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Research paper

Negligible impacts of biomass removal on Douglas-fir growth 29 years after outplanting in the northern Rocky Mountains

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ABSTRACT

To investigate the long-term impacts of biomass harvesting on site productivity, we remeasured trees in the 1974 Forest Residues Utilization Research and Development Program at Coram Experimental Forest in western Montana. Three levels (high, medium, and low) of biomass removal intensity combined with broadcast burning treatment were assigned after clearcut in western larch (*Larix occidentalis* Nutt.) stands in 1974. From 1976 to 79, twenty five 2 + 0 bare root seedlings of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) were consecutively planted in rows. In 2013, tree height, dbh (diameter at breast height), foliar N and C concentrations were measured. From cross-sectional sapwood area, growth efficiency (the ratio of 5-year-basal area increment to total leaf area) was calculated. Previous measurements from 1980, 1987, 1992, and 2001 were used for dbh and height growth analyses. At this site, none of the response variables were affected by biomass removal level. Only seedling planting year contributed significantly to affect tree mean height, dbh, volume. Growth efficiency was not affected by any treatment. These results indicate no apparent effect of biomass removal on site productivity for the range of biomass harvest levels performed.

1. Introduction

Forest biomass harvesting for bioenergy, which involves extracting biomass from a site that is above the level of extraction typically associated with conventional timber harvesting, is emerging as a source of alternative energy feedstocks, due mainly to public concerns over use of fossil fuels and climate change [1]. Conventional harvesting produces a considerable amount of woody biomass residues. Those are usually left on the ground, broadcast burned, or piled and burned to reduce wildfire hazard. Intensive removal of woody biomass residues is not a wholly new concept. Whole-tree harvesting has been practiced since the 1970s in North American forests. Moreover, further intensive harvesting methods (e.g., energy-wood harvesting; [2,3]) have been investigated in the forests of northern Europe and the northeastern United States. It seems apparent that future timber harvesting in northern Rocky Mountain forests will utilize greater levels of biomass than contemporary harvests [4], but the long-term effects of such harvests on productivity in this region have been studied very little [5].

Increased biomass removal from forest ecosystems has the potential to produce a decline in site productivity. Since branches, twigs, and foliage have higher nutrient concentrations than stemwood, their removal may cause excessive nutrient loss [6,7]. Studies of whole-tree harvesting have consistently indicated significantly greater nutrient loss than conventional harvesting methods [8–11]. The simulation efforts and nutrient budget analyses have also warned of the site productivity impacts of nutrient depletion by intensive biomass removal (e.g. [12–14]). In addition, abrupt elimination of aboveground vegetation exacerbates the temporary loss of soluble nutrients through soil leaching (e.g. [15]). Thus, the concern that biomass harvesting could adversely impact site productivity is reasonable.

Biomass harvesting for bioenergy can also influence a site's nutrient flux indirectly by altering other environmental factors. Increased biomass removal can affect the understory microclimate by altering solar radiation, soil temperature, and soil moisture [16]. Moreover, soil properties can be altered by biomass harvesting. For example, Nykvist and Rosén [17] and Staaf and Olsson [18] found that increased biomass removal can exacerbate soil acidification. By modifying organic matter dynamics, these environmental alterations can affect soil biota, consequently modifying nutrient cycling and availability [19,20]. Such complex effects of increased biomass removal make it difficult to predict the protracted impacts of biomass harvesting on site productivity, emphasizing the necessity of long-term field experiments.

Several experimental efforts in recent decades have sought to determine the consequences of biomass harvesting on site productivity.

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These have focused on the growth of regenerating stands or physiological responses (e.g., growth efficiency, foliar nutrient status) following increased biomass removal as indicators of site productivity impacts. In the United Kingdom, Proe et al. [21] reported that whole-tree harvesting led to a 13% volume reduction of Sitka spruce (*Picea sitchensis* (Bong.) Carrière) plantation seedlings compared to conventional harvesting after 12 years. In another Sitka spruce stand in North Wales, whole-tree harvesting caused an approximately 10% reduction in dbh (diameter at breast height) 23 years after planting [22]. In Sweden, increased biomass removal resulted in a 17% basal area reduction for Scots pine (*Pinus sylvestris* L.) trees after 24 years [23], and negative impacts on growth of Norway spruce (*Picea abies* (L.) Karst.) trees after 15 years [20]. From a series of experimental sites across Scandinavian countries, Jacobson et al. [24] observed reduced tree volume growth in Scots pine and Norway spruce stands (5 and 6%, respectively) 10 years after thinning with whole-tree removal. They speculated that the reason for tree growth reduction could be nutrient removals and subsequent indirect effects, but the magnitude of the negative impacts is complicated by abiotic and biotic factors – such as precipitation, soil fertility, and belowground nutrient cycling [24].

Conversely, the North American Long-Term Soil Productivity (LTSP) study yielded somewhat different results from those of northern European forests. Ten years after biomass removal treatment, Powers et al. [25] and Ponder et al. [26] failed to find consistent consequences of increased biomass removal on tree responses. Thus, tree responses to biomass harvesting appear to vary depending on regional factors such as vegetation, soil properties, and disturbance/harvest regimes.

The equivocal impacts of biomass removal emphasize the necessity for experimental efforts to evaluate site-specific long-term impacts on productivity. An opportunity to evaluate the long-term impacts of biomass harvesting on site productivity in the northern Rocky Mountains exists at western Montana's Coram Experimental Forest. In 1974, timber harvesting was conducted with three levels of biomass removal in a western larch (*Larix occidentalis* Nutt.) forest (Table 1). For four consecutive years thereafter (1976–1979), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedlings were planted within a reserved portion of each biomass removal treatment separate from the naturally regenerated stand that developed afterward. This experiment enables an isolation of the long-term effects of biomass harvesting on site productivity by holding constant or randomizing other factors that can affect seedling growth, such as genetic traits, microsite, spacing, time of initiation, and competition. The objective of this study was to investigate the long-term impact of biomass harvesting on individual tree growth. To achieve this objective, we compared tree responses such as height, diameter, volume growth, tree vigor, and foliar nutrient concentrations among three biomass removal levels.

Therefore, we tested the hypotheses:

1. If the increased biomass removal has a negative impact on forest productivity, then the lowest height, diameter, volume growth should be observed at the highest biomass removal level.
2. If the increased biomass removal decreases forest productivity, then the lowest leaf area, growth efficiency (GE), and foliar nutrient (C and N) concentration should be detected at the highest biomass removal level.

2. Methods

2.1. Study site

This study was conducted at Coram Experimental Forest (CEF; 48°25′N, 113°59′W) on the Flathead National Forest in northwestern Montana, USA, located about 9 km south of Glacier National Park. The elevation of the study site ranges from 1188 to 1615 m, with 30–80% slopes. Soils have approximately 40–80% rock-fragment content, are underlain with glacial till [27], and are classified as loamy-skeletal, isotic Andic Haplocryalfs [28]. The climate of CEF is classified as a modified Pacific maritime type [29]. Average annual precipitation is 1076 mm, primarily occurring in the form of snow from November to March [30]. Mean annual temperature is reported as 2 °C–7 °C [31].

The biomass harvesting experiment was implemented in mature stands of the Western Larch cover type (Society of American Foresters Cover Type 212; [32]) on the Upper Abbot Creek Basin. Major tree species of the study site are: western larch, Douglas-fir, subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and paper birch (*Betula papyrifera* Marshall). The study site is relatively moist and productive (western larch site index of 16.7 m at base age 50; [33]), and is predominantly classified as the subalpine fir/queencup beadlily (*Clintonia uniflora* (Menzies ex Schult. & Schult. f.) Kunth) (ABLA/CLUN) habitat type [34,35].

2.2. Experimental design

Experimentally controlled clearcuts were operationally installed in 1974 at two blocks: a higher elevation site (1341–1615 m) and a lower elevation site (1195–1390 m). Within each of these sites (blocks), three residue removal treatments (1.6 ha per treatment on average; Table 1) were designated that combined removal level with prescribed burning (i.e., high-unburned, low-burned, and medium-burned). The original experimental design contained one additional treatment (medium-unburn, also known as "understory protected"; [36,37]) but that treatment was not included in this follow-up planting experiment, presumably because that biomass removal treatment retained understory vegetation and advance regeneration that would have interfered with planted seedling survival. Removed woody materials for the high-unburned, low-burned, and medium-burned treatments were 72.3, 54.2, and 65.6%, respectively (based on aboveground woody material volumes; [38]). All trees were hand-felled, and harvested trees were removed via a skyline yarding system.

An area within each treatment was set aside for the present planted

Table 1
Design of the biomass removal treatments within harvesting units (details and data from Refs. [35,38,47]).

Treatment	Removed woody materials	Pre-harvest volume (m^3 ha^{-1})		Post-harvest volume (m^3 ha^{-1})		Removed woody materials (%)	Post-harvest treatment
		Block1	Block2	Block1	Block2		
High-Unburned (H_U)	All woody material (live and dead, standing and down) to 2.5 cm diameter	414	387	66	140	72.3	Unburned
Low-Burned (L_B)[a]	All sawtimber material (live and recently dead) to 17.8 cm dbh and 15.2 cm top diameter, 2.4 m in length, 1/3 sound	469	564	167	247	54.2	Broadcast burned
Medium-Burned (M_B)	All woody material (live and dead, standing and down) to 7.6 cm small end diameter, 2.4 m in length, 1/3 sound	570	617	121	170	65.6	Broadcast burned

[a] Followed the United States Forest Service standards in 1974.

seedling experiment, within which downslope columns of 25 seedlings were planted during each of the four consecutive years following treatment (1976–79), at planting sites cleared of existing vegetation. All seedlings were nursery-propagated Douglas-fir bare root seedlings, grown two years in the sown bed with no subsequent transplanting (2 + 0 bare root stock type). Seedlings were planted at 1.8 m spacing (equivalent to 3086 ha^{-1}). The purpose of the planted seedlings was to isolate and distinguish treatment-related responses at the individual tree level, independent of other factors such as stand density (plots located elsewhere were used to evaluate natural regeneration responses; see Ref. [39]). In order to maintain the residual planted trees in an open-grown condition and independent of density-related competition, planted trees in all treatment units were later uniformly released in the early 2000s (exact date unknown) by a precommercial thinning that removed alternating trees within each column, resulting in an effective residual spacing of 3.6 m (equivalent to 1543 ha^{-1}). Seedling mortality before release was 22% in 2001 [40], whereas only a negligible amount (2.8%) of seedling mortality has occurred after the release, an indication that the latter treatment served its purpose. At the time of this study the planted trees exhibited live crown base heights of approximately just 2.5 m, and live crown ratios exceeding 70%. As a result, factors beyond biomass removal intensity were held constant, enabling us to evaluate differences in tree-level responses among treatments with minimal additional error.

2.3. Data collection and analysis

Measurements of dbh and height were conducted in 1980, 1987, 1992, 2001, and 2013. Dbh was measured by diameter tape at 1.37 m height, and height was measured by using a height pole or laser clinometer. Individual tree volumes were computed with a volume equation using the dbh and height measurements [41]. In 2013, tree cores and foliage samples were taken from five trees in each treatment, elevation, and planting year. The 2nd, 4th, 6th, 8th, and 10th trees in a row were systematically selected. Two tree cores were taken perpendicular to each other at breast height; bark thickness was measured by caliper to nearest 100 μm and sapwood boundary was marked. Crown base height was additionally measured for crown ratio calculation in 2013.

In the lab, recent five-year radial growth and sapwood length from core samples were measured by digital caliper to the nearest 10 μm. Foliage samples were taken from a branch with no visible signs of stress (e.g. drought, shade, senescence) or damage. A twig containing current foliage was collected, transported to the lab, and oven-dried at 60 °C to constant mass, and ground to pass a 0.04-mm mesh. Subsamples of 300 mg per sample were analyzed on a LECO TruSpec CN analyzer (Leco Corp., St. Joseph, Michigan USA) for total C and N concentrations.

GE is commonly used to compare tree vigor, or efficiency of leaf area removal (growing space efficiency; [42]). GE can be expressed in stem wood production (volume or weight) per unit leaf surface area [43] or stem wood production per unit leaf surface area (e.g. [42,44,45]). For this study, the estimation of periodic stem wood production would have required additional previous measurement of tree heights and bark thicknesses, which did not exist. Thus, basal area increment was used rather than stem wood production. Leaf area was calculated from cross-sectional sapwood area and crown ratio measurements as proposed by Monserud and Marshall [46].

Since the experimental design at CEF was regarded as a split-plot design, linear mixed-effects models were used to analyze GE and foliar C and N concentrations. The biomass removal treatment was considered the whole-plot, and planting year was treated as the sub-plot. The elevation was regarded as a block [47], and treated as a random effect. The model was constructed as:

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

where y_{ijkl} = response variable, μ = grand mean, α_i = effect of biomass removal treatment (whole-plot effect), B_k = kth block effect (random effect), β_j = effect of planting year (sub-plot effect), $(\alpha\beta)_{ij}$ = the interaction between biomass removal treatment and planting year, and $\varepsilon_{(1)ik}$, $\varepsilon_{(2)ijk}$, and ε_{ijkl} are the whole-plot error, sub-plot error, and the variation among trees in a subplot, respectively.

In this study, we estimated the coefficients of response curves [48] for repeated measures of height and dbh, which can be regarded as a type of profile analysis. Since the experimental design (split-plot) of this study was intrinsically complex, adjusted univariate or multivariate approaches required additional assumptions. On the other hand, analysis of coefficients can provide straightforward inferences given our objectives. We followed the approach of Meredith and Stehman [48]; orthogonal polynomial coefficients summarized the response curves (such as linear and quadratic), and were compared among other factors, avoiding the problems of serial correlation. The assumption of variance heterogeneity was diagnosed by residual plot.

Adopting this approach, orthogonal polynomial coefficients for each individual tree were calculated. Since the measurement years were spaced unequally, the mean (Z), linear (B), and quadratic (Q) contrasts of tree height were calculated as:

$$z_{ijk} = (y_{ijk1980} + y_{ijk1992} + y_{ijk2001} + y_{ijk2013})/4 \quad (2)$$

$$b_{ijk} = (-0.682y_{ijk1980} - 0.186y_{ijk1992} + 0.186y_{ijk2001} + 0.682y_{ijk2013}) \quad (3)$$

$$q_{ijk} = (0.5y_{ijk1980} - 0.5y_{ijk1992} - 0.5y_{ijk2001} + 0.5y_{ijk2013}) \quad (4)$$

These variables were used as the coefficients, and were fitted into equation (1). Dbh and volume measures were analyzed in the same manner, but only the last 3 measures were used since the majority of seedlings had not reached the breast height until 1987.

The statistical significance of interaction terms were determined with F-tests (0.05 α-level). If the interaction term was not significant, then the reduced model was chosen. All analyses were conducted via R [49]. The package of *nlme* [50] was used to fit the mixed-effects models.

3. Results

The mean height and dbh of planted Douglas-fir trees measured in 2013 were 8.68 m (SE: 0.67 m) and 13.5 cm (SE: 0.9 cm), respectively (Fig. 1). The average individual tree volume was 0.068 m^3 (SE: 0.010 m^3). Planted trees grew an average of 42.6 cm^2 (SE: 2.1 cm^2) in basal area during the recent 5-year period. Leaf area was estimated to be 46.0 m^2 (SE: 2.4 m^2) per tree. From 5-year basal area increment and estimated leaf area, the average GE was calculated as 0.98 $cm^2\,m^{-2}$ (SE: 0.02 $cm^2\,m^{-2}$). Foliar C and N concentrations were 50.0% (SE: 0.07%) and 0.79% (0.01%), respectively (Table 2).

None of the interaction terms for biomass removal treatment by planting year were significant on height, dbh, and volume growth (Table 3). Reduced models did not detect a significant effect of the biomass removal treatment on growth curve elements (i.e., mean, slope, and curvature) of height, dbh, and volume. Even these measures in 2013 were also unaffected by biomass removal treatment (p = 0.72, 0.69, 0.90 for height, dbh, and volume, respectively). Rather, the effect of planting year on these metrics was significant (Fig. 2). There are decreasing trends of tree height, dbh, and volume as trees were planted later, but only trees planted in 1978 and 1979 (the two most recent of the four planting years) showed statistically significant size reductions.

Foliar N and C concentrations and GE were unaffected by biomass removal treatment and planting year (Table 4). The interaction terms between biomass removal treatment and planting year were consistently non-significant for those metrics. Reduced models also yielded consistent results: neither biomass removal treatment nor planting year was found to be a significant factor.

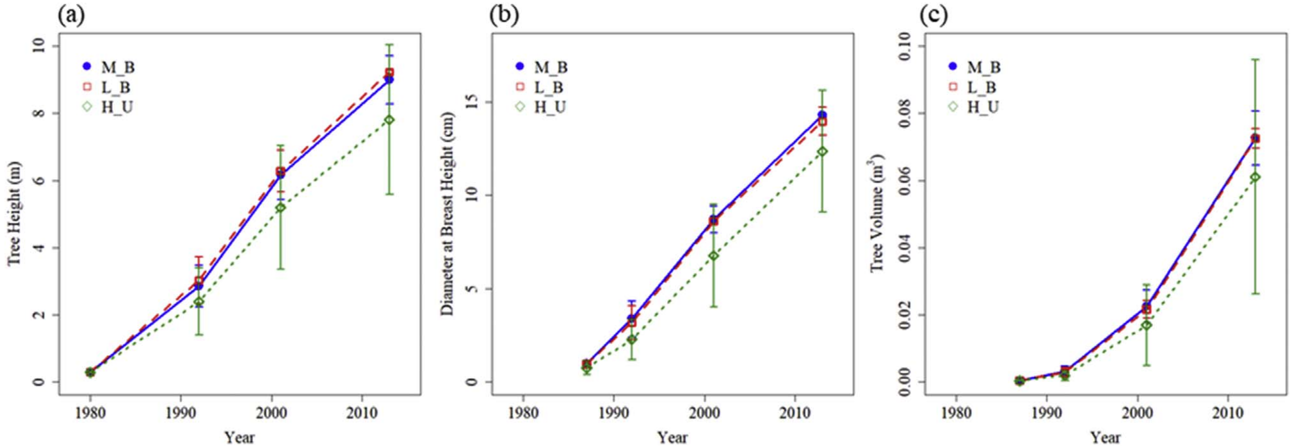

Fig. 1. Planted Douglas-fir (a) height (1980–2013), (b) dbh (1987–2013), and (c) volume (1987–2013) measurements according to biomass harvesting treatment at Coram Experimental Forest. Treatment codes are described in Table 1.

Table 2
Mean values of Douglas-fir tree responses to 3 biomass harvesting treatments 39 years after harvest. Standard errors are presented in parentheses.

Treatment	Leaf area (m^2)	5-year BA increment (cm^2)	Growth efficiency ($cm^2\ m^{-2}$)	Foliar N concentration (%)	Foliar C concentration (%)
High-Unburned (H_U)	39.8 (4.2)	35.4 (3.4)	0.95 (0.04)	0.84 (0.02)	50.1 (0.1)
Low-Burned (L_B)	49.6 (4.0)	49.8 (3.9)	1.05 (0.04)	0.77 (0.01)	50.2 (0.1)
Medium-Burned (M_B)	48.3 (4.4)	42.3 (3.3)	0.94 (0.04)	0.74 (0.02)	49.7 (0.1)
Mean (Overall)	46.0 (2.4)	42.6 (2.1)	0.98 (0.02)	0.79 (0.01)	50.0 (0.1)

Table 3
Analysis of variance table for repeated measures of planted Douglas-fir tree height, dbh, and volume.

Source	df	Error df	p-value		
			Height	dbh	Volume
Whole-unit analysis (Z)					
Mean	1	237	< 0.0001	< 0.0001	< 0.0001
Biomass removal treatment	2	2	0.538	0.906	0.695
Planting year	3	15	< 0.001	0.003	0.001
Analysis of repeated measure factor					
Linear (B) contrast					
Mean	1	237	< 0.0001	< 0.0001	< 0.0001
> Contrast × biomass removal treatment	2	2	0.784	0.960	0.982
Contrast × planting year	3	15	0.098	0.008	0.131
Quadratic (Q) contrast					
Mean	1	237	0.688	< 0.0001	< 0.0001
Contrast × biomass removal treatment	2	2	0.836	0.963	0.549
Contrast × planting year	3	15	0.223	0.081	0.390

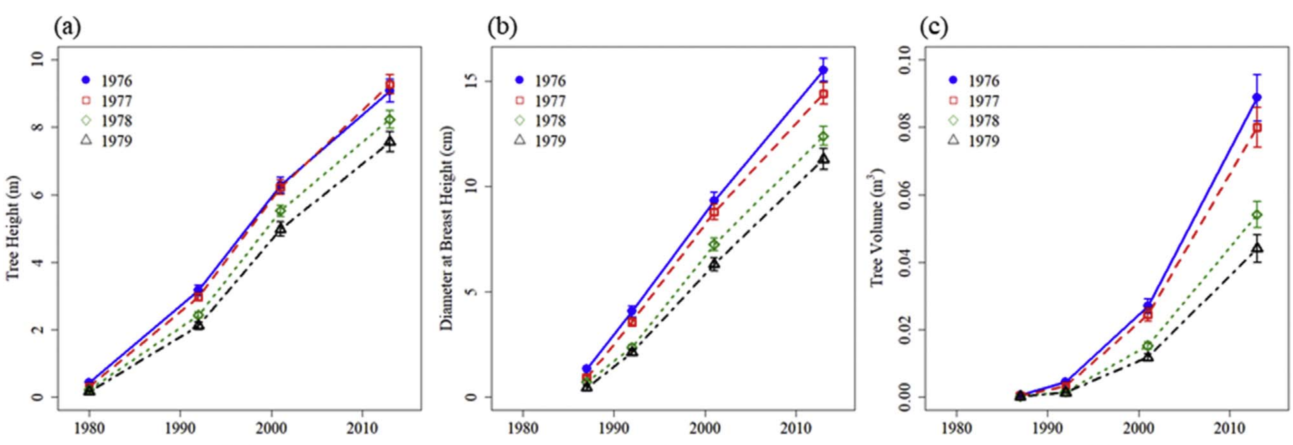

Fig. 2. Planted Douglas-fir (a) height (1980–2013), (b) dbh (1987–2013), and (c) volume (1987–2013) measurements according to year of planting at Coram Experimental Forest.

Table 4
Test statistics for foliar N and C concentrations and growth efficiency of planted Douglas-fir trees at Coram Experimental Forest.

Response variable/Variance source	df	Model with interaction			Model without interaction		
		Error df	F value	p-value	Error df	F value	p-value
Foliar N concentration							
Biomass removal treatment	2	2	2.988	0.251	2	2.782	0.264
Planting year	3	9	2.456	0.130	15	2.828	0.074
Treatment × planting year	6	9	0.709	0.651			
Foliar C concentration							
Biomass removal treatment	2	2	0.631	0.613	2	0.627	0.615
Planting year	3	9	0.670	0.576	15	1.041	0.403
Treatment × planting year	6	9	0.190	0.972			
Growth efficiency							
Biomass removal treatment	2	2	0.303	0.767	2	0.300	0.769
Planting year	3	9	1.286	0.337	15	1.249	0.327
Treatment × planting year	6	9	1.058	0.451			

4. Discussion

4.1. Biomass production

We observed no clear evidence of nutrient deficiency even after the onset of the stem exclusion stage, an indication that no long-term deterioration of site productivity due to biomass harvesting has occurred. The magnitude of negative impacts of biomass harvesting may change with time and stand developmental stages [51]. In Sweden, a basal area reduction of Scots pine only became detectable 12 years after whole-tree harvesting [23]. Such a time lag has been observed in several studies from young stands such as Sitka spruce [21] and Norway spruce [24]. However, the planted Douglas-fir trees at our study site were mature (> 34 years) enough to begin canopy closure associated with the stem exclusion stage. In this stage, nutrient demand is at its peak [26,52] (c.f. [53]) and if there are any adverse effects of the removal treatments on site productivity, the cumulative negative impact on tree growth should have been evident.

One reason for our failure to identify any differences in tree growth may be that the study site is relatively productive, like the LTSP sites in North America [25,26]. On nutrient rich sites, a slight reduction in nutrient availability does not always lead to tree growth reduction [54]. At our site, Stark [55] had previously anticipated that the amount of nutrients lost through these different removal treatments for biomass harvesting would not exceed vegetation demand during stand establishment. The forest floor and mineral soil pools in the study site retain large concentrations of nutrients even after intensive biomass removal [39,56].

Secondly, the use of a skyline yarder system for this study's harvest operations minimized soil disturbance, loss of the forest floor, and soil compaction, which are all factors typically thought to adversely impact forest productivity. The indications are that one-time intensive biomass harvesting in this moist, western larch forest type will likely cause no adverse long-term (~40 years) impacts on site productivity [25,57].

4.2. Nutrient concentrations and physiological traits

Our results did not support the hypothesis that increased biomass removal results in nutrient deficiency that negatively impacts site productivity, thus the lowest foliar nutrient content will be observed in the highest biomass removal level. Rather, the results indicated that increased nutrient loss by biomass harvesting was insufficiently severe to reduce nutrient pools, even at this study's highest (removal of all woody biomass down to a 2.5 cm top) removal level. Although the foliar N level in our result showed that the Douglas-fir trees were in a state of N deficiency [58], Moore et al. [59] reported that about 97% of Douglas-fir trees in the inland northwest occurred below the critical level (i.e., 1.4%). On the contrary, from a related study, Jang et al. [39] found the highest N contents in the study site's mineral soil layer at the highest removal level (H_U), and N contents the forest floor were more abundant than several moist/cool stands at other Montana sites [60].

Empirical studies also suggest that biomass harvesting does not necessarily reduce N availability. In Pacific coastal forests of Washington, a study of biomass removal showed no difference in the N concentration of Douglas-fir seedlings 5 years after planting [51]. Thiffault et al. [61] failed to find any apparent differences of foliar N for three conifer species (black spruce, jack pine, and balsam fir) between whole-tree and stem-only harvesting 15–20 years after clearcutting in the boreal forests of Canada. Even when effects on N concentrations are observed, they appear to be temporary. For example, Olsson et al. [62] found differences of initial (about 8 years) foliar N concentration for Norway spruce and Scots pine in Sweden; the differences were eliminated over next 8 years.

There was no impact of biomass removal treatment on foliar C concentration. Foliar carbon concentration can represent the ability of trees to produce and use carbohydrates [63]. Several other studies have reported defoliated and stressed trees as incapable of storing carbohydrates in their foliage (e.g. [64,65]). Therefore, if the growth of Douglas-fir trees in our site had been limited by nutrient depletion through biomass harvesting, then the foliar carbon concentration should have been lower in the greatest removal level (removal of all woody biomass down to a 2.5 cm top). Although the responses of foliar carbon can vary with many factors [66,67], the result of our study—on our cool and moist study site there was no difference in foliar carbon—may be consistent with the result of the foliar N contents.

Although our study did not include other macro-/micro nutrients (e.g., P, K, Ca, and Mg), concentrations in foliage have been investigated by numerous other studies. For example, Ca has been noted as one of the nutrients most vulnerable to biomass harvesting [11], due to its low mobility and decomposition rate [68]. Thiffault et al. [61] and Olsson et al. [62] observed lower levels of foliar Ca concentration in whole-tree harvesting than stem-only harvesting. However, in another study of soil properties at this study's site, Jang et al. [39] reported no significant effect of harvesting intensity on forest floor and mineral soil cations contents, including Ca. Based on this previous data, we assume no difference in the Ca concentration of planted trees attributable to harvesting intensity. Ca in the mineral soil and forest floor after harvesting and burning were generally approaching levels similar to the untreated control stand [39]; change in Ca after these treatments was either negligible (insufficient to limit foliar levels) or ephemeral. As a rule, increased biomass removal has been shown to have very little impact on other cations and phosphorus, suggesting that soil nutrient losses are minimal and foliar deficiencies are not detectable (e.g. [69–72]).

Several empirical studies testing fertilization impacts have reported that elevated nutrient availability resulted in increased GE. (e.g.

[73–75]). Samuelson et al. [76] and Albaugh et al. [75] suggested that the GE responded more significantly to nutrient availability than water availability for loblolly pine. However, GE is also determined by leaf area, which can also be affected by nutrient condition. Moreover, leaf area and basal area increment are influenced by tree size [74]. Therefore, GE can show very complex responses depending on various conditions. Despite these complexities, we observed a consistent outcome: no differences in leaf area, tree size, nor basal area increment, and consequently, no difference in GE among biomass removal treatments.

Our model indicated that there was a significant effect of planting year on height, dbh, and volume accumulation for planted Douglas-fir trees. Mason et al. [77] classified nursery seedling establishment after planting in two phases: the root-soil contact establishment and the free-to-grow phase. Our results suggest that trees planted in later years were delayed in reaching the second phase because of intensified understory competition, which resulted in lower height, diameter and volume growth trajectories than those for the earlier-planted trees. Understory shrub volume at this site rapidly recovered to 14 and 37% of the pre-harvest level within two (1976) and four (1978) years after harvesting, respectively [36]. Therefore, it appears that the later-planted trees suffered from more intensive competition by understory vegetation. To avoid this outcome, immediate replanting before understory vegetation recovery or the use of vegetation control seems critical.

Delay in tree diameter, height, and volume growth does not necessarily imply a reduction in site productivity. Egnell and Leijon [20] and Egnell [78] emphasized the question whether the observed reduction of stand growth is temporary or permanent. That is, whether increased biomass removal causes a reduction in growth potential is critical to our understanding of site impacts. In the present study, planting year proved to have non-significant effects on linear (slope) and quadratic (curvature) contrasts for height and volume growth curves; results were consistent regardless of biomass removal level (Table 3). Thus, we conclude that increased understory competition due to late planting led not to the reduction of growth potential of trees, but to a temporary retardation of seedlings in reaching the rapid growth stage. For the same reason, trees planted earlier would have benefited most from the thinning that was subsequently performed in the early 2000s.

The experimental design was established to maintain a constant growing environment for seedling growth. However, the possibility of uneven competition resulting from different mortality rates of neighboring seedlings over time could have affected seedling growth if seedling mortality had differed by treatment. However, crown closure began as late as ca. 1995 (S. Pierce, unpubl. data) and the seedling mortality rates during that time period (i.e., 1992 to 2001) were constant across the treatments (3.9% on average). Moreover, we found that seedling crown ratios at the time of this study were high, and there was consistently similar dbh growth and foliar nutrition. Thus, the competition among surviving seedlings was isolated effectively.

The original experimental design could not test the possible effects of broadcast burning effects on seedling growth. The incomplete factorial of burning and biomass removal treatments and lack of replicates make analysis of broadcast burning effects impossible. Schmidt [36] reported that understory vegetation recovered rapidly immediately after treatment, but the recovery rate was similar between burned and unburned treatments. Furthermore, in a related study, Jang et al. [39] argued that there was not enough evidence to describe a difference in understory vegetation recovery 10 years after treatment. During the field campaign, we observed that the planted trees suppressed understory vegetation, so the effect of competing understory vegetation was likely insignificant. Stark [55] had warned that burning might affect soil nutrient cycling in the study area, but recent investigations demonstrated that there were few long-term impacts of the treatments on soil properties [79]. More sophisticated research efforts with larger replicate sizes would be required to conclusively determine the effects of burning treatment on subsequently planted seedlings.

5. Conclusion

We conclude from our results that 3 levels of biomass harvesting for bioenergy production had no long-term impact on site productivity at the northern Rocky Mountains study site. Foliar C and N concentrations were not significantly influenced by any of the treatments, implying biomass harvesting is unlikely to cause the adverse long-term impacts on site productivity in moist, western larch forests. Additionally, none of the growth variables were significantly affected by biomass removal treatments. Rather, only planting year was significant in determining tree mean height, dbh, basal area increment, and total leaf area. Yet, the delay owing to late-planting seemed not to alter the growth trajectory curve of the planted trees.

This study illustrates the great value of long-term studies of biomass harvesting and productivity, but there remain knowledge gaps in the consequence of biomass harvesting. Although the experimental sites were well-preserved and the study site is located in a representative western larch-mixed conifer forest, the scope of inference and power of the statistical tests have limitations due to low replication. The impacts of biomass harvesting can vary with site productivity, and ours is one of the most productive in the region; other sites of lower productivity might exhibit different responses to the same kinds of biomass harvesting scenarios tested here. In addition, this study tested only three biomass harvesting scenarios on certain tree species, and was impossible to separate fire effects from biomass removal effects clearly due to its original experimental design. Those shortcomings also provide valuable insight for the design of further research. New work should include other forms of biomass harvesting (e.g., stump removal) and other species (e.g., species with greater nutrient requirements) with increased replicates to fill those knowledge gaps.

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