LONG-TERM EFFECTS ON DISTRIBUTION OF FOREST BIOMASS FOLLOWING DIFFERENT HARVESTING LEVELS IN THE NORTHERN ROCKY MOUNTAINS

Waste to Wisdom: Subtask 4.6.1

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ABSTRACT

With increasing public demand for more intensive biomass utilization from forests, the concerns of adverse impacts on productivity by nutrients depletion is burgeoning. We remeasured the 1974 site of the Forest Residues Utilization Research and Development Program in northwestern Montana to investigate long-term impacts of intensive biomass utilization on site productivity. The historical experiment was implemented in a western larch (*Larix occidentalis*) forest as three biomass utilization levels (high, medium, and low) combined with prescribed burning treatments (burned and unburned) under three regeneration cuttings (clearcut, group selection, and shelterwood). Tree diameter at breast height and height, root collar diameter of shrub, and soil properties (C, N, and total organic matter) in the forest floor and mineral soil layer were measured. Regenerated tree, shrub, and total aboveground biomass and total C, N, and organic matter contents of soil layers were calculated. The results indicated that there are no statistical differences among the utilization treatments for either aboveground biomass production or soil properties by the intensity of biomass extraction 38 years after harvest. Minor observed differences seem to originate not from the alternation of nutrient conditions, but from factors such as regeneration dynamics and response to burning treatment. The results imply that site productivity is generally unaffected by biomass utilization levels in this forest type.

Keywords: Biomass harvesting; Soil productivity; Western larch forest; Long-term impact; Logging residues; Regeneration dynamics

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INTRODUCTION

The increasing cost of fossil fuels and emerging public concerns to climate change have shifted the dominant viewpoint on forest woody biomass. That is, residual woody biomass after cutting, such as slash and cull, as well as snags and coarse woody debris can be an alternative feedstock to fossil fuels. On a global scale, harvesting removes less than 66% of total biomass from forests (Parrikka 2004). In northern Rocky Mountains forests, only about half of total woody biomass is typically extracted (Benson and Schlieter 1980). Even though it has been several decades since the Benson and Schlieter's 1980 report, the harvesting convention for biomass utilization in the West seems to have remained the same (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 was 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). Therefore, it is highly likely that federal policies will spur forest woody biomass utilization as a new energy feedstock, and some efforts have been already undertaken. The Energy Policy Act of 2005 and the Energy Independence and Security Act (EISA) of 2007 are the good examples of these efforts. As a result, forest harvesting involving more expanded removal of woody materials such as whole-tree harvesting or energy-wood harvesting (sensu Benjamin et al. 2010) would prevail.

Several ecological concerns of increased biomass removal have been expressed by many scientists. Increased biomass removal may 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 primarily conducted (Thiffault et al. 2011). Of primary concern is that more intensive woody biomass removal might deplete nutrient budgets, resulting in reduction of site productivity. However, since a majority of these studies addressed short-term consequences, the longterm impact on site productivity is still widely unknown. Moreover, research of the inland Northwest forests is relatively limited in this regard. Therefore, research examining the longer-term impacts of increased biomass utilization on site productivity of northern Rocky Mountains is required.

Site productivity is generally defined as the capacity of a site to produce the vegetative biomass. Diverse methods (e.g., site index) have been suggested to measure site productivity directly or indirectly (for details, see Skovsgaard and Vanclay 2008). Among them, measuring stand volume growth provides the most straightforward way to monitor the site productivity. However, the stand volume growth can be variable, since individual tree growth can be affected by various factors such as tree age, stand developmental stage, stocking level, and management history (Powers 2006). Fortunately, these sources of variation can be minimized by the controlled experiments. For example, an indirect alternative measurement of productivity might involve measuring soil properties such as soil nutrients and/or physical conditions which can provide reliable and unbiased methods to evaluate stand growth potential (Powers 2006).

In that sense, the Coram Experimental Forest in western Montana provides a timely opportunity to investigate long-term impacts of intensive biomass utilization on forest productivity. A multidisciplinary research program was conducted to confront the energy crisis in 1970s. One objective of the research effort was to reduce adverse ecological consequences while leaving minimum residual materials (Barger 1980). Various levels of biomass utilization treatments were applied under common regeneration cuttings.

This paper addresses the impact of biomass utilization intensity and prescribed fire on forest productivity 38 years after harvesting in the mixed coniferous forest of northern Rocky Mountains.

STUDY SITE – CORAM EXPERIMENTAL FOREST

This study was conducted in the Upper Abbot Creek Basin (48°25'N, 113°59'W) of Coram Experimental Forest in northwestern MT (Figure 1). Coram Experimental Forest was established in 1933, and comprises 3,019 ha of the Hungry Horse Ranger District of the Flathead National Forest. It is located 20 kilometers east of Columbia Falls, and 9 kilometers south of Glacier National Park. The elevation of the Coram Experimental Forest ranges from 1,195 to 1,615 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 890-1,270 mm, averaging 1,076 mm (Farnes et al. 1995). Most precipitation occurs in the form of snow during November - March. The mean annual temperature is 2 °C to 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 soil on the Coram Experimental Forest. The mixture of these soil components created the rich-loamy soils in this area. Although soils on the Coram Experimental Forest can be classified into 6 categories, soil on our study area is classified as a loamy-skeletal isotic Andic Haplocryalf (Soil Survey Staff, 2006) Stands in Coram Experimental Forest were classified into three potential climax vegetation associations (i.e. habitat type) by Pfister and others (1977): subalpine fir (*Abies lasiocarpa* (Hook.) Nutt/queen-cup bead lilly

(*Clintonia unifloria* (Menzies ex Schult. & Schult. f.) Kunth; (ABLA/CLUN), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco/ninebark (*Physocarpus malvaceus* (Greene) Kuntze); (PSME/PHMA), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg)/queen-cup bead lily (TSHE/CLUN). The dominant habitat type in our study area is ABLA/CLUN (Shearer and Kempf 1999).

Coram Experimental Forest has a suitable condition for a various mixture of coniferous species (Shearer and Kempf 1999). The majority of the forest is composed of western larch (*Larix occidentalis*) cover type (Society of American Foresters Cover Type 212, Eyre 1980), associated with Douglas-fir (*Pseudotsuga menziesii*), subalpine fir (*Abies lasiocarpa*), and spruce (*Picea engelmannii* and *P. glauca*), including western hemlock, (*Tsuga heterophylla*) and wester redcedar (*Thuja plicata*). Paper birch (*Betula papyrifera*), black cottonwood (*Populus trichocarpa*), and quaking aspen (*P. tremuloides*) are the main broadleaf tree species. The major shrub species include twinflower (*Linnaea borealis*), ninebark (*Physocarpus malvaceus*), shiny-leaf spiraea (*Spiraea betulifolia*), kinnikinnick *(Arctostaphylos uva-ursi*), Sitka alder (*Alnus sinuate*), Scouler's willow (*Salix scouleriana*), and huckleberry (*Vaccinium globulare*) (Shearer and Kempf 1999). The dominant conifer on our study area is western larch with a site index at base age 50 from 15.24 to 18.28 m (Schmidt et al. 1976).

METHODS

Experimental design

The experimental design consists of the combination of three regeneration cuttings (shelterwood, clearcut and group selection) with four biomass utilization levels (Figure 1). Four biomass utilization treatments are composed of three removal levels (high, medium, and low) and subsequent burning treatments (see Table 1 for experimental design details). The treatments were established in 2 replications at two different elevations (1,195 m - 1,390 m and 1,341 m - 1,615 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 from 0.1 to 0.6 ha in size) were arranged in four rows and two columns. In this case, biomass utilization subunits were randomly allocated into cluster pairs. Since our study sites are on steep slopes, 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^3/ha. 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 two of four treatments. 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, broadcastburning could not be applied to lower replication of the shelterwood units since the moisture contents of dead fuel and duff were above the prescription limits (Artley et al. 1978; Schmidt 1980). As a result, an extra treatment (i.e. low-unburn treatment) was conducted only in the lower shelterwood unit. Since this additional treatment renders the experimental design unbalanced and causes the singularity problem to analyze the interaction between regeneration cutting effect and biomass utilization effect, the treatment was excluded from the analyses.

Data collection and analysis

Historical permanent points were re-used for this project. Permanent points were monumented by metal stakes, paint, and marking tapes. From 2010 to 2011, all the permanent points were revisited and identified. A total of 40 points were located within each cutting unit.

Ten permanent points were systematically located in each biomass utilization subunit in a 2 × 5 grid at 30.5 m intervals. Eight of clusters (4 rows × 2 columns) comprised each group selection unit. Five points were allocated within each cluster. Each treatment was randomly applied to two of eight clusters, respectively.

The sampling design was established following pilot vegetation data collection in 2010. Since the pilot data showed that the current tree sizes require bigger sample size than the original sampling design, a new sampling design was developed for tree surveys. Nested circular plot systems were applied. Three concentric circular plots were established to measure trees that regenerated post-treatment using permanent point as plot center (Table 3). Shelterwood units contained residual (unharvested) trees, thus a forth (larger) plot was added to the nesting system. The plot sizes varied according to the measured tree sizes.

In summer 2012, all 280 permanent points in every cutting unit were surveyed as tree plots. 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. Measurement was used for the computation of biomass using published, species-specific biomass equations (Table 4).

Soil sampling and laboratory analyses

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 . For group selection units, three soil sampling points were assigned to each harvest gap. Each sampling point was located 30.48 m apart each other. 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 the depth recorded. Organic material <0.6 cm 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 representative 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 20-30cm). Each soil sampling depth was placed in a ziptype bag and returned to the laboratory for processing. 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 cubsamples were ground to pass a 0.04-mm mesh and analyzed for total carbon and nitrogen with a LECO-600 analyzer (LECO Corp, St. Joseph, Mich.). Total organic matter contents were measured by the weight loss after 8-h-combustion at 375°C (Ball 1964). Woody debris sampling was conducted using transects (Brown 1974) . Mineral soil carbon, nitrogen, and organic matter contents were corrected for coarse-fragment content and extrapolated to a hectare basis using the fine-fraction bulk density (Cromack et al. 1999). We did not analyze the coarse-fragment component (>2 mm), which has been found to contain appreciable amounts of carbon and nitrogen in some soils (Harrison et al. 2003; Whitney and Zabowski 2004).

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 except retained trees in shelterwood units), shrub biomass, and total aboveground biomass (regenerated tree + shrub biomass), and tested. For speciesspecific analysis, five major species (Douglas-fir, subalpine fir, Engelmann spruce, western larch, and paper birch) were selected. Shrub layer was divided into three layers (high, medium, and low) following the Brown's (1976) classification for the analyses.

Explanatory variables were regeneration cutting, biomass utilization treatment, and interaction between two factors (Table 1). Block was treated as a random effect. Since the biomass utilization treatments are compounded with burning treatment and biomass utilization levels as incomplete factorial manner, three linear contrasts were introduce to test the treatment effects within a regeneration cutting. To test the effect of biomass utilization levels, high/unburn and low/burn treatments were compared with medium/unburn and medium/burn treatments, respectively. Examining the burning treatment effect, medium/unburn and medium/burn treatment were compared with each other. For shrub biomass evaluation, above layer's biomass were tested as a covariate. All analyses were conducted through **R** (R Development Core Team 2008); *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.

RESULTS

Ecosystem biomass distribution

Mean ecosystem biomass consisting of trees, shrubs, forbs and grasses, forest floor, and mineral soil was 377.8 Mg/ha across all regeneration cutting units (Table 5; Figure 2). In the clearcut and group selection units, 347.2 and 291.9 Mg/ha of biomass were distributed from mineral soil layer to overstory vegetation. In the shelterwood unit, the biomass of trees retained from the previous harvest was approximately 29% of the total ecosystem biomass and 85% of total aboveground biomass.

In general, the 38 years after harvesting the forest floor was the biggest organic matter pool. Approximately 44% (166.6 Mg/ha) of total organic matter in the ecosystem was found in the forest floor. When the forest floor is combined with mineral soil (70.5 Mg/ha) organic matter pools), more than 60 % of total ecosystem organic matter is distributed in belowground pools. The forest floor and mineral soil organic matter pools are approximately 3 times of the organic matter biomass of aboveground vegetation including retained trees in shelterwood units.

Vegetation response to harvest and burn treatments

Total aboveground biomass (including trees, shrubs, forbs, and grasses) production in clearcut units showed the highest production 38 years after harvesting at the study site (Table 5, Figure 3-a). The mean aboveground biomass in clearcut units were 61.6 Mg/ha (SE = 5.1 Mg/ha). The mean aboveground biomass in the group selection and shelterwood were 45.9 (SE = 4.4) and 20.8 (SE = 3.6) Mg/ha, respectively. The test result of analysis of variance (ANOVA) indicated that there was insignificant evidence for the differences of biomass production among regeneration cuttings and biomass utilization levels (Table 6). The linear contrast among biomass utilization levels and burning treatments indicated that total aboveground biomass production was not affected by these factors regardless of regeneration cutting method (Table 7).

Naturally regenerated tree biomass followed a similar pattern to total aboveground biomass (Figure 3). Regenerated tree biomass accounted for 84% of total aboveground biomass. Clearcut units showed the highest tree biomass production (56.0 Mg/ha; SE = 3.1 Mg/ha). Regenerated tree biomass in the group selection and shelterwood units were 34.5 (SE= 3.5) and 19.7 (SE=2.8) Mg/ha. Unlike total aboveground biomass, the ANOVA results displayed a significant difference between regeneration cuttings and biomass utilization levels (Table 6; P<0.01. The M-U medium-unburn treatment in the shelterwood cuts had higher biomass production than H-U and and M-B treatments (consider adding p values here). Regenerated tree biomass in clearcut and group selection units was not different from each other.

Five major tree species (subalpine fir, Douglas-fir, Engelmann spruce, paper birch, and western larch) composed 96 % of total regenerated tree biomass. Mean height, dbh, and crown ratio of regenerated trees were 4.8 m, 5.1 cm, and 64.4%, respectively. Paper birch and western larch was relatively unaffected by these biomass utilization treatments (Table 7). Subalpine fir had a decreasing trend of biomass production with burning . Burning also decreased biomass of

13.3 and 12.8 Mg/ha of biomass in group selection (pvalue: 0.00416) and shelterwood units (p-value: 0.04072). However, biomass utilization intensity had no statistically significant impact on the biomass of regenerated subalpine fir trees. In contrast, Douglas-fir biomass increased 16.0 Mg/ha (P= 0.036) in the clearcut unit. However, Engelmann spruce responded in a similar manner to subalpine fir where broadcast burning decreased biomass production by 0.7 and 9.3 Mg/ha of in the medium biomass utilization level in clearcut and shelterwood units. In addition, the high biomass removal without broadcast burning decreased Engelmann spruce biomass production by 9.0 Mg/ha as compared to ??? .

Although high-stature (see if you like that name) shrub biomass seemed unaffected by biomass utilization treatments (Table 6), there was a significant difference between the M-B and L-B treatments in the group selection harvest units (Table 7). The M-B treatment in group selection increased tall shrub biomass by 13.9 Mg/ha (p= 0.009) and was the major reason there was a significant increase in total shrub biomass. Low-stature shrub biomass increased 1.1Mg/ha (p= 0.014) in H-U treatment as compared to the M-U treatment.(see comment),. The M-B low-stature shrub biomass was 1.4 Mg/ha while the M-B biomass was 1.3 Mg/ha (p= 0.038) over medium/unburn treatment in shelterwood unit. High-stature shrub biomass production was not influence by overstory tree biomass. Similarly, medium- and lowstature shrub biomass production was not influenced by high and medium shrub biomass, respectively.

Soil response to harvest and burn treatments

Forest floor organic matter, carbon, and nitrogen pools all showed a similar pattern (Figure 4-a, b, and c). The interaction terms between regeneration cutting and utilization treatment were significant for all forest floor analyses (Table 6). However, the significant differences of organic matter, carbon, and nitrogen pools along in the biomass utilization treatments were only observed in clearcut units (Table 7). Increased biomass utilization intensity (i.e. H-U vs M-U and M-B vs L-B) tended to increase OM, C, and N . In addition, broadcast burning also 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 in the clearcut.

In the mineral soil profile (0-30 cm depth), organic matter poolswereunaffected by biomass utilization treatment, regeneration cutting method, or broadcast burning? (Table 6). Carbon and nitrogen pools in mineral soil layer were significantly different among the biomass utilization treatments. However, the statistical differences of soil carbon and nitrogen pools were only found between the H-B and M-U clearcut treatments. . The H-U clearcut subunits had 24.4 Mg/ha (p<0.001) more carbon and 0.5 Mg/ha (p=0.040) more N than the M-U treatment.

DISCUSSION

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). Biomass production can be directly converted into carbon content, thus we can compare our results with results of other ecosystem carbon distribution research. Bisbing et al. (2010) reported that the mean overstory carbon content (i.e. about 50% of wood biomass) of western larch stands 40 years after harvest was 23.83 Mg C/ha, assuming the carbon contents of wood is 50%. Similary, the overstory carbon content of our study site 38 years after harvest was 22.64 Mg C/ha (excluding shelterwood units). This level of overstory biomass is one-third of the overstory biomass in old-growth western larch stands of western Montana.

Although some intensive biomass utilization treatments were installed at CEF, there are few soil impacts noted 38 years after harvesting. These sites were skylined logged and few detrimental soil impacts were noted. When this study was initiated in 1974 there was concern that the use of broadcast burning and intensive utilization of woody material would deplete a site of C, OM and nitrogen cycling abilities (Harvey et al. 1976). In particular, after 38 years woody residue on the soil surface was unaffected by the utilization and burning treatments on this site

(Table 5). In addition, due to the abundance soil surface and belowground organic matter, our study are had more than 1.5 times greater OM and C pools than other second growth western larch forests, and approximately 1/2 the amounts found in old-growth larch stands (citation). Soil carbon or organic matter pools in the forest floor and mineral soil were 133.7 Mg C/ha and 237.02 Mg OM/ha, respectively (excluding coarse woody debris C) and are slightly higher than C pools found in an old-growth western larch stand (99.28 Mg C/ha: Bisbing et al. 2010). However, in a study evaluating soil pools, Page-Dumroese and Jurgensen (2006) found that in late-successional subalpine fir and western hemlock stands in northwestern MT that forest floor and mineral soil organic matter pools ranged from 171-391 Mg/ha while carbon pools ranged from 85-178 Mg/ha. /*Menziesia ferruginea* Sm. (rusty menziesii). These three studies (ours, Bisbing et al., 2010, Page-Dumroese and Jurgensen 2006) show that there is significant variation in carbon, organic matter, and nitrogen pools depending on site and stand conditions in old-growth, second growth, and late-successional stands which makes a conclusion difficult. However, in all cases there is abundant storage or building of organic matter pools on the soil surface and in the mineral soil to ameliorate concerns that soil organic matter might be exhausted by intensive biomass utilization in this region.

Thirty-eight years after harvest and site treatment (utilization and broadcast burning), a majority of OM was in the forest floor as compared to the mineral soil. This is similar to the distribution OM in some late-successional stands in the Inland northwest, but many forest types show a pattern of greater OM in the mineral soil than in the forest floor (Page-Dumroese and Jurgensen 2006. For this CEF site, high organic matter contents in forest floor are likely related to prolific understory vegetation production. Bisbing (2010) reported that the carbon pools of adjacent old growth and second growth western larch stands in northwestern MT were 0.23 and 0.44 Mg C/ha, respectively. Carbon pools of the understory at our site was 3.42 Mg C/ha. Thus, we speculate that the abundant shrub vegetation contributed to increased depth of the forest floor and therefore greater OM pools. Thick forest floor layers are regulated by site microclimate resulting in slower or faster organic matter decomposition rates. In many inland NW stands, most of the carbon and organic matter pool are held on the soil surface (inclusive of woody residue C) whereas nitrogen pools are primarily located in the mineral soil (Page-Dumroese and Jurgensen 2006). On our study sites N was…. (add something good here),

The calculated biomass of tree regeneration excluded retained tree biomass increment in shelterwood units, therefore, biomass production of those units was lower than both clearcut and group selection units. In addition, competition with retained overstory trees in shelterwood units could limit the biomass production of seedlings after harvesting (e.g. Long and Roberts 1992; Oliver and Dolph 1992; Rose and Muir 1997). Similarly, group selection units had lower stand biomass than clearcut units which suggests that regenerated trees might be affected by the residual trees around a patch boundary (Table x or Figure x).

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. However, there is continental disagreement among these experiments. In northern Europe, tree response was reduced with increasing levels of biomass utilization. For example, a ten percent reduction of dbh for 23-year-old planted Sitka spruce (*Picea sitchensis* (Bong.) Carrière) seedlings was observed in whole-tree harvesting compared with stem-only harvesting in North Wales (Walmsley et al. 2009). In an earlier UK study, 12-year-old planted Sitka spruce seedlings after whole-tree harvesting had 32 percent less volume than stem-only harvesting (Proe et al. 1996). In the Scandinavian region, Egnell and Leijon (1999) and Jacobson et al. (2000) found consistent reductions of tree growth for Scots pine (*Pinus …* and Norway spruce (*Picea…)* stands 10-15 years after whole-tree harvesting. On the other hand, the continental-scale experiment of the North American Long-Term Soil Productivity (LTSP) study illustrates another consequence of intensive biomass utilization. The general conclusion of the LTSP study is that the intensity of biomass extraction had no impact on vegetation growth 10 years after harvesting (Powers et al. 2005). However, there is sizable variation in vegetation response to biomass utilization intensity in accordance with 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 better understanding of the consequences of intensive biomass utilization (Kranabetter et al. 2006). At the Coram EF, except for the M-U treatment in shelterwood, the results indicate that there is no evidence for reduced regenerated tree growth by biomass removal intensity, irrespective of regeneration cutting method (and burning?). 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 is that biomass of the M-U treatment in shelterwood cuts had the highest level of biomass production (Figure 3-b). However, the presence of advanced regeneration in this treatment played a critical role in the outcome. Since the M-Utreatment protected the understory vegetation (Table 1), it retained abundant advanced regeneration (Table 2). Thus, this treatment successfully enabled immediate regeneration establishment. Moreover, the delay of natural regeneration establishment on the other treatments makes this difference more obvious. Shearer and Schmidt (1999) suggested that the Coram Experimental Forest had suffered from an intense western spruce budworm (*Choristoneura occidentalis*) outbreak around the harvest year. Shearer (1980) reported that the most reproductive buds of conifers were damaged in 1974 by spruce budworm. In addition, cone production was limited, so conifer regeneration was delayed for years. Therefore, we infer that the reason M-U treatment in shelterwood units produce the same amount of biomass as group selection is not because of nitrogen nutrient changes associated with the harvest types, but because of the success of immediate regeneration.

Combining regenerated tree and shrub biomass results in no difference among treatments in the he overall aboveground biomass. Inclusion of shrub biomass results in few differences in aboveground biomass production in spite of the regenerated tree layer. This result also supports the former suggestion that the difference in regenerated tree biomass was caused by vegetation dynamics rather than soil nitrogen, OM or C conditions. Similarly, scatter plots presenting the relationship between aboveground biomass and carbon, nitrogen, and organic matter contents in the forest floor and mineral soil layer reveal no correlations, further supporting this suggestion (Figure 5).

Our results indicate that species composition is altered by biomass utilization treatments, since the response of each species differed across treatments. However, these differences can be primarily attributed to broadcast burning rather than the intensity of biomass extraction. Significanct differences wereobserved broadcast burned and unburned treatments (Table 7). Namely, the current species composition is a result of the response of each species after broadcast burning and subsequent site recovery. The most juvenile conifers are vulnerable to fire, thus broadcast burning likely killed the most of advanced regeneration. Since subalpine fir and Engelmann spruce show relatively slower initial seedling growth than other coniferous species (i.e. western larch and Douglas-fir), the elimination of advanced regeneration in company with the hindrance of immediate regeneration by the budworm may have substantially reduced the relative proportions of these species. Meanwhile, Douglas-fir seems to have benefited from broadcast burning through decreased competition.

Thirty-eight years after harvesting biomass production of the shrub layer at the study site has exceeded the pre-harvest level of shrub biomass. Biomass of the shrub layer prior to harvesting was 5.91 Mg/ha on average (Schmidt 1980) and the current shrub layer biomass is 7.0 Mg/ha;shrub biomass recovery has exceeded that of the pre-harvest stand by 20%. However, it seems that recovery of understory vegetation was completed rather early. Schmidt

(1980) reported that 56% and 75% of total shrub biomass were recovered within 2 and 4 years after harvest, respectively. Thus, we can expect that the shrub layer likely played a relatively more important role in building the forest floor organic matter pool than the regenerated trees in the early post-harvest stage.

Tall shrub layer biomass production at the M-B treatment in the group selection units has considerable biomass, mostly attributed to Rocky Mountain maple (*Acer glabrum* Torr.). Total shrub biomass was overwhelmed by the production of the maple in this treatment. In fact, the biomass of maple in this treatment was 18.7 Mg/ha (84% of total shrub biomass, whereas maple averaged 48% of biomass in other treatments) and is more than 10 times greater than the biomass of maple in other treatments. Since broadcast burning conditions in 1975 were not favorable, the fire was relatively benign (Artley et al. 1978). As a result, roots of mature maples likely survived the fire and sprouting proliferated; strengthened by increased resource availability and decreased competition. Therefore, it seems that the observed increase of the tall shrub layer was not associated with direct changes in soil N and OM.

Similar to the vegetation responses, soil response to intensive biomass harvesting is also somewhat contradictory. The meta-analysis of Johnson and Curtis (2001) suggested that whole tree harvesting tended to reduce soil carbon and nitrogen, whereas stem-only harvesting increased content of both elements. In contrast, there are several studies reporting 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. Consistent results were also found in the boreal forest of Canada (Thiffault et al. 2006). The continent-wide LTSP sites suggested that there was no decline of soil carbon contents 5 to 15 years after harvesting as long as the intact forest floor was retained (Kabzems and Haeussler 2005; Powers et al. 2005; Kurth et al. 2014).

Our findings were consistent with the results from the LTSP study. Setting aside the clearcut units, none of soil properties were affected by biomass utilization intensity. The Pearson's correlation test indicated there was no evidence for the correlation between aboveground biomass and measured soil properties (Figure 5), implying these soil properties were not the limiting factors to the aboveground biomass production. Since nitrogen often plays a limiting factor of tree growth in this region due to low nitrogen mineralization levels (DeLuca and Zoubar 2000), we expect that these results should lessen concerns that increased biomass extraction may exacerbate a long-term nitrogen limitation in this region.

It is unclear why we observed differences forest floor properties in the clearcut unit. We hypothesize that litterfall production from aboveground vegetation in clearcut units was abundant enough to begin to accumulate organic matter on forest floor. Thus, organic matter, carbon, and nitrogen contents in the forest floor responded to annual litter production. Another interesting result is that higher biomass removal treatments combined with broadcast burning in clearcut units resulted in more carbon, nitrogen, and organic matter in the forest floor than lower utilization levels. Presumably, this is 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 clearcut than other regeneration cuttings. In other words, intensive biomass removal decreased competition and increased the utilization of released nutrients, thus rapidly accelerating initial understory recovery rate. Proliferated understory vegetation annually produced abundant fresh litter. As a result, shrub and overstory tree cumulative litter production resulted in elevated levels of organic matter in forest floor. The fact that the pattern of each soil property of Figure 4-a, b, and c within clearcut units showed an identical pattern with those of shrub biomass in clearcut units at Figure 3-c makes this plausible explanation. Tuner and Long (1975) also emphasized the importance of understory vegetation on site productivity in the early development stage of coastal Douglas-fir stands. Shrubs allocate relatively more organic matter into an annual fresh litter source (i.e. leaves) than overstory trees do. Thus, prompt understory re-vegetation after harvesting might have a significant impact on preventing adverse consequences to site productivity after harvesting.

However, soil pool differences in the forest floor did not lead to the differences in mineral soil layer (Table 7). It seems that the majority of carbon from the forest floor was not incorporated into mineral soil layer, but released to atmosphere as CO_2 (Palviainen et al. 2004; Kurth et al. 2014). This also supports the presumption that the primary carbon inputs to the mineral soil pool originate not from aboveground litter fall, but from root turnover in the soil layer (Powers et al. 2005). Despite this, the importance of the organic matter pool in forest floor should not be overlooked because of other critical functions, such as the reservoir of essential nutrients and regulation of belowground microclimate and water balance.

In conclusion, we failed to find any negative consequences of intensive biomass utilization on forest productivity 38 years after harvesting. Regenerated trees showed some differences among harvesting method, and any differences in aboveground growth or composition is likely caused by inherent regeneration dynamics rather than soil C, OM, or N pools . Species composition of regenerated trees might be affected by utilization treatments, but burn treatment was a more influential factor in determining the current species composition. Furthermore, we observed no difference in soil pools to biomass utilization levels and the use of broadcast burning when the soil was cool and wet. These major findings suggest no decline of long-term site productivity by increased biomass utilization levels.

Our findings imply that more intensified biomass removal from forests would not cause the decline of long-term site productivity in this forest type. However, our results may not be appropriate for other forest types, even within the northern Rocky Mountain region. Treatment effects can vary by diverse factors such as site conditions and species composition (Thiffault et al. 2011). Less productive or drier sites might have substantially different results from this study. In addition, disturbance of the forest floor by other logging systems can result in different consequences. Whereas we were able to minimize the soil perturbation through skyline yarder technique, intensive biomass removal through ground-based harvesting operation may adversely impact soils. Differing consequences in European trials might be caused by these reasons. Therefore, subsequent studies comparing both more and less productive sites of various forest types, different soil and climate conditions, and various harvesting techniques are essential to fill the knowledge gaps.

CONCLUSION

This study indicated that on this relatively moist, cool site, long-term negative impacts of intensive biomass utilization on site productivity is not evident across all regeneration cutting methods. Observed minor differences in biomass production were derived by regeneration dynamics rather than alteration of nutrient pools. Belowground carbon, nitrogen, and organic matter contents were not correlated with aboveground biomass, implying these soil properties are not limiting factors for vegetation growth. Soil properties of mineral soil layer and forest floor were generally not affected by biomass utilization levels. The differences among soil properties at the forest floor following clearcut were attributed to recovery and cumulative biomass production of the shrub layer.

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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[1]	Max. size of retained woody materials[2]	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	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

[1] Except designated overstory shelterwood trees

[2] Live and dead down logs (small-end diameter × length); for dead down logs, they were removed if sound enough to yard.

Table 2. Volumes of all woody material (>7.62 cm diameter, unit: m^3/ha) pre- andpost-harvest (Benson and Schlieter 1980). Utilization treatment levels are listed in Table 1. Block 1 and 2 are low and high elevation replication, respectively. Numbers in parentheses of post-harvest volume column represent retained overstory tree/sapling volumes.

Harvest/Treatment	Pre-harvest Volume		Post-harvest Volume		Removed Volume	
	Block1	Block2	Block1	Block2	Block1	Block2
Shelterwood						
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 ([1]77/ 2)	270 (134/ 1)	211	200
Group Selection						
M_U	694	715	92 (0/ .1)	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

[1] M_U: medium/unburn, H_U: high/unburn, L_B: low/burn, M_B: medium/burn (refer to Table 1).

Table

Clearcut						
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

3. Plot size and radius for vegetation sampling and tree sizes measured .

Vegetation type	Classification	Plot size	Plot radius (m)	Sampled tree size
Trees	Residual trees	1/20th ha	12.62	≥25cm dbh
	Poles	1/100th ha	5.64	≥10 and <25 cm dbh
	Saplings	1/500th ha	2.52	<10 cm dbh and ≥ 137cm ht
Seedling and Shrubs	Low shrubs	1/5000th ha	0.80	<100 cm ht
	High shrubs	1/1000th ha	1.78	≥100 cm ht

Table 4. References for biomass calculations.

Vegetation layer and species	References
Trees ponderosa pine, white pine, black cottonwood	Standish *et al*. (1985)
Douglas-fir, Engelmann spruce, lodgepole pine, subalpine fir, western red cedar, western hemlock	Ung *et al*. (2008)
western larch	Gower *et al*. (1987)
All Shrubs	Brown (1976)

Table 5. Ecosystem biomass (Mg/ha) distribution of each compartment 38years after harvesting. Values in parentheses are standard error of the mean.

Regeneration Cutting	Biomass Utilization Treatment	Retained Tree	Regenerated Tree	Understory[1]	Woody Debris	Forest Floor	Coarse Roots[2]	Mineral Soil	Total Ecosystem
Clearcut	M_U[3]	-	48.1 (6.5)	5.1 (2.1)	43.2	125.9 (18.3)	12.5 (1.7)	62.4 (4.4)	297.2
	H_U	-	59.3 (7.0)	7.1 (1.7)	9.4	280.6 (73.3)	15.4 (1.8)	81.6 (8.7)	453.4
	L_B	-	61.1 (6.1)	4.7 (1.4)	58.1	123.5 (23.9)	15.9 (1.6)	71.2 (15.2)	334.5
	M_B	-	55.6 (5.2)	7.8 (3.2)	11.7	269.9 (46.6)	14.5 (1.4)	66.7 (4.3)	426.2
Group Selection	M_U	-	32.8 (5.8)	7.5 (2.3)	73.7	191.6 (40.9)	10.7 (1.5)	58.4 (5.3)	374.7
	H_U	-	35.7 (5.5)	4.1 (0.8)	76.4	137.1 (36.4)	9.3 (1.4)	71.5 (8.3)	334.1
	L_B	-	37.1 (4.5)	4.8 (2.6)	37.6	186.8 (35.5)	9.7 (1.2)	78.2 (5.9)	356.2
	M_B	-	32.6 (4.7)	18.7 (6.5)	89.5	159.4 (33.5)	8.6 (1.3)	72.9 (11.0)	381.7
Shelterwood	M_U	125.2 (11.3)	33.9 (5.0)	6.7 (3.0)	23.0	118.5 (20.3)	41.4 (3.8)	59.7 (5.3)	408.4
	H_U	105.5 (11.2)	11.2 (3.6)	4.2 (1.2)	18.9	88.1 (16.3)	30.3 (3.9)	75.7 (9.7)	333.9
	L_B	123.9 (13.6)	4.6 (2.8)	6.7 (3.2)	13.7	129.9 (36.0)	33.4 (3.2)	63.3 (4.2)	375.5
	M_B	106.5 (16.9)	9.0 (2.9)	4.8 (1.8)	35.8	187.6 (25.3)	30.0 (2.7)	83.8 (19.2)	457.5

[1] Shrub and seedling biomass was combined.

[2] Coarse roots biomass were estimated through the equation of Carins et al. (1997). The ratio of 0.26 to overstory biomass was applied.

[3] M_U: medium/unburn, H_U: high/unburn, L_B: low/burn, M_B: medium/burn (refer to Table 1).

Table 6. Result summary of ANOVA for aboveground biomass and soil properties. – should you also show the Burn treatments?

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***[1]	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 (0-30cm)						
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**

[1] Significance codes: 0 < *** < 0.001< ** < 0.01 < * < 0.05.

Table 7. Test results of the linear contrasts for aboveground biomass and soil properties (units: Mg/ha).

Response variables	H_U – M_U[1]			M_B – L_B			M_B – M_U		
	CC[2]	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**[3]	-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

[1] M_U: medium/unburn, H_U: high/unburn, L_B: low/burn, M_B: medium/burn (refer to Table 1).

[2] CC: clearcut, GS: group selection, SW: shelterwood harvest.

[3] Significance codes (p-value): 0 < *** < 0.001< ** < 0.01 < * < 0.05.

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Mineral soil (0-30cm)									
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

FIGURE CAPTIONS

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

Figure 2. Ecosystem biomass distribution of the experimental units 38 years after harvesting at Coram Experimental Forest, MT.

Figure 3. Biomass production 38 years after harvesting for (a) total aboveground, (b) regenerated trees, and (c) shrub layer. Error bar represents standard error of the mean biomass production.

Figure 4. Carbon, nitrogen, and organic matter (Mg/ha) in forest floor ((a), (b), and (c), respectively), and in mineral soil (0-30cm depth)((d), (e), and (f), respectively) 38 years after harvesting. Shaded bars represent burned treatments.

Figure 5. Scatter plot between aboveground biomass production and (a) carbon, (b) nitrogen, and (c) organic matter (Mg/ha) in forest floor (open circle) and mineral soil layer (closed circle).

P-values for Pearson's correlation test were presented with legends.