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Effects of intensive management practices on 10-year Douglas-fir growth, soil nutrient pools, and vegetation communities in the Pacific Northwest, USA

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ABSTRACT

Intensive management practices are commonly used to increase fiber production from forests, but potential tradeoffs with maintenance of long-term productivity and early successional biodiversity have yet to be quantified. We assessed soil and vegetation responses in replicated manipulations of logging debris (LD; either retained or removed) and competing vegetation control (VC; either initial or sustained annually for 5 years) for 10 years at two Douglas-fir sites that contrasted strongly in availability of soil nutrients and water. We evaluated (1) survival and growth of Douglas-fir to determine short-term effectiveness for fiber production, (2) change in soil C and nutrient pools as an indicator of longer-term effects of treatments on soil quality and ecosystem production, and (3) vegetation composition and cover for treatment effects on early successional biodiversity. Annual VC caused large increases in Douglas-fir growth at both sites, but increased survival only at the lower-productivity site. In most instances and regardless of site or treatment, soil C and nutrient pools increased following harvesting, but the increases were generally larger with lower intensity practices (LD retained and initial VC). Effects of LD were small and inconsistent at the higher productivity site, but LD retained increased Douglas-fir survival and growth and soil nutrient pools at the lower productivity site. Species diversity was reduced at both sites with annual VC because of increased Douglas-fir cover, but the magnitude was greater and the timing was earlier at the higher quality site where plant communities in all treatments had converged by year 10. Annual VC can be used to increase growth of planted Douglas-fir while maintaining soil nutrient pools for sustained ecosystem productivity, but a concurrent decrease in early successional diversity will occur with impacts increasing with site quality. Logging debris retention can have positive benefits to Douglas-fir growth and soil nutrient pools, particularly at lower quality sites. Our results demonstrate a need for careful consideration of site quality to ensure that objectives are realized with regards to fiber production and maintenance of soil productivity and biodiversity with intensive forest management.

1. Introduction

Intensive forest management has many forms, but generally involves greater biomass removals (e.g., greater utilization for bioenergy production; Berger et al., 2013) over shorter rotations coupled with increased cultural inputs such as herbicide and fertilizer applications, which in combination lead to greater fiber production (Adams et al., 2005). Intensive management practices influence processes that control nutrient retention and loss following harvest (Nambiar, 1990; Powers et al., 2005; Vitousek and Matson, 1985) and also influence plant community composition and biodiversity (Peter and Harrington, 2009, 2012). The relative merits of intensive management have been debated for decades, with supporters arguing the necessity of increased fiber production under a shrinking land base (Wagner et al., 2004; Fox, 2000; Powers et al., 1990) and expanding population, while detractors

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point to reductions in biodiversity and habitat as unacceptable outcomes at odds with concepts of sustainability (Donato et al., 2012; deMaynadier and Hunter, 1995). Although this conflict of views is unlikely to be easily resolved, controlled replicated studies can impart useful information to guide a science-based evaluation of when site conditions may be suitable for intensive forest management practices. In particular, there is a need to determine how intensive management can be used to sustain soil quality and increased fiber production while maintaining biodiversity or, at least, minimizing its loss (Betts et al., 2013).

One common intensive management practice is the use of herbicides to control competing vegetation during the early years of stand establishment. Vegetation control (VC) increases availability of soil water, nutrients, and light to the crop trees (Harrington and Tappeiner, 1991; Dinger and Rose, 2009), providing significant benefits to their survival and growth across a range of site and climate conditions (Fleming et al., 2006; Wagner et al., 2006). Although clearly effective for increasing crop tree survival and growth, modification of the plant community that results from this practice has potential to reduce long-term soil productivity if nutrient export from the site is increased (Vitousek and Matson, 1985; Smethurst and Nambiar, 1995) or if site conditions are conducive to soil C loss with VC application (Slesak et al., 2010). Some studies from the southeastern USA have documented reductions in soil C and N with VC (Shan et al., 2001; Echeverria et al., 2004; Miller et al., 2006). However, in a study involving 18 different sites in the western USA spanning an observation range of 10–35 years, Powers et al. (2013) concluded that there was no lasting effect of VC on soil C pool to a depth of 30 cm, similar to the findings of Scott et al. (2014) in 13 loblolly pine (*Pinus taeda*) plantations 15 years after treatment in the southeastern USA. Identifying mechanisms and site conditions influencing nutrient retention and efficacy of crop tree response following VC is a critical research need to be addressed in order to understand how responses to VC vary with soil and climate conditions (e.g., Powers and Reynolds, 1999; Devine et al., 2011).

Effects of VC on plant biodiversity and composition are somewhat more straightforward for short-term responses (<5 years), as VC generally causes a reduction in vegetation cover and a change in species composition (Wagner and Robinson, 2006; Peter and Harrington, 2009, 2012), which conceptually would be greatest under harvest conditions with the greatest disturbance severity (Roberts, 2007). This finding is not surprising given the causal factor and its intent, but how these short-term responses relate to longer-term outcomes is not clear. For example, Maguire et al. (2009) showed that vegetation abundance can recover rapidly following cessation of VC in coastal Douglas-fir in the Pacific Northwest, USA, reaching levels similar to the absence of VC within a few years post-control. In Ontario, Canada, Wagner and Robinson (2006) found that VC applied for up to five years caused a reduction in vegetation cover and a shift in proportional abundance of vegetation classes, but had limited effects on species richness 10 years after VC initiation. Application of VC may only temporarily delay development of vegetation communities similar to those present when VC is not used, resulting in smaller impacts to biodiversity over time. If true, it is likely that recovery periods vary depending on soil and climate conditions, as these factors have been shown to be important controllers of post-harvest vegetation dynamics (Harrington and Schoenholtz, 2010; Harrington et al., 2013). A shortened duration of the early successional stage of stand development with VC and its effects on biodiversity is also of concern (Swanson et al., 2010).

Another common intensive management practice is removal of greater amounts of logging debris (LD) during harvesting for utilization (e.g., bioenergy; Janowiak and Webster, 2010) or site preparation. Increased removal of LD (variously referred to as biomass, woody residues, organic matter, slash, etc.) has potential to influence tree growth and vegetation communities by altering resource availability and microclimate immediately post-harvest, modifying seedbed conditions, and causing changes in soil pools important to long-term productivity such as soil C (as a proxy for soil organic matter) (Powers et al., 1990). However, a large number of studies, including summary reports from the Long-Term Soil Productivity study (Powers et al., 2005; Ponder et al., 2012; Scott et al., 2014), have generally shown limited effects of increased LD removal on crop tree growth and soil C and nutrient pools across a range of site conditions and climate. When negative effects of increased LD removal have been observed, they generally have occurred on inherently nutrient-poor sites (O'Hehir and Nambiar, 2010) or where more intensive practices were employed (Egnell and Valinger, 2003; Smith et al., 2000). Using meta-analysis, Nave et al. (2010) observed that harvest-related effects on soil C were dependent on species composition and soil type, and the influence of LD removal on soil C may vary with these factors as well. Effects of variations in logging debris levels on species diversity and composition are less well understood (Kershaw et al., 2015).

Ultimately, the interactions between LD removal and VC are often of greatest interest because these practices are commonly applied together. Harrington et al. (2013) showed that effects of LD on Douglas-fir growth were dependent on site conditions and whether or not VC was applied in tandem. Similarly, Thiffault et al. (2011) in a comprehensive review, concluded that the dominant effect of LD on crop tree growth was related to its influence on vegetation dynamics (composition and abundance) and microclimate. Logging debris removal has also been shown to facilitate establishment of invasive species on some sites to the detriment of crop tree growth and native plant communities (Harrington and Schoenholtz, 2010; Peter and Harrington, 2012). Understanding the mechanisms whereby LD and VC interact to either positively or negatively influence soil and vegetation response is necessary to identify those soil and site conditions where intensive forest management can be practiced sustainably (Fox, 2000).

Here we report on decadal responses of planted coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) survival and growth, soil C and nutrient pools, and plant communities to experimental combinations of VC and LD removal. Our primary objectives were to assess the relative merits of these intensive management practices through examination of (1) crop tree growth response to assess practice effectiveness with regards to short-term fiber production, (2) soil response to assess potential for longer-term sustained fiber production and maintenance of soil functions, and (3) plant community responses to assess effects on community composition and biodiversity that may accompany intensive management practices. For these evaluations, we used data from two Douglas-fir sites in the Pacific Northwest, USA that contrast in soil and climate, and also utilize past reports from a similar study in the region to expand the inference of our findings. We used these findings to identify mechanisms whereby intensive management practices influence selected site conditions and stand growth and development, and how they vary depending on site conditions.

2. Methods

2.1. Site descriptions

The research was conducted on two sites affiliated with the North American Long-Term Soil Productivity (LTSP) study (Harrington and Schoenholtz, 2010; Powers et al., 2005), which have large differences in precipitation and soil properties that control stand productivity (Table 1). The Matlock, Washington USA site is located on the Olympic Peninsula and has soil classified as a sandy-skeletal, mixed, mesic, Dystric Xerorthents formed in glacial outwash, which is generally very deep (>5 m) with little to no slope (Soil Survey Staff, USDA–NRCS 2015). The Molalla, Oregon USA site is located in the foothills of the western Cascades and has soil classified as fine-loamy, isotic, mesic Andic Dystrudepts formed in basic agglomerate residuum with an average soil depth of 1.4 m that occurs on 0–30% slopes with a SW–NW aspect (Soil Survey Staff, USDA–NRCS 2015). The regional climate is Mediterranean, characterized by mild, wet winters and dry, warm summers with periods of drought (>2 mo) common. The Molalla site was mostly occupied by the western hemlock (*Tsuga heterophylla* (Raf.) Sarg./Oregon grape (*Mahonia nervosa* (Pursh) Nutt.)/western sword fern (*Polystichum munitum* (Kaulf) C. Presl)) and western hemlock/Oregon grape-salal (*Gaultheria shallon* Pursh) plant associations, with smaller amounts of the western hemlock/western swordfern-oxalis (*Oxalis oregana* Nutt.) and western hemlock/western swordfern plant associations (Halverson et al., 1986). The Matlock site was occupied entirely by the western hemlock/salal plant association (Henderson et al., 1989).

2.2. Experimental design and treatment application

Sites were initially clear-cut harvested with chainsaws in March (Molalla) and April (Matlock) of 2003. To confine soil disturbance, designated machine trails were marked at 20-m intervals across the site immediately after trees were felled. Following harvest, a 2 × 2 randomized complete block factorial design was installed at each site. Blocking was based on aspect (Molalla only) and proximity to logging access roads (Matlock and Molalla). Factor 1 was LD level (retained or removed) and factor 2 was VC (initial site-preparation vegetation control or annual vegetation control for 5 years). Each factorial combination was replicated four times as 0.3 ha (50 × 60-m) plots. The LD-retained treatment removed only merchantable portions of the tree, and the LD-removed treatment removed most LD in addition to the merchantable portions. Logging debris mass (estimated with the line transect method, Brown, 1974) was 22.5 (se = 3.0) and 13.5 Mg ha^{-1} (se = 3.0) in the LD retained and removed treatments, respectively, at Matlock, and 24.0 (se = 2.8) and 13.9 Mg ha^{-1} (se = 2.8) in the LD retained and removed treatments, respectively, at Molalla (Harrington and Schoenholtz, 2010). All plots received an initial application of herbicide in late summer 2003 to reduce primarily woody competing vegetation, and then only those treatments assigned annual VC were treated with herbicide in the fall or spring of each year thereafter for five years to control all competing vegetation (Harrington and Schoenholtz, 2010). Study sites were hand planted with bare-root Douglas-fir seedlings in February (Molalla) and March (Matlock) of 2004 at a 3 × 3 m spacing (1111 trees ha^{-1}). Additional information about research methodology is provided in Harrington and Schoenholtz (2010).

2.3. Soil sampling and analytical methods

Soils were sampled prior to harvesting in the winter of 2003 and again in the summer of 2013, ten years after tree harvest, with 10 cm-diameter augers. At each time period, samples were collected from two depths of the mineral soil (0–15 cm and 15–30 cm) at five points within each plot, composited by depth increment, thoroughly mixed, and a subsample was transported in plastic bags to the lab. Forest floor was sampled in 2013 at the same sample points in each plot used for sampling of mineral soil using a square 0.1 m^2 frame for collection of all forest-floor material <0.6 cm in diameter. Mineral soil samples were air-dried and then sieved to pass a 2-mm mesh. Forest floor samples were dried at 65 °C, weighed, and then milled to pass a 2-mm mesh using a Thomas Wiley Mill, (Thomas Scientific, Model 4 Wiley Mill, Swedesboro, NJ). Mineral soil and forest floor total soil C and N were measured by dry combustion using a LECO Dumas combustion technique on a Fisons NA1500 NCS Elemental Analyzer (ThermoQuest Italia, Milan, Italy). Mineral soil exchangeable Ca, Mg, and K were extracted with ammonium acetate and extract concentrations were measured with inductively coupled plasma spectroscopy (Varian Vista MPX, Varian, Palo Alto, CA, USA). Total soil P was determined by copper catalyzed digestion with sulfuric acid and digestate concentrations were measured with inductively coupled plasma spectroscopy (SPECTRO ARCOS ICP-AES, SPECTRO Analytical Instruments, Kleve, Germany). All estimates of soil C and nutrient concentrations are reported on an oven-dry (105 °C) basis.

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

Characteristic or property	Matlock	Molalla
Location (latitude, longitude)	47.206°N, 123.442°W	45.196°N, 122.285°W
Elevation (m)	35	549
Mean annual temperature (°C)	10.7	11.2
Mean annual precipitation (cm)[a]	240	160
Site index$_{50yr}$ (m)[c]	36	36
Particle size distribution (% sand/silt/clay)[d]	65/14/21	37/34/29
Total bulk density (Mg m^{-3})	1.45 (0.05)[b]	0.98 (0.02)
Coarse fragments by mass (%)	67.6 (1.3)	37.7 (2.2)
Soil water holding capacity (mm)[e]	55	142
Total soil C (Mg ha^{-1})	92.4 (5.8)	169.5 (12.0)
Total soil N (kg ha^{-1})	3300 (150)	7220 (410)
Exchangeable Ca (kg ha^{-1})	420 (43)	5050 (683)
Exchangeable Mg (kg ha^{-1})	133 (12)	2007 (350)
Exchangeable K (kg ha^{-1})	124 (5)	1430 (152)
Extractable P (kg ha^{-1})	23 (2)	5 (<1)

[a] Precipitation was estimated from the PRISM model for the period, 1950–2005 (PRISM 2015).
[b] Standard error in parentheses, $n = 8$ for bulk density at Matlock, $n = 16$ for Molalla.
[c] From Harrington and Schoenholtz (2010).
[d] Determined with the hydrometer method.
[e] Estimated with pressure plate analysis.

2.4. Douglas-fir and vegetation measurements

Survival and growth of planted Douglas-fir were monitored on a 10 × 10 grid of trees nested within each treatment plot to avoid edge effects. Stem diameter at breast height (dbh; nearest mm at 1.3 m above ground) was measured on each tree per measurement plot at the end of the 2008, 2011, and 2013 growing seasons, corresponding to 5, 8, and 10 years after treatment, respectively. Total height (nearest cm) was measured on each tree per measurement plot in 2008 and on a randomly-selected 30% sample of trees in 2011 and 2013. Height to live crown (height to lowest live branch; nearest cm) was measured on the same randomly-selected trees in 2011 and 2013.

For vegetation measurements, one circular 176.7 m^2 (7.5 m radius) sample plot was located in the center of each treatment plot. Vegetation measurements were made in June of each measurement year using USFS Pacific Northwest Region, Area 1 Ecology Program assessment protocols (Henderson et al., 1989). Plant cover was visually estimated for all vascular species on each plot. Plant associations for each plot were determined from the abundance of indicator species using published keys (Henderson et al., 1989 for Matlock and Halverson et al., 1986 for Molalla). Douglas-fir canopy cover (nearest 5%) was estimated in 2008 and 2011 as the sum of crown areas of each tree rooted within the vegetation measurement plot divided by sample area; in 2013, it was estimated visually because significant crown overlap had begun to occur.

2.5. Data analysis

For all analyses, data from each site were analyzed independently in SAS (SAS Institute, Inc., 2013) with a significance level of 0.1 because of low statistical power associated with the level of replication and high inherent variability in some of the variables (e.g., soil nutrient concentrations). Mineral soil chemical parameter estimates were averaged across sample depth increments for each time period. Change in soil C and nutrient concentrations were calculated as the difference between pretreatment and ten-year post-treatment samples, with negative values indicating absolute losses and positive values indicating gains. Effect of treatment on the change in soil C and nutrient concentrations was analyzed using mixed model analysis of variance (Proc Mixed in SAS; SAS Institute, Inc., 2013) with block modeled as a random effect and pre-treatment values used as covariates when significant. Post-treatment effects on forest floor parameters were assessed in the same manner but without use of a covariate. Confidence intervals were developed for the mean 10-year change in soil C and nutrient concentrations within a treatment to independently assess if differences were significantly different from zero. Examination of the residuals indicated assumptions of normality and homogeneity were valid. When F tests indicated significant treatment interactions, multiple comparisons with Tukey's adjustment were conducted to detect differences between treatment means.

Douglas-fir stand volume ($m^3\ ha^{-1}$) was estimated for each plot and measurement year with the equations of Bruce and DeMars (1974). To predict height of Douglas-fir for which only dbh was measured, the following linear equation was fitted to pooled data from each treatment plot with weighted least squares regression in Proc Reg (SAS Institute, Inc., 2013):

$$H = b_0 + b_1(D) \quad (1)$$

where H is height (m), D is dbh (cm), and b_0 and b_1 are regression coefficients to be estimated. A nonlinear model (Curtis, 1967) did not provide an adequate fit to the data. The weights used in the regression analysis were the reciprocal of dbh, given the assumption that they are proportional to the reciprocal of the variance for height. A parabolic volume equation was used to estimate volume of Douglas-fir having a dbh less than 1 cm.

Mean values for each Douglas-fir variable were calculated by plot and measurement year. For each site, data for a given variable were subjected to repeated-measures analysis of variance (ANOVA) in Proc Mixed (SAS Institute, Inc., 2013) to test the significance of the fixed factors, LD level, VC level, measurement year, and their interactions, after adjusting for random effects of blocks. Prior to ANOVA, an angular transformation was applied to proportionate values of Douglas-fir survival and cover, and a logarithmic transformation was applied to the Douglas-fir growth variables to homogenize their residual variances (Sokal and Rohlf, 1981). Residuals for each response variable were plotted against predicted values to check for non-homogenous variance. If a year-by-treatment interaction was detected, slicing was used in SAS to identify individual years in which differences existed among treatments. When treatment differences were detected, multiple comparisons of adjusted means were conducted with Bonferroni probabilities to control the Type I error rate (Quinn and Keough, 2002). Results are presented as back-transformed, least-squares means from the ANOVA.

Plant community floristics were compared with nonmetric multidimensional scaling (NMS) ordination (McCune and Mefford, 1999) using PC-Ord. Response variables used in the ordinations were the estimated canopy covers for all species present at time of measurement. We set the PC-Ord NMS on autopilot for thoroughness, specified use of the Sorensen distance measure, and otherwise used default settings. Default settings included 6 axes, 500 (maximum) iterations, random starting coordinates, reduction in dimensionality of 1 at each cycle with a 0.2 step length, random number of seeds, 250 runs with real data, 250 runs with randomized data, and a stability criterion of 0.0000001 standard deviations in stress over the last 15 iterations. For visual display we averaged the ordination X and Y coordinates of measurement plots and displayed them with error bars equivalent to 1 standard deviation. Ordinations were computed from 2013 data only (116 species total) to assess treatment effects after 10 years.

The significance of differences among centroid locations associated with the treatments along the X and Y axes were investigated with single factor ANOVA (Proc GLM; SAS Institute, Inc., 2013). Mean separations of the differences along each axis for the eight combinations of site $\times$ LD $\times$ VC were made with Tukey HSD tests (Proc GLM; SAS Institute, Inc., 2013). Correlation analysis was conducted among species cover values with each ordination axis (Kendal tau) (McCune and Mefford, 1999) to identify the dominant species associated with each axis. We also calculated several indicators of species diversity (i.e., species richness, Simpson, Shannon, and evenness indexes) at year 10 by plot and used ANOVA to assess treatment effects on these indicators within each site.

3. Results

3.1. Climate differences

Across the 10-year (2004–2013) duration of the study the two research sites exhibited differences in climate (Fig. 1). Summer air temperatures were consistently warmer at Molalla than at Matlock. Dormant season precipitation was considerably higher at Matlock. In specific years, summer precipitation also was higher at Matlock than at Molalla (e.g., 2007, 2008, and 2011).

3.2. Soil responses

At both sites, mineral soil C and nutrient concentrations generally increased across all treatments over the 10 year period following harvesting, and in many instances the increases were significantly greater than zero (Figs. 2 and 3). When treatment

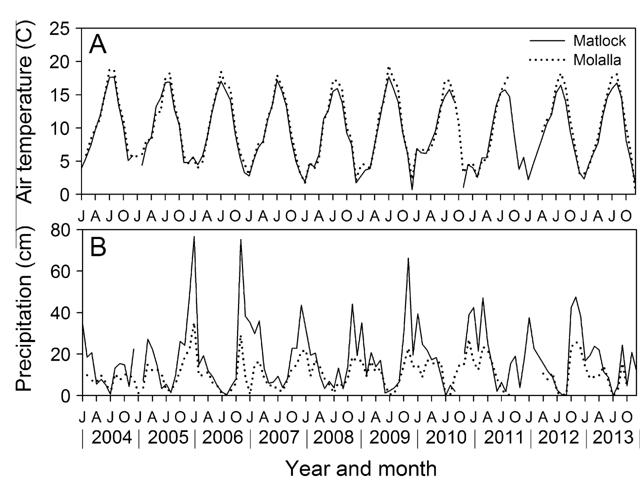

Fig. 1. Mean monthly values of: (A) air temperature at 2 m above ground and (B) precipitation at Matlock and Molalla during 10 years after logging debris and vegetation control treatments. Breaks in a given series indicate missing data.

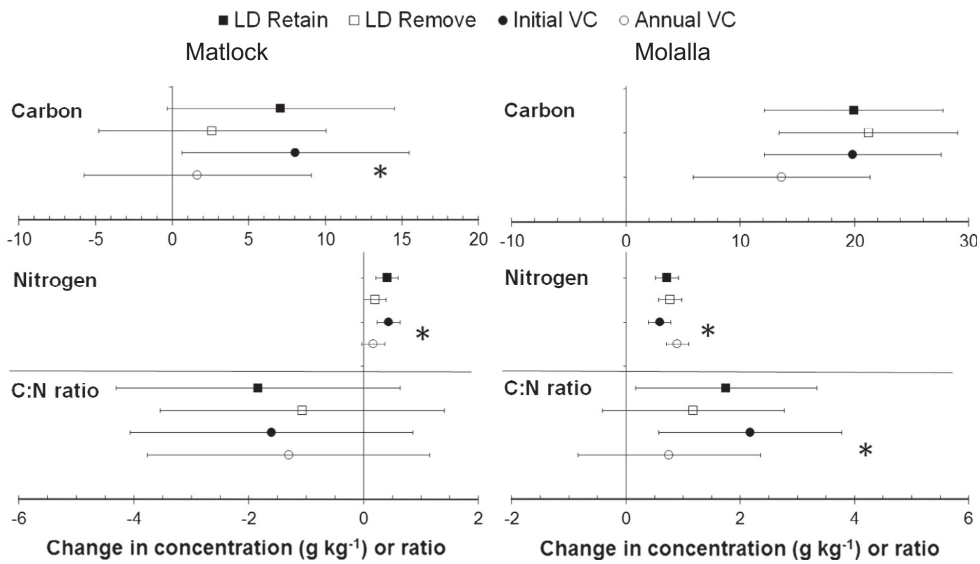

Fig. 2. Absolute change in soil carbon and nitrogen concentrations or C:N ratio for 0–30 cm soil depth by site and treatment over a 10 year period. Error bars are the 90% confidence interval of the estimate. Values with error bars that do not overlap zero are significant increases or decreases over the 10-year period. An asterisk indicates a significant difference between treatments within a given factor (main effect of logging debris (LD) or vegetation control (VC)). There were no significant interactions between the factors for C, N, and C:N at either site.

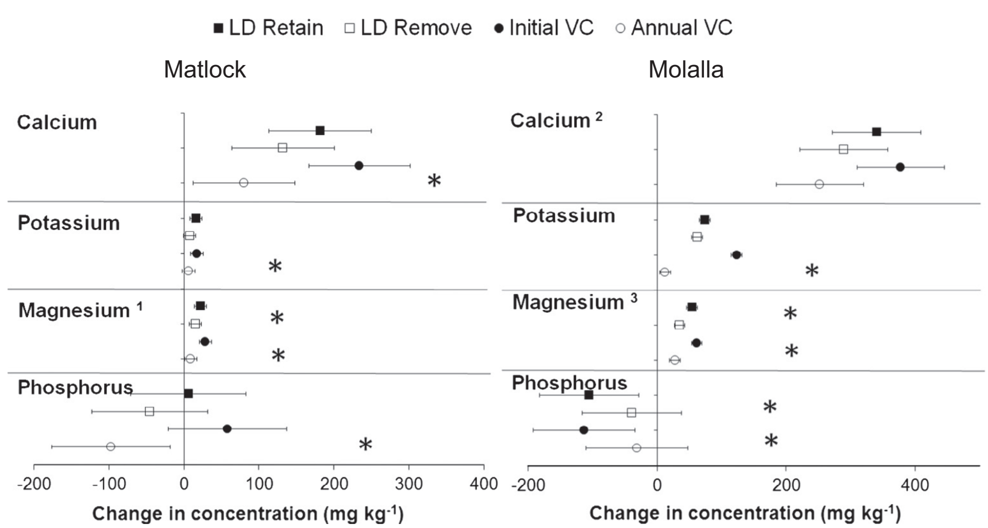

Fig. 3. Absolute change in soil cations and phosphorus concentrations for 0–30 cm soil depth by site and treatment over a 10 year period. Error bars are the 90% confidence interval of the estimate. Values with error bars that do not overlap zero are significant increases or decreases over the 10-year period. An asterisk indicates a significant difference between treatments within a given factor (main effect of logging debris (LD) or vegetation control (VC)). There were significant interactions between the factors for calcium at the Molalla site, and magnesium at both sites. See footnotes for details. [1] LD retain-initial VC greater than LD retain-annual VC (diff. = 31 mg kg^{-1}), LD remove-initial VC (diff. = 18 mg kg^{-1}), and LD remove-annual VC (diff. = 27 mg kg^{-1}). [2] LD retain-initial VC greater than LD retain-annual VC (diff. = 265 mg kg^{-1}). [3] LD retain-initial VC greater than LD retain-annual VC (diff. = 54 mg kg^{-1}), LD remove-initial VC (diff. = 39 mg kg^{-1}), and LD remove-annual VC (diff. = 53 mg kg^{-1}).

effects occurred, they were commonly associated with the VC treatment (Table 2) and generally manifested as greater increases for initial VC than for annual VC (Fig. 2). Two important distinctions from these general trends were observed. The first is related to total soil P, which tended to decrease at both sites but in opposite patterns. At Matlock, more intensive practices had greater reductions in total soil P, but at Molalla the reductions were greatest with less intensive practices (Fig. 3). The second but similar distinction occurred at Molalla, where soil N concentration increased in both VC treatments, but the increase was significantly greater with annual VC than with initial VC (Fig. 2). Soil C:N tended to decline in all treatments at the Matlock site, but increase at the Molalla site where increases were significantly higher in the initial VC treatment relative to the annual VC treatment (Fig. 2).

Compared to VC, the effect of LD manipulation was limited at both sites and usually manifested as interactions with the VC treatment (Table 2). Multiple comparisons indicated that these interactions were associated with LD retention. For soil Ca at Molalla in the LD-retained treatment, change in concentration was significantly greater with initial VC than with annual VC (see footnote in Fig. 3). For soil Mg at both sites, change in concentration was significantly greater in the LD- retained treatment with initial VC compared to all other treatment combinations (see footnote in Fig. 3). The one main effect of LD was found at Molalla, where reduction in soil P was significantly lower in the LD-retained treatment than in the LD-removed treatment (Table 2, Fig. 3).

Across all treatments, forest floor mass was approximately twice as large at Molalla as at Matlock (Table 3). At Matlock, forest

Table 2
F-statistic probabilities for the change in concentration of soil C and nutrient pools by site and treatment to a depth of 30 cm. VC = vegetation control; LD = logging debris. Significant values are in bold.

Effect	C	N	C:N	P	Ca	K	Mg
Matlock							
VC	**0.054**	**0.071**	0.837	**0.037**	**0.017**	**0.054**	**<0.001**
LD	0.152	0.132	0.604	0.407	0.372	0.101	**0.076**
VC * LD	0.106	0.432	0.335	0.231	0.232	0.420	**0.015**
Molalla							
VC	0.808	**0.070**	**0.075**	**0.025**	0.110	**0.015**	**<0.001**
LD	0.838	0.783	0.407	**0.055**	0.445	0.750	**0.011**
VC * LD	0.476	0.818	0.156	0.197	**0.060**	0.276	**0.010**

floor total C content was greater when LD was retained, which resulted from a large increase in forest floor mass rather than an increase in C concentration. Conversely, there was no difference between VC treatments for either forest floor C or N content, but C and N concentrations were significantly greater in the initial VC treatment. Similar non-significant patterns were observed at Molalla for many of the same variables.

3.3. Douglas-fir responses

From year 5–10 at Matlock, Douglas-fir survival decreased about 2 percentage points per year regardless of VC treatment (Fig. 4A). The interaction of VC and year was significant at Matlock (Table 4), and in each year survival was about 20 percentage points greater with annual VC than with initial VC. The interaction of LD and VC also was significant at Matlock, because survival was greater with annual VC than with initial VC where LD was removed (84% versus 53%, respectively) but not where LD was retained (84% versus 74%, respectively). At Molalla, the interaction of LD treatment and year was significant for Douglas-fir survival, but multiple comparisons of treatment means failed to detect any differences.

The growth trajectory for Douglas-fir height at Molalla diverged from that at Matlock because of presumed differences in site quality (Fig. 4B). By year 10, trees at Molalla averaged 1.8 and 2.8 m taller than at Matlock for initial and annual VC, respectively. Main effects of VC were significant for height at Matlock, where trees averaged 0.9 m taller with annual VC than with initial VC. Main effects of LD also were significant for height at Matlock, and height averaged 0.2 m taller where LD was retained than where it was removed (data not shown). At Molalla, height did not vary significantly among treatments ($p > 0.3$).

Canopy cover of Douglas-fir differed strongly between the two sites, with tenth-year values averaging 59% and 81% with annual VC at Matlock and Molalla, respectively (Fig. 4C). The VC-by-year interaction was significant at each site (Table 4). Douglas-fir cover was greater with annual VC than with initial VC in each year at Matlock and in years 8 and 10 at Molalla. From year 8 to 10, differences in cover between VC levels continued to diverge at Matlock but they began to converge at Molalla. Main effects of LD also were significant at Matlock, and Douglas-fir cover averaged 29% with LD retained versus 22% with LD removed.

At both sites, Douglas-fir height to live crown (HLC) varied according to the main effects of VC (Fig. 4D). From year 8 to 10, HLC averaged 4 and 8 cm greater with initial VC than with annual VC at Matlock and Molalla, respectively.

The interaction of VC and year was significant (Table 4) for Douglas-fir dbh at Matlock because stem growth was greater with annual VC than with initial VC for each of the measurement years and these differences increased with time (Fig. 4E). The VC-by-year interaction also was significant at Molalla, because dbh was 0.4 cm greater with annual VC than with initial VC in year 5 but it did not differ statistically in years 8 or 10.

Development of Douglas-fir stand volume accelerated with time resulting in strongly diverging growth trajectories for the two sites (Fig. 4F). At Matlock, both the VC-by-year and LD-by-year interactions were significant (Table 4). For each measurement year, stand volume was greater with annual VC than with initial VC. Stand volume also was greater at Matlock where LD was retained than where it was removed for years 8 (3.3 and 2.4 $m^3\ ha^{-1}$, respectively) and 10 (7.9 and 5.4 $m^3\ ha^{-1}$, respectively), but not in year 5 (0.9 and 0.7 $m^3\ ha^{-1}$, respectively). At Molalla, main effects of VC were significant, and stand volume averaged 28% greater with annual VC than with initial VC (6.8 and 5.3 $m^3\ ha^{-1}$, respectively).

3.4. Vegetation community responses

There were 89 plant species recorded at Matlock and 83 species recorded at Molalla in 2013, of which 50 were found at both sites. Average species richness per plot was higher at Matlock (35 species) than Molalla (25 species) even though the former site was occupied entirely by one plant association. Vegetation control significantly affected diversity at both sites, but LD treatments had no detectable influence and there were no VC × LD treatment interactions (Table 5). All diversity indices were significantly greater with initial VC than with annual VC at Matlock and all but evenness were significantly greater for initial VC at Molalla. Mean plant species richness at Molalla was 32 and 20 in the initial VC and annual VC treatments, respectively, whereas at Matlock it was 39 and 32, respectively. The dominant species at both sites was Douglas-fir, with dominance (e.g., crown cover, Fig. 4C)

Table 3
Forest floor characteristics by treatment and site 10 years after treatment application.

Treatment	C (%)	N (%)	C:N	Mass ($Mg\ ha^{-1}$)	C mass ($Mg\ ha^{-1}$)	N mass ($kg\ ha^{-1}$)
Matlock						
Initial VC	**48.24**[a]	**1.05**	**46.2**	3.52	1.69	36.5
Annual VC	**46.78**	**0.80**	**59.2**	3.58	1.67	28.8
LD retained	46.93	0.91	53.1	**4.33**	**2.02**	38.9
LD removed	48.09	0.94	52.3	**2.77**	**1.34**	26.4
Pooled SE	0.89	0.04	2.2	0.70	0.33	6.8
Molalla						
Initial VC	45.37	1.27	36.4	9.50	4.29	124.5
Annual VC	45.84	1.22	38.4	6.15	2.82	75.3
LD retained	45.57	1.21	38.2	9.00	4.07	113.6
LD removed	45.63	1.28	36.7	6.65	3.04	86.3
Pooled SE	0.63	0.08	2.5	1.68	0.76	24.0

[a] Values in bold indicate a significant difference ($p < 0.1$) between treatment levels within a main factor (e.g., main effects); there were no significant interaction between factors for any of the variables. VC = vegetation control; LD = logging debris.

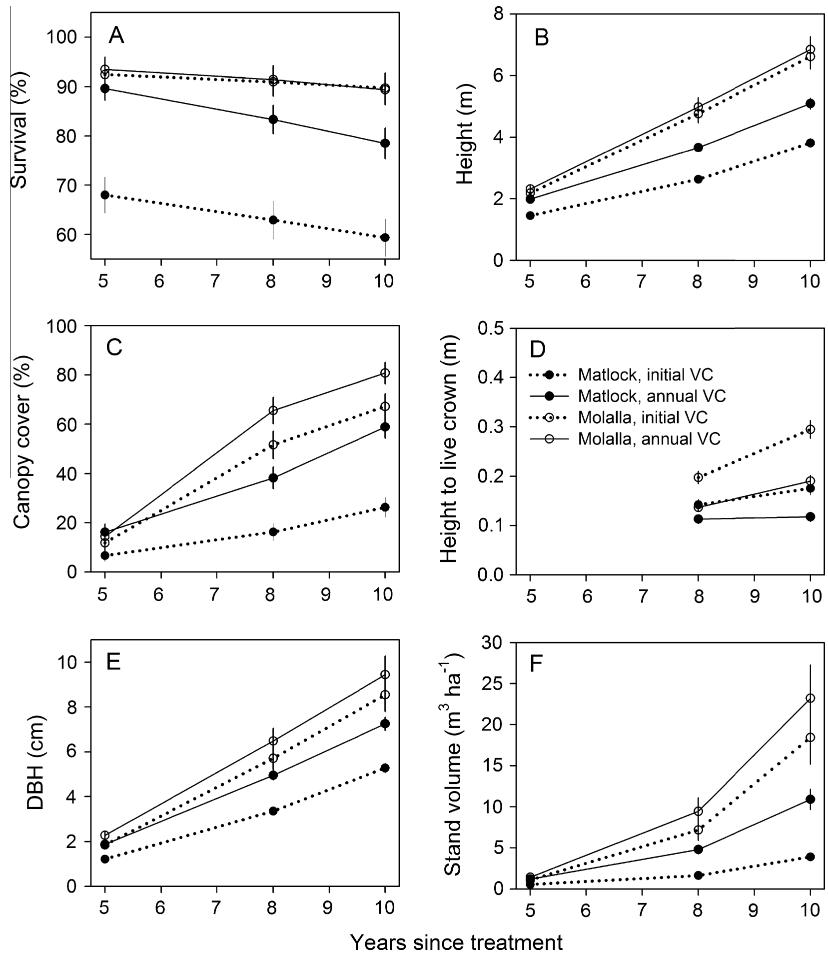

Fig. 4. Mean responses (±standard error) of Douglas-fir survival and growth responses 5, 8, and 10 years after logging debris (LD) was retained or removed followed by initial or annual vegetation control. Means have been averaged across LD levels to illustrate the dominant response of a vegetation-control-by-year interaction. See text for a description of treatment differences.

Table 4
F-statistic probabilities for Douglas-fir survival and growth responses 5, 8, and 10 years after logging debris (LD) was retained or removed followed by initial or annual vegetation control (VC). Significant values are in bold.

Site	Source of variation	df[b]		Variables[a]					
				Survival	Height	Cover	HLC	Dbh	Vol
		N	*D*	Probability > *F*					
Matlock	LD	1	9	**0.065**	**0.094**	**0.074**	0.448	0.113	**0.065**
	VC	1	9	**0.002**	**<0.001**	**0.001**	**0.005**	**<0.001**	**<0.001**
	LD × VC	1	9	**0.082**	0.767	0.757	0.590	0.860	0.370
	Year (Y)	2	24	**<0.001**	**<0.001**	**<0.001**	**0.098**	**<0.001**	**<0.001**
	Y × LD	2	24	0.870	0.908	0.326	0.724	0.126	**0.023**
	Y × VC	2	24	**0.001**	0.311	**0.006**	0.229	**0.023**	**<0.001**
	Y × LD × VC	2	24	0.532	0.288	0.308	0.279	0.961	0.642
Molalla	LD	1	9	0.430	0.661	0.407	0.892	0.428	0.295
	VC	1	9	0.824	0.306	**0.006**	**<0.001**	**0.052**	**0.045**
	LD × VC	1	9	0.726	0.328	0.316	0.226	0.413	0.516
	Year (Y)	2	24	**0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Y × LD	2	24	**0.050**	0.929	0.234	0.564	0.899	0.144
	Y × VC	2	24	0.626	0.727	**0.024**	0.482	**0.061**	0.539
	Y × LD × VC	2	24	0.418	0.675	0.814	0.548	0.890	0.885

[a] HLC = height to live crown, Dbh = diameter at breast height, and Vol = stand volume.
[b] df = degrees of freedom for the numerator (*N*) and denominator (*D*) of the *F* test.

occurring more rapidly at Molalla than at Matlock, and more rapidly with annual VC than with initial VC.

Ten years after treatment, there was greater floristic variation in the response to treatments at Matlock than at Molalla (Fig. 5). Centroid locations by treatment and site were significantly different on both axes ($P < 0.01$). All Matlock centroids were located significantly lower on the *X* axis than the Molalla centroids. Molalla treatment centroids occupied only the upper right quadrat of the

Table 5
Mean understory plant diversity indices and Douglas-fir percent canopy cover by treatment at Matlock and Molalla 10 years after treatment.

Treatment	n	Richness	Evenness	Shannon's index	Simpson's index	Douglas-fir cover
Matlock						
Initial VC	8	**38.5**[a]	**0.7**	**2.4**	**0.9**	**26**
Annual VC	**8**	**31.8**	**0.6**	**1.9**	**0.8**	**59**
LD retained	8	36.3	0.6	2.2	0.8	46
LD removed	8	34.0	0.6	2.2	0.8	38
Molalla						
Initial VC	7	**31.9**	0.6	**2.0**	**0.8**	**67**
Annual VC	8	**19.6**	0.6	**1.6**	**0.7**	**81**
LD retained	7	23.7	0.6	1.7	0.8	77
LD removed	8	26.8	0.6	1.8	0.8	71

[a] Values in bold indicate significant main effects of the treatments; there were no significant interactions between the VC and LD treatments.

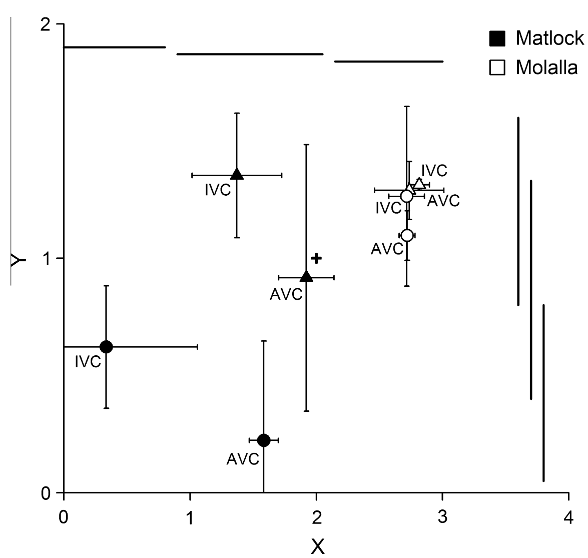

Fig. 5. Vegetation-based ordination group centroids by treatment and site in year 10. Circles indicate the LD removed treatment and triangles indicate the LD retained treatment. IVC = initial vegetation control and AVC = annual vegetation control. Error bars show ± one standard deviation for the location of each group centroid for the X and Y axes. The overall ordination centroid is indicated with a "+" symbol. Three bold parallel lines along top and right side of the figure show Tukey HSD mean separations for the individual group centroids along the X and Y axes, respectively. Groups that lie within a line segment do not differ in their location along that axis ($P = 0.10$). $N = 4$ for all treatments except the LD retained IVC treatment group at Molalla.

ordination as defined by the overall centroid. All of the Matlock treatment centroids were in the upper left or lower left quadrats when similarly defined. Higher positive tau correlations to the ordination axes were associated with the Molalla flora and more negative values were associated with the Matlock flora. Species with high positive correlations with the X axis (tau = 0.60–0.70) included the native species Douglas-fir, Cascade buckthorn (*Frangula purshiana* (DC.) A. Gray), trailing blackberry (*Rubus ursinus* Cham. & Schltdl.), and western swordfern. Douglas-fir and Cascade buckthorn are shade producing trees and western swordfern is a shade tolerant understory species. Trailing blackberry is a native ruderal species of intermediate shade tolerance which commonly persists late into succession. Germander speedwell (*Veronica chamaedrys* L.), colonial bentgrass (*Agrostis capillaris* L.), sweet vernal grass (*Anthoxanthum odoratum* L.), and oxeye daisy (*Leucanthemum vulgare* Lam.) had high negative correlations with the X axis (tau = −0.60 to −0.70); each of these species are shade-intolerant, non-native ruderal species. The two highest species correlations with the Y axis were salal (tau = 0.68) which is a shade tolerant native understory species, and hairy cat's ear (*Hypochaeris radicata* L.) (tau = −0.47) which is a shade intolerant, non-native ruderal species. Considered together, we interpret the correlations and general ordination patterns to indicate faster rates of succession where LD is retained, annual VC is applied, and where soil resources are more available for growth (i.e., at Molalla).

4. Discussion

Our primary objective was to assess the potential for intensive management practices (i.e., repeated VC for five years and increased LD removal relative to traditional utilization) to be sustainable with regards to maintaining soil C and nutrient pools, short- and long-term fiber production and plant diversity compared to less intensive practices (i.e., initial VC and LD retention). Vegetation control had a more pronounced effect on the response variables at both sites compared to LD manipulation, which had effects that were generally inconsistent or not apparent in most instances. Our findings demonstrate the overriding role that vegetation dynamics play on crop tree growth and soil nutrient pools during early years of stand establishment. Effects were much more pronounced in magnitude and duration at the lower-quality Matlock site compared to the higher-quality Molalla site, indicating that site quality has large control on the relative degree that intensive management influences fiber production, soil nutrients, and plant diversity. In general, annual VC during the first five years of stand development is effective at increasing crop tree productivity while maintaining nutrient pools important to long-term productivity, with variable effects on plant communities and related demographics that are dependent on site factors that influence Douglas-fir survival and growth. These generalities have also been observed at the nearby Fall River LTSP installation (Holub et al., 2013; Knight et al., 2014; Peter and Harrington, 2009) and are explored in more detail below.

4.1. Soil nutrient pools

Our examination of soil response ten years after VC and LD was conducted to assess potential long-term effects of these intensive management practices on site productivity given the large influence that soil has on this site attribute within the constraints of climate (Powers et al., 1990; Nambiar, 1996). The 10-year results presented here generally indicate low potential for intensive management practices to degrade soil nutrient pools important to plant growth, similar to results observed five years after treatment (Slesak et al., 2011). Furthermore, mineral soil C and nutrient pools significantly increased over the 10-year post-treatment period regardless of treatment. A number of other studies have observed similar results following application of VC and increased LD removal (Scott et al., 2014; Ponder et al., 2012; Fleming et al., 2006; Knight et al., 2014), providing consistent evidence that these types of intensive management practices have low potential to degrade the ability of soil to provide many of the resources necessary for sustained fiber production. However, we caution that impacts to soil can still occur when all LD is removed (Smith et al., 2000), on poorer quality sites than these (O'Hehir and Nambiar, 2010), and if rotation lengths are shortened (Vadeboncoeur et al., 2014).

Although risks of soil nutrient reduction appear to be low with increased LD removal and annual VC, use of less intensive management practices resulted in larger increases in soil nutrient pools, notably soil Ca, K, and Mg with initial VC, and Mg with LD retention (Fig. 3 footnotes). Further, when significant interactions were found, they were always a result of greater increases when both of the less intensive practices were applied together (the LD retained-initial VC treatment, Fig. 3). Depending on the importance of these nutrients to ecosystem functions (e.g., maintenance of fiber production and biodiversity), use of the less-intensive practices has implications for increased site resiliency with regards to emerging and future ecosystem stressors (Drever et al., 2006). Soil N, a key nutrient controlling productivity at these sites and the nearby Fall River installation (Devine et al., 2011), responded in a similar manner at the Matlock site but not at the Molalla site. A primary reason for this contrasting N response is associated with differences between sites in the amount of vegetation uptake in the initial VC treatment. Devine et al. (2011) estimated greater total aboveground biomass and N with initial VC compared to annual VC at Molalla five years after treatment, but the opposite at Matlock. Other factors contributing to the contrasting response between sites would include (1) large inherent differences in total soil N (Table 1), (2) differences in mass and quality of the forest floor (Table 3) and its potential influence on post-harvest changes in mineral soil N (i.e., physical incorporation, Yanai et al., 2003), and (3) differences in total N leaching potential, which is greater in the skeletal, coarse-textured soil at Matlock compared to Molalla (Slesak et al., 2009).

One important exception to the above discussion relates to soil P as it was the only nutrient that decreased for some of the treatments at both sites (Fig. 3). At Matlock, the trends followed the common conceptual framework that less intensive practices result in maintained or improved soil nutrient pools, but the opposite was observed at Molalla, where soil P decreased over 10 years with both initial VC and LD retention. We suggest that the contrasting response is similar to that described for soil N above. Namely, the lower total soil P pools at Molalla coupled with greater P uptake in initial VC caused a greater relative decline in that treatment compared with annual VC. Reduction in soil P with initial VC and LD retention may also be caused by altered P availability, because there was a significant LD-by-VC interaction on cover of bracken fern (*Pteridium aquilinum* (L.) Kuhn.) caused by the species having much higher cover when LD retained was combined with initial VC (25%) versus annual VC (5%) (D. Peter, unpublished data). Bracken fern can increase P availability (Mitchell, 1973) and has been shown to have greater P content in recently harvested sites compared to mature forests as a result of greater P uptake (Lederle and Mroz, 1991), with similar results for N (Griffiths and Filan, 2007).

Reductions in soil P could be of concern to long-term soil productivity given the fundamental role of P in ecosystem productivity (Vitousek et al., 2010). However, given that the apparent reductions are probably related to vegetation uptake and effectively retained on site, this concern is greatly reduced as most P in biomass will become bioavailable at some point in the future. Furthermore, the large total P pools at these sites (DeBruler, 2014) would also provide a suitable buffer to maintain bioavailable P over time even with a net loss of ecosystem P from the site. Nevertheless, there is still a risk that these apparent reductions in soil mineral P could reduce ecosystem productivity in the future, underlying a need for comprehensive assessments (e.g., deeper soil, soil pools other than <2 mm fraction, etc.) over longer terms at these sites and others (Richter et al., 2007).

4.2. Crop tree production

Our examination of Douglas-fir growth response to intensive management practices was conducted largely to assess the influence of these practices on short-term fiber production. Similar to many other studies (Harrington and Tappeiner, 1991; Dinger and Rose, 2009; Wagner et al., 2006; McDonald and Fiddler, 2010), our findings indicate that application of VC is effective at increasing crop tree growth across a range of site conditions. At the nearby Fall River installation, application of annual VC increased Douglas-fir stand volume by 45% after 10 years of growth (Holub et al., 2013). At our sites, absolute volume gains were greatest at the Molalla site, but relative gains were greatest at the Matlock site, where annual VC increased volume by 180% over initial VC (Fig. 4). Although differences in tree growth rates contributed to some of this difference among sites, the primary factor controlling relative increases in volume with annual VC at Matlock was differences in survival, as there were no detectable survival differences between treatments at Molalla (Fig. 4) or Fall River (Holub et al., 2013), but a more than 20 percentage-point increase with annual VC at Matlock.

A number of factors can influence seedling survival, but those influenced by competing vegetation are largely associated with water and nutrient supply, as light is generally not limiting to growth in the early years of stand establishment for planted Douglas-fir (Harrington, 2006). The sites in this study, together with the Fall River installation, span a gradient of soil nutrient pools, water availability, and stand productivity, which are greatest at Fall River, intermediate at Molalla, and lowest at Matlock (Devine et al., 2011). In particular, water holding capacity at the Matlock site, which is a critical soil property in this Mediterranean climate, is less than 40% of that at Molalla and Fall River and is likely a major factor influencing the VC survival response and growth in general (Harrington et al., 2013; Devine et al., 2011). Work in southwestern Oregon supports this, as a number of studies in this drier region have documented the critical importance of VC to seedling survival and growth, which has largely been attributed to improved water availability (Schneider et al., 1998). At the higher-productivity Molalla and Fall River sites, greater water holding capacity appears sufficient to favor seedling survival regardless of VC treatment. In these instances, where a threshold of soil water supply is achieved to maintain base physiological needs for survival (Wagner et al., 1989), nutrient availability (particularly N) would likely become more important to a growth response to VC, as indicated with greater VC efficacy at the high-N Fall River installation (Devine et al., 2011).

In addition to its positive effects on Douglas-fir growth, annual VC also reduced the rate of upward crown recession at both sites from year 8 to 10. The 4- to 8-cm crown recession observed with initial VC provides an early indication of how competing vegetation can influence crown length, and ultimately, stem form (Weiskittel et al., 2006).

The positive effect of LD retention on volume growth at the lower-productivity Matlock site in contrast to the lack of response at the higher-productivity Molalla (Fig. 4) and Fall River sites (Holub et al., 2013) has been reported previously (see review in Thiffault et al., 2011). At sites with soil properties that are conspicuously constraining to growth, it appears that retention of LD can be beneficial to growth of the succeeding stand. Here, the mechanism contributing to increased growth is likely associated with how LD influenced the vegetation community and competition for soil resources. In particular, retention of LD reduced abundance of the invasive shrub Scotch broom (*Cytisus scoparius* (L.) Link) at Matlock, which was directly related to Douglas-fir survival at year five (Harrington and Schoenholtz, 2010). Positive effects of LD retention could also be associated with improved water availability via a mulch effect (Roberts et al., 2005), but we did not detect such an effect at 20–40 cm soil depth within the first five years after treatment (Slesak et al., 2010; Harrington et al., 2013). Regardless of the reason, the increasing positive effect of LD retention with time on crop tree growth underscores the value of retaining LD at lower-quality sites.

4.3. Plant communities

Our examination of vegetation response to intensive management practices was conducted to assess the influence of these practices on plant diversity and community development. The significant negative effect of VC on diversity indices and composition has also been observed in a number of other studies (Pitt et al., 2004; Wilkins et al., 1993). However, our results reveal differences between sites in those vegetation metrics in general, and the magnitude of VC effect was also different between sites. The differences can largely be explained by contrasts in the rate of Douglas-fir canopy development between sites and the positive effect of VC on canopy development, as Douglas-fir cover was much greater at Molalla than Matlock and much greater with annual VC compared to initial VC (Fig. 4C). Data from the Fall River site supports this canopy effect, as ten-year plant species richness at that site was the lowest of the three sites (annual VC = 16 ± 2.6, initial VC = 23 ± 1.4), but Douglas-fir cover was the highest (annual VC = 99 ± 2.6, initial VC = 96 ± 1.4) (D. Peter unpublished data). These effects reveal a pattern of species richness reduction and decreasing understory cover across the three sites with increasing Douglas-fir cover (Peter and Harrington, 2012).

The factors driving differences in the relative dominance of Douglas-fir canopy cover are likely associated with inherent differences in climate and the capacity of soil to supply resources for Douglas-fir growth. Variations in site quality have long been recognized as a driving factor in the diversity of early successional communities following disturbance with a general decrease in diversity occurring with increasing site productivity (Huston, 1979). Our data and those from the Fall River site (Peter and Harrington, 2009, 2012) follow that general pattern, as Douglas-fir canopy cover at any given time period increased with increasing site resource availability, being greatest at Fall River, intermediate at Molalla, and lowest at Matlock. The magnitude of difference was striking: Fall River achieved 60% Douglas-fir cover in the initial VC treatments by year 6, whereas Molalla reached a comparable level of canopy cover by year 10 and levels at Matlock at year 10 were less than half those of Molalla (Fig. 4C). The more rapid increase in height to live crown at Molalla than at Matlock further emphasizes the role site quality plays in development of Douglas-fir canopy cover (Fig. 4D).

These striking differences in Douglas-fir cover are likely the primary reason contributing to variation in plant diversity among sites, notably the convergence of plant communities in the initial and annual VC treatments at Molalla, but not at Matlock by year 10. At Matlock, low Douglas-fir cover with initial VC has maintained a relatively high level of understory plant diversity at 10 years compared to other treatments and sites, although some of this diversity at Matlock is attributable to non-native, invasive species. We expect that this higher level of diversity with initial VC will decrease and the vegetation community will converge with that of annual VC as canopy cover increases, but it will take a longer period of time compared to the higher-productivity sites.

These results suggest that the influence of VC on plant diversity is heavily dependent on site, and largely manifests as reduced diversity associated with increasing crop tree productivity (biomass) and reduced light availability (Huston and DeAngelis, 1994), rather than as a direct effect of herbicide phytotoxicity. Annual VC effectively channels resources to the Douglas-fir crop, causing an increase in canopy cover and a reduction in understory plant diversity that occurs much more rapidly compared to initial VC only. Swanson et al. (2010) presented a case on the importance of the early successional stage to ecosystem biodiversity in general, noting the potential for decreased biodiversity under certain management activities that reduce the duration of this period especially when post-disturbance structural legacies are absent. Our data generally support this notion, but also highlight distinct differences in the magnitude of VC effect among sites with implications for site-specific management. Notably, it appears that annual VC can greatly increase survival and production of Douglas-fir on low-quality sites such as Matlock, while simultaneously maintaining relatively high diversity associated with the early successional stage for a longer time period compared to higher-quality sites.

5. Conclusions

The potential for negative effects of intensive management practices on long-term productivity via their influence on soil nutrient pools is low, whereas less intensive practices have potential to increase soil mineral pools, which may be beneficial for maintenance of ecosystem production capacity. In contrast, short-term effects of intensive management practices on stand growth are large, due predominantly to their influence on vegetation dynamics and related effects on resource allocation to Douglas-fir. In particular, VC had a large direct influence on vegetation and crop tree production, which was most pronounced at the lower-quality site, but LD also influenced growth at the lower-quality site by inhibiting establishment of the invasive Scotch broom. The positive influence of VC on Douglas-fir growth involves a tradeoff with plant species diversity because it was inversely related to Douglas-fir cover, which increased more rapidly with increasing VC efficacy. These patterns are consistent across the range of site conditions assessed, but are mediated by differences in resource supply that are inherently dependent on soil properties and processes. At the Matlock site with low soil quality, application of annual VC coupled with retained LD was the most effective mix of practices to maximize crop tree growth while maintaining higher plant biodiversity than other sites. Taken together, our results demonstrate that careful consideration be given to site conditions when planning intensive management to ensure that objectives are realized with regards to maintaining soil quality and plant diversity while enhancing fiber production.

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