in the shelterwood units (p = 0.023, Table 3) contributed to the significance of the interaction term. Usually, C pools were greatest in the surface mineral soil, and distributions ranged from 7 to 20% of the total soil profile.

Nitrogen pools in the mineral soil (0–30 cm) ranged from 66 to 89% of the total N pool when the forest floor and woody residue were considered. Only the group selection with M-U utilization had a lower distribution of N in the mineral soil than the control. In the 10-to 30-cm mineral soil H_U utilization treatments in both the group selection (1019 kg ha^{-1}) and shelterwood (1008 kg ha^{-1}) cutting units had the largest N pools; whereas the control stand had 1274 kg ha^{-1} N in the 10-to 30-cm mineral soil. In addition to these N pools, the group selection L_B surface mineral soil also had high N (1014 kg ha^{-1}), which was approximately 38% of the N pool distribution for that location. The total pool size of N was the highest in the control stand (6728 kg ha^{-1}).

After 38 yr, there are few significant differences in mineral soil cation pools. Only the interaction term for K in the 10-to 30-cm mineral soil depth is significant (Table

2). Additionally, there is no clear pattern of cation pool changes among the regeneration cutting and utilization treatments (Fig. 3). Potassium is higher in the mineral soil (0–30 cm depth) than in the forest floor (58–84% of the total soil pool), but the clearcut H_U (801 mg kg^{-1}) and M_B (796 kg mg^{-1}) utilization treatments had higher levels in the forest floor (Supplemental Table S3) than in either mineral soil depth. Calcium and Mg pools in either the surface or subsurface mineral horizons were much lower than the forest floor for all regeneration cuttings and utilization levels.

In the surface (0–10 cm) mineral soil, the H_U treatment in the shelterwood units had 1764 mg kg^{-1} less extractable K than the control ($p = 0.025$). In the deeper mineral soil layer (10–30 cm), the clearcut M_U and L_B treatments had smaller K pools than the control (−844, mg kg^{-1}, $p = 0.018$ and −800 mg kg^{-1}, $p = 0.028$). However, there were no statistical differences in the amounts of OM, C, and N for the entire soil profile. In the 0- to 10-cm mineral soil layer, differences were only significant for C and N concentration; these differences were detected only in the shelterwood H_U treatment. Unlike differences at the forest floor level, the H_U treatment showed the lower level of C (13.1 Mg ha^{-1}, $p = 0.023$) and N (373 kg ha^{-1}, $p = 0.048$) contents in the mineral soil layer. For the deeper mineral soil layer (10–30 cm), a difference in the K pool was observed only in the comparisons of H_U vs. M_U (680 mg kg^{-1}, $p < 0.001$) and M_B vs. M_U (672 mg kg^{-1}, $p < 0.001$), exhibiting a similar result to OM in the forest floor.

Using the NMS approach gives an overview of differences in mineral soil characteristics by woody residue treatment (Fig. 4b and 4c). The mineral soil NMS score distributions are similar to those of the forest floor, including the control. The distributed area of NMS scores for each treatment overlap, with comparable sizes between the control and treatments. Therefore, we conclude in general that soil properties were similar among the biomass harvesting treatments for the entire soil profile after 38 yr.

The ANOVA indicated that, unlike the forest floor, the mineral soil C ($p = 0.042$ for the interaction term), N ($p = 0.001$ for the interaction term), and extractable K ($p = 0.028$ for the woody residue treatment) in the upper (0–10 cm) layer were affected by regeneration cutting, woody residue treatment, and/or their interaction (Table 2). Extractable K was significantly different ($p = 0.003$) only for the regeneration cutting × woody residue interaction term in the deeper layer (10–30 cm).

DISCUSSION

Woody Residue and Forest Floor

Timber harvesting can alter both short- and long-term woody residue and forest floor C, OM, and nutrient pools. Further, increased woody biomass removal (i.e., tops, limbs, cull sections, and non-merchantable wood) for bioenergy production may alter nutrient cycles, soil quality, and other ecosystem services such as water infiltration. In addition, changes in the aboveground biomass may alter soil C pools and have implications for the global C cycle. Thirty-eight years ago when harvesting occurred at CEF, this type of forest operation and research effort was relatively new, particularly on steep slopes in the Rocky Mountains. At that time, one of the primary management objectives was to avoid adverse biological impacts on the forest ecosystem (Barger, 1979). Therefore, understanding the long-term results from these regeneration cuttings, utilization levels, and burning treatments is critical.

Preharvest woody residues in the study area ranged from about 200 to 250 Mg ha^{-1} (Benson and Schlieter, 1979), an amount that is similar to our current estimate of debris in the control stand. Similar levels of woody residue occurred within the group selection regeneration cutting units, particularly the M_U and L_B utilization treatments, and these high levels of woody debris were apparently due to windthrow and stem breakage. The group selection cutting units were characterized by small gaps that were completely surrounded by an uncut forest matrix, a stand structure that produced many opportunities for subsequent woody residue recruitment within the cut gaps. In contrast, the shelterwood and clearcut units had limited exposure to edge trees, and therefore fewer opportunities existed for woody residue recruitment. Moreover, a related study revealed that there was no decrease in overstory biomass production related to those treatments (Jang, 2015; Jang et al., 2015a) and indicated that reductions in woody residue OM pools were insufficiently severe to adversely impact long-term vegetation production.

The other regeneration harvest and utilization levels had lower quantities of woody residue than estimates for the uncut control. In the high utilization and burned units, all woody residue and forest floor material has accumulated during the last 38 yr. Expressing this increment in a linearly annualized accumulation rate (25–134 Mg ha^{-1} in 38 yr), we expect full recovery of both coarse and fine woody material within 58 to 135 yr. The shelterwood H_U units had the lowest woody residue levels and therefore may have longer recovery periods, yet we note that even this lowest level of woody residue is near the recommended level of 25 to 27 Mg ha^{-1} to maintain biological functions in these soil and timber types (Harvey et al., 1981).

Harvey et al. (1979) indicated that organic matter and forest floor material are critical for ectomycorrhizal activity and found that, in this study's shelterwood and clearcut units, greater levels of utilization and burning resulted in a significant decline in activity relative to the undisturbed control. This was attributed to the loss of OM and woody residues. Our results after 38 yr indicate that the current levels of forest floor are at or above the immediate post-harvest levels in all of the cutting and utilization treatments. Combined, the woody residue and forest floor components of these stands comprised >50% of the soil C to a depth of 30 cm in every regeneration cutting and utilization level. In addition to their role in ectomycorrhizal development, these components are critical for maintaining OM and C and are therefore important for maintaining soil productivity, nutrient availability, and water holding capacity (Van Cleve and Powers, 1995).

Nitrogen is commonly a major limiting nutrient for soil productivity (Binkley, 1991; Vitousek and Howarth, 1991). In

the western United States, soil N pools are typically much larger in the mineral soil than in the surface organic layers (Means et al., 1992; Busse, 1994; Baird et al., 1999; Page-Dumroese and Jurgensen, 2006). We observed this pattern in our harvest units, where the forest floor and woody residue together comprised approximately 20% of the N pool, and mineral soil comprised >60% of the N pool. There were no clear differences among the cutting or utilization treatments. Except for the control, <15% of the profile N pool was in the woody residue and was related to the much higher C/N ratio in the wood. In contrast, the mineral soil pool—particularly at the 10-to 30-cm depth—had the larger proportion of N. Previous analysis at this site revealed that the clearcut M_B utilization treatment had 833 kg ha^{-1} total N in the forest floor (O_1, O_2, and O_3 horizons combined; Jurgensen et al., 1981); after 38 yr, we found that N levels were approximately half of that amount (412 Mg ha^{-1}). We measured the lowest N levels in the forest floor and woody residue at the shelterwood unit H_U treatment, but it is unclear if this finding can be attributed to this cutting–utilization treatment combination or to a site-specific difference.

Other researchers have indicated that the shift from stem-only harvesting to whole-tree harvesting may result in an increased export of nutrients from the site, potentially resulting in long-term reductions in site productivity (Weetman and Webber, 1972; Boyle et al., 1973; Mälkönen, 1976; Kimmins, 1976). Many researchers are also concerned with the loss of OM, which might lead to reductions in water and nutrient retention (Stone, 1979; Powers et al., 1998). Understanding the variability in C and other nutrients in the forest floor is important for properly determining the long-term impacts of harvesting and OM removal, and they should be quantified before management activities (Powers et al., 1998). In addition, knowledge of the interactions of mineral soil, forest floor, and forest stand structure remains incomplete (Kranabetter and Banner, 2000).

Our finding of no long-term significant differences in the forest floor C and N pools is consistent with other empirical studies. In the southeastern United States, for example, there was no difference in soil C in the forest floor between whole-tree harvesting and conventional harvesting 5 yr after treatment (Laiho et al., 2003). In a recent meta-analysis, Nave et al. (2010) analyzed 75 studies and concluded that they demonstrated a lack of harvest intensity impacts on the forest floor C pool. However, evidence exists that whole-tree harvesting can cause forest floor and soil OM reductions in some cases, with emphasis on variation by site (e.g., Johnson et al., 2002; Walmsley et al., 2009).

Although we detected a significant treatment effect on forest floor OM, C, and N contents 38 yr after harvest in the clearcut units, the overall statistical significance is attributed to the differences among treatments rather than between the treatments and the control. Because it is commonly expected that C and N in the forest floor would be more sensitive to intensive biomass harvesting than the mineral soil (Nave et al., 2010; Thiffault et al., 2011; Kurth et al., 2014), we conclude that the harvesting effects were insufficiently strong to override the natural variations of OM, C, and N pools in the forest floor.

Powers et al. (2005) specified two causes for the surficial C storage reduction after harvest: reduced litterfall production due to a sparser overstory and an elevated decomposition rate due to a modified microclimate. From this perspective, the detected reduction in OM and C pools in the forest floor seem attributable to a lower input of OM through litterfall relative to decomposition rates. These differences were observed only in the contrasts between the M_U treatment and other treatments in the clearcuts (Table 3). In a separate study of the overstory at this study site, we found that overstory biomass production in the clearcut M_U treatment had less tree biomass production than other clearcut treatments; the overstory tree biomass of the clearcut H_U and M_B treatments were 59.3 and 55.6 Mg ha^{-1}, whereas the M_U treatment was 48.1 Mg ha^{-1} (Jang et al., 2015a). As a result, we conclude that lower overstory biomass of the M_U in the clearcut treatment produced less litterfall relative to decomposition at the forest floor, even though this treatment had only moderate biomass extraction.

Removal of base cations contained in the extracted woody biomass by whole-tree harvesting commonly results in extractable cation pool reduction in the forest floor (Wall, 2008). Calcium has been indicated as the nutrient most vulnerable to intensive biomass harvesting (Boyle et al., 1973; Johnson, 1982; Federer et al., 1989), but Mg and K also demand attention (Thiffault et al., 2011; Wall, 2012). In this study, changes in the forest floor cation pools had more treatment-specific results. Several contrasts between the treatments and control indicate that the utilization treatment caused some cation reductions (e.g., extractable K, from the contrast of M_U vs. control; Table 3). On the other hand, Fig. 3 indicates that those cations were more abundant in the more severely harvested treatments. For example, in the group selection units, both the H_U and the M_B treatments contained more extractable Mg than the M_U treatment.

It seems likely that cation pool differences result from changes in the post-treatment vegetation composition rather than the harvesting itself (Paré et al., 2002; Thiffault et al., 2011; Jang, 2015). Subalpine fir and Engelmann spruce twigs and branches contain 2.3 to 2.5 times the Mg of Douglas-fir; K concentrations range from 1.6 to 3 times that of Douglas-fir (Stark, 1983). Differences in Mg and K at the forest floor were observed only in contrasts with the M_U treatment. A related study of vegetation dynamics at this site (Jang, 2015) indicated that subalpine fir abundance in the group selection M_U residue treatment was high relative to other treatments and the control; abundant subalpine fir may have sequestered more Mg and K in the forest floor. In the same manner, the observed decrease in extractable Ca in the H_U and L_B treatments relative to the control can be explained by the prominence of paper birch in those treatments (Jang, 2015). Compared with subalpine fir, paper birch contains more Ca in bolewood, but less is allocated to foliage and branches (Wang et al., 2000). Consequently, a stand with higher paper birch composition stores more Ca in the boles

and branches, with lower amounts returned to the soil surface via litterfall.

Mineral Soil

Ecosystem productivity can be defined as the capacity to generate OM through photosynthesis; this is critical for sustainable harvest operations. Often mineral soil OM can be an effective instrument for monitoring changes in long-term forest productivity (Richardson et al., 1999; Fox, 2000; Seely et al., 2010). The presence of OM is important for soil porosity, gas exchange, and water holding capacity (e.g., Doran and Parkin, 1994; Morris et al., 1997; Prescott et al., 2000). Soil OM also facilitates long-term storage and release of nutrients for vegetation production (Henderson et al., 1990; Henderson, 1995).

The distribution of OM and C in the mineral soil at CEF was relatively low, whereas the N distribution was relatively abundant. Page-Dumroese and Jurgensen (2006) reported that the OM mineral soil contents (0–30 cm) in northwestern Montana were approximately 130 Mg ha^{-1}. In contrast, the soil OM at CEF ranged from 58 to 91 Mg ha^{-1}; the lowest OM pools were in the shelterwood M_U utilization treatment, while the highest OM levels were in the group selection (M_B) and control units. Similar C levels were also observed in the mineral soil. In contrast, N pools in the mineral soil at CEF averaged 1627 kg ha^{-1} at the 0- to 30-cm depth, which is similar to measurements from a previous study at the site (839 kg ha^{-1} from the 0–22-cm depth) (Jurgensen et al., 1981).

In general, we found insufficient evidence of intensive biomass harvesting impacts on soil OM, C, or N contents, a result that is similar to previous studies that reported no adverse impacts of whole-tree harvesting on mineral soil C and N contents (e.g., Olsson et al., 1996; Johnson et al., 2002; Laiho et al., 2003; Wall, 2008). This result is probably due to considerable OM inherent in the mineral soil, added contributions of OM from stump and root decomposition (Hendrickson et al., 1989; Powers et al., 2005), and the site's cool and moist climatic regime, which encourages rapid regrowth and leaf litter additions (Jang, 2015; Jang et al., 2015b). Differences among the utilization treatments for C and N contents (0–10-cm depth) were detected only in the contrast between the H_U and the M_U treatments in shelterwood cuttings. This may be attributed to the differences in vegetation composition and K levels in those two units. For example, tall shrubs such as Rocky Mountain maple and Sitka alder were abundant in the shelterwood H_U treatment and were notably less prominent in other treatment areas (Jang, 2015). Likewise, a significant reduction of extractable K was observed only in the comparison between the H_U and control treatments (Table 3). Rocky Mountain maple requires greater K levels than other shrub species (Mueggler, 1965; Haeussler et al., 1990), and therefore lower 0- to 10-cm-depth K levels in the other utilization treatments may be driven by lower stocking levels of tall shrub species (especially Rocky Mountain maple; Jang, 2015).

Among all of the measured soil characteristics at the 10- to 30-cm mineral soil depth, only an extractable K reduction was detected, and the reduction was observed only in the contrasts with clearcut units. The linear contrast test results for extractable K were consistent with the OM, C, and N contrasts at the forest floor layer. Therefore, reduced extractable K in the clearcut M_U treatment seems related to the reduction in these properties. Similarly, the extractable K reduction seems to be associated with reduced overstory biomass production. However, the reason for the extractable K reduction in the L_B treatment of the clearcut relative to the control is unclear.

At our site there were no effects of intensive biomass harvesting on soil pH. Although some trials have similarly reported little or no impact of whole-tree harvesting on soil pH (Thiffault et al., 2011), others have shown increased soil acidity associated with the loss of base cations, which may be an indicator of decreased site productivity (Augusto et al., 2002; Thiffault et al., 2011; Wall, 2012). In Norway spruce (*Picea abies* Karst.) and Scots pine (*Pinus sylvestris* L.) stands in Sweden, soil pH reductions were observed in slash-removal treatments 7 to 9 yr after harvest, an outcome that was expected to have a potential negative impact on vegetation growth (Staaf and Olsson, 1991). In Quebec, Canada, whole-tree harvesting increased soil acidity 5 to 12 yr after harvesting in moist mixed forests, signaling possible adverse impacts on soil productivity (Brais et al., 1995).

One key concern regarding intensive biomass extraction is soil compaction by elevated heavy machinery traffic (Janowiak and Webster, 2010). Soil compaction during biomass harvesting may increase the soil bulk density and thereby reduce air and water movement into and out of the soil. However, at CEF one of the explicit objectives of this biomass harvest research was to avoid incurring any adverse harvesting impacts of silvicultural activities on soil physical, chemical, and biological properties (Barger, 1979). The units were hand felled and the timber extracted with a skyline yarding system, which produced little or no impact on the soil bulk density. Average total bulk density across all regeneration cuttings and utilization treatments was 1.08 Mg m^{-3} (0–30-cm depth) 38 yr after harvesting. Notably, this is very similar to the bulk density of mature stands measured nearby (1.05 Mg m^{-3}; Page-Dumroese and Jurgensen, 2006). It is likely that ground-based harvesting systems would result in more widespread compaction, rutting, and soil displacement, particularly on steep slopes. All of those effects could alter long-term soil productivity, depending on the extent, duration, and level of compaction or soil disturbance (Page-Dumroese et al., 2010).

Because soil and vegetation were sampled with different strategies and intensities, forming a paired data set is impossible. Thus, causality inferences for the relationship between soil properties and aboveground vegetation are constrained. Nonetheless, our explanation for differences in soil characteristics via vegetation composition is consistent across soil layers. The differences in soil characteristics at the forest floor can be explained by overstory tree vegetation composition, whereas the differences in the surface (0–10 cm) mineral soil depth was explained by shrub species composition. Moreover, we found that the abundance of a certain species (i.e., subalpine fir) in the tree layer had different

effects on soil properties compared with Rocky Mountain maple in the shrub layer.

MANAGEMENT IMPLICATIONS

At CEF, it is noteworthy that 38 yr after regeneration harvesting, there are few long-term impacts on soil properties attributable to biomass removal levels and prescribed burning. The immediate biological impacts of harvesting were negative (Harvey et al., 1979), and since that time, there has been great support in the western United States for preventing harvest-related excessive losses of organic materials to maintain active ectomycorrhizal communities (Harvey et al., 1981). Because of the importance of OM, many researchers have suggested retaining as much slash, forest floor, and woody residues as is practical (Ballard, 2000; Prescott et al., 2000; Powers et al., 2005; Page-Dumroese et al., 2010), yet we found few impacts from broadcast burning (noting the moist conditions at time of burning; Artley et al., 1978), no changes in soil bulk density (noting the hand felling and skyline logging system), and limited impacts on woody residue, forest floor, and mineral soil. Additionally, related research by Jang et al. (2015a) indicated that aboveground vegetation production was unaffected by biomass utilization intensity. Although results may vary according to harvesting systems, climate, and forest types, this long-term study shows that intensive biomass extraction is not synonymous with reduced forest soil productivity.

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