



Variation in logging debris cover influences competitor abundance, resource availability, and early growth of planted Douglas-fir

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ABSTRACT

Logging debris remaining after timber harvest can modify the microclimate and growing conditions for forest regeneration. Debris also can influence tree seedlings indirectly through its effects on development of competing vegetation, although the mechanisms are poorly understood. At two sites in Washington and Oregon (USA) that differed in availability of soil water and nutrients, mechanisms were studied by which logging debris and competing vegetation interacted to influence performance of planted Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) seedlings. In a split-plot design, two levels of competing vegetation (presence and absence) and three covers of logging debris (0%, 40%, and 80%) were replicated eight times at each site on 2 × 2-m areas centered on individual Douglas-fir seedlings. Vegetation abundance, seedling growth, and resource availability were monitored for 4 years (2005–2008). Soil water depletion was lower and Douglas-fir water potential and foliar nitrogen were higher in the absence of competing vegetation, resulting in increased seedling growth. The highest seedling growth rates and foliar nitrogen contents occurred where absence of vegetation was combined with 80% debris cover. Where competing vegetation was present, 40% debris cover was associated with decreases in herb cover and soil water depletion and increases in seedling growth relative to 0% or 80% debris covers. At the Washington site where soil quality was lower, the combination of presence of vegetation and 80% debris cover was associated with a 2.4 °C average reduction in summer soil temperatures at 15 cm depth, reduced foliar nitrogen content, and the slowest rates of seedling growth. Potential effects of logging debris, such as mulching (i.e., reduced evaporation of soil water) and interception loss (i.e., reduced precipitation inputs), were minor to non-detectable from sensors buried at 20–40 cm soil depth. Results of the research suggest that retention of moderate levels of logging debris (i.e., 40% cover) after forest harvesting in the Pacific Northwest is likely to increase early growth of Douglas-fir by increasing soil water availability through reduced herb abundance. Where intensive vegetation control is practiced, retention of higher debris levels (i.e., 80% cover) may provide further benefits to seedling growth.

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1. Introduction

Management of competing vegetation is a primary silvicultural strategy for focusing productivity of forest sites on the desired tree species (Balandier et al., 2006). Limited site resources are channeled effectively to the crop, accelerating production of biomass and shortening the period until economic and other values can be realized (Walstad and Kuch, 1987). Observations of significant benefits from competing vegetation control to survival and growth

of tree seedlings are consistent throughout North America (Fleming et al., 2006) and other areas of commercial forest production in the world (Wagner et al., 2006). During the early years of forest development, vegetation control increases availability of growth-limiting soil resources, especially water and nutrients (Harrington and Tappeiner, 1991; Zutter et al., 1999; Dinger and Rose, 2009). Thus, an understanding of the mechanisms by which competing vegetation limits performance of tree seedlings is critical to the efficient practice of forest vegetation management.

Forest productivity research has identified interactions between competing vegetation and logging debris that occur soon after forest harvesting. In general, retention of logging debris in temperate zone forests inhibits development of herbaceous, and sometimes woody, species. This finding has been reported for a wide range of forest ecosystems including mixed stands of balsam fir (*Abies*

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balsamea (L.) Mill.) and paper birch (*Betula papyrifera* Marshall) in northern Minnesota (USA) (Outcalt and White, 1981), loblolly pine (*Pinus taeda* L.) plantations in the southeastern USA (Cox and Van Lear, 1985), trembling aspen (*Populus tremuloides* Michx.) in central Ontario, Canada (Hendrickson, 1988), and Sitka spruce (*Picea sitchensis* (Bong.) Carrière) in North Wales, UK (Fahey et al., 1991). Retention of logging debris in the Pacific Northwest (USA) has been shown to inhibit development of common plant competitors including Scotch broom (*Cytisus scoparius* (L.) Link) (Harrington and Schoenholz, 2010) and various non-native herbaceous species (Peter and Harrington, 2012), thereby facilitating increased survival and growth of coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) seedlings. Retention of logging debris also has been associated with mulching effects – increased conservation of soil water, usually near the soil surface (O'Connell et al., 2004; Roberts et al., 2005) – attributed to reductions in evaporation and soil temperature (Devine and Harrington, 2007). In nitrogen deficient forest ecosystems of Europe, productivities of Sitka spruce through 23 years after planting (Walmsley et al., 2009) and Norway spruce (*Picea abies* (L.) Karst) through 31 years after planting (Egnell, 2011) were greater after stem-only harvesting than after whole-tree harvesting – a response attributed to greater retention of nitrogen and other nutrients. Thus, logging debris has the potential to increase survival and growth of tree seedlings and saplings (e.g., in droughty or nitrogen deficient soils), thereby contributing to long-term sustainability of forest productivity. However, identification of applicable site characteristics and elucidation of the underlying mechanisms by which competing vegetation and logging debris interact to control forest productivity remain as important knowledge gaps.

Logging debris effects have traditionally been studied by subsampling vegetation and soil responses within experimentally treated plots, scaling the responses to the stand level, and identifying potential relationships (Scherer et al., 2000; Zabowski et al., 2000; Roberts et al., 2005; Ares et al., 2007). Although commonly used in forestry research, these approaches may be unsuitable for detecting fine-scale effects of logging debris and underlying mechanisms because debris cover can vary considerably at the plot level (>0.01 ha), especially given operational conditions (Eisenbies et al., 2005; Slesak et al., 2011a). Slesak et al. (2010) applied fixed levels of logging debris (0%, 40%, and 80% covers) around individual Douglas-fir seedlings, with and without competing vegetation, to study 2-year changes in soil nitrogen, carbon, water, and temperature. Using the same seedling-centered study, we expand on the results of Slesak et al. (2010) by identifying how the treatments influenced growth of Douglas-fir seedlings through analyses that increased the sample size, extended the period of assessment to 4 years, and interpreted responses of additional variables (i.e., vegetation abundance, seedling growth, seedling water potential, and relativized components of seedling foliar nitrogen). We hypothesized that logging debris would influence Douglas-fir growth primarily through its effects on soil water availability via three potential mechanisms: (1) changes in water consumption via altered abundance of competitor species, (2) reduced evaporation via mulching effects, and (3) reduced precipitation inputs via interception losses. We also hypothesized that (4) logging debris would influence soil nitrogen availability to Douglas-fir as indicated by changes in foliar nitrogen concentration and content.

2. Methods

2.1. Study sites

The research was conducted on two sites affiliated with the North American Long-Term Soil Productivity (LTSP) study (Har-

rington and Schoenholz, 2010; Powers et al., 2005) that differed in availability of soil water and nutrients (Table 1). The Matlock, Washington (USA) site has a very gravelly loamy sand of the Grove series (Dystric Xerorthent) formed in glacial outwash and averaging 1.5 m in depth (USDA NRCS, 2012). The Molalla, Oregon (USA) site has a cobbly loam of the Kinney soil series (Andic Dystrudept) averaging 1.4 m in depth (USDA NRCS, 2012). The Matlock and Molalla sites have almost three-fold differences in soil water holding capacities, as well as contrasting pool sizes for soil nitrogen and other nutrients (Devine et al., 2011).

The regional climate is characterized as Mediterranean with cool, wet winters and warm, dry summers having a prolonged period of drought (Franklin and Dyrness, 1973). Potential natural vegetation includes the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)/salal (*Gaultheria shallon* Pursh) plant association at Matlock (Henderson et al., 1989) and the western hemlock/Oregon-grape (*Mahonia nervosa* (Pursh) Nutt.)/swordfern (*Polystichum munitum* (Kaulf.) Presl) and western hemlock/Oregon grape-salal plant associations at Molalla (Halverson et al., 1986).

2.2. Experimental design and treatments

At each site, 48 Douglas-fir seedlings were selected for study within buffer areas separating plots of the existing LTSP study design. Details regarding methods of forest harvesting, conifer regeneration, and vegetation control were described in Harrington and Schoenholz (2010). When this individual-seedling study was initiated (March 2005), the Douglas-fir seedlings had completed their first growing season after being planted at a 3 × 3-m spacing. The experimental design at each site was a randomized complete block, split plot with two levels of competing vegetation (presence and absence) as main plots and three levels of logging debris (0%, 40%, and 80% cover) as split plots. The experimental unit was the 2 × 2-m growing space of an individual Douglas-fir. At each site eight seedlings were assigned to each of the six treatments.

Debris cover treatments were implemented by centering a 2 × 2-m PVC frame on a given seedling with frame sides parallel to the rows of adjacent planted seedlings and then covering the ground surface with logging debris 5.0–12.5 cm in diameter to create the assigned projected cover of debris (nearest 10%) as determined by visual estimation. Existing woody logging debris, free of needles and adjacent to the experimental plots at each site, was cut to lengths ≤3 m and applied randomly around assigned seedlings such that total depth did not exceed 30 cm to avoid shading of seedlings. The size distribution of debris was kept approximately the same for each level of debris cover. For seedlings assigned 0% debris cover, all logging debris was removed from the 2 × 2-m growing space. To avoid soil disturbance, no attempt was made to remove legacy wood (i.e., surficial old-growth logs at various stages of decomposition present within the growing space of approximately 5% of the assigned seedlings).

Annual herbicide treatments were applied to the main plots of the existing LTSP study assigned to receive vegetation control (Harrington and Schoenholz, 2010). To accomplish complete removal of vegetation within the growing space of designated seedlings, a supplemental non-soil-active herbicide treatment was applied annually with a backpack sprayer in May of 2005–2008 to the 2 × 2-m area. The treatment consisted of a hooded nozzle application of glyphosate (Accord® Concentrate³), triclopyr ester (Garlon®⁴), and non-ionic surfactant (X-77®) in water at product concentrations of 1%, 0.5%, and 0.5%, respectively. Herbicide expo-

³ The use of trade or firm names in this publication is for reader information and does not imply endorsement by the US Department of Agriculture of any product or service.

Table 1

Site characteristics and selected pre-treatment soil properties to a depth of 60 cm for study sites near Matlock, Washington and Molalla, Oregon (Devine et al., 2011).

Characteristic or property	Matlock	Molalla
Location (latitude, longitude)	47.206°N, 123.442°W	45.196°N, 122.285°W
Elevation (m)	118	449
Mean annual temperature (°C)	10.7	11.2
Mean annual precipitation (mm) ^a	2412	1688
Site index _{50yr} (m)	36	36
Soil particle size distribution (% sand/silt/clay) ^b	65/14/21	37/34/29
Total bulk density (Mg m ⁻³)	1.45 (0.05) ^c	0.98 (0.02)
Soil coarse fragments by mass (%)	67.6 (1.3)	37.7 (2.2)
Soil water holding capacity (mm) ^d	55	142
Soil water content at -1.5 MPa (m ³ m ⁻³) ^d	0.126 (0.004)	0.167 (0.005)
Total soil C (Mg ha ⁻¹)	92.4 (5.8)	169.5 (12.0)
Total soil N (kg ha ⁻¹)	3300 (150)	7220 (410)

^a Precipitation was estimated for the period, 1950–2005 (PRISM Climate Group, 2012).

^b Determined with the hydrometer method.

^c Standard error in parentheses; *n* = 8 for bulk density at Matlock, *n* = 16 for all others.

^d Estimated from pressure plate analyses by the Central Analytical Laboratory, Oregon State University, Corvallis, OR (Devine et al., 2011).

sure was minimized by shielding seedlings with plastic bags in 2005 and 2006 and by using a directed spray in 2007 and 2008.

2.3. Vegetation measurements

Vegetation cover (nearest 5%) was estimated visually each August (2005–2008) within a 2 × 2-m PVC frame centered around each sample seedling with frame sides placed parallel with the rows of adjacent planted seedlings. Cover values were recorded separately for each of two classes of herbs (i.e., broadleaf forbs and grasses), three classes of woody species (i.e., shrubs, tree seedlings, and vines), and the Douglas-fir seedling at plot center. Separate estimates were recorded for each plant species having a cover ≥ 20%. Stem diameter at 15 cm above ground (nearest mm) and height (nearest cm) of each Douglas-fir were measured immediately after application of the assigned logging debris covers and at the end of each of the 2005–2008 growing seasons. At study initiation, average stem diameter of Douglas-fir at Matlock (11 mm) was slightly larger than at Molalla (9 mm), but average height differed little between sites (55 and 54 cm, respectively).

To quantify soil water availability to the seedlings, day-time (1030–1600 h PDT) measurements of plant water potential were taken once on each Douglas-fir in September 2005 and monthly during the growing seasons of 2006 (June–September) and 2007 (May–August). A current-year shoot was collected at mid-crown on the south side of each seedling, placed in a plastic bag containing a wet paper towel, and brought immediately to a pressure chamber (PMS Instrument Co., Albany, Oregon). The chamber was gradually filled with nitrogen gas to identify the minimum balance pressure (nearest -0.01 MPa) required to initiate exudation of water from the cut surface of the xylem tissue.

Three current-year shoots from the second-whorl of each seedling were collected in October of 2005–2008 for estimation of foliar nitrogen concentration. Buds were stripped from the shoots of each sample, the remaining material was dried at 65 °C to a constant weight, and foliage was removed from the woody tissue. The oven-dried foliage samples were submitted to Central Analytical Laboratory, Oregon State University, Corvallis, Oregon, where they were ground to pass through a 60-mesh sieve and analyzed with a Fisons 1500 NA NCS Analyzer (ThermoQuest Italia, Milan, Italy)

using Dumas combustion techniques (Jones and Case, 1990) to determine foliar nitrogen concentration (nearest 0.1 mg g⁻¹). The dry weight of a 100-needle sample also was recorded for each seedling (nearest 0.001 g) to test for treatment effects on foliage dry weight and nitrogen content (i.e., the product of foliar nitrogen concentration and foliage dry weight).

2.4. Microclimate measurements

A CR10X weather station (Campbell Scientific, Inc., Logan, Utah) was installed at each site for recording daily precipitation (nearest mm) and hourly air temperature (nearest 0.1 °C at 2 m above ground). A soil water sensor and a soil temperature sensor were installed 45 cm away from and on opposite sides of the stem of each sample Douglas-fir along a randomly selected azimuth. Each soil water sensor (ECH₂O[®] model EC-20, Decagon Devices, Inc., Pullman, Washington) was installed vertically within a 20–40-cm depth range, and site-specific calibrations were developed for predicting volumetric water content (nearest 0.005 m³ m⁻³). Soil water measurements were logged every 4 h to a data logger (models EM-5[®] or EM-50[®], Decagon Devices, Inc., Pullman, Washington), and the data were downloaded every 4–6 weeks for the duration of the study (2005–2008). Each temperature sensor (I-button[®] model DS1921G, Maxim Integrated Products, Inc., Sunnyvale, California) was inserted into a small sealable plastic bag that was placed in the bottom of an excavated hole 15 cm in depth. Soil temperature measurements (nearest 0.5 °C) were logged by the sensor every 2 h for the duration of the study (2005–2008). Every 4–6 weeks each temperature sensor was retrieved, replaced with another sensor from a second set, and returned to the laboratory for downloading of data.

2.5. Statistical analyses

All statistical analyses were conducted in SAS (SAS Institute, Inc., 2008) with a significance level of $\alpha = 0.05$. Data from each site were analyzed separately. For each Douglas-fir, measurements of soil temperature were averaged first by day and then by month. Daily averages of soil water content for each seedling were converted to depletion by subtracting the respective first daily value of the year (i.e., for 2005, the day in March when soil water sensors were installed; for 2006–2008, January 1st) and then averaging these values by month. Monthly values of soil temperature, soil water depletion, and Douglas-fir water potential within a given year were subjected to repeated measures analysis of variance (ANOVA) using a mixed-model approach in PROC MIXED to test for significant fixed effects of vegetation level (presence or absence), debris cover (0%, 40%, or 80%), month, and their two- and three-way interactions. Annual values of vegetation cover (summed by herb and woody categories) and Douglas-fir stem volume (calculated from a parabolic equation) were analyzed similarly to test for effects of treatment, year, and their interactions. A first-order autoregressive covariance structure was used to adjust each repeated measures ANOVA for serial correlation. Blocking and replication within blocks (i.e., two replications per block from the existing LTSP study) were assigned as random effects in each ANOVA. Stem volume of Douglas-fir at study initiation was included as a covariate in the ANOVA for Douglas-fir stem volume when significant. An angular transformation (arcsine, square-root) was applied to proportionate values of vegetation cover and a logarithmic transformation was applied to Douglas-fir stem volume to homogenize the residual variances (Sokal and Rohlf, 1981). Residuals for each dependent variable were plotted against predicted values to confirm the homogeneity of residual variances. If a timing-by-treatment interaction was

detected, the PROC MIXED slicing option was used to identify individual months or years in which differences existed among treatments (SAS Institute, Inc., 2008). If an interaction was detected between vegetation and debris treatments, slicing was used to identify differences among debris covers for each vegetation level and between vegetation levels for each debris cover. When treatment differences were detected, multiple comparisons of least-squares means were conducted using Bonferroni probabilities to control the Type I error rate (Quinn and Keough, 2002). Orthogonal polynomial contrasts also were specified to test for linear and quadratic effects of debris cover (Sokal and Rohlf, 1981). Results are presented as back-transformed, least-squares means from the ANOVA. Seedling stem volume was plotted on a common logarithmic (base 10) scale to illustrate differences in relative growth rate (Hunt, 1990).

To identify three possible mechanisms by which debris influenced Douglas-fir growth through its effects on soil water availability, study hypotheses were tested with data from the first 2 years of the study (2005 and 2006) because during this period seedlings had not yet fully occupied their growing space, and therefore, their effects on belowground resource availability would be relatively small. To test for effects from altered abundance of plant competitor species resulting from variation in debris cover (Hypothesis (1)), we used ANOVA results to determine: (a) whether competitor abundance varied with debris cover, and (b) whether soil water depletion, in the presence of vegetation, varied with debris cover as a result of changes in competitor abundance. To test for a mulching effect from debris (Hypothesis (2)), we used ANOVA results to determine whether soil water depletion varied with debris cover in the absence of vegetation (i.e., no consumption of water by vegetation) and during summer drought (i.e., limited inputs from precipitation). Likewise, to test for interception losses from debris (Hypothesis (3)), we used ANOVA results to determine whether soil water depletion varied with debris cover in the absence of competing vegetation (i.e., no consumption or interception loss of water by competing vegetation) with the onset of precipitation during or soon after summer drought. We also plotted average daily values of depletion for each level of vegetation and debris cover to determine if evidence in support of Hypotheses (1–3) was apparent at a finer scale than via the monthly averages upon which the ANOVA results were based. To test for changes in nitrogen availability from debris (Hypothesis (4)), we used ANOVA results to determine whether Douglas-fir foliar nitrogen concentration, dry weight, and nitrogen content varied with debris cover. Values for the foliar nitrogen variables also were expressed as percentages of those observed at each site for the treatment, vegetation present with 0% debris cover, to enable relativized comparisons (Imo and Timmer, 1998).

Stepwise linear regression in PROC REG was used to characterize relationships of: (1) soil water content vs. competing vegetation abundance, (2) Douglas-fir water potential and foliar nitrogen concentration vs. soil water content, and (3) Douglas-fir stem volume vs. Douglas-fir water potential and foliar nitrogen concentration. Using combined data from the two sites, an indicator variable was specified to test for site differences in the regression intercept and slope of each relationship (Sokal and Rohlf, 1981). The analysis was focused on measurements from 2006 because the intensity and duration of summer drought was greatest in that year and the seedlings had not yet fully occupied their growing space. The relationships were fitted to August values of soil water content and Douglas-fir water potential to ensure that differences between vegetation treatments were consistently maximized at each site. Douglas-fir stem volume was transformed to natural logarithms to homogenize its variance in the regression relationships.

3. Results

3.1. Competing vegetation abundance

For plots in which vegetation was present, the three woody species of highest average cover were California blackberry (*Rubus ursinus* Cham. and Schltdl.) (5% cover), salal (4%), and snowberry (*Symphoricarpos albus* (L.) S.F. Blake) (4%) at Matlock and California blackberry (41%), cascara buckthorn (*Frangula purshiana* (DC.) Cooper) (3%), and Oregon grape (2%) at Molalla. The three herb species of highest average cover were hairy cat's ear (*Hypochaeris radicata* L.) (16% cover), oxeye daisy (*Leucanthemum vulgare* Lam.) (1%), and twinflower (*Linnaea borealis* L.) (1%) at Matlock and hairy cat's ear (6%), common velvet grass (*Holcus lanatus* L.) (2%), and western brackenfern (*Pteridium aquilinum* (L.) Kuhn) (2%) at Molalla. Cover of competing vegetation was highest in 2007 and declined in 2008 with increasing cover of Douglas-fir. Herb cover averaged 40% and 45% at Matlock and Molalla, respectively; whereas, woody cover averaged 26% and 55%, respectively. The combined cover of herbaceous and woody species at Matlock (56–81%) was lower than at Molalla (89–117%).

The annual herbicide treatments virtually eliminated competing vegetation around the designated seedlings at each site, resulting in herb and woody covers of $\leq 5\%$ for the study duration. For each site and year, herb, woody, and combined covers were significantly lower in the presence of vegetation control ($P < 0.001$). Because of the virtual elimination of competing vegetation via herbicides, subsequent references to this experimental factor denote absence or presence of vegetation.

Debris effects on vegetation cover were manifested as main effects for herb cover at Molalla ($P = 0.008$) and as vegetation-by-debris interactions for herb and woody covers at Matlock ($P \leq 0.018$) and for woody cover at Molalla ($P = 0.050$). Orthogonal polynomial contrasts indicated that linear effects of debris cover were significant for herb and woody covers at Matlock ($P \leq 0.005$) and quadratic effects were significant at Molalla ($P = 0.020$). With increasing debris cover at Matlock, herb cover decreased and woody cover increased (Table 2). At Molalla, 40% debris cover was associated with lower herb cover and higher woody cover than for 0% debris cover. At both sites the combined cover of herb and woody species did not vary significantly due to debris level or its interactions with vegetation level or year ($P \geq 0.164$). The reported vegetation responses to logging debris were attributed to: (1) decreased forb abundance at both sites, coupled with decreased grass abundance at Molalla, (2) increased abundance of vines at both sites, and (3) lower abundances of shrubs, tree seedlings, and vines in the 80% debris cover than in the 40% debris cover at Molalla.

3.2. Douglas-fir survival and growth

Of the 96 Douglas-fir seedlings in the study, four died at each site. At Matlock, each of the dead seedlings had grown with

Table 2

Mean cover of herb and woody species as affected by logging debris cover during 4 years at two sites for plots in which vegetation was present.

Site	Debris cover (%)	Herb cover (%)		Woody cover (%)	
		Mean	Std. error	Mean	Std. error
Matlock	0	52.8a	4.2	15.1b	4.1
	40	42.7a	4.0	25.0ab	5.0
	80	26.2b	3.4	40.2a	6.0
Molalla	0	55.7a	4.7	44.0b	6.2
	40	35.9b	4.1	70.7a	6.8
	80	43.1ab	4.4	51.6ab	6.5

Note: Means for a given site and type of vegetation cover followed by the same letter do not differ significantly among debris covers ($P > 0.05$).

competing vegetation; whereas, at Molalla, seedling mortality was split equally between the two vegetation levels. Seedling mortality did not vary consistently among logging debris covers at either site.

By the end of the study in 2008, cover of Douglas-fir differed two- to four-fold between the absence and presence of vegetation at Matlock (54% and 13%, respectively; $P < 0.001$) and Molalla (43% and 18%, respectively; $P < 0.001$). However, cover of Douglas-fir did not vary significantly due to debris level or its interactions with vegetation level or year ($P \geq 0.340$).

At each site, differences in the growth trajectories for Douglas-fir stem volume among vegetation and debris cover treatments resulted primarily from responses that occurred in 2005 (Fig. 1). The one exception is at Matlock where stem volume responses to debris cover in the absence of vegetation did not separate until 2006. After 2005, the slope of the growth trajectories (i.e., relative growth rate) declined for all treatments, especially at Matlock. At Matlock, stem volume varied according to vegetation-by-year and vegetation-by-debris interactions ($P = 0.001$). Multiple comparisons for Matlock indicated that: (1) stem volume was greater in the absence of vegetation during each year and for each debris cover, and (2) in the presence of vegetation, stem volume was greater for 40% debris cover than for 80% debris cover, but it did not differ from that for 0% debris cover. At Molalla, stem volume varied

according to a three-way interaction of vegetation, debris, and year ($P = 0.004$). Multiple comparisons for Molalla indicated that: (1) in 2006 and 2007, stem volume for 80% debris cover was greater in the absence of vegetation, and (2) in 2008, stem volume for 0% and 80% debris covers was greater in the absence of vegetation. Orthogonal polynomial contrasts indicated that, in the presence of vegetation, a quadratic effect of debris cover was significant for stem volume at Matlock ($P = 0.004$).

3.3. Air and soil temperature

Air temperature during summer months was, on average, 0.7 °C higher at Molalla than at Matlock, but it averaged only 0.2 °C higher during the other seasons – differences that exceeded the 0.1 °C precision of the air temperature sensors (Fig. 2). In 2005 and 2006 at both sites and in 2008 at Matlock, soil temperature varied as a result of vegetation-by-month and debris-by-month interactions ($P < 0.001$). Orthogonal polynomial contrasts indicated that linear effects of debris cover dominated at Matlock ($P \leq 0.001$) and quadratic effects dominated at Molalla ($P \leq 0.001$). These polynomial effects can be attributed to a linear decrease and a declining rate of decrease in soil temperature with increasing debris cover at Matlock and Molalla, respectively. In general, debris effects dominated during spring months (1.2 °C average decrease); whereas, both debris and vegetation effects occurred during summer months, resulting in a combined average decrease of 2.4 °C (Fig. 2). During the months in which debris effects were detected, higher soil temperature under 40% debris cover compared to the 80% debris cover (0.3 °C) was within the 0.5 °C precision of the soil temperature sensors. In 2007 at both sites ($P \leq 0.032$) and in 2008 at Molalla ($P = 0.007$), the three-way interaction of vegetation, debris, and month was significant. At Matlock during mid- to late summer 2007, soil temperature under 80% debris cover averaged about 1 °C higher in the absence of vegetation; whereas, in October and November 2007 under 0% debris cover, it averaged 1.0–1.3 °C lower in the absence of vegetation. At Molalla, soil temperature during the summers of 2007 and 2008 under 0% and 40% debris covers averaged 1.0–1.5 °C higher in the absence of vegetation.

3.4. Precipitation

Long-term (1950–2005) estimates indicated that Matlock received an average of 724 mm more annual precipitation than Molalla (Table 1; PRISM Climate Group, 2012). During the 4 years of the study (2005–2008), average annual precipitation measured at Matlock (2194 mm) was 981 mm greater than at Molalla (1213 mm). Growing season (i.e., April through September) precipitation at Matlock and Molalla was highest in 2005 (567 and 459 mm, respectively) and least in 2006 (320 and 260 mm, respectively) (Fig. 3). At both sites, summer (i.e., June–September) precipitation in 2006 (22–28 mm) was about half or less of that observed in 2005 (50–53 mm), 2007 (43–69 mm), and 2008 (43–68 mm).

3.5. Soil water depletion

Soil water depletion varied as a result of a vegetation-by-month interaction for each combination of site and year ($P < 0.001$). At both sites, soil water depletion was higher in the presence of competing vegetation during selected summer months of each year (Fig. 3). These differences were sustained throughout summer 2005 at Matlock and throughout summer 2006 at Molalla. In 2005 at each site, soil water depletion varied as a result of an interaction of vegetation, debris, and month ($P \leq 0.024$). In June and July of 2005 at Matlock, depletion in the presence of vegetation was less with 80% debris cover (-0.032 and $-0.060 \text{ m}^3 \text{ m}^{-3}$ for June and July, respectively) than with 0% debris cover (-0.075

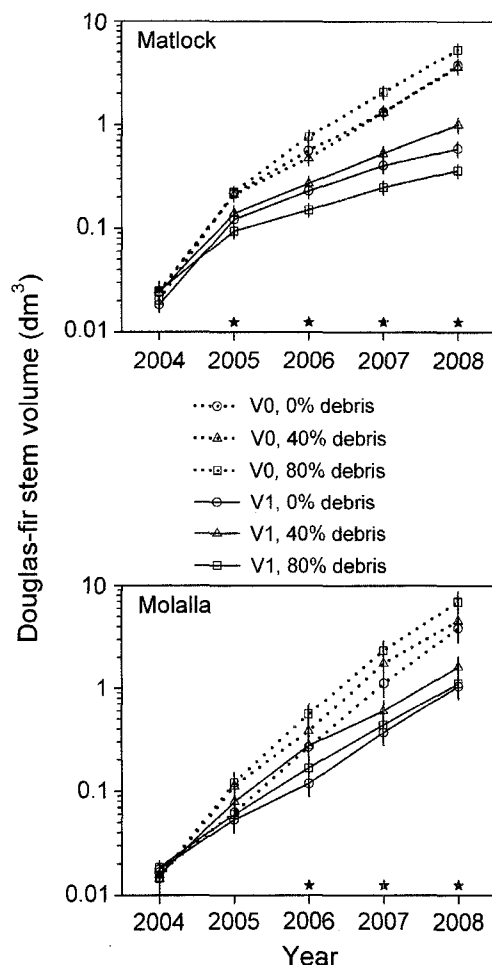


Fig. 1. Common logarithm of mean stem volume of Douglas-fir ($\pm$ S.E.) during 4 years at two sites as affected by absence (V0) and presence (V1) of competing vegetation and three levels of logging debris cover. For each site, asterisks indicate years in which stem volume differed significantly between vegetation levels ($P \leq 0.05$).

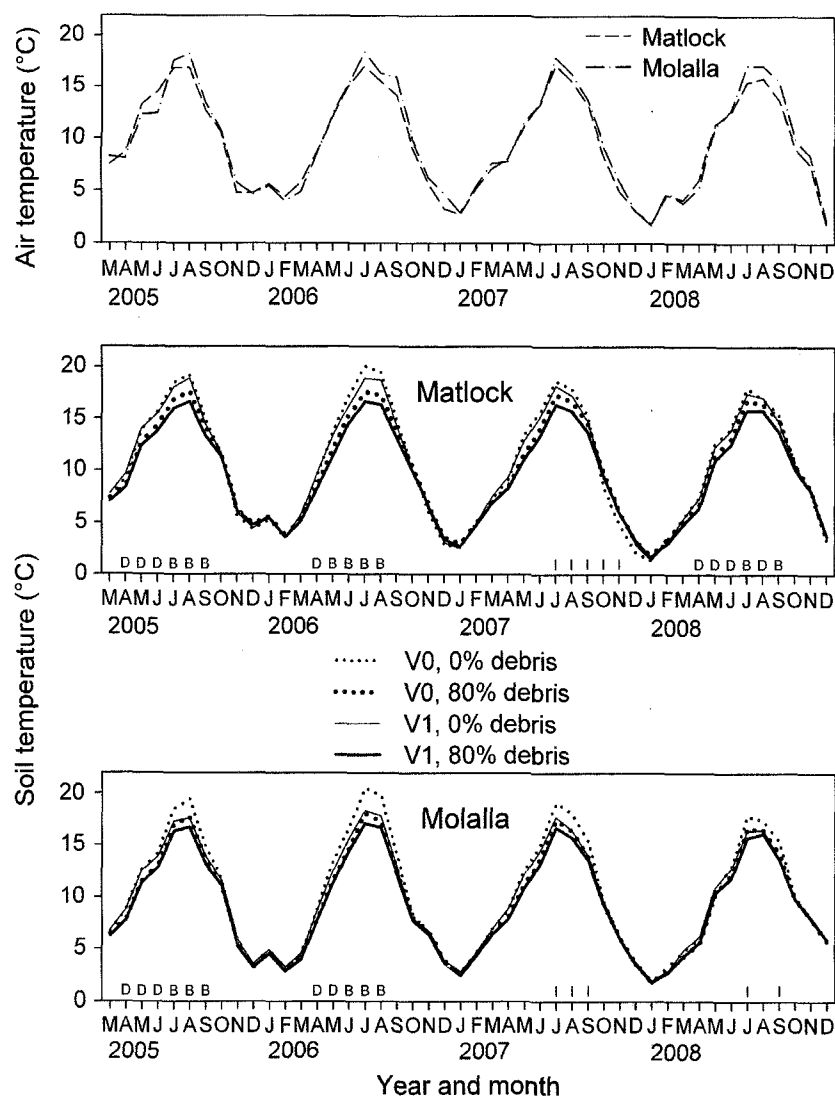


Fig. 2. Mean air temperature (2 m above ground) and soil temperature (15 cm depth) during 4 years at two sites as affected by absence (V0) and presence (V1) of competing vegetation and two levels of logging debris cover. For each site and year, letters indicate months in which soil temperature differed significantly according to main effects of debris cover (D), main effects of both debris cover and vegetation control (B), or their interaction (I) ($P \leq 0.05$).

and $-0.100 \text{ m}^3 \text{ m}^{-3}$, respectively). However, multiple comparisons of means for Molalla in 2005 did not detect differences in depletion among debris covers. Nonetheless, in the presence of vegetation, daily values of depletion clearly illustrated periods in 2005 at each site in which depletion under 40% or 80% debris covers was less than under 0% debris cover (Fig. 4). Similar differences in daily depletion values among debris covers also were observed for 2006, 2007, and 2008 (data not shown). These results, plus those described previously for debris effects on vegetation abundance, support Hypothesis (1) that debris reduced consumption of soil water as a result of reductions in herb cover.

Results from the ANOVA, however, did not support Hypothesis (2) (i.e., mulching effects) and Hypothesis (3) (interception losses). Furthermore, daily values of depletion suggested that these effects were either minor or non-detectable from the 20–40 cm depth at which the soil water sensors were installed (Fig. 4). Specifically, mulching effects of debris, as manifested by reduced rates of depletion, appeared to be small in 2005 and non-existent in subsequent years of the study. Interception losses from debris, as manifested by a limitation in the amount by which soil water increased following a precipitation event (i.e., soil water depletion increased or stayed the same), were not visually apparent in any year.

3.6. Douglas-fir water potential

At each site, mid-day water potential of Douglas-fir in September 2005 was less negative in the absence (-1.4 to -1.5 MPa) than in the presence of competing vegetation (-1.7 to -2.0 MPa) ($P \leq 0.038$), but it did not vary among debris covers ($P \geq 0.080$). In 2006 at both sites and in 2007 at Molalla, water potential varied as a result of a vegetation-by-month interaction ($P \leq 0.009$). At each site during July and August of 2006, water potential was less negative in the absence (-1.2 to -1.5 MPa) than in the presence of vegetation (-1.6 to -2.3 MPa). Similarly, at Molalla during July and August of 2007, water potential was less negative in the absence (-0.5 to -1.3 MPa) than in the presence of vegetation (-0.7 to -1.6 MPa).

In the presence of vegetation at Matlock in 2006, orthogonal polynomial contrasts indicated quadratic effects of debris cover ($P = 0.038$) because water potential in 40% debris cover (-1.6 MPa) was less negative than in 0% or 80% debris covers (-1.7 MPa). At Molalla in 2007, water potential also varied according to a vegetation-by-debris interaction ($P = 0.022$) because, for 40% and 80% debris covers, it was less negative in the absence (-0.9 and -1.0 MPa, respectively) than in the presence of

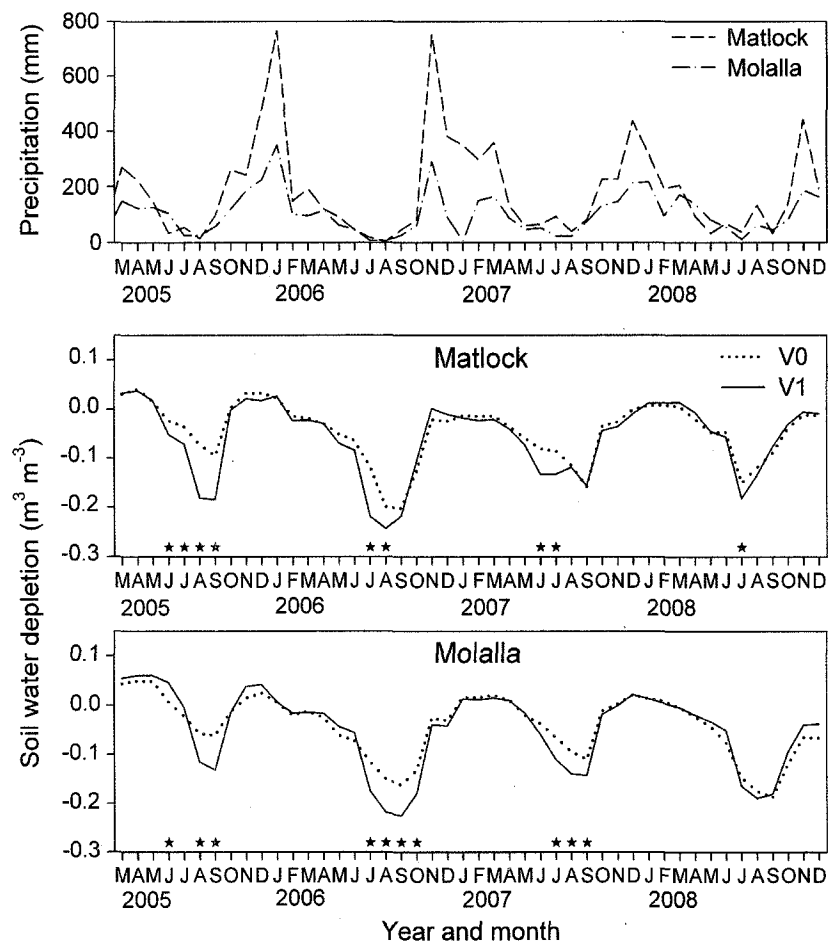


Fig. 3. Monthly precipitation and mean depletion in volumetric soil water content (20–40 cm depth) during 4 years at two sites as affected by absence (V0) and presence (V1) of competing vegetation. For each site and year, asterisks indicate months in which soil water depletion differed significantly between vegetation levels ($P \leq 0.05$).

vegetation (-1.1 and -1.2 MPa, respectively); whereas, for 0% debris cover, the difference between vegetation levels (-1.0 and -1.1 MPa for vegetation absence and presence, respectively) was not statistically significant. At Matlock in 2007, differences in water potential between vegetation levels were not significant during any of the months sampled ($P = 0.160$) because of ample summer rainfall (Fig. 3).

3.7. Douglas-fir foliar nitrogen

A vegetation-by-year interaction was significant for Douglas-fir foliar nitrogen concentration at each site ($P < 0.001$). Nitrogen concentration was higher in the absence than in the presence of competing vegetation at Matlock in 2005 (16 vs. 11 mg g⁻¹, respectively) and 2007 (13 vs. 11 mg g⁻¹) and at Molalla in 2005 (15 vs. 12 mg g⁻¹), 2006 (15 vs. 10 mg g⁻¹), and 2007 (18 vs. 14 mg g⁻¹). However, nitrogen concentration did not vary according to debris level or its interactions with vegetation level and year ($P \geq 0.194$).

At Matlock, vegetation-by-year interactions were significant for foliage dry weight ($P = 0.050$) and nitrogen content ($P < 0.001$). Multiple comparisons of foliage dry weight did not detect any differences; however, nitrogen content was higher in the absence (6.2–8.9 mg) than in the presence of vegetation (4.7–5.3 mg) in 2005, 2007, and 2008. Similarly, at Molalla, foliage dry weight did not vary significantly among treatments or their interactions with year ($P \geq 0.079$); however, nitrogen content varied as a result of main effects of vegetation (i.e., 6.9 and 5.4 mg for absence and presence of vegetation, respectively; $P = 0.008$).

Orthogonal polynomial contrasts for Matlock indicated that nitrogen content either increased or decreased linearly with increasing debris cover depending on whether vegetation was absent or present, respectively ($P = 0.043$). Likewise, polynomial contrasts for Molalla indicated that, in the absence of vegetation, foliage dry weight increased linearly with increasing debris cover ($P = 0.038$). In a graphical depiction of the relativized values (Fig. 5), it is apparent that foliage of seedlings growing with 80% debris cover in the presence of vegetation at Matlock had the lowest responses in nitrogen concentration, foliage dry weight, and nitrogen content in the study. It is also apparent that, at each site, foliage of seedlings growing with 80% debris cover in the absence of vegetation had the highest values for nitrogen content and foliage dry weight. These results support Hypothesis (4) that soil nitrogen availability to Douglas-fir changed with increasing debris cover, with the direction of the change depending on the absence (increased nitrogen availability) or presence (decreased nitrogen availability) of vegetation.

3.8. Vegetation and resource relationships

Regression analyses of the data from 2006 identified significant linear relationships that linked soil water availability to abundance of competing vegetation ($R^2 = 0.41$ – 0.47) and that linked the logarithm of Douglas-fir stem volume to soil water availability ($R^2 = 0.36$) (Fig. 6). Soil water content declined linearly with increasing cover of competing vegetation, and the regression slope was 63% more negative for herb cover than for woody cover (Fig. 6a and b). In each of the relationships of soil water to vegetation

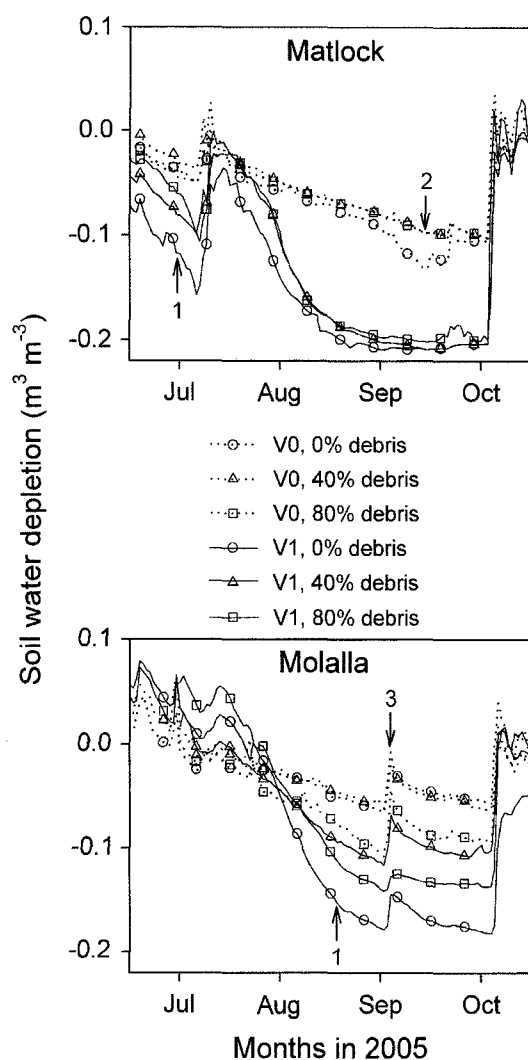


Fig. 4. Mean daily depletion in volumetric soil water content (20–40 cm depth) during summer 2005 at two sites as affected by absence (V0) and presence (V1) of competing vegetation and three levels of logging debris cover. Arrows indicate evidence for: (1) presence of variable water consumption from altered abundance of competitor species in V1 from debris, (2) presence of mulching effects in V0, and (3) absence of interception losses in V0 with the onset of precipitation after cessation of summer drought.

abundance, the regression intercept was greater for Molalla than for Matlock because of site differences in soil water content in the absence of vegetation. The regression model for Matlock predicted that herb and woody covers of 31% and 41%, respectively, were capable of depleting soil water content to the permanent wilting point (soil water content = $0.126 \text{ m}^3 \text{ m}^{-3}$; Table 1); whereas, the corresponding herb and woody covers at Molalla were 50% and 75%, respectively (soil water content = $0.167 \text{ m}^3 \text{ m}^{-3}$). Note that, within the growing space for several seedlings at each site, soil water content reached the permanent wilting point in August 2006 (Fig. 6a and b).

Douglas-fir water potential increased linearly with soil water content, and the slope of the relationship was greater for Matlock than for Molalla, indicating greater increases in water potential for a given increase in soil water content (Fig. 6c). The natural logarithm of Douglas-fir stem volume increased with water potential, and the regression slope was less for Matlock than for Molalla (Fig. 6d).

Douglas-fir foliar nitrogen concentration was not significantly related to soil water content ($P = 0.053$; data not shown). The

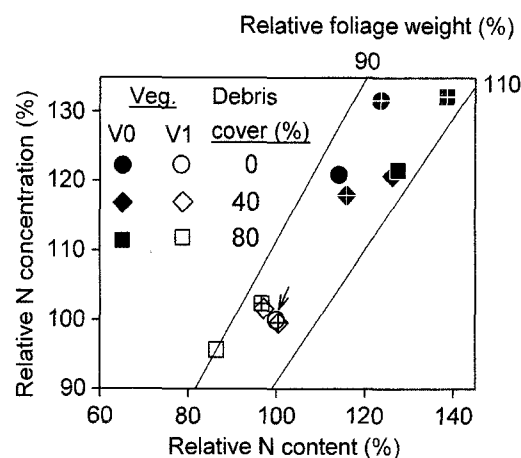


Fig. 5. Relativized foliar nitrogen and foliage dry weight responses of Douglas-fir seedlings during 2005–2008 at two sites (uncrossed symbols = Matlock; crossed symbols = Molalla) as affected by absence (V0) and presence (V1) of competing vegetation and three levels of logging debris cover. Means for each variable were expressed relative to that observed at a given site for the treatment, vegetation present with 0% debris cover (indicated by the arrow).

relationship of the logarithm of Douglas-fir stem volume to foliar nitrogen concentration was statistically significant but weak ($P = 0.008$, $R^2 = 0.07$; data not shown), and the regression intercept and slope did not vary between sites.

4. Discussion

In this seedling-centered study, soil water depletion was lower and Douglas-fir water potential and foliar nitrogen concentration were higher in the absence of competing vegetation, resulting in up to a 14-fold increase in seedling stem volume (Fig. 1). These results are typical of those observed in numerous forestry studies conducted throughout the world on the effects of competing vegetation on tree seedling growth (Wagner et al., 2006). The magnitude of seedling growth responses observed in this study emphasizes the importance of competing vegetation impacts to development of new forest stands in the Pacific Northwest.

Results of the regression analysis illustrate the important linkages that exist between vegetation abundance, soil water availability, and seedling growth in the Pacific Northwest. Soil water content decreased more rapidly with increasing cover of herbs than with increasing cover of woody species because of differences in soil water consumption among species (Dinger, 2012), and therefore, competitiveness with Douglas-fir (Fig. 6a and b). Because of differences in soil physical properties between sites (1) soil water content in the absence of vegetation (i.e., regression intercepts in Fig. 6a and b) was lower for the very gravely loamy sand at Matlock than for the cobbly loam at Molalla, and (2) increases in soil water availability (i.e., Douglas-fir water potential) for a given increase in soil water content were greater for Matlock than for Molalla (Fig. 6c). However, increases in stem growth of Douglas-fir for a given increase in soil water availability were greater for Molalla than for Matlock (Fig. 6d), probably because of innate differences in site quality that are attributable to a suite of soil chemical and physical properties (Slesak et al., 2010), as well as macroclimate. Many of the factors responsible for differences in site quality between Matlock and Molalla can be traced to their contrasting parent material and associated physical properties (Table 1), because these properties have large control over soil water holding capacity and availability, cation exchange capacity, and size of total pools of soil carbon and macronutrients. The weak

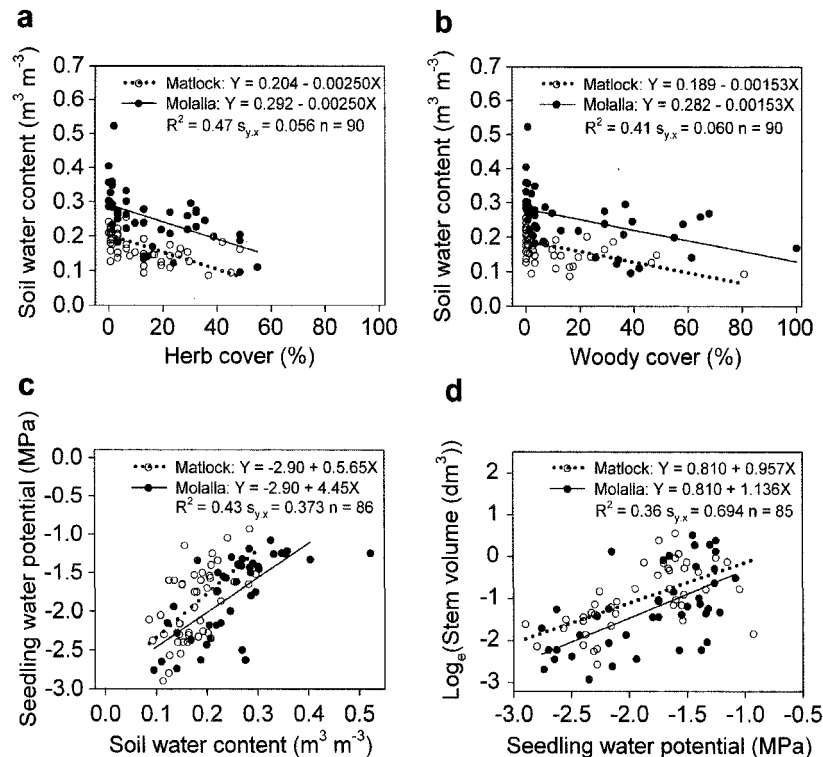


Fig. 6. Linear regression relationships of soil water content to (A) herb cover and (B) woody cover, (C) Douglas-fir water potential to soil water content, and (D) natural logarithm of Douglas-fir stem volume to Douglas-fir water potential at two sites in which presence and absence of competing vegetation and cover of logging debris were manipulated. Regression models are based on combined Matlock and Molalla data from 2006, including August measurements of soil water content and seedling water potential.

relationship observed between Douglas-fir stem volume and foliar nitrogen concentration suggests that soil nitrogen was of less importance to early growth of Douglas-fir than soil water, especially during a significant drought year (Roberts et al., 2005; Slesak et al., 2010).

Overall, seedling growth was greatest where 80% debris cover was combined with absence of vegetation. Analysis of foliar nitrogen responses indicated that, in the absence of vegetation at both sites, 80% debris cover was associated with increases, relative to 0% debris cover, in foliage dry weight and nitrogen content, but not in nitrogen concentration (Fig. 5). Although the specific mechanism by which debris stimulated seedling growth in the absence of vegetation is not clear, especially given that strong mulching effects from debris were not detected (Fig. 4; Hypothesis (2)), concurrent increases in foliage biomass and uptake of soil nitrogen were clearly involved (i.e., nitrogen sufficiency; Imo and Timmer, 1998). In 2005, soon after the debris cover treatments had been applied, Slesak et al. (2010) observed at Matlock that total soil nitrogen varied directly with logging debris cover regardless of vegetation level. Clearly, logging debris played a role in increasing availability of soil nitrogen to Douglas-fir (Hypothesis (4)).

Trends in daily soil water depletion provided evidence for a mulching effect of debris in the first year of the study at Matlock; however, the magnitude and duration of the effect was relatively small (Fig. 4; Hypothesis (2)). In previous research, mulching effects of logging debris on soil water content were only detected when the sampling range of the sensor included the soil surface (O'Connell et al., 2004; Roberts et al., 2005; Devine and Harrington, 2006; Law and Kolb, 2007). In addition, mulching effects in a 5-year study were detected over twice as frequently on a fine-textured soil than on a coarse-textured sandy soil (O'Connell et al., 2004), probably because of the greater evaporation rates from

coarse-textured soils. Soil water potentials at 10 cm depth were less negative with retention of organic matter after forest harvesting in southeastern British Columbia, but much of this effect was attributed to retention of the forest floor and not to retention of logging debris (Tan et al., 2009). In this study, soil water content was measured at 20–40 cm depth to characterize the rooting environment of Douglas-fir for the duration of the research. At a different site located 3 km from the Matlock site that had similar soils, we installed soil water sensors at a depth range of 5–25 cm and observed consistent effects of mulching from logging debris on soil water content during the first year after forest harvesting in 2012 (Harrington and Slesak, unpublished data). Thus, we hypothesize that, in the absence of vegetation, surface mulching effects of debris provided additional soil water to the seedlings which increased their growth. Failure to detect such effects in the present study is likely attributable to the depth of soil sensors (20–40 cm) and their proximity to the sample seedlings (45 cm). Interception losses from debris were not detected (Hypothesis (3)) probably also because of the depth of soil sensors used in this study, as well as the transient nature of differences in soil water with the onset of heavy precipitation after cessation of summer drought.

Where competing vegetation was present, 40% cover of logging debris reduced herb cover and thereby facilitated increases in Douglas-fir growth via greater availability of soil water (Hypothesis (1)). As discussed previously, soil water depletion for a given amount of cover was considerably greater for herbs than for woody vegetation. Trends in daily values for soil water depletion clearly showed this mechanism was operating at both sites, particularly in 2005 (Fig. 4). As a result of the enhanced availability of soil water, seedling growth was greater with 40% debris cover than with 0% or 80% debris covers at Matlock for the duration of the

study and at Molalla in 2006. The short-lived growth response at Molalla suggests that another factor, such as soil nitrogen or temperature, may have become more limiting to seedling growth than soil water. In 2006, foliar nitrogen concentration in the presence of vegetation at Molalla dropped to a level (9.9 mg g^{-1}) that is considered very severely deficient for Douglas-fir ($<10.5 \text{ mg g}^{-1}$; Ballard and Carter, 1986) and the effect on seedling growth may have carried over into subsequent years. At Matlock, where soil nitrogen pools were much smaller than at Molalla (Table 1), seedlings growing in the presence of vegetation had severe nitrogen deficiencies for the duration of the study ($10.6\text{--}12.8 \text{ mg g}^{-1}$). In contrast, seedlings growing without vegetation at Matlock had slight to moderate nitrogen deficiencies for each year ($12.6\text{--}13.9 \text{ mg g}^{-1}$) except 2005 (16.4 mg g^{-1}); whereas, seedlings growing without vegetation at Molalla had adequate levels of nitrogen for the duration of the study ($14.8\text{--}18.0 \text{ mg g}^{-1}$).

In the existing LTSP study at Matlock, Peter and Harrington (2012) found that abundance of non-native, early seral species of competing vegetation was lower, whereas that of residual forest species was higher, where logging debris was operationally retained than where it was removed after forest harvesting. In an LTSP study in northeastern British Columbia, Haussler and Kabzems (2005) found little difference in understory species composition between areas in which logging debris was retained vs. removed after harvesting trembling aspen; however, removal of the forest floor shifted species composition to favor ruderal species over those that regenerated from rhizomes and buds. Some studies comparing operational manipulations of woody debris may have failed to identify significant effects of debris cover on vegetation abundance because sampling of vegetation responses was not tied directly to experimentally controlled levels of debris, as done in the present study (Scherer et al., 2000; Law and Kolb, 2007; Peterson and Leach, 2008). In addition, the variable nature of debris cover following operational manipulation can influence detectability of surface and soil responses at the scale of a larger ($>0.01 \text{ ha}$) experimental plot (Eisenbies et al., 2005; Slesak et al., 2011a).

Changes in microclimate and edaphic features (i.e., relatively high amounts of litter cover and minimally exposed mineral soil) near the soil surface from presence of logging debris probably limited germination and development of herb species (Law and Kolb, 2007; Peterson and Leach, 2008) and favored re-growth of woody species from existing rhizomes and rootstocks. Five years after harvesting mixed hardwoods at an LTSP study site in Missouri (USA), density of vines was greater in stem-only vs. whole-tree harvested areas; however, by the ninth year the differences were no longer statistically significant (Ponder, 2008). At Molalla, herb cover was lowest with 40% debris cover because: (1) woody species were more abundant in the 40% debris cover than in the 0% or 80% debris covers, and (2) the most abundant species, California blackberry, was more effective at occupying growing space in moderate levels of debris. As a vine, California blackberry grows over logging debris and creates a canopy that is not necessarily rooted immediately below its leaves. Thus, its competition for soil resources may be displaced from its canopy, at least early in its establishment. The species probably had lower abundance in the absence of debris where herb species were more abundant because it was less aggressive as a competitor due to its prostrate growth habit.

Presence of either logging debris or competing vegetation was associated with reductions in soil temperature of similar magnitude (1.2°C average reduction) during the growing season. Debris effects on soil temperature were detected in the spring before vegetation effects because they preceded normal vegetation development. Combined effects of shading from debris and vegetation caused an average reduction in soil temperature of 2.4°C . Similar reductions in soil temperature at 10–15 cm depth from logging debris have been reported for recently harvested forest sites in

Washington near the Pacific Coast (Devine and Harrington, 2007) and on the eastern slope of the Cascade Mountains (Zabowski et al., 2000). At three LTSP study sites in southeastern British Columbia, decrease in soil temperature at 10 cm depth from logging debris (0.7°C) was only about half that reported in the present study, perhaps because of moderating effects of competing vegetation, which were not quantified in the research (Tan et al., 2009). In the present study, combined effects of 80% debris cover and vegetation reduced the range of soil temperatures during the growing season (April to September) from $6\text{--}21^\circ\text{C}$ to $6\text{--}17^\circ\text{C}$. Lopushinsky and Max (1990) estimated an optimum temperature of 20°C for root and shoot growth of Douglas-fir and other western US conifer species. We hypothesize that the combined effects of vegetation and 80% debris cover limited growth of Douglas-fir, because, despite the first-year reductions in soil water depletion from debris at Matlock, the seedlings growing with vegetation and 80% debris cover had the slowest growth rates observed in the study. Absence of vegetation and debris effects on soil temperature during the winter months, when average soil temperatures approached but never went below freezing (Fig. 2), indicates that the treatments did not affect freezing and thawing cycles in the soil that would directly impact microbial and root growth processes.

As discussed previously, soil nitrogen availability also played a role in limiting seedling growth where effects of vegetation and 80% debris cover were combined at Matlock. This limitation in seedling growth due to reduced nitrogen availability at Matlock is probably attributable to the effects of competing vegetation, as well as reduced root uptake by Douglas-fir because of lower soil temperatures. It is unlikely that this growth limitation is due to reductions in nitrogen mineralization from lower soil temperatures under debris, because, on the contrary, debris retention at Matlock was associated with increases in both soil-solution nitrogen (Slesak et al., 2009) and total soil nitrogen (Slesak et al., 2011b). Retention of logging debris after harvesting Sitka spruce similarly resulted in greater nitrate leaching because the debris inhibited re-growth of vegetation (Stevens and Hornung, 1990). Also, for a wide range of sites across North America, retention of logging debris after forest harvesting did not have a consistent influence on either soil-solution nitrogen (Mann et al., 1988) or total soil nitrogen (Sanchez et al., 2006).

5. Conclusions

Using a seedling-centered study design at two forest sites that differed in availability of soil water and nitrogen, this research has identified three interactions between competing vegetation and logging debris that modified growth of Douglas-fir during early stand development. First, the highest rates of seedling growth at each site were observed when absence of competing vegetation was combined with 80% debris cover. Although the specific mechanisms contributing to the enhanced growth were not identified, increases in foliage dry weight and nitrogen content were clearly involved. Mulching effects of debris that conserved soil water probably also played a role in facilitating changes in seedling growth in this study, although the depth of the soil water sensors likely precluded their detection. Second, in the presence of vegetation, seedling growth with 40% debris cover was greater than with 0% or 80% debris covers. This response can be attributed to increased availability of soil water, as well as soil nitrogen, as a result of reductions in herb cover from exclusion by debris. Possible temperature limitations to seedling growth from combined effects of vegetation and debris probably were not as severe from 40% debris cover as from 80% debris cover. Third, in the presence of vegetation, seedling growth with 80% debris cover at Matlock occurred at the slowest rates observed in the study. Decreases in foliage

dry weight and nitrogen content were associated with these reduced rates of seedling growth. Thus, this growth response was attributable to reductions in availability of soil nitrogen and possibly soil temperature.

The intermediate debris cover used in this study (40%) was similar to that observed in the operational debris treatments of LTSP studies at Matlock (39%) and Molalla (42%) (Harrington and Schoenholtz, 2010) and at Fall River in southwestern Washington (50%) (Devine and Harrington, 2007). Therefore, results of this research suggest that typical covers of logging debris remaining after forest harvesting in the Pacific Northwest are likely to increase growth of Douglas-fir by increasing availability of soil water and nitrogen through shifts in competitor abundance. Where intensive vegetation control is practiced, higher levels of logging debris (i.e., 80% cover) may confer even greater benefits to seedling growth from additional increases in availability of soil water and nitrogen.

Pesticide precautionary statement

This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate state and federal agencies, or both, before they can be recommended. CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife – if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.

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