



# Long-term effects on distribution of forest biomass following different harvesting levels in the northern Rocky Mountains



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## ABSTRACT

With increasing public demand for more intensive biomass utilization from forests, the concerns over adverse impacts on productivity by nutrient depletion are increasing. We remeasured the 1974 site of the Forest Residues Utilization Research and Development in northwestern Montana to investigate long-term impacts of intensive biomass utilization on aspects of site productivity. The historical experiment was implemented in a western larch (*Larix occidentalis* Nutt.) forest at three biomass utilization levels (high, medium, and low) combined with prescribed post-harvest burning treatments (burned and unburned) under three regeneration cuttings (clearcut, group selection, and shelterwood). The experiment has two replicates and was designed as a split-plot design with an imbalanced manner. Regenerated tree height and diameter at breast height, shrub root collar diameter, and soil properties (C, N, and total organic matter) of the forest floor and mineral soil layers were measured. Regenerated tree, shrub, and total aboveground biomass and total C, N, and organic matter contents of the soil layers were calculated. Results indicated that total organic matter pools at the ecosystem level were similar across regeneration cutting treatments, and there were no differences among the utilization treatments for either aboveground biomass production or soil properties 38 years after harvest. Minor differences observed among treatments seemed to originate from differences in regeneration dynamics and responses to burning treatment. Our results indicate that site productivity in this forest type was unaffected by these biomass utilization levels.

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## 1. Introduction

Logging residues such as slash and cull trees, as well as snags and coarse woody debris, have been considered as an important alternative energy feedstock due to increasing cost of fossil fuels and emerging public concerns over climate change. On a global scale, timber harvesting typically removes less than 66% of cut biomass from forests (Parikka, 2004). In northern Rocky Mountains forests, only about half of total aboveground woody biomass is typically extracted (Benson and Schlieter, 1980). The harvesting convention for biomass utilization in the western United States seems to have remained constant over past decades (see Simmons et al., 2014), and the development of a bioenergy infrastructure is still at a tentative stage.

The advantages of using forest biomass as an alternative energy feedstock over fossil fuels have been summarized as: (1) reduction

of greenhouse gas emissions, (2) improvement of sustainability for rural communities and economies through expanded economic opportunities, (3) reduction of energy costs, (4) reduction of emissions from forest waste burning treatments, (5) mitigation of dependency on foreign energy feedstock imports, and (6) local utilization and recycling of waste materials (Farr and Atkins, 2010). It seems likely that federal policies will spur forest woody biomass utilization as a new energy feedstock, and some efforts have already been undertaken. The Energy Policy Act of 2005 and the Energy Independence and Security Act (EISA) of 2007 are two examples of such policies. Forest harvesting involving a more expanded removal of woody materials – such as whole-tree harvesting or energy-wood harvesting (sensu Benjamin et al., 2010) – seems likely to occur in this region.

Increased biomass removal may possibly have undesirable impacts on soil, water, site productivity, biodiversity, and atmospheric systems (Lattimore et al., 2009). Among these impacts, the effects of intensive harvesting on site productivity have been most addressed (Thiffault et al., 2011). Of primary concern is that more intensive woody biomass removal might deplete nutrient

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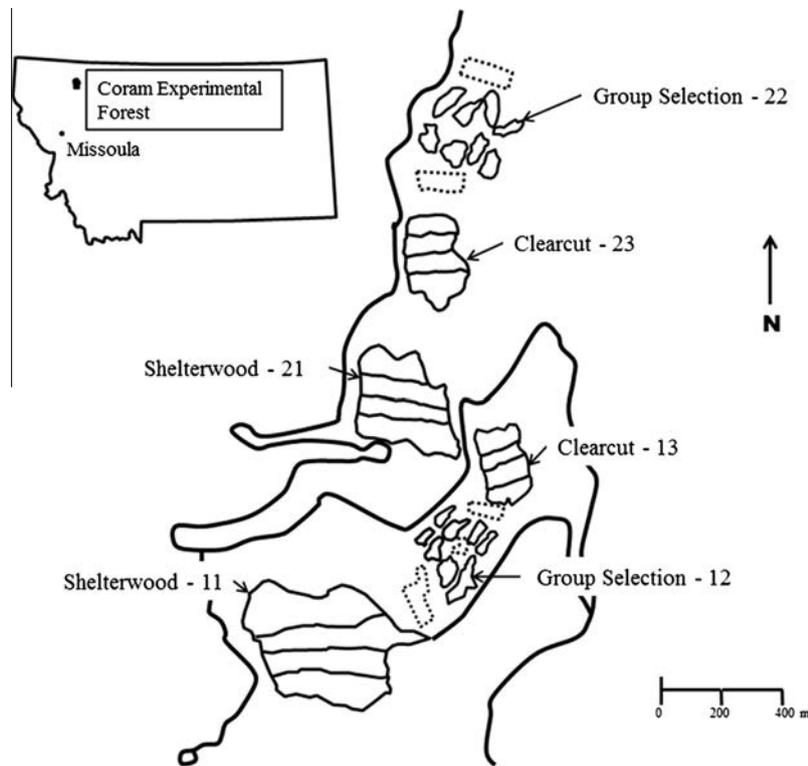


Fig. 1. Study site and the layout of experimental units at Coram Experimental Forest, MT.

budgets, resulting in the reduction of site productivity. However, since a majority of these studies (e.g., Ares et al., 2007; Fleming et al., 2006; Roberts et al., 2005) addressed short-term consequences, the long-term impact on site productivity is still widely unknown. Moreover, such research in the inland Northwest forests is relatively limited when compared with the other forest regions (Jurgensen et al., 1997). Research examining the longer-term impacts of increased biomass utilization on site productivity in this region is required.

Western forests usually require post-harvest fuel reduction treatments involving the change of organic matter pools (Agee and Skinner, 2005). Broadcast burning has provided an inexpensive and effective solution to reduce wildfire hazard. Prescribed burning treatments have been known to increase short-term site productivity through elevation of the N mineralization rate and availability of inorganic N (e.g., Covington and Sackett, 1984; DeLuca and Zouhar, 2000; Gundale et al., 2005; White, 1986). Yet, it has also been proven that burning treatments can affect soil productivity negatively in certain forest ecosystems (e.g., Monleon et al., 1997; Page-Dumroese et al., 2010). There is still insufficient research to assess the long-term impacts of prescribed burning (in company with biomass extraction) on site productivity (Carter and Foster, 2004).

Coram Experimental Forest in western Montana provides a timely opportunity to investigate the long-term impacts of intensive biomass utilization on forest productivity. Here, a multidisciplinary research program was conducted in response to the energy crisis of the early 1970s. One objective of the research effort was to reduce adverse ecological consequences while maximizing the efficiency of harvests (Barger, 1980). Biomass utilization treatment levels combined with burning treatments were applied following three common regeneration cuttings in a typical mixed coniferous forest of the northern Rocky Mountains. This paper assesses the impacts of those biomass utilization intensity and prescribed fire treatments on forest productivity 38 years afterwards.

## 2. Methods

### 2.1. Study site

The study was conducted in the Upper Abbot Creek Basin (48°25'N, 113°59'W) of Coram Experimental Forest in northwestern Montana (Fig. 1). Coram Experimental Forest was established in 1933, and comprises 3019 ha of the Hungry Horse Ranger District of the Flathead National Forest. It is located 9 km south of Glacier National Park. The elevation of Coram Experimental Forest ranges from 1195 to 1615 m (Shearer and Schmidt, 1999). Slopes range from 30% to 80%.

The climate of Coram Experimental Forest is classified as a modified Pacific maritime type (Adams et al., 2008). The annual precipitation is 890–1270 mm, averaging 1076 mm (Farnes et al., 1995). Most precipitation occurs in the form of snow during November–March. The mean annual temperature is 2–7 °C, with summer temperature ranging from 13 °C to 17 °C, and winter temperatures typically falling below –18 °C (Hungerford and Schlieter, 1984). The length of growing season is between 81 and 160 days (Adams et al., 2008).

Precambrian sedimentary rock, glacial till, and a thin surface of fine-textured volcanic ash are the main soil components of soils on Coram Experimental Forest. The mixture of these soil components created the rich-loamy soils in this area. Although soils on Coram Experimental Forest can be classified into 6 categories, soil at our study area is classified as a loamy-skeletal isotic Andic Haplocryalf (Soil Survey Staff, 2006). Stands in Coram Experimental Forest occur across three potential climax vegetation associations (i.e., habitat types; Pfister et al., 1977), the most dominant of which in our study area is the subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.)/queen-cup bead lily (*Clintonia uniflora* (Menzies ex Schult. & Schult. f.) Kunth) (ABLA/CLUN) type (Shearer and Kempf, 1999). The site index (base age 50) is 15.24–18.28 m (Schmidt et al., 1976). The majority of the forest consists of the western larch

**Table 1**

Design of the utilization treatments within harvesting units (from Benson and Schlieter, 1980; Shearer and Schmidt, 1999; Shearer and Kempf, 1999).

Treatment name	Abbreviation	Cut trees <sup>a</sup>	Max. size of retained woody materials <sup>b</sup>	Post-harvest treatment
Medium-unburn	M_U	>17.8 cm dbh	7.6 cm × 2.4 m	Understory protected/unburned
High-unburn	H_U	All trees	2.5 cm × 2.4 m	Slashed/unburned
Low-burn <sup>c</sup>	L_B	All trees	14.0 cm × 2.4 m	Slashed/broadcast burned
Medium-burn	M_B	All trees	7.6 cm × 2.4 m	Slashed/broadcast burned

<sup>a</sup> Except designated overstory shelterwood trees.<sup>b</sup> Live and dead down logs (small-end diameter × length); for dead down logs, they were removed if sound enough to yard.<sup>c</sup> 1974 Forest Service Standards.**Table 2**Volumes of all woody material (>7.62 cm diameter, unit: m<sup>3</sup>/ha) pre- and post-harvest (Benson and Schlieter, 1980). Utilization treatment levels are listed in Table 1. Block1 and Block2 are low and high elevation replication, respectively. Numbers in parentheses of post-harvest volume column represent retained overstory tree/sapling volumes.

Harvest/treatment <sup>a</sup>	Pre-harvest volume		Post-harvest volume		Removed volume	
	Block1	Block2	Block1	Block2	Block1	Block2
<i>Shelterwood</i>						
M_U	369	347	255 (113/20)	265 (129/48)	114	82
H_U	410	319	193 (21/0)	134 (84/0)	217	185
L_B	348	308	257 (112/1)	264 (37/0)	91	44
M_B	479	470	269 (177/2)	270 (134/1)	211	200
<i>Group selection</i>						
M_U	694	715	92 (0/11)	84 (0/2)	602	631
H_U	577	530	42 (0/0)	93 (0/0)	535	437
L_B	492	1042	88 (0/0)	184 (0/0)	404	858
M_B	654	581	123 (0/0)	146 (0/2)	531	435
<i>Clearcut</i>						
M_U	483	450	71 (0/2)	168 (0/3)	413	282
H_U	414	387	66 (0/0)	140 (0/1)	348	247
L_B	469	564	167 (0/0)	247 (0/0)	302	316
M_B	570	617	121 (0/0)	170 (0/3)	449	447

<sup>a</sup> M\_U: medium/unburn, H\_U: high/unburn, L\_B: low/burn, M\_B: medium/burn (refer to Table 1).

(*Larix occidentalis* Nutt.) cover type (Society of American Foresters Cover Type 212, Eyre, 1980). Western larch occurs in association with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), subalpine fir, spruces (*Picea engelmannii* Parry ex Engelm. and *Picea glauca* (Moench) Voss), western hemlock (*Tsuga heterophylla* (Raf.) Sarg), and western redcedar (*Thuja plicata* Donn ex D. Don), plus a variety of broadleaf tree and shrub species (Shearer and Kempf, 1999).

## 2.2. Experimental design

The experimental design consisted of the combination of three regeneration cuttings (shelterwood, clearcut and group selection) with four biomass utilization levels (Fig. 1, Table 1). Four biomass utilization treatments are composed of three removal levels (high, medium, and low) and subsequent burning treatments (Table 1): M\_U (medium/unburn), H\_U (high/unburn), L\_B (low/burn), and M\_B (medium/burn) treatments. The treatments were replicated at two different elevations (1195–1390 m, and 1341–1615 m).

For the clearcut (5.7 and 6.9 ha in size) and shelterwood (14.2 and 8.9 ha in size) regeneration cuttings, four biomass utilization subunits were randomly assigned to four adjacent strips stretching down slope. For the group selection cutting, eight cutting clusters averaging 0.3 ha (range 0.1–0.6 ha) were arranged in four rows and two columns; biomass utilization subunits were randomly allocated into cluster pairs. Logging was conducted in 1974 via a running skyline yarder to minimize soil disturbance and erosion. The average pre-harvest volume of woody material was 512 m<sup>3</sup>/ha, which is equivalent to 381.8 Mg/ha when we assume 0.7458 Mg/m<sup>3</sup> as a mean specific gravity of green wood and bark weight for the major tree species on our study site (Miles and

Smith, 2009). A summary of volumes for each harvesting unit and treatment is presented in Table 2.

For reduction of fire hazard and seedbed preparation, the prescribed broadcast burning treatment was assigned to two of four utilization treatments (Table 1). Prescribed broadcast burning was applied in 1975. However, the burning treatments were mild relative to the planned fire treatment due to cool and wet weather. Moreover, the broadcast burning could not be applied to one of the shelterwood units (lower) because the moisture contents of dead fuel and duff were above the prescription limits (Artley et al., 1978; Schmidt, 1980). As a result, an extra unplanned treatment (i.e., low-unburn treatment) resulted in the lower shelterwood unit. Since this additional treatment renders the experimental design unbalanced and poses a computational problem to analyzing the interaction between regeneration cutting effect and biomass utilization effect, the treatment was excluded from the analyses.

A total of 40 permanent sampling points were established in each cutting unit. The sampling points were systematically located in an 8 × 5 grid at 30.5 m intervals. As a result, ten sampling points (in a 2 × 5 grid) were assigned to each biomass utilization subunit. For group selection units, five sampling points were allocated within each cluster.

## 2.3. Data collection and analysis

### 2.3.1. Vegetation biomass

Based on nested circular plots, three concentric circular plots were established using permanent points as plot centers to measure trees that regenerated post-treatment. Shelterwood units contained residual (unharvested) trees, thus a fourth (larger) plot

was added to the nesting system. The plot sizes varied according to the measured tree sizes. Residual tree (larger than 25 cm dbh) were measured in a 12.6 m radius plot (1/20th ha), and pole-sized trees (larger than 10 cm but smaller than 25 cm dbh) were measured in a 5.6 m radius plot (1/100th ha). The plot size for saplings (smaller than 10 cm dbh) was a 2.5 m radius (1/500th ha), and only trees taller than breast height (1.37 cm) were measured.

In summer 2012, all 280 permanent points in every cutting unit were surveyed. Species of each sample tree was recorded. Dbh and height were measured with diameter tape and laser clinometer or height pole. For shrub and seedlings, root collar diameter was measured by caliper from four sampling points (out of ten) in each sub-unit. According to the height, 0.8 m (<100 cm height) and 1.78 m ( $\geq 100$  cm height) radius circular plots were established. Measurements were used for the computation of biomass using published, species-specific biomass equations. Biomass equations from Standish et al. (1985) were used for ponderosa pine, white pine, and black cottonwood. Equations by Ung et al. (2008) were used for Douglas-fir, Engelmann spruce, lodgepole pine, subalpine fir, western redcedar, and western hemlock. Biomass of western larch was estimated by Gower et al. (1987). Brown (1976)'s equations were used to estimate the shrub biomass. Forbs and grasses were clipped in the  $1 \times 1$  m plot from the five sampling points in each subunit, and were packaged and sent to the laboratory. For analysis, the samples were oven-dried to constant weight at 60 °C to measure dry weight. For downed woody debris, one line-intercept transect was established in a random direction from each soil sampling point; fuel sampling followed the protocol by Brown (1974).

### 2.3.2. Soil properties

In each clearcut and shelterwood unit, ten soil sampling points were allocated on two parallel transects in each treatment unit (five cores/transect) for a total of 40 sampling points at 30.48 m spacing. For group selection units, three soil sampling points were assigned to each cluster. At each sampling location, the forest floor ( $O_i$ ,  $O_e$ , and  $O_a$  horizons combined) was collected in a 30 cm diameter hoop and its depth was recorded. Organic material <0.6 cm in diameter (i.e., 1-h fuel) was collected. Mineral soil samples were collected using a 10 cm diameter core sampler to a depth of 30 cm (Jurgensen et al., 1977). The large size of the corer allowed us to obtain samples of the coarse-fragment components. Once the mineral soil core was collected, the sample was removed from the corer and divided into 3 sample depths (0–10, 10–20, and 20–30 cm). All live roots were hand-separated from the forest floor and mineral soil samples. Soil and root samples were dried at 80 °C and the mineral soil was passed through a 2 mm mesh sieve to remove coarse fragments. All forest floor and mineral-soil subsamples were ground to pass a 0.04-mm mesh and were analyzed for total carbon and nitrogen with a LECO-600 analyzer (LECO Corp, St. Joseph, Mich.). Total organic matter contents were measured by weight loss after 8-h combustion at 375 °C (Ball, 1964). Mineral soil carbon, nitrogen, and organic matter contents were corrected for coarse-fragment content and were extrapolated to a hectare basis using the fine-fraction bulk density (Cromack et al., 1999).

### 2.3.3. Statistical analyses

Since the experiment was treated as a split-plot design, all biomass and soil properties were analyzed via the mixed effects modeling approach. Aboveground vegetation biomass was classified into regenerated tree (trees regenerated after harvesting, excluding retained trees in shelterwood units), shrub biomass, and aboveground biomass (regenerated tree + shrub biomass). Five major species (Douglas-fir, subalpine fir, Engelmann spruce, western larch, and paper birch) were tested separately. The shrub layer

was divided into three layers (tall, medium, and short) following the Brown's (1976) classification.

Explanatory variables were regeneration cutting method, biomass utilization treatment, and interaction between these two factors. Block was treated as a random effect. Since the biomass utilization treatments are compounded with burning treatment and biomass utilization levels as in an incomplete factorial manner, three linear contrasts were introduced to test the treatment effects within a regeneration cutting. That is, to test the effect of biomass utilization levels, the M\_U treatment was compared with the H\_U treatment, and the L\_B treatment was compared with the M\_B treatment, respectively. To examine the burning treatment effect, the M\_U and M\_B treatments were compared. For shrub biomass evaluation, the next-higher shrub layer's biomass were tested as a covariate. Pearson's correlation test was used to investigate the relationship between (1) tree vs. shrub layer biomass production, and (2) aboveground and dead/belowground biomass. All analyses were conducted through R (R Development Core Team, 2008); the *lme4* (Bates et al., 2014) package was used to fit the mixed effects model, and *multcomp* (Hothorn et al., 2014) was used for testing the linear contrasts.

## 3. Results

### 3.1. Ecosystem biomass distribution

Mean woody biomass occurring in trees, shrubs, forbs and grasses, woody debris, forest floor, and mineral soil was 423.4 Mg/ha across all regeneration cutting units (Table 3). In the clearcut and group selection units, 422.7 and 426.0 Mg/ha of biomass were distributed from mineral soil layer to overstory tree layer. In the shelterwood unit, the biomass of trees retained from the previous harvest (116.8 Mg/ha) was approximately 27% of the total ecosystem biomass (428.5 Mg/ha) and 82% of total aboveground live vegetation biomass (142.5 Mg/ha).

Thirty eight years after harvesting, the forest floor was the largest organic matter pool. Approximately 39% (166.6 Mg/ha) of total organic matter in the ecosystem was found in the forest floor. Combined with mineral soil (70.5 Mg/ha) organic matter pools, more than 56% of total ecosystem organic matter was distributed in dead/belowground pools. These forest floor and mineral soil organic matter pools were approximately 3 times the biomass of aboveground vegetation, including retained trees in shelterwood units.

### 3.2. Vegetation response to harvest and burn treatments

Total aboveground biomass (including regenerated trees, shrubs, forbs, and grasses, but except retained trees in shelterwood) in clearcut units was the highest 38 years after harvesting (Table 3). In 2012 the mean aboveground biomass in clearcut units was 62.6 Mg/ha (SE = 5.1 Mg/ha). The mean aboveground biomass in the group selection and shelterwood units were 43.9 Mg/ha (SE = 4.4 Mg/ha) and 20.8 Mg/ha (SE = 3.6 Mg/ha), respectively. Analysis of variance (ANOVA) indicated that there were no significant differences (at 0.05 significance level) in biomass among either regeneration cuttings or biomass utilization levels (Table 4). The linear contrast among biomass utilization levels and burning treatments indicated that total aboveground biomass production was not affected by these factors regardless of the regeneration cutting method (Table 5).

Mean height and dbh of regenerated trees were 4.8 m and 5.1 cm, respectively. Regenerated tree biomass accounted for 84% of total aboveground biomass. Clearcut units produced the highest regeneration tree biomass (56.1 Mg/ha; SE = 3.1 Mg/ha), followed

**Table 3**

Ecosystem biomass (Mg/ha) distribution of each compartment 38 years after harvesting. Values in parentheses are standard errors of the means.

Regeneration cutting	Biomass utilization treatment	Retained tree	Regenerated tree	Understory <sup>a</sup>	Forbs and grasses	Above-ground Total	Woody debris	Forest floor	Coarse roots <sup>b</sup>	Mineral soil	Dead/below-ground total	Total ecosystem
Clearcut	M_U <sup>c</sup>	–	48.1 (6.5)	5.1 (2.1)	0.2 (0.1)	53.4	51 (9)	125.9 (18.3)	12.5 (1.7)	62.4 (4.4)	251.8	305.2
	H_U	–	59.3 (7.0)	7.1 (1.7)	0.2 (0.1)	66.6	59 (19)	280.6 (73.3)	15.4 (1.8)	81.6 (8.7)	436.6	503.2
	L_B	–	61.1 (6.1)	4.7 (1.4)	0.5 (0.2)	66.3	82 (15)	123.5 (23.9)	15.9 (1.6)	71.2 (15.2)	292.6	358.9
	M_B	–	55.6 (5.2)	7.8 (3.2)	0.1 (0.0)	63.5	99 (21)	269.9 (46.6)	14.5 (1.4)	66.7 (4.3)	450.1	513.6
	Mean (SE)	–	56.1 (3.1)	6.2 (1.1)	0.3 (0.1)	62.6	73 (9)	201.9 (24.5)	14.6 (0.8)	70.6 (4.8)	360.1	422.7
Group selection	M_U	–	32.8 (5.8)	7.5 (2.3)	0.2 (0.1)	40.5	213 (40)	191.6 (40.9)	10.7 (1.5)	58.4 (5.3)	473.7	514.2
	H_U	–	35.7 (5.5)	4.1 (0.8)	0.7 (0.5)	40.5	86 (20)	137.1 (36.4)	9.3 (1.4)	71.5 (8.3)	303.9	344.4
	L_B	–	37.1 (4.5)	4.8 (2.6)	0.7 (0.4)	42.6	183 (60)	186.8 (35.5)	9.7 (1.2)	78.2 (5.9)	457.7	500.3
	M_B	–	32.6 (4.7)	18.7 (6.5)	0.8 (0.2)	52.1	70 (24)	159.4 (33.5)	8.6 (1.3)	72.9 (11.0)	310.9	363.0
	Mean (SE)	–	34.5 (2.5)	8.8 (2.1)	0.6 (0.2)	43.9	134 (20)	168.1 (18.0)	9.6 (0.7)	70.4 (4.1)	382.1	426.0
Shelterwood	M_U	125.2 (11.3)	33.9 (5.0)	6.7 (3.0)	0.3 (0.2)	166.1	37 (7)	118.5 (20.3)	41.4 (3.8)	59.7 (5.3)	256.6	422.7
	H_U	105.5 (11.2)	11.2 (3.6)	4.2 (1.2)	0.1 (0.0)	121.0	27 (10)	88.1 (16.3)	30.3 (3.9)	75.7 (9.7)	221.1	342.1
	L_B	123.9 (13.6)	4.6 (2.8)	6.7 (3.2)	0.4 (0.1)	135.6	77 (16)	129.9 (36.0)	33.4 (3.2)	63.3 (4.2)	303.6	439.2
	M_B	106.5 (16.9)	9.0 (2.9)	4.8 (1.8)	0.2 (0.1)	120.5	52 (9)	187.6 (25.3)	30.0 (2.7)	83.8 (19.2)	353.4	473.9
	Mean (SE)	116.8 (6.5)	19.7 (2.9)	5.7 (1.4)	0.3 (0.1)	142.5	54 (7)	127.5 (12.8)	35.5 (1.8)	69.0 (5.1)	285.0	428.5

<sup>a</sup> Shrub and seedling biomass were combined.<sup>b</sup> Coarse roots biomass was estimated through the equation of Cairns et al. (1997). The ratio of 0.26 to overstory biomass was applied.<sup>c</sup> M\_U: medium/unburn, H\_U: high/unburn, L\_B: low/burn, M\_B: medium/burn (refer to Table 1).**Table 4**

Results summary of ANOVA for aboveground biomass and soil properties.

Source of variance	Harvest (H)		Utilization (U)		H × U	
	F value	p-value	F value	p-value	F value	p-value
Total aboveground biomass	7.258	0.121	0.367	0.777	1.447	0.208
Regenerated tree biomass	16.986	0.056	0.813	0.488	3.825	0.001**
Subalpine fir	2.743	0.267	20.321	<0.0001*** <sup>a</sup>	0.774	0.591
Douglas-fir	4.661	0.177	3.191	0.025*	3.280	0.004**
Engelmann spruce	2.593	0.278	8.517	<0.0001***	2.376	0.030*
Paper birch	1.014	0.496	1.506	0.214	1.951	0.074
Western Larch	9.842	0.092	2.755	0.044*	2.095	0.055
Shrub biomass	1.186	0.458	2.592	0.059	1.524	0.181
High	0.838	0.544	2.668	0.054	1.616	0.154
Medium	0.271	0.787	1.932	0.131	1.306	0.265
Low	0.213	0.824	6.280	<0.001***	1.523	0.182
Forest floor						
Organic matter	2.879	0.258	1.944	0.125	2.307	0.036*
Carbon contents	3.384	0.228	2.298	0.078	2.770	0.014*
Nitrogen contents	2.416	0.293	1.796	0.150	2.912	0.010*
Mineral soil (0–30 cm)						
Organic matter	0.029	0.972	1.639	0.183	0.493	0.813
Carbon contents	0.332	0.751	7.247	<0.001***	2.441	0.029*
Nitrogen contents	0.785	0.560	5.494	0.001**	3.143	0.007**

<sup>a</sup> Significance codes: 0 < \*\*\* < 0.001 < \*\* < 0.01 < \* < 0.05.

by the group selection and shelterwood at 34.5 Mg/ha (SE = 2.5 Mg/ha) and 19.7 Mg/ha (SE = 2.9 Mg/ha), respectively (Table 3). Unlike total aboveground biomass, differences in regenerated tree biomass were significant among both regeneration cuttings and biomass utilization levels (Table 4;  $P < 0.01$ ). The M\_U treatment in the shelterwood units had higher biomass production than H\_U and M\_B treatments ( $P = 0.005$ , and 0.01, respectively). Regenerated tree biomass in clearcut and group selection units did not differ.

Five major tree species (subalpine fir, Douglas-fir, Engelmann spruce, paper birch, and western larch) composed 96% of total regenerated tree biomass (Fig. 2). Paper birch and western larch were unaffected by the biomass utilization treatments (Table 5). Subalpine fir and Douglas-fir responded only to the burning treatment, since the significant differences in biomass production were detected only in the contrast between burned vs. unburned treatment. Burning treatment reduced subalpine fir biomass by 13.3

and 12.8 Mg/ha in the group selection ( $P = 0.004$ ) and shelterwood units ( $P = 0.041$ ), respectively. In contrast, the burning treatment increased Douglas-fir biomass by 16.0 Mg/ha ( $P = 0.036$ ) in the clearcut unit. Engelmann spruce responded in a similar manner to subalpine fir, where broadcast burning decreased biomass production by 0.7 and 9.3 Mg/ha at the medium biomass utilization level in the clearcut and shelterwood units, respectively. In addition, the high biomass removal without broadcast burning decreased Engelmann spruce's biomass production by 9.0 Mg/ha as compared to the medium biomass removal without broadcast burning.

Although tall shrub biomass seemed generally unaffected by biomass utilization treatments (Table 4), there was a significant difference between the M\_B and L\_B treatments in the group selection harvest units (Table 5). The M\_B treatment in the group selection increased 13.9 Mg/ha of tall shrub biomass relative to the L\_B treatment ( $P = 0.009$ ), and was the major reason for a significant

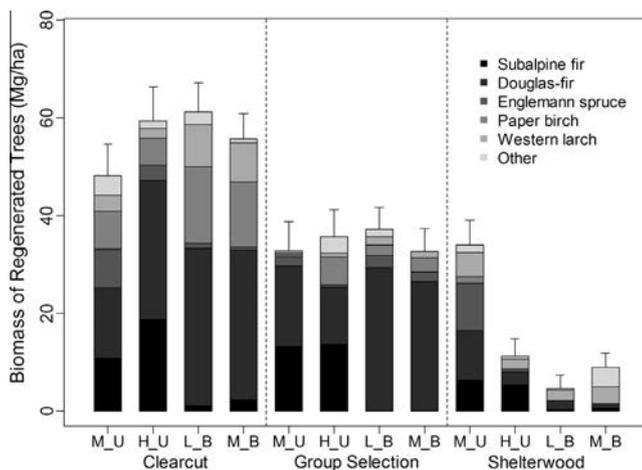
**Table 5**  
Test results of the linear contrasts for aboveground biomass and soil properties (units: Mg/ha).

Response variables	H_U – M_U <sup>a</sup>			M_B – L_B			M_B – M_U		
	CC <sup>b</sup>	GS	SW	CC	GS	SW	CC	GS	SW
Total aboveground biomass	17.620	11.392	–14.358	–3.852	12.038	3.408	2.856	17.339	–25.661
Regenerated tree biomass	11.181	2.834	–24.007** c	–5.475	–4.442	4.388	7.565	–0.202	–30.035*
Subalpine fir	7.976	0.363	–2.728	1.215	–0.251	0.286	–8.515	–13.311**	–12.789*
Douglas-fir	13.912	–4.683	–8.253	–1.571	–2.751	–0.878	16.215*	10.057	–12.015
Engelmann spruce	–4.796	–1.343	–8.992***	–0.439	–0.335	0.000	–0.744*	0.161	–9.333**
Paper birch	–2.226	5.254	–1.100	–2.252	1.013	0.000	5.669	2.566	–0.362
Western Larch	–1.196	0.330	–2.853	–0.764	–0.623	1.202	4.783	0.630	–1.496
Shrub biomass	2.085	–3.369	–2.539	3.058	13.941**	–1.848	2.702	11.231	–1.878
High	1.457	–4.486	–3.853	3.470	13.946**	–2.475	2.132	10.572	–3.367
Medium	0.302	–0.004	0.238	0.146	–0.419	0.005	0.134	–0.252	–0.189
Low	0.319	1.111*	0.593	–0.533	0.349	0.594	0.423	0.889	1.271*
Forest floor									
Total organic matter	154.450*	–54.460	–35.040	146.180*	–26.200	57.640	143.790*	–33.580	64.440
Carbon contents	100.160**	–36.150	–14.110	86.050*	–19.510	32.630	89.070*	–11.800	33.270
Nitrogen contents	2.779**	–1.142	–0.575	2.347*	–0.399	0.576	2.044	–0.344	0.804
Mineral soil (0–30 cm)									
Total organic matter	19.217	13.138	15.973	–4.553	–6.289	20.522	4.271	13.533	24.139
Carbon contents	25.437***	12.466	15.903	12.959	–7.971	0.802	7.160	12.630	4.638
Nitrogen contents	0.526*	0.416	0.561	0.361	–0.518	0.102	0.149	0.355	0.207

<sup>a</sup> M\_U: medium/unburn, H\_U: high/unburn, L\_B: low/burn, M\_B: medium/burn (refer to Table 1).

<sup>b</sup> CC: clearcut, GS: group selection, SW: shelterwood harvest.

<sup>c</sup> Significance codes (*p*-value): 0 < \*\*\* < 0.001 < \*\* < 0.01 < \* < 0.05.



**Fig. 2.** Biomass production 38 years after harvesting for regenerated trees. Error bar represents standard error of the mean biomass production.

increase in total shrub biomass. Short shrub biomass was 1.1 Mg/ha ( $P = 0.014$ ) greater in the H\_U treatment as compared to the M\_U treatment for group selection. Short shrub biomass of the M\_B treatment was 1.3 Mg/ha ( $P = 0.038$ ) greater than the M\_U treatment in the shelterwood unit. Tall shrub biomass production was unaffected by overstory tree biomass (Pearson's correlation test;  $p = 0.416$ ). Similarly, medium and short shrub biomass production was not influenced by high ( $p = 0.075$ ) and medium ( $p = 0.825$ ) shrub biomass, respectively.

### 3.3. Soil response to harvest and burn treatments

Forest floor organic matter, carbon, and nitrogen pools showed similar patterns in 2012 (Fig. 3). The interaction terms between regeneration cutting and utilization treatment were significant for all forest floor analyses (Table 3). However, differences in organic matter, carbon, and nitrogen pools among biomass utilization treatments were significant only in the clearcut units (Table 5). Increased biomass utilization intensity (i.e., H\_U vs. M\_U, and M\_B vs. L\_B) tended to increase organic matter, carbon and nitrogen. In addition, broadcast burning increased total organic matter

(143.8 Mg/ha;  $P = 0.046$ ) and carbon pools (89.1 Mg/ha;  $P = 0.019$ ) in the medium utilization subunits of the clearcut units.

Within the mineral soil profile (0–30 cm depth), organic matter pools were unaffected by biomass utilization treatment, or by regeneration cutting (Table 4). Carbon and nitrogen pools were significantly different among the biomass utilization treatments, but only between the H\_U treatment and M\_U treatment in clearcut units: the H\_U subunits had 25.4 Mg/ha ( $P < 0.001$ ) more carbon and 0.5 Mg/ha ( $P = 0.040$ ) more nitrogen than the M\_U treatment.

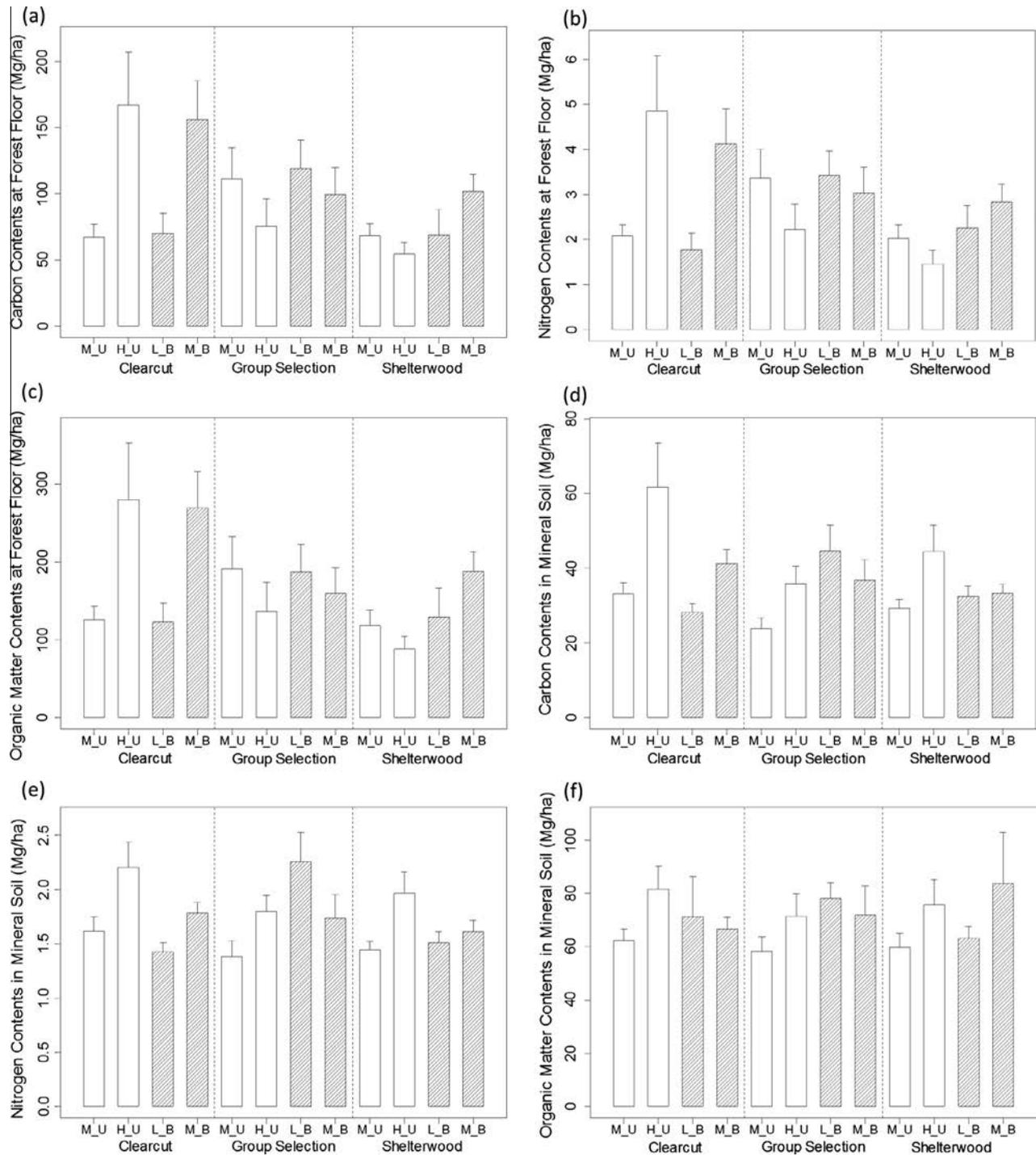
None of the soil properties of the forest floor and the mineral soil layer was related to aboveground biomass production. Pearson's correlation test results indicated that carbon contents in the forest floor ( $P = 0.124$ ) and the mineral soil layer ( $P = 0.437$ ) had no correlation with the aboveground biomass production. Likewise, we failed to detect any correlation in terms of neither nitrogen content ( $P = 0.181$  for forest floor,  $P = 0.623$  for the mineral soil) nor total organic matter content ( $P = 0.140$  for forest floor,  $P = 0.865$  for the mineral soil, respectively).

## 4. Discussion

### 4.1. Ecosystem biomass and C, N distribution

We had little pre-harvest tree biomass data for our study sites. However, we refer to a recent study conducted in nearby western larch forest (Bisbing et al., 2010). Bisbing et al. (2010) reported that the mean overstory content (i.e., about 50% of wood biomass) of western larch stands 40 years after harvest was 23.83 Mg C/ha. Excluding shelterwood units, the overall overstory carbon content of our study site 38 years after harvest was 22.64 Mg C/ha. Seemingly, the aboveground biomass production of our site did not differ from second-growth stands harvested by the conventional harvesting standard. This level of overstory biomass was 15.7% of the overstory biomass in old-growth western larch stands of western Montana (144.23 Mg C/ha; Bisbing et al., 2010).

There were few soil impacts noted 38 years after harvest. Since these sites were skylined logged, few if any detrimental soil impacts during harvesting were expected. After 38 years, organic matter on the soil surface was unaffected by the utilization and burning treatments. Rather, more intensive and burning



**Fig. 3.** Carbon, nitrogen, and organic matter (Mg/ha) in forest floor ((a), (b), and (c), respectively), and in mineral soil (0–30 cm depth) ((d), (e), and (f), respectively) 38 years after harvesting. Shaded bars represent burned treatments.

treatments actually increased organic matter on the soil surface in clearcut units (Table 3). Due to the abundant soil surface and belowground organic matter pools, the levels of organic matter and carbon pools of our study site were found within the ranges of those pools in the second growth western larch forests with similar age class and old-growth stands (Bisbing et al., 2010). We also found that the similar aboveground vegetation and coarse root biomass production with second-growth stands reported by Bisbing et al. (2010).

Soil carbon or organic matter pools in the forest floor and mineral soil were similar or slightly higher than carbon pools found in

an old-growth western larch stand (99.28 Mg C/ha: Bisbing et al., 2010). In addition, Page-Dumroese and Jurgensen (2006) found that in late-successional subalpine fir and western hemlock stands in northwestern Montana, forest floor and mineral soil organic matter pools ranged from 171 to 391 Mg/ha, while carbon pools ranged from 85 to 178 Mg/ha. Together, these three studies (ours, Bisbing et al. (2010) and Page-Dumroese and Jurgensen (2006)) show that there is significant variation in carbon, organic matter, and nitrogen pools depending on site and stand conditions. However, in all cases there was abundant storage or building of organic matter pools on the soil surface and in the mineral soil, which

should ameliorate concerns that soil organic matter might be exhausted by intensive biomass utilization.

#### 4.2. Vegetation response to harvest and burn treatments

Regeneration biomass of the shelterwood units was lower than both clearcut and group selection units, presumably because competition with retained overstory trees in shelterwood units limited the growth rate or stocking level of seedlings after harvest (e.g., Long and Roberts, 1992; Oliver and Dolph, 1992; Rose and Muir, 1997). Similarly, the result that group selection units had lower stand biomass than clearcut units suggests that regenerated trees were affected by the residual trees around cutting cluster boundaries (c.f. Table 3).

Although this study was implemented with a unique set of biomass utilization levels, the results are comparable to empirical studies contrasting the consequences between whole-tree harvesting and conventional (i.e., stem-only) harvesting. In northern Europe, tree response has been shown to decline with increasing levels of biomass utilization. For example, whole-tree harvesting reduced the dbh for 23-year-old planted Sitka spruce (*Picea sitchensis* (Bong.) Carrière) seedlings by ten percent, versus stem-only harvesting in North Wales (Walmsley et al., 2009). In an earlier study, whole-tree harvesting reduced the volume of planted Sitka spruce seedlings by 32% after 12 years, relative to conventional harvesting (Proe et al., 1996). In Scandinavia, Egnell and Leijon (1999) and Jacobson et al. (2000) found consistent reductions of tree growth for Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H. Karst.) stands 10–15 years after whole-tree harvesting, versus stem-only harvesting.

On the other hand, the continent-scale North American Long-Term Soil Productivity (LTSP) study illustrates another consequence of intensive biomass utilization (Powers et al., 2005). The general conclusion of the LTSP study is that biomass extraction intensity had no impact on vegetation growth 10 years after harvesting. However, there is substantial variation in vegetation response to biomass utilization intensity for species, soil disturbance, and elapsed time after harvesting (e.g., Egnell and Valinger, 2003; Kranabetter et al., 2006). Thus, examining the response of each species is necessary for a better understanding of the consequences of intensive biomass utilization (Kranabetter et al., 2006). At the CEF, except for the M\_U treatment in shelterwood, the results indicate that there was no evidence for reduced regenerated tree growth by biomass removal intensity, irrespective of regeneration cutting method and burning treatment. Therefore, our findings in this cool, wet ecosystem are generally consistent with those of the LTSP study.

One of the most prominent differences observed in this study was that the M\_U treatment in shelterwood cuts had the highest level of biomass production. However, the outcome was probably not due to difference in nutrients but to the presence of advance regeneration in this treatment. Since the M\_U treatment protected the understory vegetation, it retained abundant advance regeneration. Delay of natural regeneration on the other treatments exacerbated this difference. Shearer and Schmidt (1999) noted that the CEF had suffered from an intense western spruce budworm (*Choristoneura occidentalis* Freeman) outbreak around the harvest year, and Shearer (1980) reported that reproductive buds of conifers were damaged severely in 1974 by spruce budworm. Cone production was limited, so conifer regeneration was delayed for years; Shearer and Schmidt (1999) noted that the majority of regeneration (besides western larch) established after 1980. Therefore, we infer that the reason M\_U treatment in the shelterwood units produced the same amount of biomass as group selection was because of the success of immediate regeneration.

The combination of regenerated tree and shrub biomass was not different among treatments. In other words, even those few differences in regenerated tree biomass were offset by the inclusion of shrub biomass. This suggests that the difference in regenerated tree biomass was likely caused by different vegetation dynamics. The fact that there was no relationship between aboveground biomass production and carbon, nitrogen, and organic matter contents in the forest floor and mineral soil layers supports this theory.

#### 4.3. Soil response to harvest and burn treatments

Previous studies of soil responses to intensive biomass harvesting has produced conflicting results. A meta-analysis by Johnson and Curtis (2001) indicates that whole-tree harvesting tends to reduce soil carbon and nitrogen, whereas stem-only harvesting increased content of both elements. In contrast, several studies report no impact of biomass removal intensity on soil carbon or nitrogen budgets. Olsson et al. (1996) found no difference of soil carbon and nitrogen pools between whole-tree harvesting and stem-only harvesting in Swedish boreal forests 15–16 years after harvesting. Similar results were also found in the boreal forest of Canada (Thiffault et al., 2006). At the North America LTSP sites, treatments that retained an intact forest floor prevented any decline in soil carbon contents 5–15 years after harvesting (Kabzems and Haeussler, 2005; Powers et al., 2005; Kurth et al., 2014).

Our findings were generally consistent with the results from the LTSP study. Aside from the clearcut units, none of our measured soil properties were affected by biomass utilization intensity. The Pearson's correlation test between aboveground biomass and measured soil properties implies these soil properties were not limiting factors to aboveground biomass production.

It was unclear why the clearcut units exhibited differences in forest floor properties. We hypothesize that litterfall production in the clearcut units was sufficiently abundant to initiate organic matter accumulation on the forest floor, and that organic matter, carbon, and nitrogen contents in the forest floor responded to that litter production. Another result in the clearcut units is that higher biomass removal treatments and broadcast burning in clearcut units produced greater carbon, nitrogen, and organic matter in the forest floor than did the lower utilization levels. Presumably, this was related to the rapid recovery rate and cumulative organic matter production of the shrub layer. Schmidt (1980) reported that the recovery rate of the shrub layer four years after harvesting was higher in the clearcuts than other regeneration cuttings. In other words, intensive biomass removal decreased competition and increased the utilization of released nutrients, thus rapidly accelerating the understory recovery rate. Prolific understory vegetation annually produced abundant fresh litter, and resulted in elevated levels of forest floor organic matter. The fact that the pattern of each soil property within clearcut units showed an identical pattern with those of shrub biomass in clearcut units made this a plausible explanation. Turner and Long (1975) emphasized the importance of understory vegetation on site productivity in the early development stage of coastal Douglas-fir stands. Shrubs annually allocate relatively more organic matter into a fresh litter source (i.e., leaves) than do overstory trees. Thus, prompt understory re-vegetation after harvesting might have a significant impact on preventing adverse consequences to site productivity after harvesting.

## 5. Conclusion

We found that total organic matter pools at the ecosystem level were similar regardless of regeneration cuttings, and conclude that

there were no negative consequences of intensive biomass utilization on forest productivity 38 years after harvesting. This study indicated that at this relatively moist and cool site, long-term negative impacts of intensive biomass utilization on site productivity were not evident across all regeneration cutting methods. Regenerated trees showed some differences among regeneration cutting methods, but any differences in aboveground growth or composition was likely caused by inherent regeneration dynamics rather than disruption of soil carbon, organic matter, or nitrogen pools. Observed minor differences in biomass production among the biomass utilization treatments were also explained by regeneration dynamics rather than alteration of nutrient pools. The species composition of regenerated trees might be affected by utilization treatments, but the burning treatment seemed to be the factor of primary influence in determining species composition.

Furthermore, we observed no difference in soil pools associated with biomass utilization levels and the use of broadcast burning (albeit, burning) when the soil was cool and wet. Belowground carbon, nitrogen, and organic matter contents were not correlated with aboveground biomass, implying these soil properties were not limiting factors for vegetation growth. Soil properties of the mineral soil layer and forest floor were generally unaffected by biomass utilization levels. The few observed differences among soil properties at the forest floor followed clearcutting, and were attributed to the recovery and cumulative biomass production of the shrub layer, rather than to changes in soil properties.

These findings imply that intensified biomass removal from this forest type should not cause a decline in site productivity. Our results may not extend to other forest types, even within the northern Rocky Mountain region. Treatment effects can vary by diverse factors such as site conditions and species composition, so lesser productive, drier sites might exhibit different results. In addition, disturbance of the forest floor by other logging systems could produce different consequences. Whereas the skyline yarder technique used at our site minimized soil perturbation, intensive biomass removal through ground-based harvesting operations are more likely to adversely impact soils. Differences between our results and those from European trials might be caused by these factors. We conclude that subsequent studies comparing both more and less productive sites of various forest types, soil and climate conditions, and harvesting techniques are essential to fully understanding the relation of biomass utilization to site productivity for that range of circumstances.

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