Effects of logging debris treatments on five-year development of competing vegetation and planted Douglas-fir

Timothy B. Harrington and Stephen H. Schoenholtz

Abstract: Although considerable research has focused on the influences of logging debris treatments on soil and forest regeneration responses, few studies have identified whether debris effects are mediated by associated changes in competing vegetation abundance. At sites near Matlock, Washington, and Molalla, Oregon, studies were initiated after timber harvest to quantify the effects of three logging debris treatments (dispersed, piled, or removed) on the development of competing vegetation and planted Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*). Each debris treatment was replicated with initial and annual vegetation control treatments, resulting in high and low vegetation abundances, respectively. This experimental design enabled debris effects on regeneration to be separated into effects mediated by vegetation abundance and those independent of vegetation abundance. Two to three years after treatment, covers of Scotch broom (*Cytisus scoparius* (L.) Link) at Matlock and trailing blackberry (*Rubus ursinus* Cham. & Schltdl.) at Molalla were over 20% greater where debris was piled than where it was dispersed. Debris effects on vegetation abundance were associated with 30% reductions in the survival of Douglas-fir at Matlock (r^2 = 0.62) and the stem diameter at Molalla (r^2 = 0.39). Douglas-fir survival and growth did not differ among debris treatments when effects were evaluated independent of vegetation abundance (i.e., with annual vegetation control), suggesting negligible short-term effects of debris manipulation on soil productivity.

Résumé : Bien qu'un nombre considérable de travaux de recherche aient mis l'accent sur l'influence que les traitements des déchets de coupe exercent sur les sols et les réactions de la régénération forestière, peu d'études ont déterminé si les effets des déchets de coupe sont le fait de changements dans l'abondance de la végétation compétitrice associés au traitement de ces déchets. Dans des stations situées à proximité de Matlock, Washington, et Molalla, Oregon, des études ont été entreprises à la suite d'opérations de récolte pour quantifier les effets de trois traitements des déchets de coupe (dispersés, empilés ou enlevés) sur le développement de la végétation compétitrice et du douglas de Menzies typique (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) en plantation. Chaque traitement des déchets de coupe a été répété en y ajoutant un traitement initial ou annuel de maîtrise de la végétation compétitrice, ce qui a entraîné une abondance respectivement élevée ou faible de la végétation. Ce plan d'expérience a permis de distinguer deux types d'effets des déchets de coupe sur la régénération : ceux qui dépendent de l'abondance de la végétation et ceux qui sont indépendants de l'abondance de la végétation. Deux à trois ans après les traitements, le couvert de genêt à balais (*Cytisus scoparius* (L.) Link) à Matlock et de ronce sauvage (*Rubus ursinus* Cham. & Schltdl.) à Molalla était 20 % plus élevé aux endroits où les déchets de coupe avaient été empilés plutôt que dispersés. Les effets des déchets de coupe sur l'abondance de la végétation étaient associés à des réductions de 30 % de la survie à Matlock (r^2 = 0,62) et du diamètre de la tige du douglas de Menzies à Molalla (r^2 = 0,39). La survie et la croissance du douglas de Menzies étaient la même peu importe le traitement des déchets de coupe lorsque les effets étaient évalués indépendamment de l'abondance de la végétation (c.-à-d. avec la maîtrise annuelle de la végétation), ce qui indique que les effets à court terme du traitement des déchets de coupe sur la productivité du sol sont négligeables.

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Introduction

Residual woody debris is an important feature of the environment affecting forest regeneration after a disturbance, such as timber harvest. Among the observed effects of woody debris on microclimate are decreased summer temperatures of soil surface layers by shading and insulation (Proe et al. 2001; Devine and Harrington 2007), increased maximum air temperatures from reduced surface air movement and increased convective heating (Lopushinsky et al. 1992; Zabowski et al. 2000), and increased conservation of soil water through reduced exposure and mulching (O'Connell et al. 2004; Roberts et al. 2005). Woody debris also acts as a physical barrier that intercepts rainfall (Swank et al. 1972) and thereby reduces soil erosion (Hartanto et al. 2003). Such changes in microclimate influence a broad range of soil and plant processes, including mineralization of soil nutrients, plant water use, and shoot and root growth.

Woody debris can influence forest regeneration through changes in the plant community. The presence of woody debris creates conditions that select for plant species that germinate and survive on organic residues (Harmon and Franklin 1989; Kennedy and Quinn 2001; Shields et al. 2007). The removal of woody debris favors species that establish on exposed forest floor or mineral soil via wind-dispersed or stored seeds (Peterson and Leach 2008). Additionally, woody debris can have a suppressive mulching effect on postdisturbance recovery of vegetation (Law and Kolb 2007), and it can provide habitat conducive to rodents that forage on tree seedlings (Hacker and Coblentz 1993) and thereby reduce seedling growth (Lopushinsky et al. 1992).

The potential effects of organic matter removal and soil compaction on soil productivity have been the focus of considerable research (e.g., the North American Long-Term Soil Productivity (LTSP) Experiment (Powers et al. 2005)). For a variety of forest ecosystems, greater rates of soil nitrate leaching have been observed during the first 2 to 3 years after timber harvest where woody debris was retained versus removed (Hendrickson et al. 1989; Smethurst and Nambiar 1990*a*; Strahm et al. 2005). Despite these higher rates of leaching, total carbon and nitrogen pools on forest sites throughout North America and Europe did not differ between retention and removal of woody debris for up to 16 years after treatment (Olsson et al. 1996; Carter et al. 2002; Sanchez et al. 2006). In general, the survival and growth of planted tree seedlings early in stand development has differed little between retention and removal of woody debris (Smethurst and Nambiar 1990*b*; Zabowski et al. 2000; Fleming et al. 2006).

Although management treatments, such as removing, piling, or burning of woody debris, are practiced routinely throughout the world for site preparation after timber harvest, limited research has attempted to separate the effects of debris treatments on forest regeneration into effects mediated by vegetation abundance versus those independent of competing vegetation abundance (Morris and Lowery 1988; Powers et al. 2005). In many of the LTSP studies, the presence and absence of a vegetation control was included as a split-plot treatment to test main-plot effects of organic matter removal and soil compaction independent of competing vegetation abundance (Fleming et al. 2006). However, few LTSP studies have identified the responses of forest regeneration to organic matter and soil compaction treatments that were mediated by associated changes in competing vegetation abundance (Powers and Fiddler 1997), either because such responses were uncommon or because the studies did not specifically test for these associations.

The research objective of this study was to quantify the effects of dispersing, piling, or removing logging debris on the five-year survival and growth of planted Douglas-fir seedlings. Each treatment was replicated with an initial and an annual vegetation control to enable debris effects to be partitioned into those mediated by versus those independent of vegetation abundance, respectively. The research tested the hypothesis that Douglas-fir responses to manipulations of logging debris were manifested indirectly through the effects of the debris treatments on competing vegetation abundance.

Methods

Study sites

Replicated studies were installed on each of two sites that differ in soil texture and annual precipitation (Table 1). The first site, located on the Olympic Peninsula 8 km northwest of Matlock, Washington, has a very gravelly loamy sand of the Grove soil series (Dystric Xerorthent) formed in glacial outwash and averaging 1.5 m in depth (USDA NRCS 2009). Estimated average (1971–2000) annual precipitation is 249 cm (PRISM Group 2008). The second site, located in the foothills of the western Cascade Mountains 24 km northeast of Molalla, Oregon, has a cobbly loam of the Kinney soil series (Andic Dystrudept), averaging 1.4 m in depth (USDA NRCS 2009). The average annual precipitation is 174 cm. The corresponding soil orders in *The Canadian System of Soil Classification* (Soil Classification Working Group 1998) are the Regosols and Brunisols for Matlock and Molalla, respectively. The two sites differ strongly in terms of soil nitrogen pools (2246 kg N·ha^{-1} for Matlock versus 4338 kg N·ha^{-1} for Molalla; Slesak et al. 2009) and soil water-holding capacity[2] (per 1.25 m soil profile, 170 mm for Matlock and 297 mm for Mollala). 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). The potential natural vegetation is characterized by 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.) C. Presl) and the western hemlock – Oregon-grape – salal plant associations at Molalla (Halverson et al. 1986). At study initiation (fall 2002), the sites were dominated by mature stands of Douglas-fir with scattered machine trails from a low thinning in 1993 (Molalla) or timber salvage after a 1998 ice storm (Matlock).

Experimental design and treatments

The experimental design at each site is a randomized complete block with six treatments arranged as a factorial combination of three conventional logging debris treatments and two vegetation control treatments randomly assigned to plots within each of four replicate blocks (Table 2). Matlock and Molalla are considered affiliate sites of the LTSP experiment. Treatment plots are 50 m × 60 m in dimension (0.3 ha). Blocking was based on aspect (Molalla only) and proximity to logging access roads (Matlock and Molalla). After locating plot corners and assigning treatments, the existing stand of Douglas-fir at each site was clear-cut harvested via directional felling with chainsaws during March–April 2003. To confine soil disturbance, designated machine

[2] Estimated from pressure plate analyses by the Central Analytical Laboratory, Oregon State University, Corvallis, Oregon.

Table 1. Characteristics of the study sites.

Characteristic	Matlock	Molalla
Latitude, longitude	47.206°N, 123.442°W	45.196°N, 122.285°W
Elevation (m above sea level)	35	549
Aspect, slope	Flat, 0%	NW to SW, 0% to 30%
Soil series, texture	Grove, very gravelly loamy sand	Kinney, cobbly loam
Annual precipitation (cm)*	249	174
Douglas-fir 50 year site index (m)	36	36
Preharvest stand age (years)	45	56

*Thirty-year (1971–2000) average annual precipitation estimated from the PRISM Group (2008).

Table 2. Factorial arrangement of the three logging debris treatments and two vegetation control treatments at Matlock and Molalla.

	Vegetation control treatments	
Logging debris treatments	Initial (a single site preparation herbicide treatment)	Annual (a site-preparation herbicide treatment plus annual herbicide treatments)
Dispersed — removal of merchantable logs (minimum piece-size diameter 12.7 cm and length 3.7 m) with retention of logging debris in place (logs were delimbed with a chainsaw).	Debris dispersed with initial vegetation control	Debris dispersed with annual vegetation control
Piled — removal of merchantable logs and moving of logging debris >5.1 cm diameter into piles 3 to 4 m in diameter.	Debris piled with initial vegetation control	Debris piled with annual vegetation control
Removed — removal of merchantable logs and logging debris >5.1 cm diameter.	Debris removed with initial vegetation control	Debris removed with annual vegetation control

trails were marked at 20 m intervals along the 60 m dimension of each plot immediately after trees were felled. Machine traffic was confined to the trails during the removal of logs and removal or piling of logging debris as specified by treatment. Logs were not skidded but rather transported to the road by tracked loaders (i.e., shovel logging). A tracked excavator with a clamshell bucket was used to remove or pile debris as specified by treatment. All preharvest woody debris was left in place, and debris treatments were completed within 30 days of logging before materials had dried to the point of needle fall.

A site-preparation herbicide treatment (triclopyr at Matlock and glyphosate at Molalla) was applied to all plots in late summer 2003 with backpack sprayers to reduce the abundance of woody vegetation and prevent overtopping of Douglas-fir to be planted the following winter (hereafter referred to as initial vegetation control) (Table 3). In early 2004, plug+1 Douglas-fir seedlings grown from a local seed source near each site were hand-planted at spots premarked on a 3 m × 3 m grid. Seedling locations were offset up to 1.5 m from assigned grid points to accommodate piles of woody debris in the piled treatment. Immediately after planting, seedlings averaged 6 and 7 mm in stem diameter at 15 cm above ground and 44 and 45 cm in height at Matlock and Molalla, respectively. Annual herbicide treatments were applied to designated plots in the fall or spring of 2004–2008 with the goal of reducing cover of herbaceous and woody vegetation to ≤20% and thereby provide experimental conditions for quantifying debris effects independent of vegetation abundance (Table 3). At Matlock, three additional treatments of triclopyr herbicide were applied selectively on all plots to control Scotch broom (*Cytisus scoparius* (L.) Link). This highly competitive, non-native shrub reproduces prolifically from seed stored in the soil (Bossard 1993). At Matlock, broom seed probably was introduced during the 1998 salvage harvest. To ensure the long-term integrity of the study at Matlock, an eradication treatment (basal stem application of triclopyr in W.E.B.® emulsifiable mineral oil (Wilbur–Ellis Company, Fresno, California)) was applied to the Scotch broom on all plots in summer 2007.

Measurements and statistical analyses

The mass of logging debris on the forest floor was estimated in summer 2003 with the planar-intersect technique (Brown 1974). Random starting points and azimuths were used to locate five 10 m transects in each plot. Measurements of debris frequency and diameter were taken along each transect and applied to the equations in Brown (1974) to estimate mass of logging debris. In the piled treatment, only the area between piles was sampled for logging debris mass. Needles and woody debris <6 mm in diameter were collected within a square 0.25 m^2 frame positioned at the midpoint of transects 1, 3, and 5 for each plot. The debris samples were returned to the laboratory where they were separated into needle and woody fractions and dried to a constant mass (nearest 0.1 g) at 65 °C. In December 2006, height and width (nearest 0.1 m) of each pile of logging debris were measured in the piled treatment. Twenty of the premarked grid points for planted seedlings were randomly selected per plot as reference points for visually estimating cover (nearest 5%) of woody logging debris and exposed mineral soil in summer 2003. Cover measurements were taken within a 2 m × 2 m frame centered on each reference point. During the summers of 2004–2008, cover also was es-

Table 3. Herbicide treatments used to control competing vegetation.

Site	Application date	Study year*	Herbicide(s)	Herbicide rate(s)	Method of application
Matlock	20 Sept. 2003	0	Triclopyr ester	2.8 kg a.i.·ha^{-1} with surfactant†	Broadcast foliar
	10 Dec. 2003	0	Sulfometuron	0.2 kg a.i.·ha^{-1}‡	Broadcast
	27 Oct. 2004	1	Triclopyr ester	2.5% suspension in water§	Directed foliar
	22 Apr. 2005	2	Glyphosate + clopyralid	1.5% + 0.75% solution in water‡	Broadcast foliar
	22 Apr. 2006	3	Glyphosate + clopyralid	1.5% + 0.75% solution in water‡	Broadcast foliar
	20 Apr. 2007	4	Glyphosate + clopyralid	1.5% + 0.75% solution in water‡	Broadcast foliar
	6 June 2007	4	Triclopyr ester	20% solution in W.E.B.® mineral oil§	Directed basal stem
	29 May 2008	5	Glyphosate + clopyralid	1.5% + 0.75% solution in water‡	Broadcast foliar
	29 May 2008	5	Triclopyr ester	20% solution in W.E.B.® mineral oil§	Directed basal stem
Molalla	5 Aug. 2003	0	Glyphosate	2.2 kg a.i.·ha^{-1} in water with surfactant†	Broadcast foliar
	30 Oct. 2003	0	Sulfometuron	0.2 kg a.i.·ha^{-1} in water‡	Broadcast
	12 Oct. 2004	1	Glyphosate + sulfometuron	1.1 + 0.2 kg a.i.·ha^{-1} in water‡	Broadcast foliar
	5 May 2006	3	Glyphosate + atrazine	1% solution in water + 4.9 kg a.i.·ha^{-1}‡	Broadcast foliar
	10 May 2007	4	Clopyralid + atrazine	0.8 + 4.9 kg a.i.·ha^{-1} in water‡	Broadcast foliar
	14 May 2008	5	Triclopyr ester + 2,4-D ester	2% + 2% suspension in water with surfactant‡	Broadcast foliar

*Growing seasons since planting Douglas-fir seedlings in early 2004.
†Applied to all plots.
‡Applied to annual vegetation control plots only.
§Applied to Scotch broom only.

timated for two categories of competing vegetation: herbaceous species and nonconifer woody species. Separate estimates were recorded for each plant species having a cover ≥20%. Herbaceous competitors that were abundant at each site included hairy cat's ear (*Hypochaeris radicata* L.), oxeye daisy (*Leucanthemum vulgare* Lam.), and western brackenfern (*Pteridium aquilinum* (L.) Kuhn.). Common woody competitors included salal, trailing blackberry (*Rubus ursinus* Cham. & Schltdl.), and Oregon-grape. Survival and growth of planted Douglas-fir were monitored on a 10 × 10 grid of seedlings nested within each treatment plot. Stem diameter at 15 cm height (nearest mm) and total height (nearest cm) were measured on each seedling immediately after planting and at the end of each year from 2004 to 2008. Study years 1 to 5 refer to the number of growing seasons since planting Douglas-fir in early 2004.

All statistical analyses were conducted in SAS (SAS Institute Inc. 2005) with a significance level of $\alpha = 0.05$. Plot means for variables of logging debris mass and forest floor cover were subjected to analysis of variance (ANOVA) using a mixed-model approach in PROC MIXED to test for significant effects of the debris treatments, vegetation treatments, and their interaction. Blocking was assigned as a random effect in the ANOVA for variables of logging debris mass and forest floor cover. Plot means for the annual measurements of herbaceous and woody covers; cover of the dominant woody competitor at each site; and Douglas-fir survival, stem diameter, and height were subjected to repeated-measures ANOVA in PROC MIXED. Each model accounted for random effects of blocks and plots within blocks. Initial Douglas-fir size at planting was included as a covariate in the ANOVA for Douglas-fir growth when significant. An angular transformation was applied to the cover variables and Douglas-fir survival, and a logarithmic transformation was applied to logging debris mass and Douglas-fir growth variables to homogenize their residual variances (Sokal and Rohlf 1981). Residuals for each response variable were plotted against predicted values to check for nonhomogeneous variance. If a year-by-treatment interaction was detected, slicing was used to identify individual years in which differences existed among treatments (SAS Institute Inc. 2005). If an interaction was detected between debris and vegetation treatments, slicing was used to identify differences among debris treatments for a given vegetation treatment and between vegetation treatments for a given debris treatment. When treatment differences were detected, multiple comparisons of adjusted means were conducted using Bonferroni probabilities to control the Type I error rate (Quinn and Keough 2002). Results are presented as back-transformed, adjusted means from the ANOVA. Cover responses for woody vegetation are reported only for the dominant woody competitor at each site to simplify presentation of the results. To quantify debris effects that were mediated by vegetation responses, regression analyses of plot means were conducted with PROC REG on data from each site to identify the strongest associations of Douglas-fir survival or growth in year 5 with cover of the dominant woody competitor in years 1 to 5.

Results

Logging debris abundance

Three months after timber harvest, needle mass did not differ significantly among logging debris treatments at Matlock or Molalla (Table 4), although values for the dispersed treatment (5.1 to 7.9 Mg·ha^{-1}) were consistently greater than those for the piled or removed treatments (3.0 to 3.7 Mg·ha^{-1}) (Table 5). At both sites, the mass of woody logging debris was 55%–76% greater where debris was dispersed than where it was piled or removed ($P \leq 0.009$). Treatment differences were similar for the total mass of logging debris ($P \leq 0.024$). Cover of woody logging debris was

Table 4. Analysis of variance results for mass of logging debris and cover by forest floor condition three months after logging debris was dispersed, piled, or removed.

		df*		Probability >*F*				
				Logging debris mass			Forest floor cover	
Site	Source of variation	N	D	Needles	Wood	Total	Wood	Soil†
Matlock	Debris treatment (D)	2	15	0.170	0.008	0.018	0.002	0.122
	Vegetation control (V)	1	15	0.522	0.981	0.884	0.780	0.839
	D × V	2	15	0.450	0.895	0.760	0.642	0.834
Molalla	D	2	15	0.108	0.009	0.024	<0.001	0.268
	V	1	15	0.834	0.095	0.240	0.181	0.436
	D × V	2	15	0.522	0.580	0.967	0.144	0.726

Note: Two levels of vegetation control (initial and annual) were applied to assigned plots nine months after the debris treatments.

*df, degrees of freedom for the numerator (N) and denominator (D) of the *F* test.

†Soil is exposed mineral soil.

Table 5. Average mass of logging debris and cover by forest floor condition with standard errors (SE) 3 months after logging debris was dispersed, piled, or removed.

			Logging debris treatment			
Site	Category	Variable	Dispersed	Piled	Removed	SE
Matlock	Debris mass ($Mg \cdot ha^{-1}$)	Needles	5.1a	3.0a	3.6a	1.3
		Wood	17.4a	10.2b	9.9b	2.0
		Total	22.5a	13.2b	13.5b	3.0
	Forest floor cover (%)	Wood	38.8a	26.9b	22.3b	3.4
		Soil*	2.6a	4.8a	5.8a	1.6
Molalla	Debris mass ($Mg \cdot ha^{-1}$)	Needles	7.9a	3.7a	3.5a	1.4
		Wood	16.1a	10.4b	10.4b	1.6
		Total	24.0a	14.1ab	13.9b	2.8
	Forest floor cover (%)	Wood	42.3a	27.1b	24.3b	2.9
		Soil*	2.8a	4.3a	4.4a	0.8

Note: For each row, means followed by the same letter do not differ significantly among treatments ($P >$ 0.05).

*Soil is exposed mineral soil.

44%–74% greater where debris was dispersed than where it was piled or removed ($P \leq 0.002$). However, cover of exposed mineral soil did not differ significantly among debris treatments ($P \geq 0.122$), ranging from 3% to 6%. In year 3, the piles of logging debris in the piled treatment averaged 3.0 and 3.5 m in diameter and 1.0 and 1.1 m in height at Matlock and Molalla, respectively. Pile densities averaged 105 and 60 ha^{-1} and covered 25% and 19% of the plot area in the piled treatment at Matlock and Molalla, respectively.

Competing vegetation abundance

At Matlock, herbaceous and woody covers each varied significantly ($P \leq 0.012$) as a result of year-by-debris and year-by-vegetation interactions (Table 6). However, multiple comparisons of means for each year failed to detect significant differences in herbaceous cover among debris treatments. In each year, herbaceous cover after annual vegetation control (4%, 16%, 20%, 33%, and 11% in years 1, 2, 3, 4, and 5, respectively) was less than after initial control (7%, 50%, 47%, 45%, and 50%, respectively). Scotch broom was the dominant woody competitor at Matlock, and its cover varied as a result of a year-by-debris-by-vegetation interaction ($P \leq$ 0.020; Table 6). Where initial vegetation control was applied, broom cover was less where debris was dispersed than where it was piled (years 2 and 3) or removed (year 3 only) (Fig. 1). Where annual vegetation control was applied, broom cover in year 3 was less where debris was dispersed than where it was removed. In addition, broom cover after annual vegetation control was less than after initial control in years 2 (piled treatment only) and 3 (each debris treatment).

At Molalla, only the year-by-vegetation interaction was significant ($P < 0.001$) for herbaceous and woody covers (Table 6). Herbaceous cover after annual vegetation control in years 3, 4, and 5 (28%, 17%, and 9%, respectively) was less than after initial vegetation control (47%, 45%, and 50%, respectively). Trailing blackberry was the dominant woody competitor at Molalla, and its cover varied as a result of year-by-debris and year-by-vegetation interactions ($P \leq$ 0.003; Table 6). In year 2, blackberry cover was less where debris was removed or dispersed than where it was piled, and in years 2, 3, and 5, it was less after annual vegetation control than after initial control (Fig. 2).

Douglas-fir survival and growth

Survival of Douglas-fir at Matlock varied significantly ($P \leq$ 0.001) as a result of a year-by-debris interaction (Table 6).

Table 6. Analysis of variance (ANOVA) results for cover of competing vegetation, and survival, stem diameter, and height of Douglas-fir during 5 years after logging debris was dispersed, piled, or removed followed by initial or annual vegetation control.

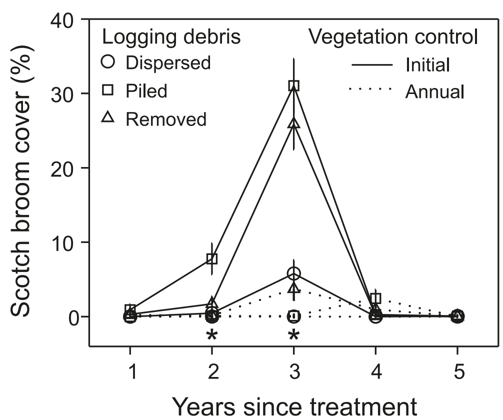
		df*		Probability >*F*						
				Competing vegetation cover†				Douglas-fir		
Site	Source of variation	N	D	Herbs	Woody	Scotch broom	Trailing blackberry	Survival	Diameter	Height
Matlock	Debris treatment (D)	2	15	0.592	0.684	0.001		0.580	0.322	0.506
	Vegetation control (V)	1	15	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
	D × V	2	15	0.348	0.522	0.059		0.242	0.274	0.303
	Year (Y)	4	72	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
	Y × D	8	72	0.012	0.002	0.001		0.001	0.132	0.084
	Y × V	4	72	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
	Y × D × V	8	72	0.241	0.630	0.020		0.155	0.002	<0.001
	Covariate‡	1	72	—	—	—		—	<0.001	—
Molalla	D	2	15	0.304	0.496		0.889	0.301	0.492	0.880
	V	1	15	<0.001	<0.001		<0.001	0.469	<0.001	0.950
	D × V	2	15	0.617	0.606		0.697	0.494	0.135	0.144
	Y	4	72	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001
	Y × D	8	72	0.975	0.151		0.003	0.192	0.255	0.641
	Y × V	4	72	<0.001	<0.001		<0.001	0.001	<0.001	<0.001
	Y × D × V	8	72	0.398	0.837		0.844	0.436	0.009	0.232

*df, degrees of freedom for the numerator (N) and denominator (D) of the *F* test.

†Scotch broom and trailing blackberry were the dominant woody competitors at Matlock and Molalla, respectively.

‡Initial stem diameter was included as a covariate in the ANOVA for Douglas-fir stem diameter at Matlock.

Fig. 1. Effects of the interaction of logging debris and vegetation control treatments on five-year cover responses of Scotch broom (with standard error bars). Asterisks indicate years in which cover differed significantly ($P \le 0.05$) among treatments.



Although fifth-year survival where debris was dispersed (84%) exceeded that where debris was removed (75%), the difference was marginally significant ($P = 0.062$) (Fig. 3). At each site, the year-by-vegetation interaction was significant for Douglas-fir survival ($P \le 0.001$). At Matlock, survival after annual vegetation control in years 3, 4, and 5 was 5%, 19%, and 21% greater, respectively, than after initial control. At Molalla, survival equaled or exceeded 93% for the study duration, and multiple comparisons failed to detect significant differences between vegetation treatments for any year ($P \ge 0.071$; data not shown).

The year-by-debris-by-vegetation interaction was significant ($P \le 0.009$) for Douglas-fir stem diameter at each site (Table 6). At Matlock, diameter in year 2 was 3 mm greater

Fig. 2. Main effects of logging debris (upper graph) and vegetation control treatments (lower graph) on five-year cover responses of trailing blackberry (with standard error bars). Asterisks indicate years in which cover differed significantly ($P \le 0.05$) among treatments.

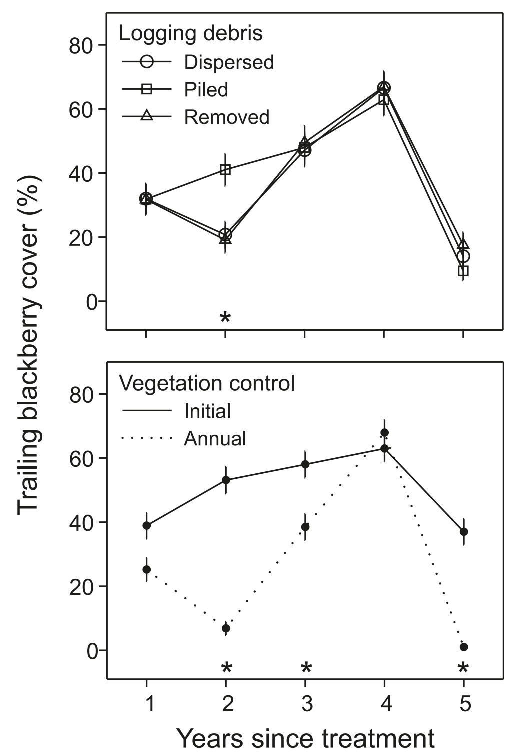
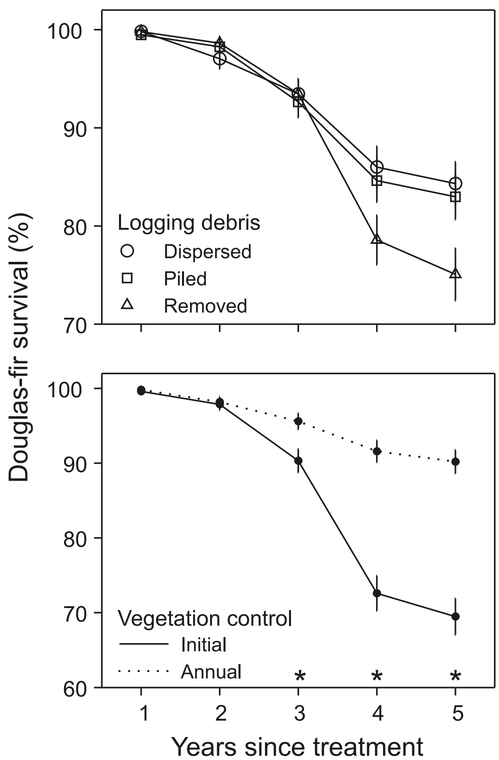


Fig. 3. Main effects of logging debris (upper graph) and vegetation control treatments (lower graph) on five-year survival responses of Douglas-fir at Matlock (with standard error bars). Asterisks indicate years in which survival differed significantly ($P \leq 0.05$) among treatments.



after annual vegetation control than after initial control where debris was removed, and in years 3, 4, and 5 it was greater for each debris treatment (Fig. 4). At Molalla, stem diameter in years 3 and 4 was greater after annual vegetation control than after initial control where debris was piled, and in year 5 it was greater for each debris treatment. However, stem diameter of Douglas-fir growing with annual vegetation control did not differ among debris treatments at either site.

The year-by-debris-by-vegetation interaction was significant for Douglas-fir height at Matlock ($P < 0.001$) but not at Molalla ($P = 0.232$) (Table 6). At Matlock, height was greater after annual vegetation control than after initial control in year 4 where debris was dispersed or removed, and in year 5 it was greater for each debris treatment (Fig. 4). At Molalla, the year-by-vegetation interaction was significant for Douglas-fir height ($P < 0.001$), and height in year 5 was greater after annual vegetation control than after initial control. As found for stem diameter, height of Douglas-fir after annual vegetation control did not differ among debris treatments at either site.

Douglas-fir and vegetation relationships

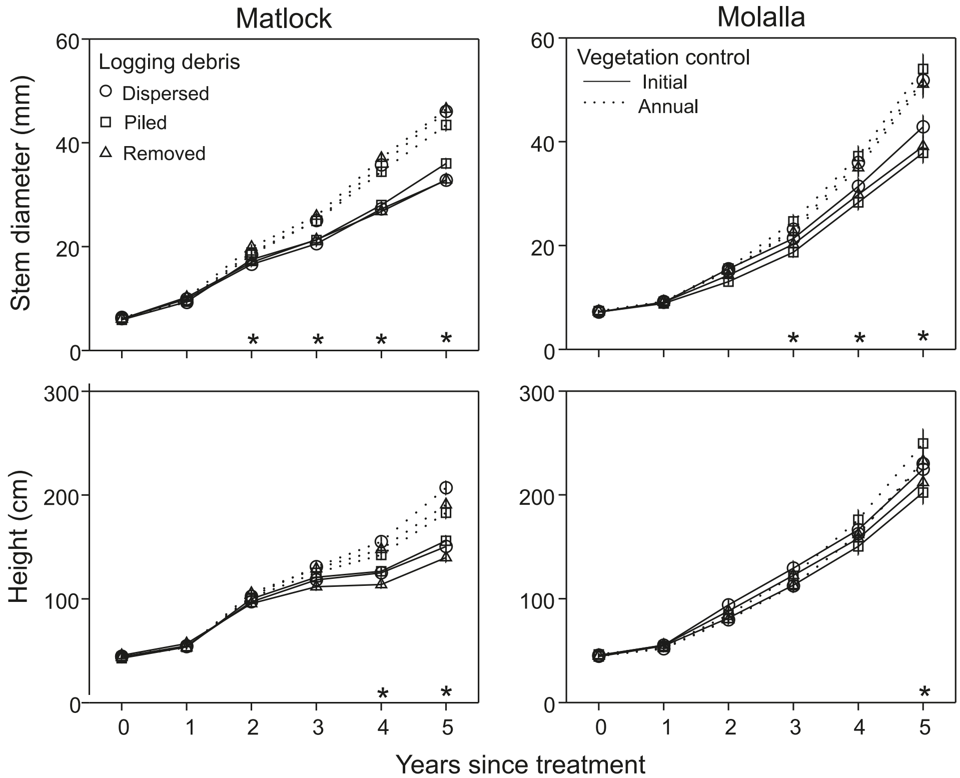
Douglas-fir survival in year 5 at Matlock was most strongly related to Scotch broom cover in year 3 ($r^2 = 0.62$, $P < 0.001$), when broom cover differed most among debris treatments (Fig. 5). As broom cover increased from 0% to 40%, the predicted survival of Douglas-fir decreased 30%. At Molalla, Douglas-fir stem diameter in year 5 was most strongly related to trailing blackberry cover in year 2 ($r^2 = 0.39$, $P = 0.001$), when blackberry cover differed most among debris treatments (Fig. 5). As blackberry cover increased from 0% to 80%, the predicted stem diameter of Douglas-fir decreased 30%.

Discussion

By the second or third year of the research, cover of a key woody competitor at each site (i.e., Scotch broom at Matlock and trailing blackberry at Molalla) was substantially greater where debris was piled or removed than where it was dispersed. This vegetation response accounted for 39% to 62% of the variation in the fifth-year regeneration performance of Douglas-fir. Thus, the research clearly demonstrates, as hypothesized, that logging debris treatments can influence forest regeneration indirectly through their effect on competing vegetation abundance. In a comparison of 25 replicated studies of the LTSP experiment, Fleming et al. (2006) found that regeneration responses to vegetation control did not vary among combinations of organic matter removal and soil compaction (OM-C) treatments, leading the authors to conclude that treatment effects were not mediated by changes in vegetation abundance, contrary to the findings of the present study. In the one LTSP study in which a vegetation-mediated response to OM-C treatments was observed, Powers and Fiddler (1997) found that seedling growth of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex. Hildebr.) was increased by compaction of a clay soil because the treatment reduced cover of competing vegetation. The authors noted that where competing vegetation was controlled, compaction had the opposite effect of reducing growth. Although the findings of Powers and Fiddler (1997) were considered a result of confounding from competing vegetation, they suggest that vegetation-mediated responses may be more common than reported in the literature because previous research often did not specifically seek to identify associations between OM-C treatments and vegetation abundance.

Although the mechanisms for observed changes in vegetation abundance from the debris treatments were not the focus of this study, some inferences can be made from the results. At Matlock, piling or removing debris reduced cover of woody materials by an average of 14% relative to the dispersed treatment, yet these treatments increased cover of exposed mineral soil by only 2% to 4%. Therefore, reduced cover of debris, and not increased cover of exposed soil, probably facilitated the observed increases in Scotch broom cover where debris was piled or removed. Previous research suggests that germination and establishment of Scotch broom may not be directly associated with soil disturbance (Sheppard et al. 2000; Parker 2001). Increased cover of logging debris in the dispersed treatment may have inhibited Scotch broom germination by modifying microclimate at the soil surface. Law and Kolb (2007) found similarly that cover and biomass of perennial grasses was lower in the presence than in the absence of debris piles, leading them to speculate that re-

Fig. 4. Effects of the interaction of logging debris and vegetation control treatments on five-year growth responses of Douglas-fir stem diameter and height (with standard error bars). Asterisks indicate years in which growth differed significantly ($P \leq 0.05$) among treatments.



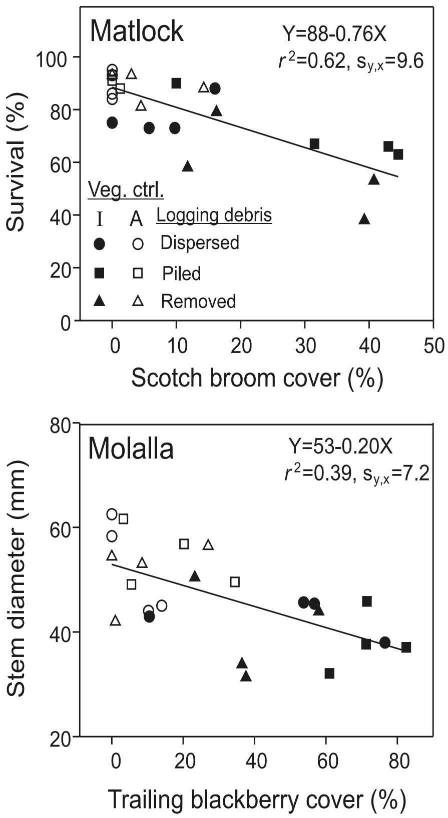
ductions in light and temperature from debris restricted tiller production.

Because mass and cover of logging debris differed little between areas where debris was removed compared with where it was piled (i.e., the area between piles), other factors probably facilitated the observed increases in blackberry cover in the piled treatment at Molalla. This abundance response occurred despite strong reductions in blackberry cover in year 2 from annual vegetation control. One explanation is that the piles acted as refugia for blackberry, shielding the species from herbicide effects and enabling it to recolonize the piled treatment more rapidly than the other debris treatments. At Fall River, an affiliate study of the LTSP experiment in southwestern Washington, redwood – sorrel (*Oxalis oregana* Nutt.), white insideout flower (*Vancouveria hexandra* (Hook.) C. Morren & Decne.), and evergreen violet (*Viola sempervirens* Greene) in the vegetation control treatment were able to avoid herbicide injury and exploit “spray shadows” under woody debris because of their short stature and shade tolerance (Peter and Harrington 2009).

Douglas-fir responded to differences in woody competitor abundance according to the resource limitations of each site. As noted previously, the soil at Matlock has only 57% of the water-holding capacity of the soil at Molalla. Scotch broom competition probably imposed severe drought conditions in the glacial-outwash soil at Matlock, as observed on similarly coarse-textured soils in New Zealand (Richardson et al. 2002). As a result, survival and height growth of Douglas-fir declined, despite the relative insensitivity of these variables to competition (Wagner 2000). Soil drought at Matlock probably also exacerbated previous Douglas-fir injuries from severe frosts, Cytospora canker (*Cytospora abietis* Sacc.), and Douglas-fir twig mining beetle (*Pityophthorus orarius* Bright), each of which contributed to terminal and branch shoot dieback in years 3 and 4 (D. Omdal, Washington State Department of Natural Resources, personal communication, 2008). Typically height growth of Douglas-fir accelerates almost exponentially during juvenile development (Harrington et al. 1995), but top dieback is evident in the decelerating pattern observed in all treatments in years 2 through 4 at Matlock, especially those with initial vegetation control. Recovery of a more normal pattern of Douglas-fir height growth is evident in year 5 after eradication of Scotch broom.

Significant reductions in Douglas-fir survival at Molalla were not observed for any of the treatments probably because resource needs of the planted seedlings were met by the higher water-holding capacity of its soil regardless of differences in vegetation abundance. Differing survival responses at Matlock and Molalla support the supply-minus-demand theory of resource competition (Davis et al. 1998) that predicts a negative correlation between net resource supply (gross supply minus consumption by competing vegetation) and competition intensity. At Matlock, extreme levels of competition probably were achieved even at low levels of Scotch broom cover — perhaps as little as 20% (Powers and Reynolds 1999) — because its soils have such low water-holding capacity. The probability of mortality for a young conifer is believed to increase after it loses the abil-

Fig. 5. Regression relationships of Douglas-fir survival in year 5 versus Scotch broom cover in year 3 at Matlock (upper graph) and Douglas-fir stem diameter in year 5 versus trailing blackberry cover in year 2 at Molalla (lower graph). Levels of vegetation control include initial (I) and annual (A) herbicide applications.



ity to plastically respond to competition with growth reductions (Wagner 2000). Thus, where initial vegetation control was applied at Matlock, Douglas-fir survival plummeted in year 4 after successive reductions in tree growth in years 2 and 3.

Growth responses of Douglas-fir to the debris and vegetation treatments are in general agreement with those observed at Fall River, a site of substantially higher productivity because of its greater nitrogen availability and soil water-holding capacity (Ares et al. 2007). When combined with annual vegetation control, the debris treatments were not associated with significant differences in Douglas-fir growth at either Matlock or Molalla, as found at Fall River (Ares et al. 2007). This finding is in accordance with other research at Matlock and Molalla in which available soil nitrogen and Douglas-fir foliar nitrogen did not differ between the debris-dispersed and debris-removed treatments during the first 2–4 years after timber harvest (Slesak et al. 2010). Therefore, treatments for managing logging debris such as those tested in this study are likely to have negligible short-term effects on soil productivity in western Oregon and Washington. In longer-term studies, reductions in stand growth have been observed 11–15 years after organic matter removal treatments; however, the responses resulted from more intensive practices than those studied here, including removal of all small-diameter debris (Egnell and Valinger 2003) and removal of the forest floor or topsoil (Smith et al. 2000).

Conclusions

Piling or removing logging debris was associated with reductions in Douglas-fir regeneration performance, relative to dispersing debris, because the debris treatments facilitated increases in interspecific competition. This result, observed on sites of contrasting soil texture and precipitation, suggests that debris effects manifested by changes in vegetation abundance are more common than have been reported in the literature, and it underscores the need to understand the dynamics of key competitor species as they respond to disturbances associated with forest harvesting and plantation establishment. However, soil productivity as observed within the timeframe of this study was not influenced by the debris treatments because no differences in regeneration performance were detected when treatment effects were evaluated independent of vegetation abundance.

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References

Ares, A., Terry, T., Harrington, C., Devine, W., Peter, D., and Bailey, J. 2007. Biomass removal, soil compaction, and vegetation control effects on five-year growth of Douglas-fir in Coastal Washington. For. Sci. **53**: 600–610.

Bossard, C.C. 1993. Seed germination in the exotic shrub *Cytisus scoparius* (Scotch broom) in California. Madroño, **40**: 47–61.

Brown, J.K. 1974. Handbook for inventorying downed woody material. USDA For. Serv. Gen. Tech. Rep. INT-16.

Carter, M.C., Dean, T.J., Zhou, M., Messina, M.G., and Wang, Z. 2002. Short-term changes in soil C, N, and biota following harvesting and regenerating loblolly pine (*Pinus taeda* L.). For. Ecol. Manage. **164**(1–3): 67–88. doi:10.1016/S0378-1127(01)00590-4.

Davis, M.A., Wrage, K.J., and Reich, P.B. 1998. Competition between tree seedlings and herbaceous vegetation: support for a theory of resource supply and demand. J. Ecol. **86**(4): 652–661. doi:10.1046/j.1365-2745.1998.00087.x.

Devine, W.D., and Harrington, C.A. 2007. Influence of harvest residues and vegetation on microsite soil and air temperatures in a young conifer plantation. Agric. For. Meteorol. **145**(1–2): 125–138. doi:10.1016/j.agrformet.2007.04.009.

Egnell, G., and Valinger, E. 2003. Survival, growth, and growth allocation of planted Scots pine trees after different levels of biomass removal in clear-felling. For. Ecol. Manage. **177**(1–3): 65–74. doi:10.1016/S0378-1127(02)00332-8.

Fleming, R.L., Powers, R.F., Foster, N.W., Kranabetter, J.M., Scott, D.A., Ponder, F., Jr., Berch, S., Chapman, W.K., Kabzems, R.D., Ludovici, K.H., Morris, D.M., Page-Dumroese, D.S., Sanborn, P.T., Sanchez, F.G., Stone, D.M., and Tiarks, A.E. 2006. Effects of organic matter removal, soil compaction, and vegetation control on 5-year seedling performance: a regional comparison of Long-Term Soil Productivity sites. Can. J. For. Res. **36**(3): 529–550. doi:10.1139/x05-271.

Franklin, J.F., and Dyrness, C.T. 1973. Natural vegetation of Oregon and Washington. USDA For. Serv. Gen. Tech. Rep. PNW-8. pp. 38–43.

Hacker, A.L., and Coblentz, B.E. 1993. Habitat selection by mountain beavers recolonizing Oregon Coast Range clearcuts. J. Wildl. Manage. **57**(4): 847–853. doi:10.2307/3809088.

Halverson, N.M., Topik, C., and Van Vickle, R. 1986. Plant association and management guide for the western hemlock zone. Mount Hood National Forest. USDA For. Serv., Pacific Northwest Region, Portland, Ore. R6-ECOL-232A-1986. pp. 62–65.

Harmon, M.E., and Franklin, J.F. 1989. Tree seedlings on logs in *Picea–Tsuga* forests of Oregon and Washington. Ecology, **70**(1): 48–59. doi:10.2307/1938411.

Harrington, T.B., Wagner, R.G., Radosevich, S.R., and Walstad, J.D. 1995. Interspecific competition and herbicide injury influence 10-year responses of coastal Douglas-fir and associated vegetation to release treatments. For. Ecol. Manage. **76**(1–3): 55–67. doi:10.1016/0378-1127(95)03558-R.

Hartanto, H., Prabhu, R., Widayat, A.S.E., and Asdak, C. 2003. Factors affecting runoff and soil erosion: plot-level soil loss monitoring for assessing sustainability of forest management. For. Ecol. Manage. **180**(1–3): 361–374. doi:10.1016/S0378-1127(02)00656-4.

Henderson, J.A., Peter, D.H., Lesher, R.D., and Shaw, D.C. 1989. Forested plant associations of the Olympic National Forest. USDA For. Serv. Rep. R6-ECOL-TP 001-88. pp. 350–353.

Hendrickson, O.Q., Chatarpaul, L., and Burgess, D. 1989. Nutrient cycling following whole-tree and conventional harvest in northern mixed forest. Can. J. For. Res. **19**(6): 725–735. doi:10.1139/x89-112.

Kennedy, P.G., and Quinn, T. 2001. Understory plant establishment on old-growth stumps and the forest floor in western Washington. For. Ecol. Manage. **154**(1–2): 193–200. doi:10.1016/S0378-1127(00)00622-8.

Law, D.J., and Kolb, P.F. 2007. The effects of forest residual debris disposal on perennial grass emergence, growth, and survival in a ponderosa pine ecotone. Rangeland Ecol. Manag. **60**(6): 632–643. doi:10.2111/06-034R4.1.

Lopushinsky, W., Zabowski, D., and Anderson, T.D. 1992. Early survival and height growth of Douglas-fir and lodgepole pine seedlings and variations in site factors following treatment of logging residues. USDA For. Serv. Res. Pap. PNW-RP-451.

Morris, L.A., and Lowery, R.F. 1988. Influence of site preparation on soil conditions affecting stand establishment and tree growth. South. J. Appl. For. **12**(3): 170–178.

O'Connell, A.M., Grove, T.S., Mendham, D.S., and Rance, S.J. 2004. Impact of harvest residue management on soil nitrogen dynamics in *Eucalyptus globulus* plantations in south western Australia. Soil Biol. Biochem. **36**: 39–48.

Olsson, B.A., Staaf, H., Lundkvist, H., Bengtsson, J., and Rosén, K. 1996. Carbon and nitrogen in coniferous forest soils after clear-felling and harvests of different intensity. For. Ecol. Manage. **82**(1–3): 19–32. doi:10.1016/0378-1127(95)03697-0.

Parker, I.M. 2001. Safe site and seed limitation in *Cytisus scoparius* (Scotch broom): invasibility, disturbance, and the role of cryptograms in a glacial outwash prairie. Biol. Invasions, **3**(4): 323–332. doi:10.1023/A:1015855515361.

Peter, D.H., and Harrington, C. 2009. Six years of plant community development after clearcut harvesting in western Washington. Can. J. For. Res. **39**(2): 308–319. doi:10.1139/X08-170.

Peterson, C.J., and Leach, A.D. 2008. Salvage logging after windthrow alters microsite diversity, abundance and environment, but not vegetation. Forestry, **81**(3): 361–376. doi:10.1093/forestry/cpn007.

Powers, R.F., and Fiddler, G.O. 1997. The North American long-term soil productivity study: progress through the first 5 years. *In* Proceedings of the 18th annual Forest Vegetation Management Conference, Sacramento, California,14–16 January 1997. Forest Vegetation Management Conference, Redding, Calif. pp. 88–102.

Powers, R.F., and Reynolds, P.E. 1999. Ten-year responses of ponderosa pine plantations to repeated vegetation and nutrient control along an environmental gradient. Can. J. For. Res. **29**(7): 1027–1038. doi:10.1139/cjfr-29-7-1027.

Powers, R.F., Scott, D.A., Sanchez, F.G., Voldseth, R.A., Page-Dumroese, D., Elioff, J.D., and Stone, D.M. 2005. The North American long-term soil productivity experiment: findings from the first decade of research. For. Ecol. Manage. **220**(1–3): 31–50. doi:10.1016/j.foreco.2005.08.003.

PRISM Group. 2008. PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate mapping system [online]. Oregon State University. Available from http://www.prism.oregonstate.edu [accessed 15 December 2008].

Proe, M.F., Griffiths, J.H., and McKay, H.M. 2001. Effect of whole-tree harvesting on microclimate during establishment of second rotation forestry. Agric. For. Meteorol. **110**(2): 141–154. doi:10.1016/S0168-1923(01)00285-4.

Quinn, G.P., and Keough, M.J. 2002. Experimental design and data analysis for biologists. Cambridge University Press, Cambridge, UK. pp. 49–50.

Richardson, B., Whitehead, D., and McCracken, I.J. 2002. Root-zone water storage and growth of *Pinus radiata* in the presence of a broom understorey. N. Z. J. For. Sci. **32**: 208–220.

Roberts, S.D., Harrington, C.A., and Terry, T.A. 2005. Harvest residue and competing vegetation affect soil moisture, soil temperature, N availability, and Douglas-fir seedling growth. For. Ecol. Manage. **205**(1–3): 333–350. doi:10.1016/j.foreco.2004.10.036.

Sanchez, F.G., Tiarks, A.E., Kranabetter, J.M., Page-Dumroese, D.S., Powers, R.F., Sanborn, P.T., and Chapman, W.K. 2006. Effects of organic matter removal and soil compaction on fifth-year mineral soil carbon and nitrogen contents for sites across the United States and Canada. Can. J. For. Res. **36**(3): 565–576. doi:10.1139/x05-259.

SAS Institute Inc. 2005. The SAS system for Windows. Version 9.1. Cary, N.C.

Sheppard, A., Hodge, P., and Paynter, Q. 2000. Factors affecting broom regeneration in Australia and their management implications. Plant Prot. Q. **15**: 156–161.

Shields, J.M., Webster, C.R., and Nagel, L.M. 2007. Factors influencing tree species diversity and *Betula alleghaniensis* establishment in silvicultural openings. Forestry, **80**(3): 293–307. doi:10.1093/forestry/cpm013.

Slesak, R.A., Schoenholtz, S.H., Harrington, T.B., and Strahm, B.D. 2009. Dissolved carbon and nitrogen leaching following variable logging-debris retention and competing-vegetation control in Douglas-fir plantations of western Oregon and Washington. Can. J. For. Res. **39**(8): 1484–1497. doi:10.1139/X09-067.

Slesak, R.A., Harrington, T.B., and Schoenholtz, S.H. 2010. Soil and Douglas-fir (*Pseudotsuga menziesii*) foliar nitrogen responses to variable logging-debris retention and competing vegetation control in the Pacific Northwest. Can. J. For. Res. **40**(1): 254–264. doi:10.1139/X09-188..

Smethurst, P.J., and Nambiar, E.K.S. 1990*a*. Distribution of carbon and nutrients and fluxes of mineral nitrogen after clear-felling a *Pinus radiata* plantation. Can. J. For. Res. **20**(9): 1490–1497. doi:10.1139/x90-197.

Smethurst, P.J., and Nambiar, E.K.S. 1990*b*. Effects of slash and litter management on fluxes of nitrogen and tree growth in a young *Pinus radiata* plantation. Can. J. For. Res. **20**(9): 1498–1507. doi:10.1139/x90-198.

Smith, C.T., Lowe, A.T., Skinner, M.F., Beets, P.N., Schoenholtz, S.H., and Fang, S. 2000. Response of radiata pine forests to residue management and fertilisation across a fertility gradient in New Zealand. For. Ecol. Manage. **138**(1–3): 203–223. doi:10.1016/S0378-1127(00)00397-2.

Soil Classification Working Group. 1998. The Canadian system of soil classification [online]. 3rd ed. Agriculture and Agri-Food Canada Publication 1646. Available from http://sis.agr.gc.ca/cansis/references/1998sc_a.html [accessed 4 December 2009].

Sokal, R.R., and Rohlf, F.J. 1981. Biometry. 2nd ed. W.H. Freeman and Company, New York. pp. 419–421, 427–428.

Strahm, B.D., Harrison, R.B., Terry, T.A., Flaming, B.L., Licata, C.W., and Petersen, K.S. 2005. Soil solution nitrogen concentrations and leaching rates as influenced by organic matter retention on a highly productive Douglas-fir site. For. Ecol. Manage. **218**(1–3): 74–88. doi:10.1016/j.foreco.2005.07.013.

Swank, W.T., Goebel, N.B., and Helvey, J.D. 1972. Interception loss in loblolly pine stands of the South Carolina Piedmont. J. Soil Water Conserv. **27**: 160–164.

[USDA NRCS] United States Department of Agriculture, National Resources Conservation Service. 2009. Official soil series descriptions [online]. Available from http://soils.usda.gov/technical/classification/osd/ [accessed 4 December 2009].

Wagner, R.G. 2000. Competition and critical-period thresholds for vegetation management decisions in young conifer stands. For. Chron. **76**(6): 961–968.

Zabowski, D., Java, B., Scherer, G., Everett, R.L., and Ottmar, R. 2000. Timber harvesting residue treatment: Part 1. Responses of conifer seedlings, soils, and microclimate. For. Ecol. Manage. **126**(1): 25–34. doi:10.1016/S0378-1127(99)00081-X.