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Twenty-year response of Douglas-fir to logging debris manipulation and vegetation control at two sites with contrasting soil quality

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ABSTRACT

Reforestation practices have potential to alter site productivity and influence forest stand development. We evaluated the effects of logging debris (LD) manipulation (LD dispersed, LD piled, and LD removed) and competing vegetation control (VC; initial VC only or annual VC for five years) on Douglas-fir stand characteristics at two sites in western Washington and Oregon, USA that contrasted strongly in soil quality (SQ). Annual VC had a pronounced effect on stand volume compared to initial VC, but the magnitude of effect was greater at the low SQ site (~50 % increase in volume) than at the high SQ site (~25 % increase). Volume effects of VC at the low SQ site were due to differences in proportionate survival between treatments (0.15 lower with initial VC vs. annual VC) and will likely persist to end of rotation; effects at the high SQ site were due to greater growth with annual VC, but differences between VC treatments are decreasing with time. Effects of LD treatments were muted and primarily associated with the piling treatment. Total volume was ~25 % greater with LD piling compared to LD removal at the low SQ site only. At both sites, soils sampled under piles had higher extractable nutrients and nitrogen mineralization compared to soils between piles, which may have provided benefits to tree growth at the low SQ site. The contrasting site responses and decreasing effects of VC treatment at the high SQ site highlight the importance of understanding mechanisms of treatment response when making inferences for similar sites.

1. Introduction

Concerns regarding impacts of forest harvest and site preparation practices on long-term site productivity have existed for decades (Powers et al., 1990, Burger, 2009). These concerns persist because of the long timeframes in forest development coupled with inherent variability in natural systems which combine to create uncertainty regarding long-term outcomes. This is particularly true for potential impacts to soils which strongly control site productivity via influence on water and nutrient supply to plants. Although many soil properties influence resource supply, there is broad recognition that soil organic matter has a disproportionate influence on these processes (e.g., Schoenholtz et al., 2000) and that any practices which reduce soil organic matter (or soil carbon (C) as a surrogate) or increase loss of site nutrient capital have a higher likelihood of being unsustainable over time (Powers et al., 1990, Grigal, 2000). Two practices that have received attention in this regard are the removal of logging debris and use of vegetation control, which are known to directly (Powers et al., 2005, Johnson et al., 1982) and indirectly (Slesak et al., 2009, 2010, Strahm et al., 2005) increase loss of C and nutrients following harvesting. These practices are commonly used in production forestry for a variety of reasons including increased wood utilization (Titus et al., 2021) and preparation of the site to create favorable growing conditions for crop trees (Fleming et al., 2006). Given this, there is a need to understand how stand level responses to logging debris removal and competing vegetation control influence stand productivity over the course of a rotation.

The Long Term Soil Productivity (LTSP) Study (Powers et al., 1990) is one of the most comprehensive efforts to understand how organic matter (e.g., logging debris) manipulation, competing vegetation control, and soil compaction influence forest stand development across North America. Summary results from that study generally indicate that logging debris removal has limited effects on tree growth as long as the forest floor is retained (Powers et al., 2005, Ponder et al., 2012, Scott et al., 2014). When negative effects of logging debris removal on survival and growth have been found, they generally occur on sites with low quality soils that are poorly buffered to reductions in nutrient

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availability (e.g., O'hehir and Nambiar, 2010, Curzon et al., 2021). Effects of logging debris are also associated with its influence on vegetation dynamics (Harrington and Schoenholtz, 2010, Thiffault et al., 2011, Peter and Harrington, 2018), and how those dynamics influence the competitive environment of planted crop trees (Harrington et al., 2013). Effects of competition control (usually with the use of herbicides) are generally more straightforward, where survival and growth respond favorably (Wagner et al., 2006, Fleming et al., 2006) and effects become more pronounced with intensity of application, including multiple applications for periods of up to five years after planting (Flamenco et al., 2019, Maguire et al., 2009).

Most studies that have evaluated these practices were limited in duration (~10–15 years) following treatment, and it is unclear if observed effects to tree and stand growth are maintained for longer time periods. In a comprehensive review, Thiffault et al. (2011) concluded that early effects of logging debris removal (referred to as woody biomass) on stand productivity were driven by its influence on microclimate and competing vegetation, and that longer term effects are associated with reduced nutrient availability when nutrient demand is greatest following crown closure (Oliver and Larson, 1996). Similarly, Littke et al. (2020) found that effects of sustained vegetation control on stand growth decreased following crown closure at a high productivity site and speculated that similar responses would occur later at less productive sites where crown closure occurs later in stand development. Long-term assessment of growth responses to logging debris and vegetation control treatments are essential to fully evaluate these practices across a range of site and soil conditions to determine those situations where they may not be suitable to maintain site productivity.

In 2003, an experiment was established to evaluate the effects of logging debris manipulation and vegetation control treatments at two sites with contrasting productively largely associated with distinct differences in soil quality (SQ). Logging debris treatments included retained and dispersed logging debris, removal of logging debris, and piling of logging debris that were crossed with initial vegetation control with or without 5 years of sustained vegetation control. Previous reports found consistent positive effects of sustained vegetation control, which were most pronounced at the low SQ site (Slesak et al., 2016). Effects of logging debris manipulation on stand growth were muted at the high SQ site, but there were clear beneficial effects of logging debris retention (dispersed or piled) at the low SQ site because it inhibited establishment of the invasive shrub Scotch broom (*Cytisus scoparius*) (Harrington and Schoenholtz, 2010, Peter and Harrington, 2018). There was also evidence that piling provided additional beneficial effects to tree survival at the low SQ site (Harrington et al., 2020). Here we report on the 20-year stand response to these experimental treatments, which is the approximate mid-point of stand rotations for production forestry of coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) in the region. Our objectives were to quantify 1) stand response 20 years after treatment and compare with previously reported trends to determine if treatment effects were changing with time as these sites have now achieved crown closure since last measurement, and 2) effects of logging debris piling on soil properties and tree growth to evaluate if benefits of piling may be associated with increased soil resource supply.

2. Methods

2.1. Site characteristics and experimental design

The study was conducted at two sites that contrast strongly in soil properties important to site productivity (Table 1); we refer to these sites as the low and high SQ sites throughout the manuscript. The low SQ site is located near Matlock, Washington (47.206°N latitude, 123.442°W longitude) and the high SQ site is located near Molalla, Oregon (45.196°N latitude, 122.285°W longitude). The region has a Mediterranean climate with cool wet winters and warm dry summers with periods of drought. Mean total precipitation (30-year normals, 1991–2020, Prism Climate Group) is 2455 mm (327 mm May-Sept) and 1671 mm (295 mm May – Sept) at the low and high SQ sites, respectively. Mean annual temperature is 10.5℃ and 9.7℃ at the low and high SQ sites, respectively (Prism Climate Group). Soils at the low SQ site are classed as Dystric Xerorthents (Grove Series, Soil Survey Staff, USDA-NRCS) which were developed from glacial outwash with a loamy sand texture and high rock content. Soils at the high SQ site are classed as Andic Dystrudepts developed from basalt residuum with a loamy texture. Differences in soil texture and rock content are reflected in a more than two-fold difference in soil water holding capacity between the sites (Table 1). Soil water capacity is a critical property influencing SQ and site productivity in this region given the periods of prolonged summer drought. Potential natural vegetation at the low SQ site is the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)/salal (*Gaultheria shallon* Pursh) plant association (Henderson et al., 1989); the high SQ site has the western hemlock/Oregon-grape (*Mahonia nervosa* (Pursh) Nutt.)/swordfern (*Polystichum munitum* (Kaulf.) Presl) and western hemlock/Oregon grape-salal plant associations (Halverson et al., 1986).

Table 1
Site characteristics and selected pre-treatment soil properties from samples collected to a depth of 60 cm for the high SQ site near Molalla, OR, and the low SQ study site near Matlock, WA.

Characteristic or property	High SQ site	Low SQ site
Location (latitude, longitude)	45.196 °N, 122.285 °W	47.206 °N, 123.442 °W
Elevation (m)	449	118
Mean annual temperature (°C)	9.7	10.5
Mean May-Sept precipitation (mm)[a]	295	327
Site index$_{50\ yr}$ (m)[c]	36	36
Particle size distribution (% sand/silt/clay)[d]	37 / 34 / 29	65 / 14 / 21
Bulk density (Mg m^{-3})[#]	0.98 (0.02)	1.45 (0.05)[b]
Coarse fragments by mass (%)	37.7 (2.2)	67.6 (1.3)
Soil water holding capacity (mm)	142	55
Total soil C (Mg ha^{-1})	169.5 (12.0)	92.4 (5.8)
Total soil N (kg ha^{-1})	7220 (410)	3300 (150)
Exchangeable Ca (kg ha^{-1})	5050 (683)	420 (43)
Exchangeable Mg (kg ha^{-1})	2007 (350)	133 (12)
Exchangeable K (kg ha^{-1})	1430 (152)	124 (5)
Extractable P (kg ha^{-1})	5 (<1)	23 (2)

[a] Precipitation was estimated from the PRISM model for period 1991–2020 (PRISM 2024)
[b] Standard error in parentheses, n = 8 for bulk density at Matlock, n = 16 for all others.
[c] from Harrington and Schoenholtz, (2010)
[d] determined with the hydrometer method

The experimental design is a randomized complete block 3 × 2 factorial with four replications that was established at each site. Factor 1 was type of logging debris (LD) manipulation as follows: LD Dispersed, where only merchantable portions of the trees (minimum piece-size diameter 12.7 cm and length 3.7 m) were removed and slash was evenly spread across the plot; LD Piled, where only merchantable material was removed (same as dispersed) but the remaining slash was moved into small piles (3.0 – 3.5 m width, Harrington et al., 2020); and LD Removed, where all slash greater than 5.1 cm was removed from the plots. Logging debris mass in the dispersed treatment was 60–70 % greater (22.5–24.0 Mg ha^{-1}) than the removed treatment (13.5–13.9 Mg ha^{-1}) (Harrington and Schoenholtz, 2010). Factor 2 was vegetation control (VC) via herbicide as either 1) initial VC, where herbicide was applied in the summer after harvesting prior to planting (analogous to an operational site preparation treatment), or 2) the same initial application plus annual VC applications for five years after planting. Treatments were applied to plots 0.3 ha in size (50 ×60 m) in spring (logging debris) or summer (vegetation control) 2003 (and 5 years thereafter for the annual VC treatment) and then plots were planted with plug + 1 bare-root seedlings of coast Douglas-fir in spring 2004 at a 3- x 3-m spacing (1111 trees ha^{-1}).

The high SQ site was partially burned during a series of largescale wildfires that occurred across Oregon in September 2020 (collectively known as the Labor Day fires). The surrounding area of the site was heavily burned, where adjacent stands of similar age that had recently been precommercially thinned were almost totally consumed during the fire, possibly due to increased airflow coupled with greater fuel loading (pers. obs., R. Slesak). In the experimental study area, three plots had high mortality from spot fires and were determined to no longer be viable for the study; treatment combinations at these plots were LD removed-annual VC (plot 23), LD removed-initial VC (plot 5), and LD dispersed-annual VC (plot 14). Across the remaining plots, a total of 471 trees were partially burned, typically with charring of the lower bole produced by low intensity surface fire. Of these, 162 were recorded as dead during the most recent measurement (Supplemental Table S1).

2.2. Stand measurements

Douglas-fir survival and growth were measured on an interior 10 × 10 grid of 100 trees in each plot at periodic intervals with the most recent measurement occurring in 2024 prior to growth initiation. Stem diameter was measured (to the nearest millimeter) on each tree at a height of 1.3 m (i.e., DBH). Total height and height to live crown (i.e., lowest live branch to the nearest decimeter) were measured on a subset (~30 %) of randomly selected trees from each plot using a hypsometer. Growth measurements were compared with previous measurements in the field; remeasurements were conducted in rare instances when the estimate was lower than the previous measurement. All data were entered into data recorders and files were checked for accuracy upon return to the lab.

2.3. Soil collection and processing

Soil samples were collected in piled LD treatments at each site in the fall of 2020 to assess differences in soil chemistry between soil directly under piles versus in areas away (~3 m from pile edge) from pile influence. Pile locations and dimensions were recorded in December 2006 (Harrington et al., 2020); we used this list to randomly select 10 piles from three plots (3–4 piles per plot) in the piled LD-Initial VC treatment at each site. Bucket augers were used to collect mineral soil samples at a depth of 0–20 cm from three locations under each pile, and at three locations that were ~5 m at random azimuths from pile edge. Care was taken to remove any forest floor or decomposed pile material prior to sampling. Samples from under piles or at areas away from piles were composited in the field, thoroughly mixed, and a subsample was bagged and transported to the lab. Samples were air-dried and then sieved to pass a 2 mm mesh.

A 2-week aerobic incubation was conducted to estimate potential mineralizable N for each of the composite samples. For initial N estimates, 6 g (+/- 0.01 g) of air-dried soil were mixed with 30 ml of 2 M KCl, placed on shaker table for 60 min, and then filtered through Whatman 42 filter paper. Another 6 g sample was incubated in a covered glass jar at 30 % moisture content and a temperature of 20°C for 14 days and then extracted in the same manner as the initial sample. Three blanks, where 30 ml of KCI solution without soil was processed in the same manner, were included with the initial and final extraction. Samples were frozen immediately after extraction and then defrosted prior to measurement using a colorimetric flow-through analyzer (Lachat, Loveland, CO). A subsample from each composite was also analyzed for total C and N using a LECO Dumas combustion technique on a Fisons NA1500 NCS Elemental Analyzer (ThermoQuest Italia, Milan, Italy), and analyzed for Mehlich-3 extractable P, Ca, Mg, and K using ICP-NMS (Varian Vista MPX, Varian, Palo Alto, CA, USA). For all soil analytical tests (including KCI extracts), lab standards and duplicates per 10 samples were run for QA/QC.

2.4. Data analysis

Data from each site were analyzed separately and we focused assessment on the most recent measurement period only. Plot means were calculated for proportionate survival, DBH, total height, height to live crown, and total volume. We used measured tree heights from the subset of trees on each plot to estimate tree height of non-height trees using linear regression height-diameter models that were developed for each plot. Individual tree volume was then calculated using the equation from Bruce and DeMars (1974), and values were summed within plots to calculate total stem volume per unit area (m^3 ha^{-1}). Effects of logging debris treatment, vegetation control treatment, and their interactions on stand metrics (proportionate survival, DBH, total height, crown height, and total volume) were assessed using generalized linear mixed models with block modeled as a random effect. We used a beta distribution for the proportion survival model, and a gaussian distribution in models for the remaining response variables.

To assess effects of piles on tree performance, we determined tree distance from the nearest pile in each associated plot ($n = 8$) and separated trees into two distance categories: trees < 1.5 m from pile edge and > 1.5 m from pile edge. Mean survival, DBH, and height were calculated for each plot, and differences between distance categories were assessed using a generalized linear mixed model with distance category modeled as a fixed effect and plot modeled as a random effect. We used a similar approach to assess the effect of piles on soil chemical properties, where sample location (under the pile or ~3 m away from pile) was modeled as a fixed effect, and plot and pile nested within plot were modeled as random effects; a gaussian distribution was used.

All analyses were calculated in R version 4.4.0 (R Core Team, 2024) using the package *glmmTMB* (Brooks et al., 2017) for model fitting. When significant effects were observed, we conducted pairwise comparisons among treatments using Tukey's honesty significance difference test in *emmeans* (Lenth, 2024) to detect statistical differences among treatments. Model residuals were evaluated with *DHARMa* (Hartig, 2021) and an alpha level of 0.05 was used to determine statistical significance in all tests.

3. Results

3.1. Treatment effects on survival and growth

There were significant main effects of treatments on proportionate survival at both sites. At the high SQ site, there was a significant effect of logging debris (LD) treatment on survival (Table 2) where dispersed LD had higher survival (0.84 +/- 0.02) than the removed LD treatment (0.72 +/- 0.07); the piled treatment had intermediate survival (0.78 +/-

Table 2
F Statistic probabilities for effects of logging debris (LD) manipulation, vegetation control (VC), and their interaction on stand characteristics at the high and low soil quality (SQ) sites. Significant values are shown in bold.

Effect	Survival	DBH	Height	Crown Height	Total Volume
High SQ Site					
LD	**0.028**	0.182	0.398	0.903	0.163
VC	0.315	**< 0.001**	**0.004**	0.258	**0.016**
LD x VC	0.993	0.089	**0.043**	0.241	0.742
Low SQ Site					
LD	0.055	0.142	**0.023**	0.064	**0.004**
VC	**< 0.001**	**0.043**	**< 0.001**	**< 0.001**	**< 0.001**
LD x VC	0.052	**< 0.001**	**0.009**	0.089	0.060

0.04) that was not different from the dispersed or removed treatments. In contrast, at the low SQ site effects on survival were associated with vegetation control; initial VC had lower survival (0.57 +/- 0.05) compared to the annual VC treatment (0.72 +/- 0.03).

There were significant main effects and interactions for the growth variables DBH, height, and total volume that varied by site. At the high SQ site, DBH was 1.4 cm (+/- 0.36 cm) greater with annual VC relative to initial, but there was no effect of LD treatment (Fig. 1). For that site, model results indicated a significant interaction between LD and VC treatment on height (Table 2), but multiple comparisons failed to detect differences among any of the treatment combinations (Fig. 1). Annual VC resulted in 37.4 m^3 ha^{-1} (+/- 16.0 m^3 ha^{-1}) greater volume than initial VC, likely caused by the effect of treatment on diameter growth. There was no effect of LD treatment on total volume at the high SQ site despite the differences in survival reported above. At the low SQ site, there was significant interaction between the treatment factors on both DBH and height (Table 2). For DBH, the initial VC-dispersed LD treatment was lower than either the annual VC-dispersed LD or initial VC-piled LD treatments (Fig. 1). Effects on height were due to vegetation control in the dispersed and removed treatments where annual VC had greater height than initial VC (Fig. 1). Both LD and VC treatments influenced volume at the low SQ site. The piled treatment had 19.5 m^3 ha^{-1} (+/- 5.9 m^3 ha^{-1}) greater volume than the removed LD treatment; the dispersed treatment was intermediate in volume and not different from the piled or removed treatments (Fig. 1). For VC, total volume with annual VC was 31.8 m^3 ha^{-1} greater (~50 %) than that for the initial VC only treatment (Fig. 1).

3.2. Effects of debris piles on soils and individual trees

There were significant differences in soil chemical properties between areas under LD piles and areas away from piles at both sites; chemical properties were generally higher under piles with differences most prevalent at the high SQ site (Table 3 and Supplemental S1). Net N mineralization was greater under piles relative to areas away from piles at both sites, which was associated with significantly higher total N at the high SQ site (Table 3). Similarly, extractable Ca and P were also

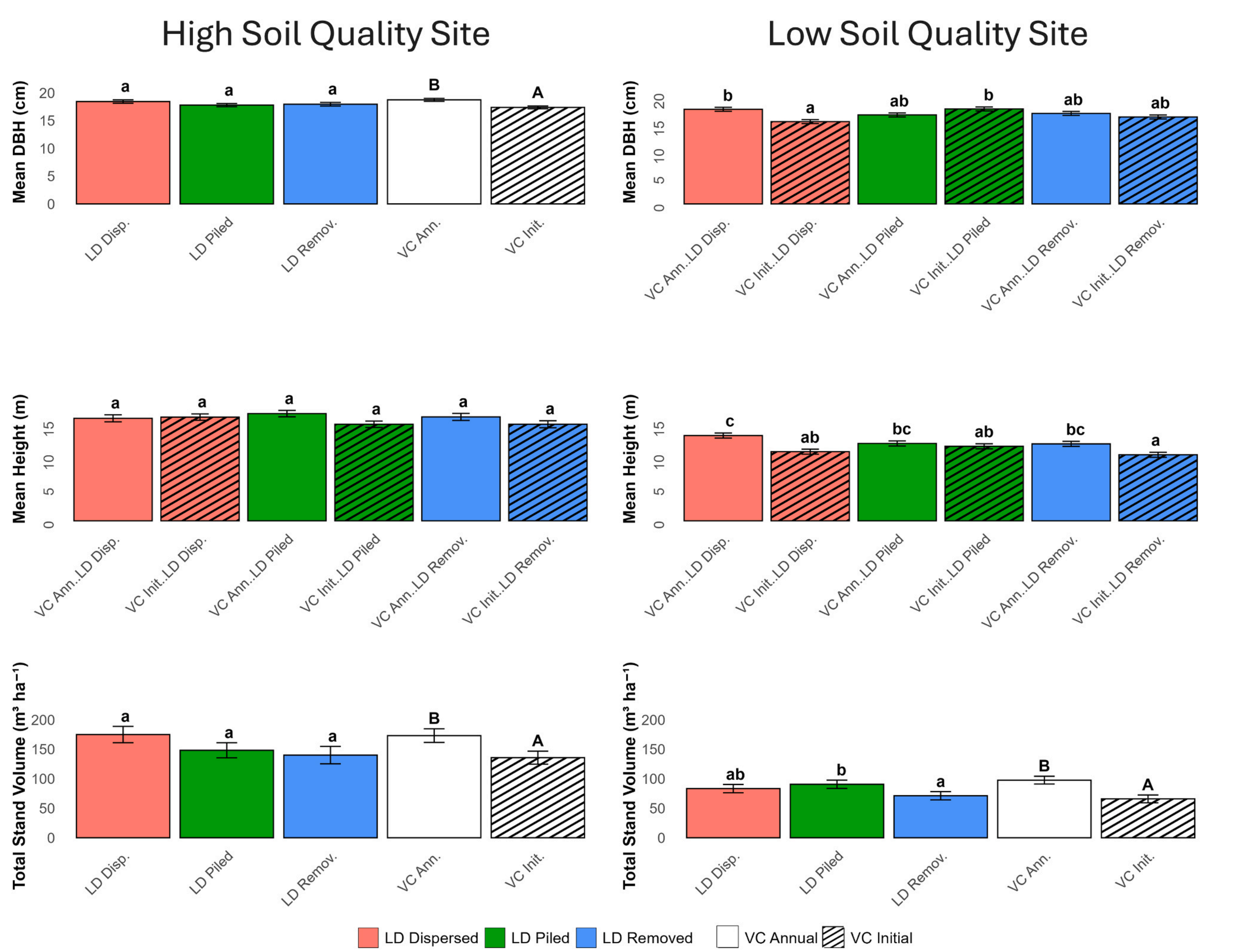

Fig. 1. Main or interactive effects of logging debris (LD) manipulation and vegetation control (VC) treatments on mean diameter (upper panels), tree height (mid panels), and total volume (bottom panels) at the high soil quality (SQ) (left panels) and low SQ (right panels) sites. Treatment means containing different letters are significantly different; error bars are standard error of the mean. Note that some of the treatment labels have been abbreviated to fit within the legend space.

Table 3
Mean soil chemical properties under logging debris (LD) piles and away from piles at the high soil quality (SQ) and low SQ sites. Value in parentheses are standard error of the mean. Bold values within a given site-soil combination are significantly different.

Variable	High SQ site		Low SQ site	
	Under pile	Away from pile	Under pile	Away from pile
Soil total C (%)	13.3 (2.0)	10.6 (2.0)	7.1 (1.0)	7.8 (1.0)
Soil total N (%)	**0.52 (0.05)**	**0.43 (0.05)**	0.30 (0.02)	0.26 (0.02)
Ammonification (mg N kg^{-1} soil day^{-1})	4.4 (0.3)	3.9 (0.3)	1.8 (0.3)	1.3 (0.3)
Nitrification (mg N kg^{-1} soil day^{-1})	**0.8 (0.3)**	**0.2 (0.3)**	0.0 (0.0)	0.0 (0.0)
Net N mineralization (mg N kg^{-1} soil day^{-1})	**4.0 (0.4)**	**3.2 (0.4)**	**1.3 (0.3)**	**0.4 (0.3)**
Soil extract. Ca (mg kg^{-1})	**2270 (230)**	**1390 (230)**	**670 (90)**	**370 (90)**
Soil extract. Mg (mg kg^{-1})	**300 (40)**	**250 (40)**	70 (9)	70 (9)
Soil extract. K (mg kg^{-1})	330 (50)	350 (50)	100 (20)	70 (20)
Soil extract P (mg kg^{-1})	**10 (1)**	**5 (1)**	**40 (5)**	**30 (5)**

Table 4
Mean tree proportionate survival, diameter, height, and number of trees growing near logging debris piles and away from piles for trees in the pile treatment at each site. Values in parentheses are the standard error of the mean. SQ = soil quality.

	High SQ site		Low SQ site	
Variable	Near pile	Away from pile	Near pile	Away from pile
DBH (cm)	17.4 (0.6)	17.0 (0.6)	17.0 (0.4)	16.1 (0.5)
Height (m)	15.5 (0.3)	15.2 (0.4)	11.6 (0.4)	11.5 (0.4)
Survival (%)	0.78 (0.05)	0.79 (0.04)	0.74 (0.04)	0.65 (0.08)
Count (n)	473	327	397	403

greater under piles than areas away from piles at both sites, but the magnitude of difference was greatest at the high SQ site.

There was no effect of proximity to logging debris piles on tree survival or growth at either of the sites (Supplemental Table 2). Mean diameter, height, and survival (for the low SQ site only) were consistently greater in close proximity to piles, but differences were not significant (Table 4).

4. Discussion

Site preparation practices such as logging debris removal and competing vegetation control are used during reforestation to facilitate successful stand establishment of planted trees (Fargione et al., 2021, Briggs, 2007). Although common, there is potential for these practices to cause long-term reductions in site productivity due to increased loss of site nutrient capital beyond what occurs with removal of wood products following harvest (Powers et al., 1990, Ponder et al., 2012). Because of this, it is important to quantify the effects of these practices on stand development to evaluate their utility in achieving sustained yield over time. Our results indicate that competing vegetation control and logging debris manipulation have pronounced and prolonged effects on stand characteristics that vary between sites with contrasting soil qualities. In general, competing vegetation control for a period of five years has resulted in increased growth of crop trees at both sites relative to initial control only, while effects of logging debris manipulation are generally more muted and concentrated in the piling treatment at the low SQ site.

4.1. Effects of competing vegetation control

Competing vegetation control is generally effective at increasing seedling survival and early growth across a wide range of conditions (Fleming et al., 2006, Wagner et al., 2006). In the PNW it is typically applied during site preparation to increase the availability of growth limiting resources to seedlings (Briggs, 2007), particularly the availability of soil water given prolonged periods of summer drought that occur in the region (Harrington and Tappeiner II, 1991, Dinger and Rose, 2009). Our initial VC treatment is analogous to this practice; longer periods of continuous vegetation control such as our annual VC treatment are less common but may be necessary for successful establishment or to maximize productivity (Maguire et al., 2009). The increases in total volume at the high SQ site with annual VC are due largely to increased growth, as there was no difference in survival between the VC treatments (Table 2). In contrast, greater volume with annual VC at the low SQ site was primarily due to differences in survival; annual VC had ~25 % greater survival than initial VC and there were limited differences in DBH and growth between treatments (Fig. 1).

In an earlier report, Harrington et al. (2020) attributed differences in VC effects between the sites to differences in dominant competitive species. At the low SQ site, higher mortality in the initial VC treatment was caused by the invasive shrub, Scotch broom (Harrington and Schoenholtz, 2010, Harrington et al., 2020), which is highly competitive on the coarse textured, low fertility soils at that site (Carter et al., 2022). Because of that mortality, the large differences in volume growth between the two treatments (~50 % increase with annual VC relative to initial VC) are likely to persist over time. At the high SQ site, the relative volume increase with annual VC was more moderate (25 %), and the magnitude of effect has decreased since the last measurement where annual VC had ~30 % greater volume relative to initial VC (Harrington et al., 2020). Littke et al. (2020), in an assessment of these sites and one additional very high SQ site, suggested that the benefit of annual VC may decrease with time following crown closure when nutrient demand is maximized (Thiffault et al., 2011), with this reduction being most pronounced and occurring earlier at sites with higher nutrient capital (high SQ sites). Our findings support this possibility, but further measurements are needed to determine if the effect of annual VC on volume growth continues to decline at our higher SQ site. Regardless, our data indicates that annual VC may be most effective at low SQ sites given the large increases in survival and total volume observed in that treatment.

4.2. Effects of logging debris manipulation

Removal or manipulation of logging debris following harvest has potential to impact long-term soil productivity via a reduction in C and nutrient inputs to soil and exacerbation of mechanisms influencing loss of these elements following forest harvest (via leaching, heterotrophic respiration; Slesak et al., 2009, 2010, Strahm et al., 2005, Vitousek and Matson, 1985). At shorter time scales (<10 years) effects of logging debris manipulation on tree performance are more directly tied to its influence on vegetation dynamics following harvest (Thiffault et al., 2011, Harrington et al., 2013). However, a large number of studies, including results from the Long-term Soil Productivity Network that conducted similar treatments to those here (Powers et al., 2005, Ponder et al., 2012, Scott et al., 2014), have generally found limited effects of logging debris removal on tree and stand growth at moderate to higher SQ site types. Our results at the higher SQ site align with this general response, with the exception of lower survival with LD removal compared to when it was dispersed. A similar non-significant difference was observed at year 15, where proportionate survival was higher with

LD dispersed (0.91 +/- 0.03) compared to LD removed (0.84 +/- 0.04) (Harrington et al., 2020). Higher mortality across all treatments during this remeasurement was a result of the fire in 2020, and it may have possibly caused the significantly lower mortality in the LD removal treatment. It is difficult to assess this possibility (or others, e.g., that fire-induced mortality was influenced by treatment), but the null effects of logging debris treatment on other stand variables at this site indicate that effects on survival have not affected overall stand productivity.

Effects of logging debris treatment at the low SQ site were primarily associated with the LD piled treatment, which increased total volume by ~25 % compared to logging debris removal. There are multiple mechanisms whereby piles may benefit tree growth including physical protection from the sun and wind early after planting, or increased availability of water (arising from a mulch effect, as well as localized absence of competing vegetation) or nutrients (arising from increased inputs). In the case of the latter, our findings show that piling has beneficial effects on soil chemical properties at both low and high SQ sites, notably increases in indices of N availability which is a critical element often limiting to tree growth in the region (Gessel et al., 1973). We have previously shown beneficial effects of logging debris retention on soil C and N at these sites at smaller scales (≤1 m, Slesak et al., 2010, 2011) and earlier in stand development (≤ 5 years); these more recent findings demonstrate that concentrated piling of logging debris can affect soil chemistry up to at least 17 years when the soil sampling occurred. Harrington et al. (2020) found that survival of trees growing near piles was 0.16 higher than those away from piles at year 15. We did not observe differences in survival or growth in trees near or distant from piles at either site (Supplemental Table S2), but these variables were consistently higher for trees growing in close proximity to piles at the low SQ site (Table 4), apparently causing significant effects on total volume when aggregated to the plot scale.

The positive effects of piling on soil chemistry occurred at both sites, but there was no evidence that these benefits to soil nutrition influenced stand growth at the higher SQ site. We think the lack of growth response to piling at the higher SQ site is a result of factors other than nutrient supply being limiting to growth at that site. When positive effects of logging debris on tree growth have been found elsewhere, they generally occur at sites with low fertility soils that are poorly buffered to reductions in C and nutrient inputs (O'hehir and Nambiar, 2010, Curzon et al., 2021). Our results align with those studies and concepts surrounding limitations to tree growth (Burger, 2009), highlighting the importance of logging debris retention at low SQ sites that inherently have low, poorly buffered soil nutrient pools (e.g., Table 1). This response has important implications for logging debris management following harvesting if wood production is a primary objective.

4.3. Inference

This study was conducted at two Douglas-fir sites in western Washington and Oregon and direct inference is limited to these sites. As outlined above, we attribute the different responses between sites primarily to differences in soil properties that control soil quality (Table 1), but other factors likely influenced the response including variation in climate or differences in plant competitive community (Harrington et al., 2020). However, findings from our sites contribute to broader inference of similar studies and our understanding of how practices at time of reforestation vary in their influence across a range of conditions. These studies include the Fall River and NARA affiliate studies in the PNW region (Littke et al., 2021), and installations of the Long Term Soil Productivity Study across N. America (~100, Page-Dumroese et al., 2021). Our findings align with reports from these studies, where response to treatments is influenced by site-specific and regional differences in soil properties such as soil texture (Page-Dumroese et al., 2021). Long-term, rotation-length assessments of these experiments are critical to provide inference across the range of conditions and at relevant time scales for operational management.

5. Conclusion

Our findings indicate that practices following harvest or during reforestation can have lasting effects on stand development and characteristics that control productivity. The consistent benefits of annual VC to volume growth at both sites demonstrate the utility of this practice if the cost can be justified, in particular at the low SQ site where the magnitude and anticipated duration of VC effect is high. Although effects of LD treatments on tree and stand growth were more muted compared to VC, retention of LD in piles has a positive influence on soil properties important to site productivity, which was associated with increased growth at the low SQ site where nutrient pools are inherently low. Additional benefits of LD piling may accrue over time to positively influence long-term productivity. Overall, our findings highlight the critical importance of soil quality (within the constraints of climate) when evaluating the use of establishment practices to achieve management objectives related to wood production.

CRediT authorship contribution statement

Slesak Robert: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis. **Timothy B. Harrington:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Scout M. Dahms-May:** Writing – review & editing, Visualization, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.123434.

Data availability

Data will be made available on request.

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