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Logging debris and herbicide treatments improve growing conditions for planted Douglas-fir on a droughty forest site invaded by Scotch broom

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ABSTRACT

Logging debris has the potential to benefit forest regeneration by increasing resource availability, modifying microclimate, and altering plant community structure. To understand potential mechanisms driving these benefits, we initiated research at a forested site on the Olympic Peninsula, WA that contained the invasive, nonnative competitor, Scotch broom (*Cytisus scoparius*). Immediately after harvesting the stand of mature coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) in late 2011, two levels of logging debris retention were created on replicated plots: 18.9 and 9.0 Mg ha^{-1}, with debris depths averaging 32 and 17 cm, respectively. Within each plot, three herbicide treatments (aminopyralid (A), triclopyr ester (T), and A + T) and a non-sprayed control were applied to split plots in August 2012. Douglas-fir seedlings were planted in early 2013, and microclimate and seedling performance were monitored through 2016. During the growing seasons of 2012–2014, soil water content was greater and soil temperature was lower under heavy debris than under light debris. Survival of planted Douglas-fir seedlings declined an average of 45 and 11 percentage points after intense summer droughts in 2015 and 2016, respectively, but it averaged 7–10 percentage points greater in heavy debris than in light debris during this period. Douglas-fir stem diameter growth was consistently greater in heavy debris than in light debris, with the exception of treatment A + T where diameter did not differ between debris treatments. A reciprocal regression model (R^2 = 0.55) predicted that total stem volume of Douglas-fir increased from 19 to 84 dm^3 ha^{-1} as Scotch broom cover decreased from 20% to 0% as a result of the logging debris and herbicide treatments. There were limited treatment effects on mineral soil chemical and physical properties, but forest floor mass and nutrient content were increased in the heavy debris treatment. Five years after forest harvesting (2016), logging debris mass in heavy debris differed little from that in light debris at study initiation, indicating a substantial reduction in fuels and the potential for severe wildfire. Results suggest that, on gravelly soils and possibly other droughty forest ecosystems in the Pacific Northwest, heavy debris will benefit planted Douglas-fir by improving growing conditions and by limiting abundance of nonnative competitors, such as Scotch broom.

1. Introduction

During forest harvesting and site preparation, machine traffic, logging debris treatments, and herbicide treatments are important vectors of disturbance that redistribute growth-limiting site resources (i.e., soil water and nutrients) among crop and non-crop species (Fig. 1). These vectors can be managed to limit abundance and manipulate species composition of competing vegetation. If vegetation abundance is managed at low levels (e.g., < 20% cover; Dinger and Rose, 2009), or if it is less competitive because of the species composition, additional resources can become available to the crop species (Davis et al., 1998). Site factors including soil texture and annual precipitation regulate how these resources are made available to existing vegetation and whether available resources are sufficient to maintain survival and increase growth of planted tree seedlings. Thus, vegetation management treatments are particularly critical on forest sites in the Pacific Northwest that are encumbered by annual summer droughts, as well as those with coarse-textured soils, because soil water is often the primary resource limiting early growth of planted conifers (Newton and Preest, 1988).

Controlling competing vegetation with herbicides or other treatments during forest regeneration provides a direct and rapid method for channeling resources to planted tree seedlings (Walstad and Kuch, 1987). Because of the assumed cost-effectiveness of vegetation control, treatments are often prescribed routinely and independent of the

Abbreviation: A + T, combination of aminopyralid and triclopyr herbicides in a single treatment

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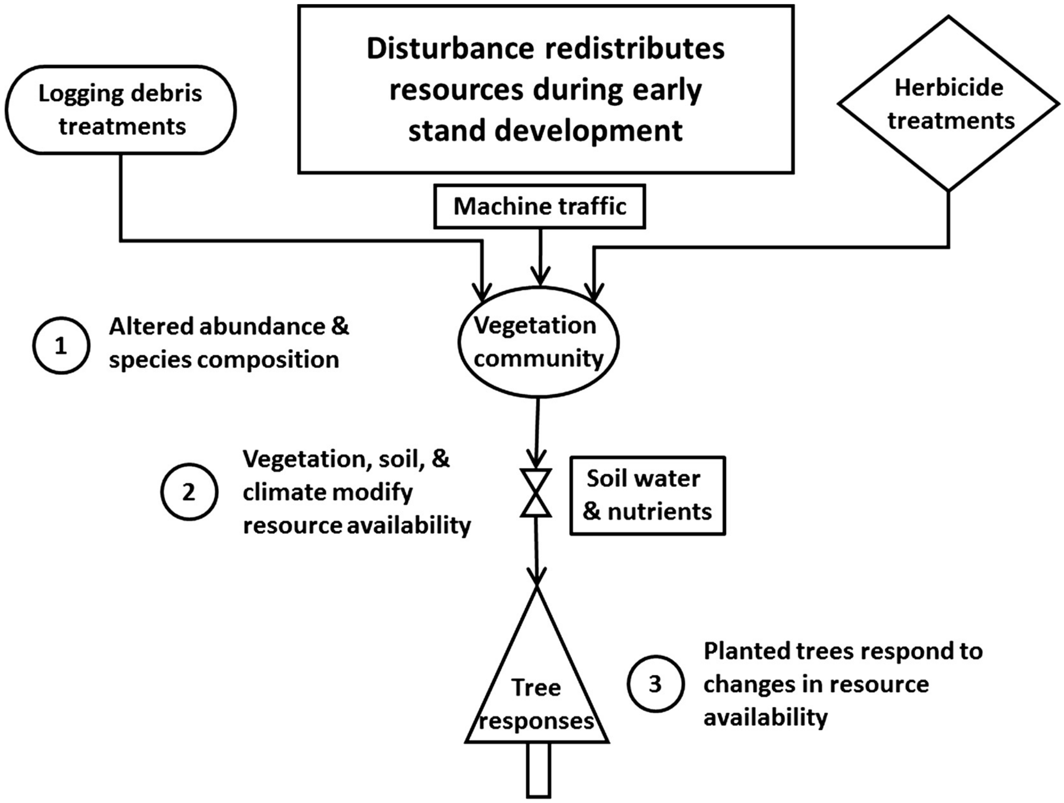

Fig. 1. Conceptual model of how disturbance redistributes growth-limiting resources to vegetation during early stand development. (1) Logging debris treatments, machine traffic, and herbicide treatments are common vectors of disturbance during forest harvesting and site preparation that can be managed to limit abundance and manipulate species composition of competing vegetation. (2) Site factors of soil texture and annual precipitation regulate how additional resources, especially soil water, are made available to planted conifers, (3) potentially enabling them to maintain their survival and increase their growth.

methods in which the previous stand was harvested. Yet the method and intensity of forest harvesting can have important consequences on subsequent development of the early seral plant community, depending on intensity and spatial extent of soil disturbance and the amount and configuration of residual logging debris. For example, removal of logging debris, and the soil disturbance associated with this activity, can stimulate invasions of nonnative plants, such as Scotch broom (*Cytisus scoparius* (L.) Link), oxeye daisy (*Leucanthemum vulgare* Lam.), and sweet vernalgrass (*Anthoxanthum odoratum* L.) (Harrington and Schoenholtz, 2010; Peter and Harrington, 2012; Peter and Harrington, 2018). These species, found throughout western Washington and Oregon, are both highly competitive and difficult to control because of their prolific regeneration. Therefore, the cost of effective vegetation control will likely depend on specific harvesting methods and their influence on the recalcitrance of the post-harvest plant community. An integrated approach is needed that jointly considers the objectives of forest harvesting and forest regeneration in a similar context to accomplish both activities without exacerbating costs of one activity over those of the other.

Retention of logging debris in a dispersed pattern during harvesting has the potential to limit harvesting and site preparation costs, reduce vegetation control costs, and improve forest productivity. For example, cut-to-length harvesting systems de-limb and process the logs at the stump, leaving behind the non-merchantable debris. Compared to conventional whole-tree harvesting via shovel logging (10–15 Mg ha^{-1} of logging debris mass), retention of logging debris by stem-only harvesting (20–25 Mg ha^{-1}) has been shown to decrease cover of herbaceous species and Scotch broom, increase soil water content, and increase accretion of soil carbon and nitrogen in western Washington and Oregon (Roberts et al., 2005; Harrington and Schoenholtz, 2010; Slesak et al., 2011; Harrington et al., 2013). These short-term changes in plant community structure and soil resource availability following logging debris retention have been associated with longer-term increases in forest productivity, including greater volume growth of coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) during the first 10–15 years after planting (Ares et al., 2007; Holub et al., 2013; Slesak et al., 2016; S. Holub, personal communication). In addition, logging debris tends to be a more significant source of organic matter for coarse textured soils (Wan et al., 2018) and wetter and cooler climates (Thiffault et al., 2011) than for the converse conditions. However, there are some potential real or perceived drawbacks to logging debris retention. In the North American Long-Term Soil Productivity (LTSP) study, retention of logging debris was associated with small decreases in tree survival attributable to increased difficulty of planting (Fleming et al., 2006). Retention of logging debris could also be less desirable to forest managers if it increases the cost of vegetation control treatments, provides habitat for small mammals that cause damage to planted tree seedlings (Sullivan and Sullivan, 2014), or increases risk of wildfire for a period after harvesting (Stephens et al., 2012). Quantifying the above benefits and drawbacks would be useful to determine if and when logging debris retention is an effective practice to decrease management costs and improve overall stand productivity.

To expand the knowledge base of our conceptual model (Fig. 1), we initiated research in 2011 to compare efficacy of logging debris and herbicide treatments for controlling competing vegetation and to determine if synergisms exist to increase regeneration performance when these treatments are combined. We selected a study site likely to be invaded by Scotch broom soon after forest harvesting to create a suitable test environment for our experimental treatments. The research had the following objectives: (1) quantify treatment effects on soil water, soil chemistry, and soil temperature, (2) compare performance of planted Douglas-fir among treatments, (3) describe competitive relationships between Douglas-fir performance and abundance of the primary competitor species, and (4) assess changes in plant community

Table 1
Selected soil chemical and physical properties (means followed by standard deviations in parentheses) of the forest floor and mineral soil to a depth of 30 cm at the Dry Bed Creek study site. All analyses were conducted in 2012.

Soil property	Estimate
Bulk density (Mg m^{-3})[a]	1.26 (0.22)
Coarse fragments (% of mass)	66 (5)
Soil texture (% sand/silt/clay)[b]	82/11/7
Forest floor mass (Mg ha^{-1})	26.6 (63.6)
Forest floor total carbon (%)	48.0 (2.2)
Forest floor total nitrogen (%)	1.1 (0.1)
Mineral soil total carbon (%)[c]	9.4 (2.3)
Mineral soil total nitrogen (%)[c]	0.3 (0.05)
Mineral soil phosphorus (mg kg^{-1})[d]	7 (4)
Mineral soil calcium (mg kg^{-1})[e]	179 (43)
Mineral soil magnesium (mg kg^{-1})[e]	40 (9)
Mineral soil potassium (mg kg^{-1})[e]	59 (10)

[a] Determined with the sand cone method (Blake and Hartge, 1986).
[b] Determined with the hydrometer method.
[c] Measured with dry combustion.
[d] Determined with the Bray method (Bray and Kurtz, 1945).
[e] Determined with Mehlich extraction (Mehlich, 1984).

structure following treatment (Peter and Harrington, 2018).

2. Materials and methods

2.1. Study site

The Dry Bed Creek study site, located about 2.6 km south-southwest of Matlock, WA, USA (47.215°N, 123.417°W), was identified as suitable for our study of logging debris and herbicide treatment effects on performance of planted Douglas-fir for the following two reasons. First, the pre-harvest Douglas-fir stand contained Scotch broom, indicating a high likelihood of soil-stored seed (Bossard, 1990) and subsequent rapid invasion by this highly competitive species soon after forest harvesting (Harrington and Schoenholtz, 2010). Scotch broom was likely introduced in 1996 during a salvage thinning of ice-storm damaged trees (Randall Greggs, personal communication). Second, the site has coarse-textured soils (Table 1) known to be extremely droughty during the summer months, thereby providing a treatment opportunity for improving growing conditions for planted conifer seedlings. The soils are very gravelly loamy sands of the Grove series (Dystric Xerorthent) formed in glacial outwash and averaging 1.5 m in depth (USDA NRCS, 2009) with relatively low amounts of nitrogen and moderately high amounts of phosphorus and extractable macronutrients. The dominant plant association is *Tsuga heterophylla* (Raf.) Sarg./*Gaultheria shallon* Pursh/*Xerophyllum tenax* (Pursh) Nutt. (Henderson et al., 1989). Long-term (1981–2010) average annual precipitation is 238 cm yr^{-1}, of which only 22% (52 cm) occurs during the growing season (April-September) (PRISM Climate Group (2017)).

2.2. Treatments and experimental design

The experimental design is a randomized complete block with six replications of eight treatments arranged as a split plot. In late summer 2011, prior to forest harvesting, we installed a total of 12 main plots, each 52 m × 36 m in dimension. The main plots were arranged as two columns of six plots, each of which were blocked according to distance from the main logging road because pre-harvest vegetation inventories indicated that abundance of Scotch broom decreased with distance from the main access road. From each pair of main plots from the adjacent columns, one plot was randomly assigned a "heavy" logging debris treatment (20–25 Mg ha^{-1}) and the other plot was assigned a "light" logging debris treatment (10–15 Mg ha^{-1}). Each main plot was then divided into four split plots, each 21 m × 18 m in dimension. Split plots were randomly assigned to receive one of the following four herbicide treatments: (1) aminopyralid (Milestone®) applied at a rate of 0.5 L ha^{-1} plus 0.25% Syl-Tac® surfactant, (2) triclopyr ester (Forestry Garlon® XRT) applied at a rate of 2.9 L ha^{-1} plus 2.5% SuperSpread® methylated seed oil, (3) the combination of the aminopyralid and triclopyr treatments (A + T), and (4) a non-sprayed control. A 10-m wide corridor designated for machine traffic ran through the center of each main plot, separating the split plots. This plot design allowed machine access on two sides of each of the 48 split plots for forest harvesting and application of the debris treatments.

An inventory of each of the 48 split plots, based on a circular 0.01-ha sample area at plot center, indicated the following average characteristics of the pre-harvest Douglas-fir stand: breast-height age, 58 years; dominant/co-dominant tree height, 35.2 m; stem density, 254 trees ha^{-1}; stand basal area, 37.6 m^2 ha^{-1} (based on 5-m^2 basal-area-factor prism counts); total stem volume, 442.1 m^3 ha^{-1} (Bruce and DeMars, 1974); site index$_{50\ year}$, 33.0 m (King, 1966); and total density of live and dead Scotch broom, 815 plants ha^{-1}. Greenhouse germination of 96 soil samples (0.1 m^2 area and 3 cm depth per sample; two samples per split plot) collected throughout the study site in October 2011 indicated an average minimum density of 9375 viable seeds ha^{-1} of Scotch broom.

Forest harvesting occurred in December 2011. Trees were felled, bucked, and de-limbed with chainsaws, and logs were extracted via a tracked loader that stayed on the designated machine trails; thus, individual split plots were kept free of soil disturbance from machine traffic. In January 2012, a tracked excavator fitted with a clamshell bucket, also operating from designated machine trails, moved the logging debris to create the two levels according to the treatment assigned to each main plot. Heavy and light debris levels were based on photographs of the stem-only and whole-tree harvest treatments, respectively, from the Matlock and Molalla LTSP studies (Harrington and Schoenholtz, 2010). The total cost for applying the logging debris treatments was \$645 (US) ha^{-1}. In February 2012, logging debris depth averaged 32 and 17 cm for heavy and light debris treatments, respectively, based on 21 systematically located points per split plot. Line-transect estimates of logging debris mass (Brown, 1974) conducted on each split plot in August 2012 indicated mean values of 18.9 and 9.0 Mg ha^{-1} for the heavy and light debris treatments, respectively. In December 2016, five years after forest harvesting, the same methods were used to estimate logging debris mass for the non-sprayed control split plots. Specific gravity values of logging debris for the > 0.6–2.5, > 2.5–7.6 cm and > 7.6 cm diameter classes for 2012 were those given in Brown (1974) for sound material (0.48, 0.40, and 0.40, respectively); whereas, those for 2016 were derived from collected samples (0.48, 0.40, and 0.29, respectively). A fractional loss rate (k, yr^{-1}) for total debris mass was calculated using the following equation (Olson, 1963):

$$k = -(\log_e(M_{2016}) - \log_e(M_{2012}))/t \quad (1)$$

where M_{2012} and M_{2016} are values of total debris mass per split plot in 2012 and 2016, respectively, and t = 4 years between measurements.

In August 2012, the herbicide treatments were applied to the previously assigned split plots with backpack sprayers calibrated for a spray volume of 94 L ha^{-1}. Douglas-fir seedlings (1 + 1 stocktype) from a local seed source were hand-planted with shovels on a 3- × 3-m grid in February 2013. Planters were allowed to deviate up to 30 cm from the grid point in order to find a suitable planting spot. To reduce animal damage, a Vexar® mesh tube (91 cm length × 10 cm width, Terra Tech LLC, Eugene, OR, USA) was installed over each Douglas-fir seedling. Immediately after planting and in the subsequent dormant seasons of 2014–2016, the following measurements were taken on each of 25 seedlings per split plot: stem diameter at 15 cm height (mm), total height (cm), and descriptive information on seedling vigor and damage.

A total of 24 soil water sensors (ECH$_2$0® model EC-20, Meter Group, Inc., Pullman, WA, USA) were installed at 5–25 cm depth in April 2012; shallow placement of each sensor was done to detect potential water-conserving (i.e., "mulching") effects of the logging debris (Roberts et al., 2005). Soil water sensors were installed in the following treatments: two debris levels (heavy and light) × two herbicide treatments (A + T and the non-sprayed control) × six replications. To be representative of debris treatment conditions, soil water sensors were randomly assigned to the following debris depth classes: 0–5 cm (eight sensors in light debris plots), 10–20 cm (four sensors each in heavy and light debris plots), and 25–35 cm (eight sensors in heavy debris plots). During the growing seasons of 2012–2016, soil water content was measured approximately every two weeks with a ProCheck® data recorder (Meter Group, Inc., Pullman, WA, USA). A soil temperature sensor (Thermochron® iButton® model DS1921G, Maxim Integrated Products, Inc., Sunnyvale, CA, USA) was placed in a PVC protector cap and installed in April 2012 at 5-cm depth near each soil water sensor. Each soil temperature sensor had the same debris depth class as the nearby soil water sensor. Soil temperature was logged every two hours, and these data were downloaded every 3 to 6 months. Annual precipitation data for Matlock, WA, located 2.6 km from the study site, were obtained from the National Centers for Environmental Information (NOAA NCEI, 2017; Peterson and Vose, 1997).

Soil samples were collected prior to forest harvesting (October 2011) and at the end of the experiment (December 2016) to assess treatment effects on chemical properties and bulk density. As with the soil moisture sensors, we limited our sampling to the A + T and non-sprayed control treatments to allow for assessment of logging debris and herbicide treatment effects. For each sample period, forest floor samples were collected at two locations in each plot using square frames with an area of 0.1 m^2, composited, and placed in sealed plastic bags for transport and storage. Mineral soil samples were collected at four locations approximately 7.5 m from plot center in each of the cardinal directions. Samples were collected at 0–15 and 15–30 cm depth increments and composited by depth for each plot. All mineral soil samples were air-dried, sieved to pass a 2-mm mesh, and archived prior to chemical analysis. Forest floor samples were dried at 65 °C and weighed to determine dry mass. The sample was then ground in a Wiley mill to a size of 2 mm and archived. Bulk density was estimated in the non-sprayed control plots in October 2011 and December 2016 using the sand cone method (Blake and Hartge, 1986).

Pre- and post-treatment samples were analyzed at the same time to account for any analytical errors associated with method, processing, and analytical machine. For forest floor and mineral soil samples, total soil carbon and nitrogen were measured on a 1-g pulverized subsample with dry combustion using a LECO Dumas combustion technique on a Fisons NA1500 NCS Elemental Analyzer (ThermoQuest Italia, Milan, Italy). Available soil phosphorus and extractable macronutrients were only analyzed on mineral soil samples. Available soil phosphorus was estimated using the Bray extraction method followed by calorimetric estimation of phosphorus concentrations on a spectrophotometer (Spectronic 20 Genesys, Model 4001, Thermo Electron Corporation, Waltham, MA, USA) (Bray and Kurtz, 1945). The Mehlich method (Mehlich, 1984) was used to extract soil calcium, magnesium, and potassium, and extract concentrations were measured with inductively coupled plasma spectroscopy (Varian Vista MPX, Varian, Palo Alto, CA, USA). All estimates are reported on an oven dry (105 °C) basis.

2.3. Statistical analyses

All statistical analyses were performed in SAS software version 9.4 (SAS Institute, Inc, 2013) with a significance level of $\alpha = 0.05$. Values of logging debris mass estimated in the first and fifth years after forest harvesting for non-sprayed control split plots were subjected to a repeated-measures, mixed-model analysis of variance (ANOVA) in Proc Mixed with random effects for blocks and fixed effects for logging debris treatment and year. Likewise, the fractional loss rate (k) in total debris mass was subjected to ANOVA with random effects for blocks and fixed effects for logging debris treatment. The soil temperature data from designated split plots were averaged first by day and then by month. For each of the five years of the study (2012–2016), monthly means of soil temperature were subjected to a repeated-measures, mixed-model ANOVA in Proc Mixed with random effects for blocks and fixed effects for logging debris treatment, herbicide treatment, month, and their interactions. Likewise, for each growing season, biweekly measurements of soil water content were subjected to a repeated-measures, mixed-model ANOVA in Proc Mixed. The maximum value of soil water content observed for each split plot was used as a covariate when significant ($P < 0.1$) to adjust each soil water ANOVA for variability among microsites. A first-order autoregressive covariance structure was used to adjust each repeated measures ANOVA for serial correlation. Given the presence of a significant treatment-by-timing interaction, slicing was performed to identify individual timings within each year in which soil temperature or soil water content differed among the debris and herbicide treatments. To assess the relative effects of logging debris depth on soil temperature and soil water content, ANOVA was repeated for data from each year after replacing the class variable for debris treatment with that for debris depth class.

Effects of treatment on the change in soil chemistry were assessed using the same approach as described above, except that time effects were not included in the models and pretreatment values were used as covariates. Absolute change in soil parameters was used as the primary response variable which was calculated as the difference between pretreatment and post-treatment values, where positive values indicate gains and negative values indicate reductions. After initial assessment, we decided to analyze and present mineral soil properties for the combined 0–30 cm depth using the arithmetic mean of the two depth increments because trends and conclusions did not differ when evaluating depth increments separately. When significant treatment effects were detected, multiple comparisons were performed to assess differences among treatment means using Bonferroni probabilities to control the Type I error rate (Quinn and Keough, 2002).

Values of Douglas-fir survival, stem diameter, total height, and incidence of chlorosis were averaged by year and split plot. Stem volume of each surviving seedling was calculated with a parabolic equation and values were summed by split plot to provide an index of total stem volume. Each Douglas-fir variable was subjected to a repeated-measures, mixed model ANOVA with random effects for blocks and fixed effects for logging debris treatment, herbicide treatment, year, and their interactions. As done for the microclimate data analyses, slicing was performed to identify years in which a Douglas-fir response variable differed among treatments. Multiple comparisons of Douglas-fir treatment means were conducted using Bonferroni probabilities to control the Type I error rate. Prior to ANOVA, an angular transformation (arcsine, square-root) was applied to proportionate values of soil water content, Douglas-fir survival, and Douglas-fir chlorosis incidence, and a logarithmic transformation was applied to logging debris mass and each Douglas-fir growth variable to homogenize the residual variances (Sokal and Rohlf, 1981). Residuals for each dependent variable were plotted against predicted values to confirm the homogeneity of the residual variances.

Using split-plot means ($n = 48$) from the last year of the study (2016), linear and non-linear regression analyses were conducted to describe relationships of Douglas-fir total volume to cover of the primary competitor species. Peter and Harrington, 2018 visually estimated percentage of canopy cover (0–100%) for each vascular species within a 0.01-ha circular subplot (r = 5.64 m) centered within each split plot using the methods described in Henderson et al. (1989). A given competitor species was selected for modeling if Douglas-fir total volume had a significant negative correlation with that species' cover.

3. Results

3.1. Logging debris mass

Logging debris consisted almost entirely of branches and non-merchantable tops less than 12.7 cm in diameter and less than 3.7 m in length, very few large pieces were left because of defects, and legacy wood was sparse or absent. Mass of logging debris in non-sprayed split plots varied according to the main effects of debris treatment ($P = 0.015$) and year ($P = 0.001$), but the debris-by-year interaction was not significant ($P = 0.975$). This finding indicates that the four-year changes in logging debris mass were independent of debris treatment. Similarly, fractional loss rates (k) did not differ statistically between the heavy and light debris treatments (0.133 and 0.148 yr^{-1}, respectively; $P = 0.838$). From 2012 to 2016, logging debris mass on non-sprayed control split plots decreased from 20.3 to 10.8 Mg ha^{-1} in the heavy debris treatment and from 8.6 to 4.2 Mg ha^{-1} in the light debris treatment – a loss of about half of the total mass in each treatment. Note that, by 2016, mass in the heavy debris treatment (10.8 Mg ha^{-1}, std. error = 2.2) had declined to a value that did not differ statistically from that in the light debris treatment in 2012 (8.6 Mg ha^{-1}, std. error = 1.8).

3.2. Microclimate

Annual precipitation was 276, 174, 254, 243, and 269 cm in 2012, 2013, 2014, 2015, and 2016, respectively; whereas, growing-season (April-September) precipitation was 44, 75, 58, 33, and 30 cm, respectively (Fig. 2a). Note that, although 2013 had the lowest annual precipitation, it had the highest growing season precipitation. The growing seasons of 2015 and 2016 were extraordinarily dry, given their low precipitation values.

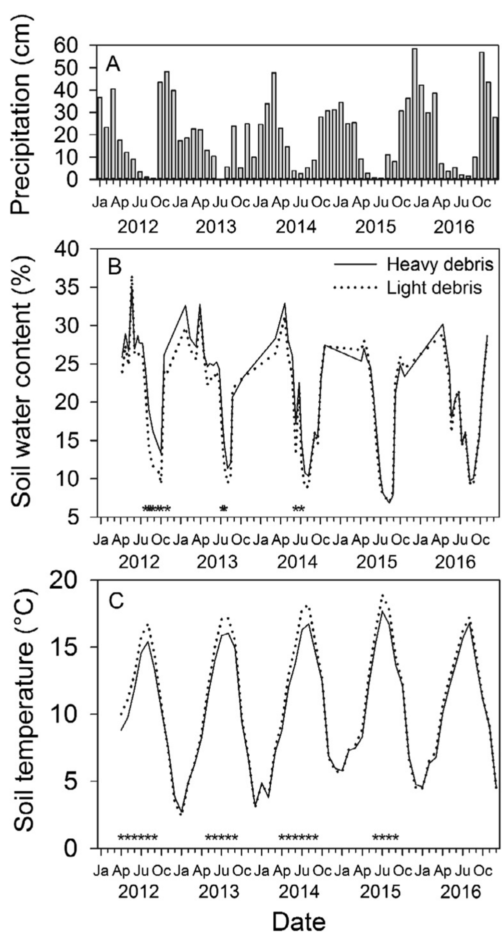

Fig. 2. Microclimate variables of: (a) monthly precipitation, (b) soil volumetric water content at 5–25 cm depth, and (c) soil temperature at 5 cm depth during five years after application of logging debris treatments in January 2012. Asterisks indicate timings in which soil water content or soil temperature differed between logging debris treatments.

In the growing seasons of 2012–2014, soil water content varied as a result of the interaction of logging debris treatment and year ($P < 0.002$). In 2012, soil water content averaged 3–5 percentage points greater under heavy debris than under light debris from early August to mid-October (Fig. 2b). Similar responses were observed in the growing seasons of 2013 and 2014 but for shorter durations. Soil water content did not differ significantly between debris treatments in 2015 and 2016. In 2012 and 2013, the interaction of herbicide treatment and year was marginally significant for soil water content ($P = 0.058$ and 0.064, respectively). In September and October 2012, soon after application of the herbicide treatments, and in August 2013, soil water content averaged 2 percentage points higher in the aminopyralid + triclopyr (A + T) treatment than in the non-sprayed control (data not shown). During the driest periods of 2012, 2013, and 2014, soil water content was greater for the 25–35 cm debris depth class (14–19%) than for either of the 0–5 or 10–20 cm depth classes (10–14%) (data not shown).

Soil temperature varied as a result of the interaction of logging debris treatment and month during the years of 2012–2015 ($P < 0.001$). During late spring and throughout the summer of these years, soil temperature was 0.5–1.5 °C cooler under heavy debris than under light debris (Fig. 2c). In 2016, soil temperature did not differ between debris treatments ($P > 0.095$). There was no detectable effect of the herbicide treatments on soil temperature ($P > 0.334$). During the warmest periods of 2012–2015, soil temperature was lower for the 10–20 and 25–35 cm debris depth classes (14–18 °C) than for the 0–5 cm depth class (16–20 °C) (data not shown).

3.3. Soil properties

Effects of treatment on soil chemical properties generally were not significant, with the exception of a main effect of herbicide treatment on the change in extractable potassium ($P = 0.017$). In that instance, the change in potassium concentration was positive and significantly greater (i.e., an absolute increase over time) in the non-sprayed control than in the A + T treatment which showed little change over time (estimated difference between treatments of 23 ± 8 mg kg^{-1}). Extractable magnesium and calcium were also higher (non-significant) in the non-sprayed control than in the A + T treatment, and the heavy debris treatment had consistently higher positive change in extractable macronutrients than the light debris treatment. There was no effect of treatment on carbon and nutrient concentrations in the forest floor (data not shown), but the change in total mass was positive and significantly greater in the heavy debris treatment than in the light debris treatment ($P = 0.004$) with an estimated difference of 11.3 ± 1.9 Mg ha^{-1} between the two treatments. The change in bulk density also did not differ significantly between debris treatments ($P = 0.157$), but bulk density declined significantly in the light debris treatment by 0.18 Mg m^{-3} (95% confidence limit: 0.02 to 0.34 Mg m^{-3}).

3.4. Douglas-fir performance

Despite the obstacles presented by the heavy debris treatment, tree planters were able to plant a Douglas-fir seedling within 30 cm of each grid point on the split plots. Overall, regeneration performance of Douglas-fir was greater in heavy debris than in light debris. The one exception was in the A + T treatment where regeneration performance did not differ between debris levels (described below). Douglas-fir chlorosis varied according to the three-way interaction of logging debris treatment, herbicide treatment, and year ($P = 0.039$; Table 2). In the first year after planting (2013), incidences of chlorosis for seedlings growing in light debris in the non-sprayed control (14% of seedlings), triclopyr (14%), and aminopyralid (13%) treatments were greater than that for seedlings growing in heavy debris in the triclopyr treatment (1%). In 2014, incidence of chlorosis for seedlings in the light debris/

Table 2
F-statistic probabilities from the analysis of variance for variables of Douglas-fir performance during four years after application of logging debris and herbicide treatments. Bold text indicates variables for which a given source of variation is significant at $P \le 0.05$.

Source of variation	df[a] N	df[a] D	Dependent variable: Chlorosis	Survival	Stem diameter	Height	Total volume
			Probability > *F*				
Logging debris (D)	1	5	**0.045**	**0.020**	**0.003**	**0.003**	**0.005**
Herbicide (H)	3	29	0.083	0.436	0.079	0.641	0.197
D × H	3	29	0.642	0.930	0.183	0.282	0.480
Year (Y)	3	119	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**
D × Y	3	119	**0.001**	0.480	**0.001**	**0.001**	**0.001**
H × Y	9	119	0.172	0.342	**0.028**	0.148	0.074
D × H × Y	9	119	**0.039**	0.787	**0.021**	0.364	0.330
Covariate[b]	1	119	–	–	**0.001**	**0.001**	0.086

[a] df = degrees of freedom for the numerator (N) and denominator (D) of the *F* test.
[b] When significant at $P \le 0.1$, initial (2012) values of each seedling growth variable were used to adjust the ANOVA for potential variation that existed at the time of planting.

non-sprayed control (8%) was greater than that for each of the heavy debris and herbicide treatment combinations (0.0–0.1%). Chlorosis incidences in 2015 (1–5%) and 2016 (0–2%) did not differ statistically among treatments.

Survival of Douglas-fir seedlings varied according to the main effects of logging debris treatment ($P = 0.020$; Table 2). Averaged across the four growing seasons (2013–2016), survival in heavy debris (74%) was eight percentage points greater than in light debris (66%). The vast majority of the seedling mortality occurred in 2015 – a year of exceptionally low growing-season precipitation (Fig. 3a). By 2016, Douglas-fir survival averaged 37% and 26% in the heavy and light debris treatments, respectively.

The three-way interaction of logging debris treatment, herbicide treatment, and year was significant for Douglas-fir stem diameter ($P = 0.021$; Table 2). Beginning in 2014, stem diameter of seedlings growing in herbicide treatments with heavy debris began to diverge from that of seedlings growing in those with light debris with the exception of the A + T treatment (Fig. 3b). For the study duration, stem diameter in the A + T treatment did not differ between the heavy and light debris levels. In 2015 and 2016, values of stem diameter in the light debris/A + T treatment and in each herbicide treatment with heavy debris were greater than that in the light debris/non-sprayed control.

Douglas-fir height varied according to the interaction of logging debris treatment and year ($P = 0.001$; Table 2). From 2014 to 2016, height of seedlings growing in heavy debris averaged 11–14 cm greater than that of seedlings growing in light debris (Fig. 3c). Douglas-fir total volume also had a significant interaction between logging debris treatment and year ($P = 0.001$; Table 2). Total volume of seedlings growing in heavy debris was 42%, 47%, and 60% greater than that of seedlings growing in light debris in 2014, 2015, and 2016, respectively. Development of total volume accelerated in 2014 and then declined in 2015 because of mortality losses associated with the extreme summer drought (Fig. 3d). In 2016, total volume rebounded for seedlings growing in heavy debris while it stayed relatively constant for those growing in light debris.

Douglas-fir total volume was significantly correlated with cover of two competitor species: Scotch broom ($r = -0.52$, $P < 0.001$) and sweet vernalgrass ($r = -0.39$, $P = 0.007$). Scatterplots indicated the presence of a reciprocal relationship for Scotch broom and a negative linear relationship for sweet vernalgrass. The following function was fitted simultaneously to both competitor species in Proc NLIN:

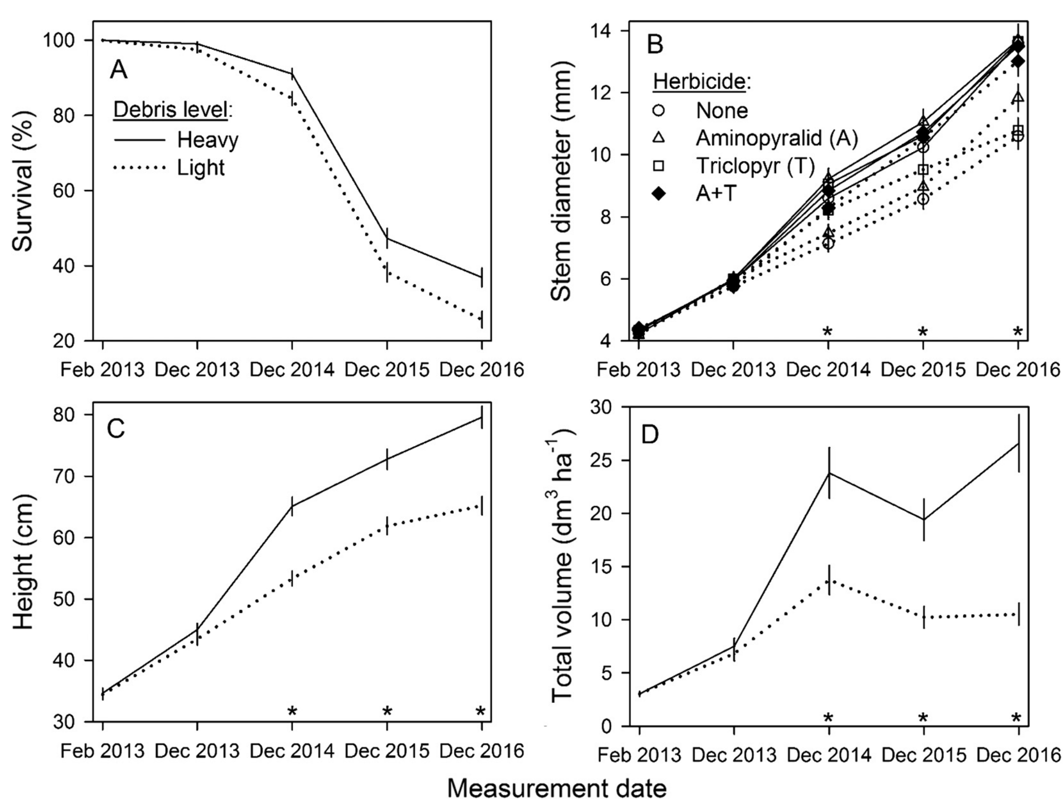

Fig. 3. Average (a) survival, (b) stem diameter, (c) height, and (d) total stem volume (± standard errors) of planted Douglas-fir after application of logging debris and herbicide treatments. Douglas-fir seedlings were planted in February 2013. Asterisks indicate years in which response variables differed among the logging debris and herbicide treatments (exception: survival differed according to the main effects of the logging debris treatment).

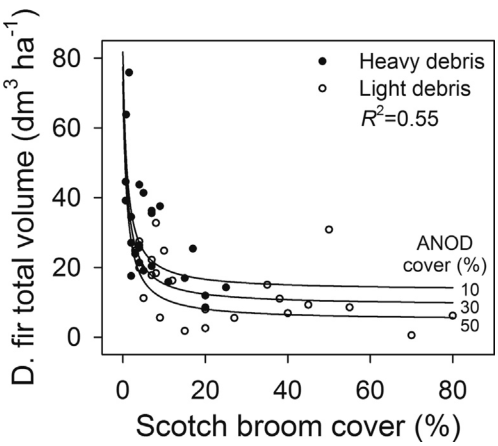

Fig. 4. Competition threshold relationships of Douglas-fir total stem volume to covers of Scotch broom and sweet vernalgrass (ANOD; *Anthoxanthum odoratum*) in 2016, five and four years after application of logging debris and herbicide treatments, respectively.

$$TV = 15.5 - 0.214(ANOD) + 68.4(1/(CYSC + 1)) \quad (2)$$

where TV is Douglas-fir total volume ($dm^3\,ha^{-1}$), ANOD is cover (%) of sweet vernalgrass, and CYSC is cover of Scotch broom. The model had a root mean-squared error of 10.4, a sample size of 48, and an estimated coefficient of determination (R^2) of 0.55, derived from the regression of predicted total volume versus observed total volume. In the absence of sweet vernalgrass, the fitted model (2) predicts a fourfold increase in Douglas-fir total volume as Scotch broom cover varies from 20% to 0% because of the logging debris and herbicide treatments (Fig. 4). Given a Scotch broom cover of 20%, the model predicts a twofold increase in Douglas-fir total volume as sweet vernalgrass cover varies from 50% to 10% as a result of the treatments. The relationship with Scotch broom is clearly a competition threshold because as Scotch broom cover decreased from 80% to 20% in the absence of sweet vernalgrass, the model predicts only a 15% increase in Douglas-fir total volume. Note that, with the exception of a single split plot, Scotch broom cover in the heavy debris split plots did not exceed 20%, whereas it was up to 80% in the light debris split plots. The outlier in Fig. 4 (50% cover of Scotch broom and 31 $dm^3\,ha^{-1}$ total volume of Douglas-fir) came from a split plot that had 15% cover of sweet vernalgrass. Other split plots having similar abundance of broom (40–55%) but considerably lower total volume of Douglas-fir (7–9 $dm^3\,ha^{-1}$) also had higher abundances of sweet vernalgrass (30–40%).

4. Discussion

4.1. Logging debris mass

In the five years since forest harvesting, each of the logging debris treatments lost about half of its mass, yet values continued to differ strongly between the two treatments. Fractional loss rates (0.133–0.148 yr^{-1}) were within the range of values reported for Douglas-fir logging debris during 2–5 years after forest harvesting (0.006–0.205 yr^{-1}; Edmonds et al., 1986). Because mass in the heavy debris treatment in 2016 differed little from that initially present in the light debris treatment in 2012, perceived increases in wildfire risk in the heavy debris treatment lasted for about 5 years after forest harvesting. Since cessation of burning by Native Americans in the mid-1800 s, fire return intervals at Joint Military Base Lewis-McChord (near Tacoma, WA) have been estimated to range from 12 to 91 years, with an average of 38 years (Peter and Harrington, 2014). Therefore, it appears that a five-year increase in wildfire risk from a heavy debris treatment would be outweighed by the benefits the debris provides to forest regeneration, including increased survival and growth of planted seedlings and decreased abundance of aggressive, nonnative competitors such as Scotch broom and sweet vernalgrass (Peter and Harrington, 2018).

4.2. Microclimate

The heavy debris treatment modified microclimate to conserve soil water and decrease soil temperature. Similar short-term increases in soil water from logging debris, usually near the soil surface, have been observed in previous research (O'Connell et al., 2004, Roberts et al., 2005, Harrington et al., 2013). These increases in soil water have been attributed to reductions in evaporation and soil temperature (Devine and Harrington, 2007). However, the recovering vegetation community and severe summer droughts worked together to diminish differences in microclimate between the two debris levels such that they were no longer statistically detectable for soil water content by the fourth year (2015) and for soil temperature by the fifth year (2016). Note that the temperature reductions from heavy debris (0.5–1.5 °C) were adequate to limit germination of Scotch broom based on laboratory experiments (Harrington, 2009). Other factors associated with the debris treatments, such as reduced light intensity and modified light quality, probably also regulated Scotch broom germination to a point that seedling density varied eightfold between debris treatments by the fourth year of the study (Peter and Harrington, 2018). Note that to fully reap the benefits of logging debris retention, including increased soil water, reduced soil temperature, and reduced abundance of competing vegetation, Douglas-fir seedlings should be planted as soon after forest harvesting as possible.

4.3. Soil properties

The lack of significant treatment effects on the change in soil carbon and nutrient concentrations suggests a limited influence of available nutrients on the response of Douglas-fir to the treatments. Other factors, such as soil water and soil temperature, had a greater influence on regeneration performance of Douglas-fir. However, changes were consistently higher and positive with greater debris retention and absence of herbicides. Both of these practices influence processes that control nutrient dynamics following forest harvesting including mobilization, uptake, and leaching (Vitousek and Matson, 1985; Smethurst and Nambiar, 1995; Slesak et al., 2009), generally resulting in greater retention than observed after debris removal and annual vegetation control with herbicides. At the nearby Matlock LTSP study with similar soils to the Dry Bed Creek study, Slesak et al. (2016) observed similar responses in which soil nutrient pools were increased 10 years after application of heavy debris and initial (first-year) vegetation control treatments. In the current study we expected that nutrient retention would have been greater in heavy debris than in light debris, but apparently it was not in sufficient quantities to cause a detectable change in mineral soil pools. Although Scotch broom is capable of fixing up to 111 $kg\,ha^{-1}$ of nitrogen per year in aboveground tissues and returning 17 $kg\,N\,ha^{-1}$ per year to the soil as leaf and stem litterfall (Watt et al., 2003), the species did not achieve levels of cover that were measurable or that differed between debris treatments until the last year of the study (Peter and Harrington, 2018).

The significant increase in forest floor mass with the heavy debris treatment is almost assuredly associated with greater inputs from the logging debris in that treatment. Although there was no effect of logging debris treatment on nutrient concentrations, the absolute mass of nutrients present in the forest floor is much higher in the heavy debris treatment than in the light debris treatment. For example, the increase in nitrogen associated with an 11.3 $Mg\,ha^{-1}$ increase in forest floor mass is approximately 140 $kg\,ha^{-1}$. These increases in nitrogen and other nutrients in forest floor pools may have positive effects on Douglas-fir growth following crown closure when nutrient demand increases (Cole and Gessel, 1992). Thus, a longer-term positive growth response to debris retention is possible.

4.4. Douglas-fir performance

In this study, retention of logging debris was associated with increased survival and growth of Douglas-fir during four years after planting. These responses were observed in a Mediterranean climate on a droughty glacial outwash soil subject to regular summer droughts of varying intensity, as well as competition from several aggressive, nonnative plant species. As discussed below, the planted seedlings responded to improved growing conditions in heavy debris attributable to a combination of increased soil water conservation and decreased competitor abundance. Similar facilitative benefits of logging debris on conifer seedling establishment have been reported for a wide variety of forest ecosystems, including lodgepole pine (*Pinus contorta* Douglas ex Loudon) in central British Columbia (Wei et al., 2012), Norway spruce (*Picea abies* (L.) Karst.) in southern Sweden (Jacobson et al., 2017), and maritime pine (*Pinus pinaster* Aiton) in southeastern Spain (Castro et al., 2011; Marañón-Jiménez et al., 2013). In these studies, short-term (< 5 years) conifer seedling responses were associated with an improved microclimate from shading and mulching effects of the debris and reduced abundance of competing vegetation; whereas, longer-term (> 10 years) responses were associated with addition of nitrogen and other nutrients to the soil as the debris decomposed.

In the first year after planting (2013), higher incidence of Douglas-fir chlorosis was associated with the light debris treatment – specifically for seedlings in the non-sprayed control, aminopyralid, and triclopyr treatments. However, chlorosis incidence in the A + T treatment did not differ between the two debris levels. This finding indicates a compensatory response to the most intensive herbicide treatment, resulting in the same level of tree vigor regardless of debris level. Marginally-significant increases in soil water content from the A + T treatment in 2013 likely played a role in decreasing Douglas-fir chlorosis in the light debris treatment.

Similar to findings for Douglas-fir chlorosis, stem diameter also demonstrated a compensatory response to the A + T treatment that resulted in similar seedling growth regardless of debris level. But for the other herbicide treatments, stem diameter continued to diverge between the heavy and light debris treatments. Once again, higher soil water content in the heavy debris treatment likely stimulated increases in seedling growth. While the heavy debris treatment, by itself, helped to conserve soil water, the species composition of the resulting vegetation community likely also played a role. For example, dominant species in the heavy debris treatment included the native shrubs, trailing blackberry (*Rubus ursinus* Cham. & Schltdl.) and trailing snowberry (*Symphoricarpos hesperius* G.N. Jones); whereas, non-native grasses (e.g., sweet vernalgrass and colonial bentgrass (*Agrostis capillaris* L.) and Scotch broom were dominant species in the light debris treatment (Peter and Harrington, 2018). Soil water depletion would be expected to vary in magnitude and possibly timing between these two widely different plant communities. Divergence in Douglas-fir stem diameter among treatments was greatest in 2014 when cover of sweet vernalgrass averaged 23% and 8% in the light and heavy debris treatments, respectively; whereas, cover of Scotch broom was only 2% and 1%, respectively (Peter and Harrington, 2018).

The severe drought of summer 2015 was a turning point in the study in which Douglas-fir survival declined an average of 45 percentage points for the two logging debris treatments, resulting in an overall reduction in Douglas-fir total volume. While it is difficult to predict the course of the study in the absence of this catastrophic outcome, it is clear that the heavy debris treatment lessened the impacts of the drought while it kept Scotch broom cover below 20% (with the exception of a single split plot having cover of 25%; Fig. 4). For example, in 2016 – another year of low growing season precipitation (30 cm) – Douglas-fir total volume rebounded in the heavy debris treatment; whereas, it did not change in the light debris treatment.

Two plant species were identified as the primary competitors with Douglas-fir in this study: Scotch broom and sweet vernalgrass. Scotch broom cover developed slowly during the first three years after forest harvesting, averaging only 1% in 2014 (Peter and Harrington, 2018). However, two years later Scotch broom cover averaged 7% in heavy debris and 24% in light debris – a treatment difference almost identical to that observed for the heavy (stem-only harvesting) and light (whole-tree harvesting) debris treatments in the nearby Matlock LTSP study (Harrington and Schoenholtz, 2010). The inverse relationship observed between Douglas-fir total volume and Scotch broom cover in 2016 indicates a competition threshold in which volume increased very little as Scotch broom cover varied from 80% to 20%, but it increased fourfold as Scotch broom cover decreased from 20% to 0%. The negative linear relationship of Douglas-fir total volume to sweet vernalgrass cover indicates smaller and proportionate reductions in Douglas-fir performance with increasing abundance of this grass species. This competition threshold relationship likely resulted from combined effects of a substantial seed bank of Scotch broom (> 9000 seeds ha^{-1}), which stimulated rapid development of cover, and the episodic mortality of Douglas-fir associated with the 2015 and 2016 growing seasons. Had the study occurred on a different site having a smaller Scotch broom seed bank and a milder series of growing seasons, it is unlikely we would have observed such a steep inverse relationship between Douglas-fir total volume and Scotch broom cover.

5. Conclusions

This research has highlighted the benefits to Douglas-fir regeneration of retaining logging debris after forest harvesting. The heavy debris treatment did not restrict planting of Douglas-fir at the study site and it had a finite period of increased wildfire risk that was estimated to last about 5 years. By modifying microclimate and plant community structure, heavy debris improved survival, vigor, and growth of the planted Douglas-fir seedlings. These benefits were observed on a coarse-textured, droughty soil subject to periodic summer droughts and severe competition from an aggressive nonnative shrub, Scotch broom.

Research results suggest there is a need to consider how the intensity of organic matter removal and soil disturbance associated with forest harvesting increases the recalcitrance of the recovering plant community and thereby diminishes potential regeneration success. A coordinated system of forest harvesting and site preparation could prevent development of nonnative plant communities that are especially difficult to manage for conifer regeneration. Further research is needed to identify other regions of the Pacific Northwest and elsewhere in which logging debris retention can be used to improve forest regeneration.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2018.02.042.

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