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

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ABSTRACT

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 (approx. 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), carbon (C), nitrogen (N), calcium (Ca), potassium (K), and magnesium (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, likely due to the minimal soil effects associated with the forest harvesting operations that were employed (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 mineral soil itself. At this moist-cool forest, intensive biomass utilization, with or without broadcast burning, had few long-term impacts on soil properties soil C, OM, and nutrients.

Abbreviations: OM, organic matter; LTSP, Long-term Soil Productivity; CEF, Coram Experimental Forest; NMS, non-metric multidimensional scaling; ANOVA, analysis of variance

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 shift 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 source of nutrients for vegetation growth. In addition, OM can improve soil productivity by supporting carbon (C) cycling and sequestration, nitrogen (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 micro-fauna (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 1970's (*e.g.*, Weetman and Webber, 1972; White, 1974; Kimmins, 1977) 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).

Since 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 above-ground 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, phosphorus (P), potassium (K), calcium (Ca), and magnesium (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 carbon 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 are 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 site preparation techniques is critical for understanding the processes leading to soil changes and site resilience.

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 years 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, but data from the oldest stands on fairly infertile sites indicate resilience (Scott et al., 2014). Other empirical studies are not mature enough to draw a conclusion about the long-term impacts (Wall, 2012), and the consequences of intensifying harvest operations should be assessed at local or regional scales.

Although harvesting intuitively seems likely to negatively impact site organic matter 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 years 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 1,195 to 1,615 m, and 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 1,076 mm, ranging from 890 to 1,270 mm (Farnes et al., 1995); precipitation occurs predominantly during winter as snow. Average temperatures in summer and winter are 6 °C , and –7 °C, respectively (Adams et al., 2008), and the average annual temperature is 2 °C to 7 °C (Hungerford and Schlieter, 1984). Mean length of the growing season as estimated by the frost-free days near the study site is approximately 81 days (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 a loamy-skeletal isotic Andic Haplocryalf (Soil Survey Staff, 2006).

The original experiment was conducted in the old-growth forests (>200 years) without any harvesting history. Western larch 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 (*Larix occidentalis* Nutt.), 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 sporatically. 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 subalpine fir/queencup beadlily (*Clintonia uniflora* (Menzies ex Schult. & Schult. f.) Kunth) (ABLA/CLUN) 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; Figure 1). The biomass utilization treatments were nested in each 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 an upper slope and lower slope location. 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 ½ 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 8 groups (patch cuts) averaging 0.3 ha in size (range: 0.1-0.4 ha). All timber within each group was cut; 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 biomass utilization 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: M_U (medium/unburned), H_U (high/unburned), L_B (low/burned), and M_B (medium/burned) (detailed descriptions of the biomass utilization treatments are summarized in Table 1).

Logging was conducted in the fall of 1974. All trees were hand-felled, and logs were removed from 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. For dead woody materials, if they were more than 1/3 sound, they were removed. Fine woody materials such as branches and tops were bundled and removed manually. Mean pre-harvest volume of woody material was 512 m^3 ha^{-1}. On average, 36.5%, 83.8%, and 71.0% of total woody biomass was removed in the shelterwood, group selection, and clearcut units, respectively. Broadcast burning was conducted in early September 1975. However, burning condition were unfavorable (cool and wet) and as a result, none of the designated areas were severely burned (based on observed loss of surface OM, color change in the mineral soil; Artley et al., 1978).

The experimental units were conserved intact without any additional 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 et al. 2015). For shelterwood units, the mean biomass of retained trees was 116.5 Mg ha^{-1}. The tree-layer biomass for control was 194.6 Mg ha^{-1} (data not shown).

Soil Sampling

For each clearcut and shelterwood unit, ten soil sampling points were allocated on two parallel transects (five cores per transect) within each sub-plot unit (biomass utilization treatment unit), for a total of 40 sampling points per unit. 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 were located close (approx. <15 m) to the uncut forest. Additionally, a total of 37 points (3-6 points per unit) were sampled in the uncut patches adjacent to the group selection units. Soil samples were collected from 20 sampling points in upper control unit, where the locations were not influenced by the edges of other regeneration cutting (i.e., clearcut). Since the uncut patches adjacent to the group selection units and the uncut control units are located proximately (Figure 1) and had the consistent vegetation/soil properties, they were combined and treated as control to reduce variations.

The entire forest floor (O_i, O_e, and O_a horizons combined) and material less than 0.6 cm (e.g., twigs) in diameter were collected from within a 30 cm diameter hoop and the depth recorded as an average of four points around the edge sampling point. 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 3 sample depths (0-10, 10-20, and 20-30 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, ten 15.2 m line-intercept transects were established to estimate the biomass of woody residue 0.6-7 cm and >7 cm sound, rotten, and buried wood. We followed the wood-classification categories and specific gravity values outlined in Brown (1974) to estimate mass. Woody residue <0.6 cm in diameter was sampled as part of the forest floor.

Laboratory Analyses

Before sieving, total soil bulk density was calculated from the large core samples after they were dried to 80°C and weighed. After drying, mineral soil was sieved through a >2 mm mesh screen to remove coarse-fragments which were then weighed so that 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, St. Joseph, MI). Mineral soil K, Ca, and Mg were extracted with pH neutral ammonium acetate and measured through a Perkin Elmer Atomic Absorption Spectrometer (Model 5100PC). Forest floor samples were ashed, dissolved in 6 mol/L nitric acid, and analyzed for K, Ca, and Mg on the Perkin Elmer Atomic Absorption Spectrometer. Mineral soil pH was measured on a 1:2 (v v^{-1}) soil:deionized water slurry. Total OM contents were measured by the weight loss after 8 h combustion at 375°C (Ball 1964). Mineral soil nutrients, C, and OM pools were calculated using 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). NMS 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).

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

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

where y_{ijkl}= response variable, μ = grand mean, α_i = effect of regeneration cutting treatment *i* (whole-plot effect), B_k = k^{th} block effect (random effect), β_j = j^{th} biomass utilization treatment effect (sub-plot effect), $\alpha\beta_{ij}$ = interaction between whole-plot and sub-plot effects, and $\epsilon_{(1)ik}$, $\epsilon_{(2)ijk}$, and $\epsilon_{ijkl}$are the whole-plot, sub-plot error terms, and the variation among sampling points in a subplot, respectively. If the effect of biomass utilization was statistically significant (with 0.05 alpha level), then linear contrasts were tested to examine the difference 1) between the treated vs. the control, and 2) among the treatments. Since the untreated control has only one level both on whole-plot and sub-plot, computation was infeasible. Thus, response variables were subtracted from the mean of the control to test hypothesis 1, and the controls were excluded for testing hypothesis 2. 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 (Table 2). In the shelterwood and clearcut units, total woody debris 38 years 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 control come from sound, rotten, and buried wood >7.5 cm 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 (Table 2). After 38 years, 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 the H_U treatment (59 Mg ha^{-1}, SE: 11) (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); Table 2 and 3). The woody residue OM pools generally follow 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 follow OM content. The control and M_U treatment in group selection had the highest C pool sizes, compared to all other cutting and utilization intensity treatment combinations. Carbon 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 treatment were 42 Mg ha^{-1} (SE: 7), 36 Mg ha^{-1} (SE: 5), 28 Mg ha^{-1} (SE: 5), respectively. Likewise, N contents for those biomass utilization 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}), 153 kg ha^{-1} (SE: 27 kg ha^{-1}), respectively (for detail, see Table 3). N contents of the woody residues are relatively low and account for only a small percentage of the total woody residue – mineral soil (0-30 cm) pool (Table 3). Not unexpectedly, woody residue contains only 2-10% of the total ecosystem N pool. In the group selection M_U treatment, the woody residue component contained 10%

of that treatment N (Table 3), which is 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) (Table 3).

There were several significant differences in OM, C, and N content among utilization treatments and the control. Regeneration cutting, biomass utilization treatment, and their interaction terms significantly influenced the woody residue mass, C, and N contents (Table 4). However, the significant differences were the result of 1) difference between the treatments and control, and 2) OM distribution in the L_B and M_U treatment, especially in the group selection unit. As Table 5 indicates, the differences were statistically significant only in the contrasts between those biomass utilization treatments in the group selection cutting units.

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 mirrors the forest floor OM pool size (Table 3). In all three regeneration cuttings, C pool size is 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 11-34% of the total ecosystem N pool. . Similarly, extractable Ca and Mg distributions are high in the forest floor: 56-75% Ca and 57-72% Mg (Table 5). The extractable Ca pool was highest in the control (mean: 10881 mg kg^{-1}; SE: 504), however, the 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) (Table 5). Pool size also reflects the distribution of cations in the forest floor and mineral soil, but does not follow the same trends as OM, C, and N pools. For example, C pools are often highest in the forest floor, and this is also the case for Ca and Mg, but K pools are variable. In the

group selection cuttings, the K pool is highest in the upper mineral soil depth (0-10 cm) in the M_U and H_U utilization treatments, but is highest in the forest floor after broadcast burning in both the low and moderate utilization intensity units. In the shelterwood cutting units, all utilization treatments have 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 is highest in the forest floor; the M_U and L_B units have 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 biomass utilization treatment, displaying the integration of all measured variables. As shown in Figure 2a, all utilization treatments overlap in the NMS-projected two-dimensional space as compared to the control. Thus, soil properties are 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 4). The analysis of variance (ANOVA) test results detail changes in forest floor properties (Table 4). For the R×B interaction term (regeneration cutting × biomass utilization), all chemical properties in the forest floor were statistically significant (OM, p=0.0361; C, p=0.0151; and N, p=0.0117; Table 4). However, differences in OM, C, and N in the forest floor were significant only for the clearcut treatment (Table 6). Organic matter, C, and N were significantly higher in the H_U treatment and compared to 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 treatment (M_U treatment). Significant Mg differences were only noted 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 ($p<0.001$, $p=0.005$). Although the interaction term for the forest floor soil chemical properties were all significant (Table 4), only extractable 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).

Mineral Soil

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

In the mineral soil, OM pool size ranged from 7-22% of the soil profile OM content. Organic matter content was variable within the same regeneration cutting treatment. Utilization level plus broadcast burning altered which mineral soil depth had the largest OM pool. However, among the utilization treatments there was no consistent pattern of OM accumulation (Table 3). There is 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, group selection with M_B utilization resulted in the largest C pools (38 Mg ha^{-1}) within the 0-10 cm soil depth, while the clearcut with H_U utilization had the highest C (27 Mg ha^{-1}) within the 10-30 cm soil depth. Usually, C pools were greatest in the surface mineral soil, and distributions ranged from 7-20% of the total soil profile.

The largest N pools were located in the 10-30 cm soil depth with 16-30% of the total profile pool. However, when compared to the forest floor, N contents in the mineral soil were relatively low and represent a small portion of the total soil pool. The mineral soil (10-30 cm depth) in the H_U treatments in both the group selection (1019 kg ha^{-1}) and shelterwood (1008 kg ha^{-1}) cutting units had the largest N pools. 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 18% of the N pool distribution for that location.

After 38 years, there are few significant differences in mineral soil cation pools. Only the interaction term for K in the 10-30 cm mineral soil depth is significant (Table 6). Additionally, there is no clear pattern of cation pool changes among the regeneration cutting and utilization treatments (Table 4). K is generally higher in the mineral soil than in the forest floor (22-62% of the 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. Ca and Mg pools in both the surface and subsurface mineral horizons are 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 lesser K pools than the control (-844, $p=0.018$ and -800 mg kg^{-1}, 0.028). However, there were no statistical differences in the amounts of OM, C, and N for the entire soil profile. In the 0-10 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 versus M_U (680 mg kg^{-1}, $p<0.001$) and M_B versus M_U (672 mg kg^{-1}, $p<0.001$), exhibiting a similar result with OM in the forest floor.

Using the NMS approach gives an overview of differences in mineral soil characteristics by biomass utilization treatment (Figure 2b and 2c). The mineral soil NMS score distributions are similar to those of the forest floor, including control. The distributed area of NMS scores for each treatment overlapped with comparable sizes between the control and treatments. Therefore, we conclude in general that soil properties are similar among the biomass harvesting treatments for the entire soil profile after 38 years.

The ANOVA indicated that, unlike forest floor, mineral soil C ($p=0.0417$ for the interaction term), N ($p=0.001$ for the interaction term), and extractable K ($p=0.0283$ for the biomass utilization treatment) in the upper (0-10 cm) layer were affected by regeneration cutting, biomass utilization treatment, and/or their interaction (Table 5). Extractable K was only significantly different ($p=0.0025$) for the interaction term (R×B) 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 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.

Pre-harvest of woody residues in the study area ranged from about 200-250 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 woody residue recruiting into 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 (Table 2). Moreover, a related study revealed that there was no decrease in overstory biomass production of those treatments (Jang, 2015; Jang et al., 2015a), indicating the reductions in woody residue OM pools were not severe enough to cause an adverse consequence on 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-burning units, all of the woody residue and forest floor has accumulated during the last 38 years. Expressing this increment in a linearly annualized accumulation rate (25-134 Mg ha^{-1} in 38 years), we expect full recovery of both coarse and fine woody material within 58-135 years. The shelterwood H_U units have the lowest woody residue levels and therefore may have longer recovery periods. Yet, even this lowest level of woody residue is near the recommended level of 25-27 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 organic matter and woody residues. Our results after 38 years 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 organic matter 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 comprise 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, less than 15% of the profile N pool is in the woody residue and is related to the much higher C:N ratio in wood. In contrast, the mineral soil pool – particularly at the 10-30 cm depth – has 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 years, we found that N levels are 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 is attributed to this cutting-utilization treatment combination or to a site-specific difference.

Other researchers have noted 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 Weber, 1972; Boyle et al., 1973; Mälkönen, 1976; Kimmins, 1977). In fact, many researchers are also concerned with the loss of organic matter which might lead to reductions in

water and nutrient retention (Stone, 1979; Powers et al., 1998). Variability in C and other nutrients in the forest floor is important for determining the long-term impacts of harvesting and OM removal, and should be quantified prior to 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 of soil C in the forest floor between whole-tree harvesting and conventional harvesting 5 years after treatment (Laiho et al., 2003). In a recent meta-analysis, Nave et al. (2010) analyzed 75 publications 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 years after harvest in the clearcut units, overall statistical significance is attributed to the differences among treatments, rather than between the treatments versus control. Since 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 organic matter, 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 sparser overstory, and elevated decomposition rate due to modified microclimate. From this perspective, the detected reduction of organic matter and C pools of the forest floor seem to attributable to a lower input of organic matter through litterfall relative to decomposition rates. These differences were observed only in the contrasts between the M_U treatment and other

treatments in clearcuts (Table 6). 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 Mg ha^{-1} 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 clearcut 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 utilization treatment caused some cation reductions (*e.g.*, extractable K, from the contrast of M_U vs. control; Table 5). On the other hand, Table 6 indicates that those cations were more abundant in the more severely harvested treatments. For instance, in group selection units, both the H_U and the M_B treatments contained more extractable Mg than the M_U treatment.

It seems apparent that those cation pool differences result from differences in the resulting 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 2.3-2.5 times the Mg that 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) indicates that subalpine fir abundance in the in the group selection M_U treatment is high relative to other treatments and the control; that abundant subalpine fir

may have sequestered more Mg and K from the forest floor. In the same manner, the observed decrease in extractable Ca in the H_U and L_B treatment relative to the control can be explained by the prominence of paper birch in those treatments (Jang, 2015). Compared to subalpine fir, paper birch contains more Ca in wood, but less Ca is allocated to foliage and branches (Wang et al., 2000). Consequently, a stand with higher paper birch composition stores more Ca, and lower amounts of Ca are returned to the 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 (Seely et al., 2010; Richardson et al., 1999; Fox, 2000). 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, 2000). OM also facilitates long-term storage and release of nutrients for vegetation production (Henderson et al., 1990; Henderson, 1995).

The distribution (content %) 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, soil OM at CEF ranged from 58-91 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 0-30 cm depth, which is similar to measurements from a previous study at the site (839 kg ha^{-1} from 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; Liaho et al., 2003; Wall, 2008). This result is likely 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 only detected in the contrast between the H_U and the M_U treatments in shelterwood cutting. This may be attributed to the difference in vegetation composition and K levels at the 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, significant reduction of extractable K was only observed in the comparison between the H_U and control (Table 6). Rocky Mountain maple requires greater K levels other shrub species (Mueggler, 1965; Haeussler et al., 1990), and therefore lower 0-10 cm 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 10-30 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 organic matter, C, and N contrasts at the forest floor layer. Therefore, reduced extractable K in the clearcut M_U treatment seems related to the reduction of 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 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, and 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 7-9 years 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 5-12 years 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 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 soil bulk density. Average total bulk density across all regeneration cuttings and utilization treatments was 1.08 (0-30 cm depth) 38 years after harvesting. Notably, this is very similar to the bulk density of mature stands measured nearby (1.05; 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).

Since soil and vegetation were sampled with different strategies and intensities, forming a paired dataset is impossible. Thus, causality inferences for the relationship between soil properties and above-ground 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 as compared with Rocky Mountain maple in the shrub layer.

MANAGEMENT IMPLICATIONS

At CEF, it is noteworthy that 38 years 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) indicates that above-ground 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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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 (Vol %)	Fire treatment
Medium-unburned	M_U	>17.8 cm dbh	7.6 cm × 2.4 m	62.9	Uuburned
High-unburned	H_U	All trees	2.5 cm × 2.4 m	72.3	Uuburned
Low-burned§	L_B	All trees	14.0 cm × 2.4 m	54.2	Burned
Medium-burned	M_B	All trees	7.6 cm × 2.4 m	65.6	Burned

† Except designated overstory shelterwood trees.
‡ Live and dead, standing and down logs (small-end diameter × length); for dead down logs, they were removed if 1/3 sound.
§ 1974 Forest Service standards.

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

Dependent variable	Regeneration Cutting (R)		Biomass utilization (B)		R×B	
	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**
Carbon (Mg ha^{-1})	12.33	<0.001***	2.86	0.039*	3.61	0.002**
Nitrogen (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*
Carbon (Mg ha^{-1})	6.80	0.128	0.43	0.734	2.72	0.015*
Nitrogen (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	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
Carbon (Mg ha^{-1})	1.28	0.439	3.19	0.026*	2.25	0.042*
Nitrogen (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	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
Carbon (Mg ha^{-1})	3.067	0.246	0.24	0.871	1.93	0.079
Nitrogen (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**

† Significance codes: 0 < *** < 0.001< ** < 0.01 < * < 0.05.

Table 3. P-values for the linear contrasts testing the difference of soil properties among the biomass utilization treatments.

	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
Carbon (Mg ha^{-1})	1.000	0.965	1.000	0.005**	0.013*	0.001**	1.000	0.997	0.462
Nitrogen (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*
Carbon (Mg ha^{-1})	0.998	0.989	0.994	0.938	1.000	1.000	0.007**	0.763	0.021*
Nitrogen (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)									
Carbon (Mg ha^{-1})	0.023*	1.000	0.965	0.998	0.614	0.991	0.927	0.894	0.994
Nitrogen (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***

† High vs. Medium: H_U – M_U, Medium vs. Low: M_B – L_B, Burn vs. Unburn: M_B – M_U (refer to Table 1 for abbreviations).

‡ Significance codes: 0 < *** < 0.001< ** < 0.01 < * < 0.05.

Figure Captions

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

Figure 2. The non-metric multidimensional scaling points distribution for soil properties by the biomass utilization treatments at the (a) forest floor, (b) 0-10 cm mineral soil layer, and (c) mineral soil layer 10-30 cm depth 38 years after harvesting at Coram Experimental Forest of Montana. Each line indicates the convex hull for the biomass utilization treatment (M_U: medium/unburned, H_U: high/unburned, L_B: low/burned, and M_B: medium/burned, for detail, refer Table 1).

Figure 3. Distribution of (a) woody debris mass by size class and (b) carbon in woody residue, forest floor, and mineral soil 38 years 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 detail, refer Table 1).

Figure 4. Extractable (a) Ca, (b) Mg, and (c) K distribution in forest floor and mineral soil 38 years 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 detail, refer Table 1).

Fig. 1

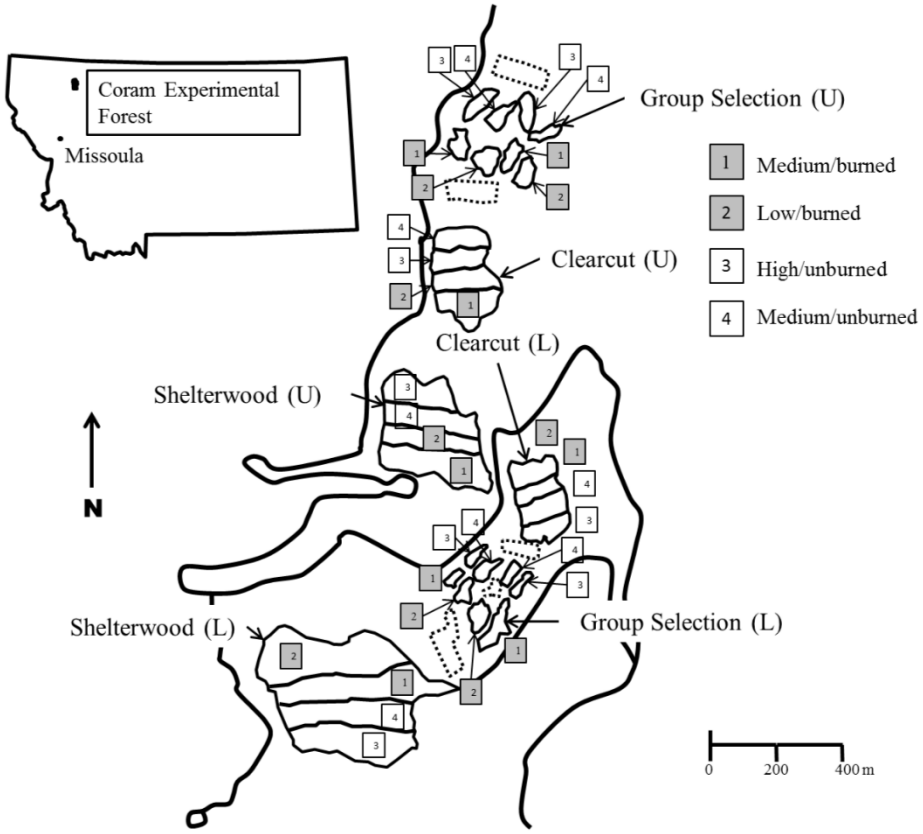
Coram Experimental Forest
Missoula
Group Selection (U)
Clearcut (U)
Clearcut (L)
Shelterwood (U)
Shelterwood (L)
Group Selection (L)
N
1 Medium/burned
2 Low/burned
3 High/unburned
4 Medium/unburned
0
200
400 m

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Fig. 2

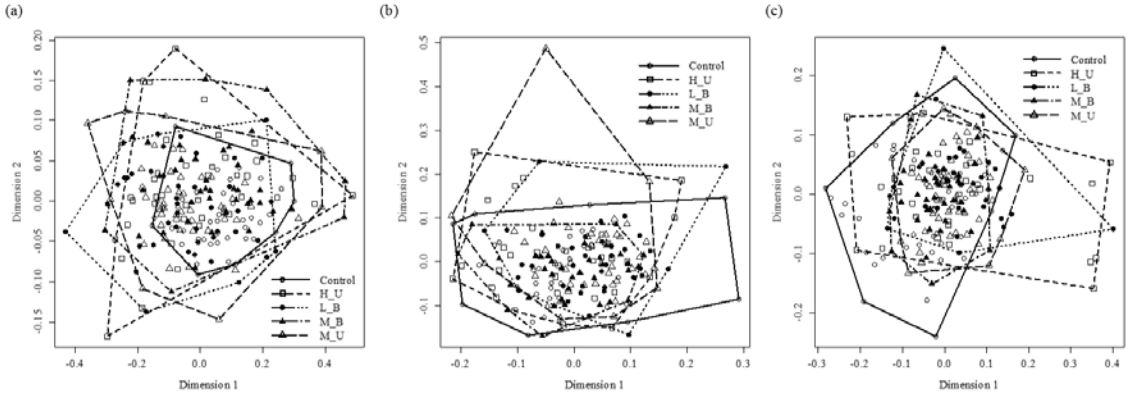

Fig. 3

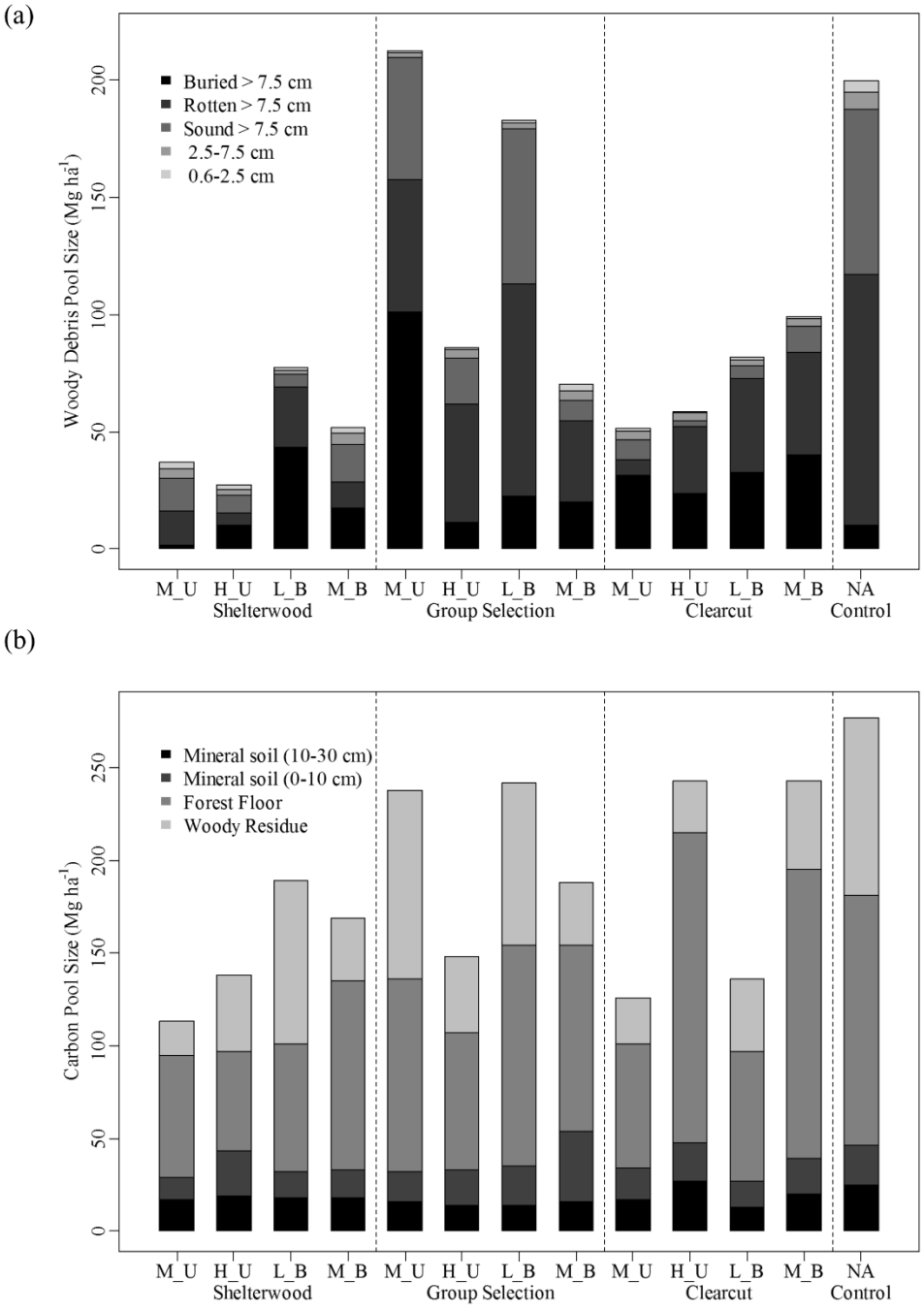
(a)
Buried > 7.5 cm
Rotten > 7.5 cm
Sound > 7.5 cm
2.5-7.5 cm
0.6-2.5 cm
Woody Debris Pool Size (Mg ha-1)
0
50
100
150
200
M_U H_U L_B M_B M_U H_U L_B M_B M_U H_U L_B M_B NA
Shelterwood
Group Selection
Clearcut
Control
(b)
Mineral soil (10-30 cm)
Mineral soil (0-10 cm)
Forest Floor
Woody Residue
Carbon Pool Size (Mg ha-1)
0
50
100
150
200
250
M_U H_U L_B M_B M_U H_U L_B M_B M_U H_U L_B M_B NA
Shelterwood
Group Selection
Clearcut
Control

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Fig. 4