Forest Ecology and Management 305 (2013) 60–66

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Tree growth ten years after residual biomass removal, soil compaction, tillage, and competing vegetation control in a highly-productive Douglas-fir plantation

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ARTICLE INFO

Article history:
Received 12 February 2013
Received in revised form 16 May 2013
Accepted 17 May 2013

Keywords:
Residual biomass removal
Soil compaction
LTSP
Soil productivity
Competing vegetation control
Sustainability

ABSTRACT

Forest residual biomass harvesting is a potential concern in regions where this primarily branch and needle material is removed to provide a source of renewable energy or where total-tree yarding takes place. Concern arises from the removal of nutrients present in residual biomass, as well as from heavy equipment trafficking used to collect the material. The Fall River Long-term Soil Productivity (LTSP) Trial in western Washington State, USA was designed to study potential impacts on Douglas-fir tree growth of residual biomass removal on a productive soil in the Pacific Northwest region. The objective of this investigation was to examine the effects of residual biomass removal, soil compaction, tillage following compaction, and competing vegetation control on subsequent stand productivity through 10 growing seasons. The size and growth rate of Douglas-fir trees planted in the Fall River LTSP Trial were not significantly affected by any residual biomass removal level, indicating substantial resilience to high levels of residual biomass harvest at this productive site with deep, nutrient-rich soil. Soil compaction, without other soil disturbance or displacement, had no negative effects on tree growth or tree size over the 10-year growing period. Tillage following soil compaction also led to a modest, but not significant, increase in tree growth and size. In the years during and shortly after complete vegetation control, trees grew faster and were larger where non-tree vegetative competition was reduced. Water availability during the growing season appears to be a growth-limiting factor at this site where annual precipitation is high but very little falls during the summer growing season. Tree growth will continued to be monitored to see how the trees will respond to the treatments as inter-tree competition and crown biomass increase water and nutrient demand.

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1. Introduction

As demand increases for renewable fuels to replace fossil fuels, it is conceivable that more forest residual biomass could be removed to provide that fuel in conjunction with the conventional harvest of trees for lumber and fiber. Removal of residual biomass, primarily branches, tops, and needles with relatively high nutrient concentrations, has the potential to additionally reduce site nutrient stores compared to traditional timber harvest, which removes mostly low-nutrient-concentration bole wood along with bark. The additional equipment traffic needed to access and deliver the residual biomass material to market might also lead to detrimental soil compaction (Nabmiar, 1996). Therefore a working hypothesis to test, relative to the practices that might occur from additional biomass harvesting, is that a reduction in site nutrient capital or an increase in detrimental soil compaction could lead to less forest productivity in subsequent rotations, reducing the sustainability of harvesting plantation forests from the site if ameliorative treatments are not applied.

The North American Long-term Soil Productivity (LTSP) Study was initiated in 1989 as a long-term, multi-agency cooperative effort to investigate the consequences of organic matter/woody biomass removals and soil compaction on fundamental forest productivity on a range of sites across the forested regions of the US and Canada (Powers et al., 2005). 'Core' LTSP treatments include a 3 × 3 factorial of residual biomass removal and soil compaction. Many also include a competing-vegetation-control component. 'Affiliate' sites typically have a subset of the core treatments and may have other related treatments, depending on regional

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http://dx.doi.org/10.1016/j.foreco.2013.05.031

interests. The Fall River LTSP Trial, the focus of this report, is one such affiliate site.

The objective of the Fall River LTSP Trial was to examine the long-term effects on subsequent stand productivity of: (1) residual biomass removal, (2) soil compaction and tillage following compaction, and (3) vegetation control. This report summarizes the effects of these treatments on tree growth after 10 growing seasons. A key feature of this trial, in contrast to many other studies of site productivity, is the inclusion of ameliorative treatments that land managers could employ to reverse any productivity losses that might occur because of the removal of residual biomass. Thus, a tillage-following-compaction treatment was contrasted with a compaction-only treatment to test if tillage could be used to restore compacted soil. A fourth set of treatments involving fertilization is planned to test if fertilization could compensate for removal of nutrients in slash, but is not yet implemented. A secondary objective of this study is to examine the roles that water and nitrogen availability play in controlling the growth of young trees by looking across the gradients in water-availability and nutrient-stores created by the applied treatments.

2. Materials and methods

2.1. Site description

The Fall River LTSP site is located at 46°43'N, 123°25'W in southwest Washington State, USA, between Raymond and Centralia, WA. The primary commercial tree species in the region, and the species of interest in this study, is coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco var. *menziesii*). The average elevation of the site is 340 m, with westerly facing slopes ranging from 0% to 15%. Annual air temperatures measured on site from 2000 to 2009 averaged 9.8 °C, with a January average of 4.2 °C and a July average of 15.5 °C. Annual precipitation was around 1700 mm, but only 125 mm on average fell between June 1 and August 31, which usually resulted in growing-season water deficits typical to this region.

Soils at the site are in the Boistfort series (Medial over Clayey, Ferrihydritic over Parasesquic, Mesic Typic Fulvudands), are more than 1.5-m deep with 2–4% coarse fragments and originate from Miocene basalt with volcanic ash influence. The clay loam soil had sand, silt, and clay contents of 30.2%, 36.3%, and 33.5%, respectively, in the 17-cm-deep A horizon, while the textural components in the deeper silty clay loam horizons averaged about 12%, 47.5%, and 40.5% (Ares et al., 2007b). The total pre-harvest nitrogen and carbon content of the site to a soil depth of 80 cm, was 14,671 kg ha^{-1} and 582 Mg ha^{-1} respectively (Ares et al., 2007b). Approximately 90% of the pre-harvest total site nitrogen and 40% of the total site carbon were in the soil to 80 cm depth.

The pre-harvest stand was 47-years-old with total tree biomass of 395 Mg ha^{-1} (Harrison et al., 2009) and basal area of 70 m^2 ha^{-1} when harvested (Ares et al., 2007b). Basal area was 55% Douglas-fir and 45% western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) at harvest. Site productivity is high, with Douglas-fir 50-year site index values ranging from 41 to 43 m on the study plots. Additional pre-harvest site and soil characteristics can be found in Ares et al. (2007b).

2.2. Treatments

The seven treatments applied in this trial (Table 1) were designed to address the aforementioned study objectives. It would not have been practical to test all possible combinations of all factors of interest in a complete factorial design, so the treatments examine each of the three objectives individually, while controlling for the other factors to avoid potential confounding effects. First, 4 levels of residual biomass removal were compared by removing different amounts and types of residual biomass without creating soil compaction (these plots all received vegetation control). Secondly, soil compaction, tillage following compaction, and non-compacted conditions were compared to each other on the bole-only level of residual biomass removal (these plots all received vegetation control). Thirdly, vegetation-controlled and non-vegetation-controlled treatments were compared at the bole-only level of biomass removal without soil compaction.

Each of the 48 tree measurement plots (15 × 70 m, 0.105 ha) were established with a 7.5-m buffer that resulted in 30 × 85 m (0.255 ha) treatment plots. Treatments were applied in April to July of 1999. Details of each component of the treatments can be found in Ares et al. (2007b), but brief descriptions follow:

Bole only biomass removal treatments had stem wood greater than approximately 10-cm diameter and greater than 3-m length removed, mimicking a saw-log-only harvest. All other fresh residual biomass material was dispersed on these plots. Legacy old-growth logs and branches, collectively called downed woody debris (DWD), remained on these plots along with fresh and old stumps, and forest floor material. The Bole only biomass removal treatment, without soil compaction (explained below) and with competing vegetation controlled (i.e. suppressed, explained below), serves as the baseline to which all other treatments are compared.

Bole only to 5-cm biomass removal treatment plots had all the "bole only" material removed plus all intact or broken stem wood greater than 5-cm diameter. This removal mimics a pulp-wood merchantability-limit harvest. Plots in this treatment had competing vegetation controlled and were not compacted.

Total-tree biomass removal treatment plots had all boles, live limbs, and foliage removed with a combination of heavy equipment and hand labor. Some legacy DWD was inadvertently removed by the equipment during this clean-up process. These plots all had competing vegetation controlled and were not compacted.

Total-tree + DWD biomass removal treatment plots had all "total-tree" material removed; in addition, all dead branches and all dead and down old-growth logs in various states of decay were removed. Fresh and old-growth stumps and snags were left in place to avoid excessive disturbance. Fine litter and forest floor remained although some was inadvertently removed when limbs and tops where removed mechanically. These plots all had competing vegetation controlled and were not compacted.

No soil compaction treatments were harvested using cable-yarding to elevate and extract logs during harvest without soil compaction. Measurement plot areas were not compacted, but in the treatment plot buffer areas some trafficking was done to achieve the desired residual biomass levels.

Soil compaction consisted of eight equally-spaced traffic lanes parallel to the long axis of the plots. Every lane was trafficked once and every other lane was trafficked twice (back and forth) using a 40-Mg Caterpillar hydraulic excavator (model CAT 330L), with 70-cm tracks to simulate operational trafficking with 58.8 kPa ground pressure. This treatment resulted in around 40–50% of the area of the plot being trafficked. Bulk density to 30 cm in the traffic lanes was increased from 0.63 Mg m^{-3} to 0.82 Mg m^{-3}, with minimal displacement of surface organic matter or mineral soil (Ares et al., 2005).

The Compaction + Tillage treatment was accomplished on a subset of compacted plots by using a pair of 60-cm-long tillage tines on a Caterpillar (model CAT 322BL) hydraulic excavator bucket to loosen and lift compacted soil in the trafficked areas.

Competing vegetation control was carried out on all but the designated non-vegetation-control plots to remove any cofounding effects of competing vegetation by treatment. Vegetation control

Table 1
Detailed description of the treatments applied to plots at the Fall River LTSP Trial and number of plots of each treatment per block.

Treatment name	Biomass removal	Veg. control	Soil compaction	Tillage	Plots per block
1. Bole only	Bole only	Yes	No	No	2
2. Bole only 5 cm	Bole only 5 cm	Yes	No	No	2
3. Total tree	Total tree	Yes	No	No	2[a]
4. Total tree + DWD	Total tree + DWD	Yes	No	No	2
5. Soil compaction	Bole only	Yes	Yes	No	1
6. Compacted/tilled	Bole only	Yes	Yes	Yes	1
7. No veg. control	Bole only	No	No	No	2

The second plot per block is assigned to be fertilized at a later date, but fertilization has not yet occurred.
"Veg. control" = Competing vegetation control.
[a] Except block 4 for where $n = 1$, because of a dropped outlier plot.

consisted of an intensive schedule of repeated herbicide sprays targeting complete vegetation control for 5 years (see Ares et al., 2007b). Vegetation control was very effective, leaving only 53.1 kg ha^{-1} or 3% cover of non-Douglas-fir competing vegetation in Year 5, while non-vegetation-controlled plots averaged 2940 kg ha^{-1} or >100% cover of competing vegetation (Devine et al., 2011). Competing plant species are documented in Peter and Harrington (2009).

2.3. Tree stocking and tree measurements

Douglas-fir seedlings (1 + 1 nursery stock) were planted by hand within treatment plots at 1600 trees ha^{-1} on a fixed grid (2.5 m by 2.5 m spacing) in March 2000. Survival across all treatments averaged 93–95%, which left an average of 159 stems per plot. Stem diameter at breast height (1.3 m) (DBH) and total height were measured on all trees at age 5 and age 10 and annually, except Year 9, on all trees in the bole only with vegetation control and bole only without vegetation control plots. Total plot-level tree volume was calculated for all treatments using Year 10 individual tree DBH and height and summing individual tree volumes (Bruce and DeMars, 1974) by plot. Plot tree volume is used as the primary response variable of interest because it combines DBH and height into one summary value. Age 10 plot-level basal area, plot-level annual basal area growth increment from Year 5 to Year 10 (hereafter basal area growth), average tree height by plot, and plot-level annual height growth increment from Year 5 to Year 10 (hereafter height growth), were also calculated. Year 5 results for all treatments have been reported in Ares et al. (2005) and Roberts et al. (2005) and will not be presented in detail here.

For reference, "relative density" (RD, metric, Curtis, 1982) across the treatments ranged from 4.6 in the non-vegetation-control treatment to 5.6 in the Compacted/tilled treatment. Similarly, "stand density index" (SDI, Reineke, 1933) ranged from 169 in the non-vegetation-control treatment to 209 in the Compacted/tilled treatment. RD and SDI for other treatments varied predictably with basal area, given equivalent stocking. At age 10, lower-branch mortality and crown-lift of about 0.5 m had occurred.

2.4. Experimental design

A randomized complete block design, with 4 blocks, was used in the assignment and application of the treatments. Soil compaction plots and tillage-following-compaction plots had only one plot each per block. All other treatments had two plots per block because of the plots slated for future fertilization (Table 1). Plot 53, on the far north end of Block 4, was dropped from the analysis. This plot grew much more slowly and had noticeably less basal area and volume at age 10 than other vegetation-controlled plots in the study, even though it had a similar number of trees per ha. It was determined that Plot 53 had over 20% less soil nitrogen than the other plots at the site (Knight, Erica unpublished) suggesting that the underlying difference was related to decreased nutrient availability and not to a treatment effect. The analysis remained "complete" because the other "total-tree" plot in Block 4 represented that treatment in that block. Dropping the outlier reduced the total number of plots used in the study from 48 to 47.

Analysis of variance using a general linear model (GLM, Minitab 16) was used to test for differences among blocks and treatments (all 7 treatments simultaneously) for each parameter of interest. The GLM accounted for the slight imbalance created by having two plots per block for some treatments and 1 plot per block for others. Total degrees of freedom (df) were 46, with 3 df for Block, 6 df for Treatment and 37 Error df for all tests. F-protected pair-wise comparisons among treatments, as appropriate given the stated study objectives, were performed using Tukey's HSD (honestly significant difference) at $\alpha = 0.05$. A variety of other methods of statistical analysis were also explored, all yielding similar results to the GLM as described.

The scope of inference in this study is limited to the plots on the site itself. The site was selected to be representative of highly-productive intensively-managed Douglas-fir plantations in the local region of southwest Washington but, as is common with studies of this type, the location was not selected at random. One critical limitation for site selection was that the site be uniform and large enough to support the desired replication, and this limited the pool of potential locations from which to choose. Extrapolation of the results should be made with caution, especially to regions with less soil fertility and less site productivity.

3. Results

3.1. Residual biomass removal

The four levels of residual biomass removal had no significant effect ($p > 0.05$ for all pair-wise comparisons) on tree volume (Fig. 1), basal area, basal area growth, average tree height, and height growth (Table 2). The relative differences between the baseline bole-only means and the total-tree means (the greatest differences) were −6.4%, −3.8%, −3.5%, −1.8%, and −1.2% for the respective measures indicating that the lack of significance was not caused by excessively low statistical power.

3.2. Soil compaction and tillage following compaction

Soil compaction and tillage-following-compaction were not statistically different from the baseline bole-only treatment ($p > 0.05$ for all pair-wise comparisons) for tree volume (Fig. 1), basal area, basal area growth, average tree height, and height growth (Table 2). The relative differences between the baseline bole-only means and the tillage-following-compaction means (the greatest differences) were 5.5%, 4.5%, 4.2%, 0.9%, and −1.1% for the respective measures,

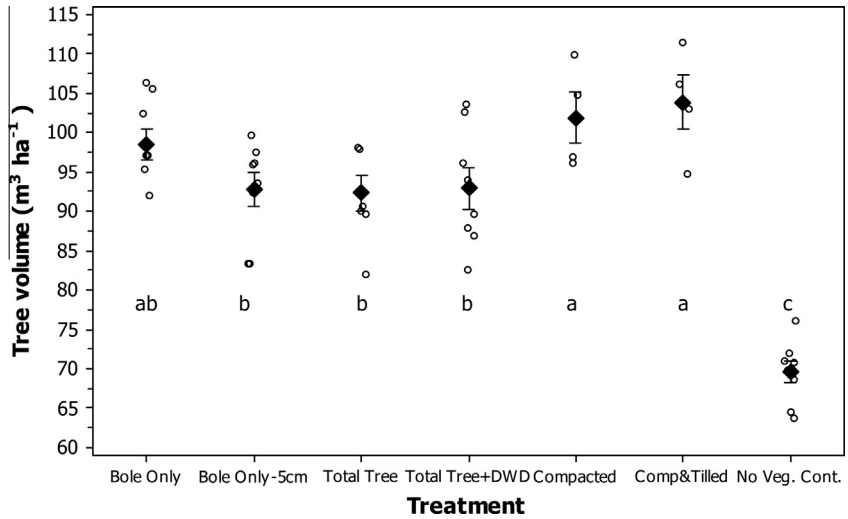

Fig. 1. Plot level tree volumes at the Fall River LTSP Trial for *Pseudotsuga menziesii* var. *menziesii* calculated by summing individual tree values determined using Bruce and DeMars (1974). Treatment averages (filled diamonds) and standard error bars are shown along with the individual plot values (open circles). ANOVA Block $p < 0.0001$, Treatment $p < 0.0001$. Treatments with the same letter are not statistically different using Tukey's HSD at $\alpha = 0.05$. "Bole only" is the baseline treatment to which all others are compared. "Comp&Tilled" is compacted and tilled. "No Veg. Cont." is No vegetation control. All other treatments had vegetation control. See Table 1 for full treatment explanation.

Table 2
Plot level tree measurements by treatment for *Pseudotsuga menziesii* var. *menziesii* after 10 growing seasons and annual growth increments between Year 5 and Year 10 at the Fall River LTSP Trial.

	df	Basal area (m^2 ha^{-1})	Basal area growth (m^2 ha^{-1} $year^{-1}$)	Height (m)	Height growth (m $year^{-1}$)
ANOVA p-values					
Block	3	<0.001	<0.001	0.006	0.104
Treatment	6	<0.001	<0.001	<0.001	0.016
Error	36				
Total	46				
Treatment means	*n*				
Bole only[a]	8	19.4 ab	3.37 ab	8.83 a	1.06 a
Bole only 5 cm	8	18.9 b	3.28 b	8.69 a	1.04 ab
Total tree	7	18.7 b[b]	3.25 b[b]	8.67 a	1.04 ab
Total Tree + DWD	8	18.9 b	3.30 b	8.67 a	1.04 ab
Soil Compaction	4	20.0 a	3.47 a	8.82 a	1.05 ab
Compacted/Tilled	4	20.3 a[b]	3.51 a[b]	8.91 a	1.05 ab
No veg. control	8	15.5 c	2.81 c	8.16 b	1.02 b
Standard error[c]		0.2–0.3	0.03–0.04	0.06–0.08	0.01

Treatments with the same letter are not statistically different using Tukey's HSD at $\alpha = 0.05$.
[a] Baseline treatment to which all others are compared.
[b] Tukey's HSD versus Bole Only $p > 0.1 < 0.2$, suggestive of borderline non-significance.
[c] Accounting for block effects. The ranges in standard error are a result of the differences in within block replicates among treatments. Greater standard errors correspond to fewer replicates.

again suggesting that a lack of statistical power was not a primary driver in failing to detect differences.

3.3. Competing vegetation control

Not controlling competing vegetation resulted in a 29% decrease ($p < 0.0001$) in tree volume (Fig. 1). Consistent with the volume decrease, trees on the non-vegetation-controlled plots had significantly less basal area (−20%), basal area growth (−17%), height (−7.6%), and height growth (−3.7%) versus the baseline bole-only with vegetation control (Table 2). Tree survival was the same with and without vegetation control (data not shown).

The time-series data (Figs. 2 and 3) indicates that annual tree growth differences attributed to vegetation control have decreased over time. Direct vegetation control effects on annual growth differences appear to have diminished for basal area and height as shown by the parallel pattern of vegetation-controlled and non-vegetation-controlled plots (Figs. 2a and 3a) and by the convergence of annual rates of basal area growth and height growth between treatments by Year 10 (Figs. 2b and 3b).

4. Discussion

4.1. Residual biomass removal

Various reviews of the effects of removing the branch and needle biomass remaining after a conventional timber harvest in temperate and boreal forests have observed that the majority of studies find no effect on subsequent tree growth (Thiffault et al., 2011; Ponder et al., 2012, Wall, 2012). Wall (2012) reports that 70–85% of studies showed no effect or a positive effect of residual biomass removal on tree growth depending on the tree metric used (DBH, height, or volume). The results of the current study are consistent with that general finding and showed no significant effects of residual biomass removal on any of the tree metrics observed after 10 years at this site. The Fall River LTSP Trial would be a

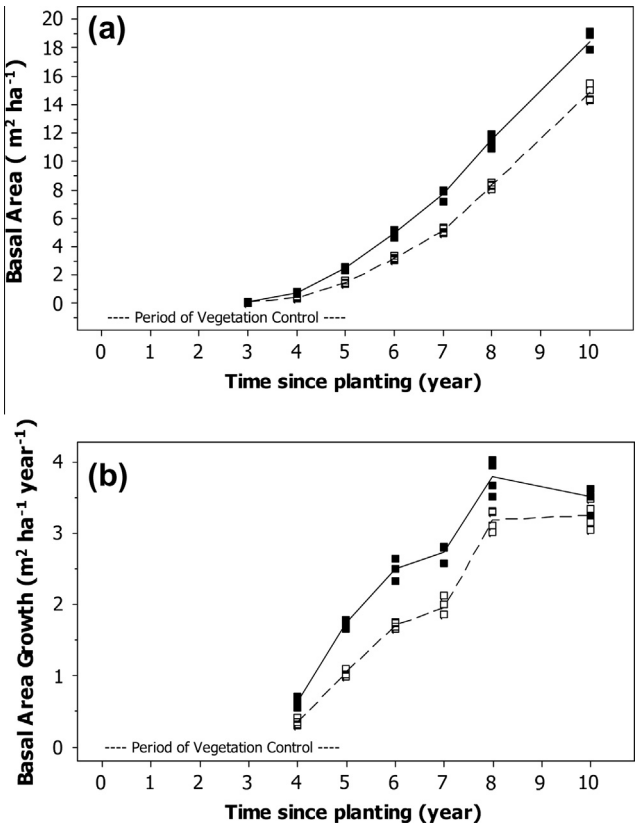

Fig. 2. Tree basal area through time for *Pseudotsuga menziesii* var. *menziesii* grown at the Fall River LTSP Trial. Filled symbols have had extensive vegetation control through year 5; open symbols have had no vegetation control. Symbols represent the average for each of 4 blocks. (a) Plot level basal area. (b) Plot level annual basal area growth increment.

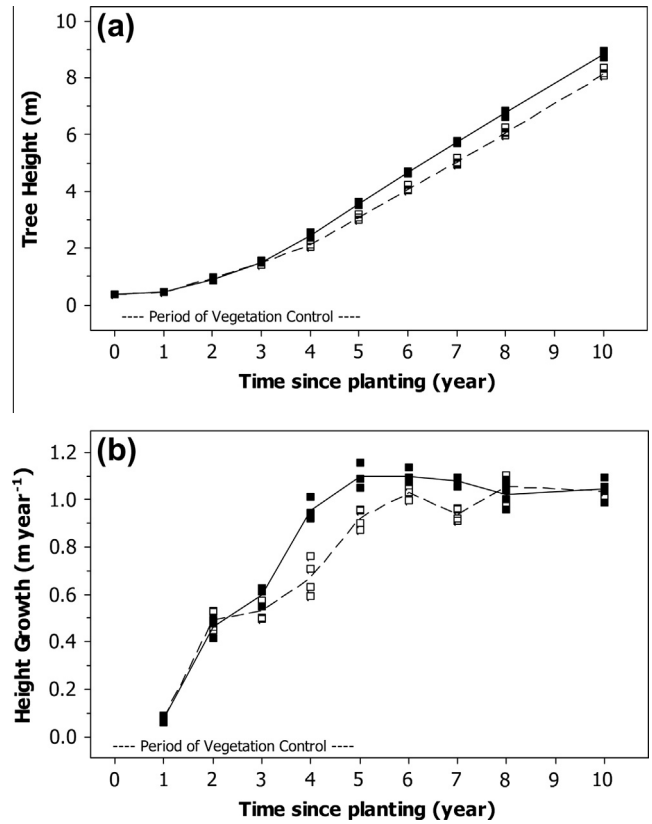

Fig. 3. Tree height through time for *Pseudotsuga menziesii* var. *menziesii* grown at the Fall River LTSP Trial. Filled symbols have had extensive vegetation control through year 5, open symbols have had no vegetation control. Symbols represent the average for each of 4 blocks. (a) Plot level average tree height. (b) Plot level annual tree height growth increment.

"resilient site" rather than a "sensitive site" based on the classification of residual biomass removal risk by Rauland-Rasmussen et al. (2007).

Relative tree growth differences at the Fall River LTSP Trial, were small on average, generally on the order of 6% or less. Although an extensive effort was made to select a uniform site and define appropriate blocking to minimize or account for variation on the site, a 6% difference in growth could have existed among these groups of plots because of random spatial variability in site productivity.

In contrast, there are other notable studies in Europe in particular (e.g., Egnell, 2011, and see Thiffault et al., 2011, Wall, 2012) and occasionally elsewhere (Thiffault et al., 2011; Ponder et al., 2012, Wall, 2012) that have documented significant productivity losses from the removal of forest residual biomass. Sites affected by residual biomass removal often have less soil nutrient capital (e.g., Egnell, 2011, 2530 kg ha^{-1} of N in trees, forest floor, and soil to 50 cm) and are in colder climates (Morris and Miller, 1994) than the Fall River LTSP Trial so the residual biomass removals were a larger proportion of the total site nutrient stores (e.g., Egnell, 2011, 262 kg ha^{-1} of N in removed biomass or 10% of the total N stores on site) and the foliar biomass is a significant source of readily available nutrients. Tree productivity losses in Egnell (2011) were 25% after 31 years, but differences were leveling off at that point.

The most severe biomass removals at the Fall River LTSP Trial averaged 800–900 kg ha^{-1} of nitrogen removed (Ares et al., 2007b), fully 3 times the absolute amount removed in Egnell (2011), but that accounted for only 6–7% of the total nitrogen content on the Fall River LTSP site to 80 cm soil depth. Since nitrogen typically limits Douglas-fir growth in the Pacific Northwest (Date, 1973), one might expect that removals of this magnitude could have the potential to reduce tree growth, so it remains a possibility that a small effect of biomass removal occurred but cannot be detected statistically. However, foliar nutrient analysis at age five indicated that the foliar-N concentrations across residual biomass removal and vegetation control treatments were similar and well above deficiency levels (Ares et al., 2007a). Foliage samples at age 11 also showed no difference in foliar N concentrations between vegetation controlled and non-vegetation-controlled trees (Devine et al., 2013). Thus, it appears that at this stage of stand development N is not limiting growth at this site. Even if the severe, non-operationally-practical removals of residual biomass in this trial did reduce nitrogen stores a significant amount, correcting that loss could be accomplished with roughly four applications of the industry standard 224 kg ha^{-1} of nitrogen as urea fertilizer over a rotation, and thus, is a manageable amount to add back to the site if productivity losses from nutrient limitation are observed later in this rotation or subsequent rotations.

Despite the potentially negative growth effects resulting from nutrient loss, residual biomass removals can have positive effects (Thiffault et al., 2011), like earlier soil warming in the spring and generally greater surface-soil temperatures during the growing season (Devine and Harrington, 2007; Terry and Ares, 2007). In the first five years of stand growth at the Fall River LTSP trial, greater soil temperatures and more soil degree-days accumulated in the total-tree + treatment as compared to the bole only. More direct-soil insolation led to the additional warmth when residual biomass was removed and could have resulted in earlier (and thus greater)

root growth in the spring, although roots were not directly investigated (Devine and Harrington, 2007). It is possible that the beneficial effects of warmer soil could have counter-acted any negative impact caused by nutrient removal. Regardless of the mechanism, residual biomass removals resulted in no, or very small, effects on tree size through Year 10.

4.2. Soil compaction and tillage following compaction

Contrary to conventional wisdom about the detrimental effects of soil compaction, moderate soil compaction without displacement of top soil often has no effect or a positive effect on planted tree biomass compared to non-compacted soil (Ponder et al., 2012). Detrimental soil disturbance can be associated with deep ruts, soil puddling, lateral displacement or removal of topsoil and/or disruption of soil hydrology (Heninger et al., 2002). Detrimental soil compaction can occur especially on finer textured soils, but it appears to be the exception rather than the rule on LTSP sites where compaction was applied without severe displacement of soil (Ponder et al., 2012). Moderate compaction improves water holding capacity, thus extending water availability through dry spells, which can be beneficial to tree growth in areas with a pronounced growing season water deficit (Ares et al., 2005).

In the present study, soil compaction appeared to have resulted in a small, but non-significant, beneficial effect on tree volume, basal area, and basal area growth. Although not convincingly positive, this is strong evidence that soil compaction was, at a minimum, not detrimental in the current study and this is in line with the 5-year results at the Fall River LTSP Trial (Ares et al., 2005, 2007a) and many other LTSP sites (Ponder et al., 2012).

Tillage as a method of ameliorating detrimental soil compaction was not actually addressed in the current study, since the level of compaction achieved was not detrimental. However, tillage after compaction did result in some non-significant increases in tree volume, basal area, and basal area growth at Year 10, so tillage does appear promising as a method for increasing tree growth when soil is compacted. Indeed, previous studies have shown tillage to be effective at restoring productivity to detrimentally compacted soils (Heninger et al., 2002). Increased macropore space and less soil strength in the tilled areas (Ares et al., 2005) may have enabled roots to rapidly penetrate to deeper soil where access to soil water would allow growth longer into the dry season. Tillage generally increases nutrient mineralization (Silgram and Shepherd, 1999), so increased nutrient availability could have been a potential mechanism by which trees benefited from the tillage. However, in the current study baseline soil nutrient levels were high (Ares et al., 2007b). Thus, it is not clear that more nutrients would benefit tree growth, so water availability seems the most likely reason for the modest growth increases.

The tilled plots in this study were kept virtually free of competing vegetation and thus caution is required if extrapolating effects to situations where competing vegetation is not controlled to the same extent as in this study. Tillage can alter soil microclimate, which can stimulate seed germination (Mohler, 1993). Without vegetation control, increases in resource competition from elevated levels of non-tree vegetation, relative to non-tilled, may negate any positive effects seen from the tillage.

4.3. Competing vegetation control

Reducing vegetative competition has been widely shown to positively affect crop tree growth in Douglas-fir (Cole and Newton, 1987; Maguire et al., 2009; Harrington et al., 2013) as well as other species (Ponder et al., 2012). Vegetation control at the Fall River LTSP Trial showed the most clear and convincing increases in tree growth both at Year 5 (Devine et al., 2011) and Year 10 of any of the treatments in this study. Process studies were included in the investigation to evaluate mechanisms of treatment response. It appears water availability is the major factor contributing to the increase in tree growth at this site when competing herbaceous vegetation is controlled (Slesak et al., 2010; Devine et al., 2011) and where significant overtopping/shading of crop trees is not occurring.

Convergence of the annual rates of basal area (Fig. 2b) and height growth at age 10 (Fig. 3b) shows the weakening, over time, of the effect of herbaceous vegetation control on tree growth. This is likely because full crown closure and the resulting reduction of vegetative competition in both treatments occurred by Year 10 as the trees shade-out the competition. Vegetation control appears to be exhibiting a Type B response (Hughes et al., 1979), where early gains in growth are maintained but no further gains from the treatment occur after a certain point in stand development. This type of growth response was also described by Snowdon and Waring (1984) which they described as Type 1 treatment response. Future measurements will assess if this trend continues, at least up to the point when severe tree-to-tree (intraspecific) competition takes place, at which time absolute treatment differences may begin to diminish.

4.4. Growth limiting resources

Plot-level tree volume across treatments in the current study (Fig. 1) follows a pattern of increasing size that is consistent with the pattern of expected water availability in those treatments. While not always statistically significant, this pattern may indicate that water availability is an important controlling factor at this site. The theoretically driest condition exists where competing vegetation was not controlled. Here soil moisture is depleted rapidly since vegetative competition for water is high. Next driest is the total tree + DWD treatment, where the removal of organic matter allowed the soil to warm and dry more quickly. The baseline condition is the bole only standard treatment where competing vegetation was kept low and branches and needles act as mulch to conserve water. Next lower in water-stress is the soil compaction treatment, where soil physical property changes allow the soil to hold water longer into the growing season. The treatment with the greatest water availability and greatest growth is the compacted and tilled, where roots can penetrate to deeper soil horizons to access water stored there. This correspondence is consistent with our hypothesis that, in spite of the substantial annual precipitation at this site, water availability and lack of rainfall during the summer growing season may be a significant factor limiting tree growth rates and affecting treatment response. Furthermore, growing-season water deficit has been shown to be an important growth-limiting factor at other coastal Douglas-fir sites in this region (Carter and Klinka 1990).

Nitrogen availability, another potential driver of productivity, appears less likely to be controlling treatment differences at the Fall River LTSP Trial because of the large soil N pool remaining and the relatively modest amount of nitrogen removed by even the heaviest organic matter removal treatments. Foliar N levels at age 5 were not different in treatments which did or did not receive vegetation control (Ares et al., 2007a; Slesak et al., 2010), and there were no differences in foliar N across organic matter removal treatments at age 5. Foliage samples taken eleven years after planting also showed no difference in foliar N concentrations between vegetation controlled and non-vegetation-controlled treatments (Devine et al., 2013). Furthermore, a nearby stand on the same soil series was non-responsive to nitrogen fertilization in a Stand Management Cooperative study (Ettl, Greg, University of Washington; pers. com., 2013). The lack of nutrient differences across treatments, although not conclusive, further implicates water limitation

as the factor controlling the differences observed. Soil water holding capacity and water availability are critical factors regulating tree growth in the Pacific Northwest because of the summer dry season. This study suggests that water availability during the summer is important on this very nutrient-rich and productive site, so water limitation could be even more pronounced on coarser-textured and shallower sites in the region with less water holding capacity.

5. Conclusions

Through stand-age 10, the Douglas-fir trees at the Fall River LTSP Trial were not significantly affected by the removal of residual biomass, in the form of tree branches and tops, at rates that exceeded the removal amounts that might be implemented operationally. Results indicate a high level of resilience to an operational residual biomass harvest at this productive site with deep, nutrient-rich, and high-water-holding-capacity soils. Neither soil compaction, without soil puddling or displacement, nor tillage following compaction had any significant effects on tree growth, but the trends were toward a positive effect. Complete control of competing vegetation clearly increased tree growth by reducing competition for site resources by vegetation other than crop trees. We suspect the competition was primarily for water during the growing season, because that was the factor most consistent with the results at this and other regional sites. Subsequent investigations will determine how stands will respond to treatments as crown biomass, nutrient demand, and inter-tree competition increase with time.

Acknowledgments

Funding for the installation, ongoing maintenance, and measurement of the study was provided by Weyerhaeuser NR Company, the National Council for Air and Stream Improvement (NCASI) and the USDA Forest Service Pacific Northwest Research Station. This study is a product of the Sustainable Forestry Component of Agenda 2020, a joint effort of the US Department of Agriculture Forest Service, Research and Development Program and the American Forest and Paper Association. Numerous individuals from the above organizations and from the University of Washington provided input to and assistance with the study. Statistical consulting on this manuscript was provided by Weyerhaeuser's Statistics, Mathematics and Operations Research group, and David Marshall. We also acknowledge thorough reviews by Julie D. Spears and two anonymous reviewers.

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