Stumps fumigated with chloropicrin: effects on surrounding plants[1]

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Abstract: Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stumps, both healthy and infected by *Phellinus weirii* (Murr.) Gilbertson, were fumigated with chloropicrin at a clearcut site on Washington's Olympic Peninsula. Vegetation cover on plots adjacent to treated and untreated stumps was evaluated to determine fumigant effects on vascular plants and moss. Ninety-eight vascular plant species were recorded during the course of the study. Only those species with 40% or greater frequency (14) and mosses were included in the analysis of individual species cover. We found that *Trientalis latifolia* Hook. may be sensitive and act as an early indicator of chloropicrin effects in the clearcut habitat of this study. Three years following application to stumps, chloropicrin had little or no effect on other surrounding vegetation. The general lack of interaction effects between distance of plot to stump and fumigation treatment leads to the conclusion that the chloropicrin largely stayed in the stumps during the first 3 years following treatment. Effects attributed to harvest methods, study layout, and pretreatment conditions were detected. Species richness decreased with distance from the former stand edge. Higher mean species richness in the control plots was significantly correlated with distance to former stand edge. The results also demonstrate the potential magnitude and legacy of edge effects in forest stands and the need to account for those effects in study design.

Résumé : Des souches de douglas taxifolié (*Pseudotsuga menziesii* (Mirb.) Franco), saines ou infectées par *Phellinus weirii* (Murr.) Gilbertson, ont été fumigées avec de la chloropicrine dans un site coupé à blanc situé sur la péninsule Olympic dans l'État de Washington. La couverture végétale a été évaluée dans des parcelles adjacentes à des souches traitées et non traitées pour déterminer les effets du fumigant sur les plantes vasculaires et les mousses. Quatre-vingt dix huit espèces de plantes vasculaires ont été recensées au cours de l'étude. Seule les espèces dont la fréquence atteignait 40% ou plus et les mousses ont été inclues l'analyse de la couverture par des espèces individuelles. Nous avons découvert que *Trientalis latifolia* Hook. est probablement sensible et pourrait agir comme indicateur précoce des effets de la chloropicrine dans l'habitat coupé à blanc que nous avons étudié. Trois ans après l'application sur les souches, la chloropicrine avait peu ou pas d'effets sur le reste de la végétation avoisinante. L'absence généralisée d'effets d'interaction entre la distance séparant la parcelle et la souche et la fumigation porte à conclure que la chloropicrine demeurait presque entièrement dans les souches au cours des trois premières années après le traitement. Des effets attribuables aux modes de récolte, au dispositif expérimental et aux conditions qui préavalaient avant le traitement ont été détectés. La richesse en espèces diminuait à mesure qu'on s'éloignait de la bordure du peuplement présent avant la coupe. Une richesse moyenne en espèces plus élevée dans les parcelles témoins était significativement corrélée avec la distance de la bordure du peuplement qui avait été coupé. Les résultats démontrent également l'importance et les conséquences potentielles des effets de bordure dans les peuplements forestiers et la nécessité de tenir compte de ces effets dans la conception d'expériences.
[Traduit par la Rédaction]

Introduction

Laminated root rot

Laminated root rot, caused by *Phellinus weirii* (Murr.) Gilbertson, is widespread throughout the range of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). The disease reduces growth in wood volume annually by about 4.4×10^6 m^3 in the northwestern United States and British Columbia (Nelson et al. 1981) and may affect 8% of commercial forest land in the central portion of the species' range (Thies and Sturrock 1995).

When Douglas-fir dies from laminated root rot, the pathogen continues to live saprophytically in butts and large roots for as long as 50 years (Childs 1963; Hansen 1976, 1979). Infection in a young stand begins when roots of young trees contact residual stumps and roots from the preceding stand. The infection spreads between living trees through root contacts (Wallis and Reynolds 1965). Immediate establishment of Douglas-fir or other highly susceptible species on a site occupied by laminated root rot often results in more disease and heavier losses in the new stand (Wallis and Reynolds 1965).

Fumigation is one means of reducing inoculum of some root-rotting fungi (Thies 1984). Treatment of stumps with chloropicrin[3] has been shown to dramatically reduce the amount of laminated root rot inoculum on a forest site (Thies and Nelson 1987), and chloropicrin has been labeled by the U.S. Environmental Protection Agency for this use. Potentially widespread general use of this chemical necessitates the gathering of

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[3] This paper reports the results of research only. Mention of a pesticide does not constitute a recommendation for use by the U.S. Department of Agriculture, nor does it imply registration under the *United States Federal Insecticide, Fungicide, and Rodenticide Act* as amended. Also, mention of a commercial or proprietary product does not constitute recommendation or endorsement by the U.S. Department of Agriculture.

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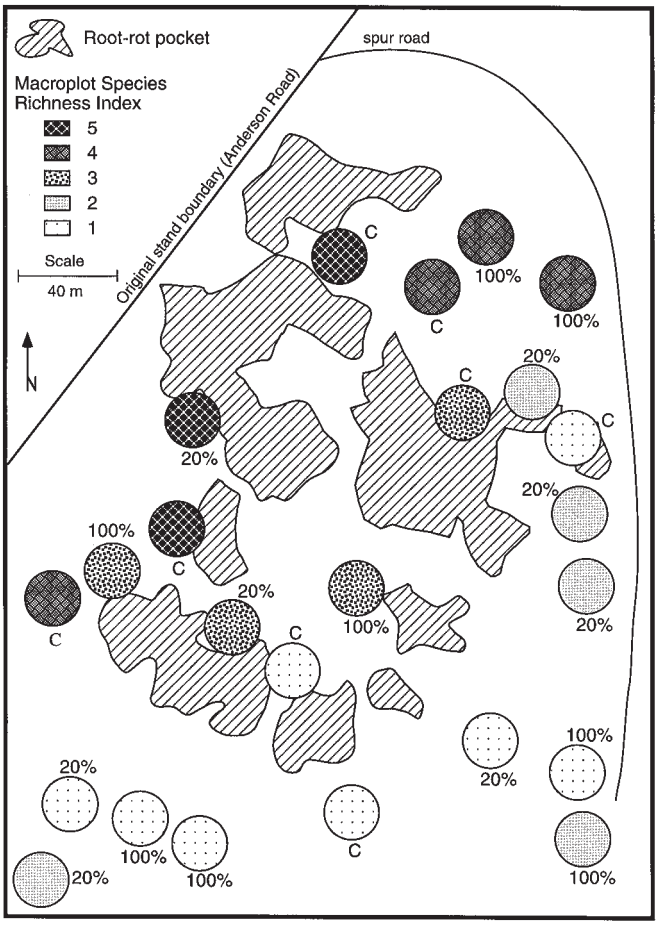
Fig. 1. Map of root-rot pockets and macroplots (coded by species richness index) within the study area. The richness index was determined by the mean number of vascular plant species present in a plot over six sample periods where 1 = 22–31, 2 = 32–36, 3 = 37–40, 4 = 41–44, 5 = 45–48. Fumigation treatment shown as percentage of recommended dosage and C = control.



information on nontarget organisms. Few such studies exist, and direct assessment of the movement of chloropicrin in ecosystems has not been ascertained.

Ecological impacts of chloropicrin

Chloropicrin (trichloronitromethane) is a general biocide that has been used as a soil fumigant and studied for its effectiveness in reducing specific organisms. Reports of fumigant application to soil, as well as directly to wood, to destroy particular fungi have been reviewed (Filip 1976; Filip and Roth 1977; Thies and Nelson 1982). The presence of columns of stained or advanced decayed wood, forming "ducts" from the stump top to infected portions of the root system, suggested fumigation as a means of eradicating laminated root rot from stumps (Thies and Nelson 1982).

Most research has concentrated on the effects of combinations of methyl bromide and chloropicrin fumigants on disease-causing organisms. Combinations of methyl bromide and chloropicrin control a variety of soilborne diseases in forest tree nurseries (Peterson and Smith 1975) and reduce populations of various other fungi (Mughogho 1968; Sakuwa et al. 1984; Trappe et al. 1984; Sumner et al. 1985; Himelrick 1986; McGraw and Hendrix 1986; Jones and Hendrix 1987; Nelson et al. 1995). Chloropicrin (alone, or in combination with other biocides) also has documented effects on bacteria, fungi, nematodes, and amoebae (Rhoades 1983; Ingham and Thies 1996).

Examination of the literature does not provide a broad basis for predicting the effects of chloropicrin applied to stumps on adjacent nontarget plants. However, Luoma and Thies (1994) found that total plant cover and individual species cover for *Berberis nervosa* Pursh and the moss *Stokesiella oregana* (Sull.) Robins were significantly reduced in the chloropicrin treatment plots 10 growing seasons after Douglas-fir trees were fumigated with chloropicrin.

The maximum distance chloropicrin diffuses in a root system or the rate at which it leaves the root system is not known. Two growing seasons after treatment, the odor of chloropicrin was commonly detected when roots were cut 1 m or less from the treated stump and occasionally detected when roots were cut as far as 2.4 m from the stump (Thies and Nelson 1987). Morrell et al. (1994) assessed chloropicrin concentrations and distributions 10 years after the fumigant was placed in the base of live Douglas-fir at the same study site used by Luoma and Thies (1994). Chloropicrin was detected by odor at the time the trees were cut and by chemical analysis of the wood. Castellano et al. (1993) found that after two growing seasons, Douglas-fir seedlings inoculated with *Rhizopogon* sp. perform equally well whether planted near chloropicrin-fumigated stumps or nonfumigated control stumps. Increasing moisture levels (20% of field capacity and above) and decreasing temperature reduce volatilization rates of chloropicrin (Tanagawa et al. 1985). Thus, we anticipate that dissipation of chloropicrin from a treated stump and surrounding soil on a site in the Pacific Northwest occurs over several years.

In this paper, we discuss changes in species abundance of vascular plants and moss that occurred 3 years after the application of chloropicrin to stumps for laminated root rot control. We also present serendipitous findings of a species richness gradient from the former edge of the forest stand toward the interior. Our evaluation of the impacts on plants is being paralleled by observations on the same plots by others for ectomycorrhizae (Castellano et al. 1993), soil microarthropods (Moldenke and Thies 1996*a*, 1996*b*), and soil foodweb organisms (Ingham and Thies 1996). Concurrent efforts monitored similarly fumigated living Douglas-fir trees at a site in the north Oregon Coast Range (Luoma and Thies 1994; Thies and Nelson 1996). The combined data will provide a clearer picture than we currently have of the impact of chloropicrin in Pacific Northwest temperate forest ecosystems.

Methods

Study area

The study area is an 8-ha clearcut with very low relief (≤2% slope) on the Olympic Peninsula near Matlock, Wash. (47°15′N, 123°25′W); mean elevation is 55 m, mean annual precipitation is 125 cm, and soil in the study area is a Hoodsport gravelly sandy loam (Haplorthod). The Hoodsport soil series formed in glacial deposits of 50–75 cm of loose ablation till overlaying very compact lodgment till. The site is class III (McArdle et al. 1961) and supported a 65-year-old naturally regenerated second-growth stand that was predominantly Douglas-fir (99% by harvest volume). Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) constituted the remainder of the overstory. Understory shrubs were primarily salal (*Gaultheria shallon* Pursh) with some

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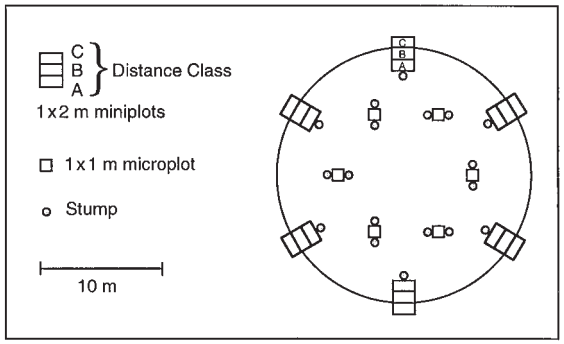
Fig. 2. Schematic layout of stump-centered vegetation sample plots within treatment macroplot.



sword fern (*Polystichum munitum* (Kaulf.) Presl) and a lesser component of twin flower (*Linnaea borealis* L.). Before clear-cutting, the site was part of a contiguous forest stand bordered by an access road and a recent clearcut to the west (Fig. 1).

Disease control study

A disease control study was established to determine the degree of reduction in laminated root rot reappearance in a replacement stand when stumps were treated with chloropicrin. Stumps were fumigated during October 1988, and the area was planted during February 1989. Plots were observed yearly to record seedling growth and mortality. Those results will be reported separately. The current study took advantage of plots and treated stumps established for the disease control study by monitoring treated areas and quantifying changes in plant species richness and cover.

The study area was subdivided, systematically searched, and the location of each *P. weirii* colonized stump mapped following the methods of Thies and Hoopes (1979). Using a map depicting stump locations, circular, 0.04-ha, nonoverlapping macroplots were established in locations that included concentrations of colonized stumps (Fig. 1). Within each macroplot, stumps received the same fumigant treatment.

Treatments

Treatments included two levels of chloropicrin fumigation and an untreated control. Macroplots were randomly assigned to each category. Eight macroplots of each treatment category were sampled in this study. Fumigation involved application of chloropicrin at either 100 or 20% of the labeled dosage to all stumps in a treated macroplot. The number of stumps in macroplots ranged from 12 to 44. The dosage was about 3.3 mL chloropicrin/kg stump and root biomass (Thies and Nelson 1987).

Application of fumigant

Fumigant application holes, 3.2 cm in diameter, were drilled vertically into each stump top either at fungus-stained areas when present or in unstained wood. Stumps with a diameter of ≤32.5 cm had a minimum of four holes drilled, one in each quadrant of the stump top; larger stumps had at least eight application holes drilled with at least two in each quadrant of the stump top. To avoid drilling through the stump, holes extended only slightly below the soil line. The total dose of chloropicrin was divided equally among all holes in a stump. After fumigant application, each hole was plugged tightly with a hemlock dowel that was sealed to resist passage of the fumigant. Thies and Nelson (1987) provide additional details of calculation of treated biomass, determination of dosage, and fumigant application.

Vegetation sampling

The study was designed to be analyzed as a two-factor ANOVA based on fumigation treatment and placement of sample plots relative to stumps. Spring and fall samples were included to measure vegetational changes during the growing season. Beginning with the spring following logging and fumigation (1989), vegetation was sampled twice yearly (June and September) for 3 years. Each macroplot was thoroughly searched during each sample period to determine vascular plant species richness. For mapping purposes (Fig. 1), a species richness index was developed to classify macroplots by mean number of vascular plant species present in a macroplot over the six sample periods. The species richness index was determined for each macroplot as follows: 1 = 22–31 species present, 2 = 32–36, 3 = 37–40, 4 = 41–44, 5 = 45–48.

Within each macroplot, stump-centered mini- and microplots were monitored for changes in vegetation. Percent cover of each vascular plant species and total moss cover (primarily *S. oregana*, with minor amounts of other species included) were assessed by two methods (Fig. 2): (1) eighteen 1 × 2 m miniplots placed in groups of three by distance from stump class (miniplots were arranged radially outward from six stumps on the periphery of the treatment macroplot and located at distances of 0–1 (distance class A), 1–2 (class B), and 2–3 m (class C) from the stump) and (2) six 1-m^2 microplots located between adjacent stumps.

The study sampled a total of 144 miniplots (48 in each distance class) and 48 microplots. The miniplots were placed to have the potential for detecting gradient effects away from stumps without being affected by other fumigated stumps in the same macroplot. The miniplots closest to stumps were designated class A, those farthest class C, with class B in-between (Fig. 2). The microplots were placed adjacent to two or more stumps so as to maximize the potential for exposure to the fumigant source. In cases where stumps were on opposite sides of a microplot, 0.5 m was the approximate maximum distance that plants in microplots were from the fumigant source. In contrast, the closest miniplot to a stump (class A) had <25% of its area within 0.5 m of a stump. Corners of the plots were marked with Fiberglas stakes, and PVC pipe plot frames were used to ensure measurement of the same locations from year to year.

Data analysis

In addition to canopy removal, the logging operation induced site variation through slash deposition, vegetation crushing, and soil compaction. Because of the several sources of impacts to the postharvest vegetation, sampling was designed to test fumigant effects on summer growth in addition to absolute differences in species abundance among treatments.

Comparisons among treatments for individual dominant or highly constant species and total vegetative cover were made by use of two-way ANOVA. Grouping factors were fumigant treatment (three levels) and distance relative to stump (four levels). The general null hypotheses tested was that species cover and changes in species cover do not differ among all treatment and distance classes. To reduce the likelihood of spurious significant results, the number of individual species comparisons (15) was limited to those species with constancy values (percentage of plots with the species present) ≥40%. Data values were transformed to more closely meet the assumptions of normal distribution and constant variance. A logit transformation was used on within-season individual species cover values (Sabin and Stafford 1990). Total cover received a square root transformation. Seasonal growth values were transformed using arcsine, hyperbolic arcsine, or arctangent formulas. Transformation of species richness values was not necessary to meet the assumptions of normal distribution and constant variance. Main effects were assessed only after the absence of interactions was demonstrated. Fisher's protected least significant difference (LSD) was used as a multiple comparison procedure ($p \leq 0.05$) only when the overall ANOVA p-value was ≤0.1.

Results and discussion

The two most frequently encountered vascular plant species in this study (Table 1), *G. shallon* (salal) and *Rubus ursinus*

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Table 1. Plant species encountered in all stump-centered plots (n = 576) during 1991, acromyms, constancy (%), and constancy the first spring following cutting (1989) in macroplots grouped by species richness index (see also Fig. 1).

Species	Acronym	Overall constancy*	Richness index group†				
			1	2	3	4	5
Trees							
Acer circinatum Pursh	ACCI	6	88	100	25	100	33
Acer macrophyllum Pursh	ACMA				25	50	33
Alnus rubra Bong.	ALRU	+					
Cornus nuttallii Audubon ex Torr. & A. Gray	CONU	+					
Pinus monticola D. Don	PIMO	1					
Prunus emarginata (Douglas ex Hook.) Walp.	PREM	4	38			50	33
Pseudotsuga menziesii (Mirb.) Franco‡	PSME	27	NR	NR	NR	NR	NR
Salix sp.	SALIX	1					
Tsuga heterophylla (Raf.) Sarg.	TSHE	1		40			
Shrubs							
Amelanchier alnifolia Nutt.	AMAL	4	63	40	50	25	67
Berberis nervosa Pursh	BENE	7	63	40	75	25	33
Chimaphila umbellata (L.) W. Bartram	CHUM	1	13				
Cornus canadensis L.	COCA	4		20	25		33
Corylus cornuta Marshall	COCO	+					
Gaultheria shallon Pursh	GASH	95	100	80	100	75	100
Holodiscus discolor (Pursh) Maxim.	HODI	1				25	33
Linnaea borealis L.	LIBO	60	100	100	100	100	100
Lonicera ciliosa (Pursh) DC.	LOCI	8	25	20	50	25	67
Oemleria cerasiformis (Torr. & A. Gray ex Hook. & Arn.) J.W. Landon	OECE	4	13	40	50	75	100
Physocarpus capitatus (Pursh) Kuntze	PHCA	1	13			25	33
Rhamnus purshiana DC.	RHPU	7	50	100	25	25	67
Ribes lobbii A. Gray	RILO	+					33
Ribes sanguineum Pursh	RISA	+					
Rosa gymnocarpa Nutt.	ROGY	11	88	80	75	100	67
Rubus laciniatus Willd.	RULA	3					
Rubus leucodermis Douglas ex Torr. & A. Gray	RULE	+					
Rubus parviflorus Nutt.	RUPA	13	13	20	25	25	67
Rubus spectabilis Pursh	RUSP	+					
Rubus ursinus Cham. & Schltdl.	RUUR	90	100	100	100	100	100
Sambucus sp.	SAMBU	+					
Symphoricarpos mollis Nutt.	SYMO	19	75	100	100	100	100
Vaccinium parvifolium Sm.	VAPA	28	100	100	100	100	100
Herbs							
Achlys triphylla (Sm.) DC.	ACTR	2				25	67
Adenocaulon bicolor Hook.	ADBI	2		20		75	33
Agoseris grandiflora (Nutt.) Greene	AGGR	1	38	20			67
Agrostis exarata Trin.	AGEX	+					
Agrostis tenuis Sibth.	AGTE	2		20	50		100
Aira caryophyllea L.	AICA	1					33
Anaphalis margaritacea (L.) Benth. & Hook.	ANMA	5	13	20	50		33
Anthoxanthum odoratum L.	ANOD	5			75	25	67
Asarum caudatum Lindl.	ASCA	1					
Blechnum spicant (L.) Sm.	BLSP	1		20		50	33
Bromus vulgaris (Hook.) Shear	BRVU	2	50		25	50	
Campanula scouleri Hook.	CASC	14		60	75	50	100
Carex laeviculmis Meinsh.	CALA	21	38	60	25	25	67
Chrysanthemum leucanthemum L.	CHLE	13		20	50	25	100
Cirsium arvense (L.) Scop.	CIAR	1					
Cirsium brevistylum Cronquist	CIBR	2			25		
Cirsium vulgare (Savi) Tenore	CIVU	40	50	60	75	75	100
Claytonia sibirica L.	CLSI	2				25	33
Collomia heterophylla Hook.	COHE	2					33
Crepis nicaeensis Balb. ex Pers.	CRNI	71	25	20	100	75	67

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Table 1 (*concluded*).

Species	Acronym	Overall constancy*	Richness index group†				
			1	2	3	4	5
Herbs							
Dicentra formosa (Andrews) Walp.	DIFO	+					
Digitalis purpurea L.	DIPU	+					
Disporum smithii (Hook.) Piper	DISM	6	25		75	50	100
Elymus glaucus Buckley	ELGL	3			25	25	100
Epilobium angustifolium L.	EPAN	67	100	60	75	50	33
Epilobium minutum Lindl.	EPMI	1					
Epilobium paniculatum Nutt.	EPPA	66	13	40	50	50	33
Epilobium watsonii Barbey	EPWA	63	75	100	25	100	100
Festuca occidentalis Hook.	FEOC	39	13	40	75	50	100
Festuca subuliflora Scribn.	FESU	3					33
Fragaria virginiana Duchesne	FRVI	4			50		33
Galium triflorum Michx.	GATR	29	25	60	75	50	33
Gnaphalium purpureum L.	GNPU	+					
Goodyera oblongifolia Raf.	GOOB	1	13			25	
Hieracium albiflorum Hook.	HIAL	24	13		50		67
Holcus lanatus L.	HOLA	3			25	25	67
Hypochaeris radicata L.	HYRA	88	100	60	100	100	100
Juncus sp.	JUNCU	+					
Lactuca biennis (Moench) Fernald	LABI	1					
Lactuca muralis (L.) Fresen.	LAMU	6				25	33
Lotus crassifolius (Benth.) Greene var. *subglaber* (Ottley) C.L. Hitchc.	LOCR	23			75	75	100
Lotus micranthus Benth.	LOMI	+	38	20			
Luzula campestris (L.) DC.	LUCA	61	88	100	25	100	
Luzula parviflora (Ehrh.) Desv.	LUPA	4	13		75		100
Maianthemum dilatatum (A.W. Wood) A. Nelson & J.F. Macbr.	MADI	1				25	
Melica smithii (Porter ex A. Gray) Vasey	MESM	+					67
Melica subulata (Griseb.) Scribn.	MESU	+					
Microseris sp.	MICRO	2					
Osmorhiza chilensis Hook. & Arn.	OSCH	+	13	40	50	75	100
Plantago lanceolata L.	PLLA	+				25	
Polystichum munitum (Kaulf.) C. Presl	POMU	21	88	100	100	100	100
Prunella vulgaris L.	PRVU	4				25	33
Pteridium aquilinum (L.) Kuhn	PTAQ	24	75	100	100	75	100
Ranunculus uncinatus D. Don var. *parviflorus* (Torr.)	RAUN	7		40	75	100	100
Rumex acetosella L.	RUAC	2		20			67
Senecio jacobea L.	SEJA	1		20	25	50	33
Senecio sylvaticus L.	SESY	67	25	100	100	100	100
Sonchus asper (L.) Hill	SOAS	7				25	
Stellaria longipes Goldie	STLO	+					
Stokesiella oregana (Sull.) Robins	MOSS	97	NR	NR	NR	NR	NR
Trientalis latifolia Hook.	TRLA	65	38	80	75	100	67
Trifolium repens L.	TRRE	1					
Trillium ovatum Pursh	TROV	2	25	20	50		
Trisetum canescens Buckley	TRCA	6		20	50	25	
Trisetum cernuum Trin.	TRCE	6		20		50	100
Veronica officinalis L.	VEOF	39	63	80	100	100	100
Viola sempervirens Greene	VISE	32	38	100	75	75	33

*Percentage of plots with the species present; +, <1%.

†Richness index groups are the mean number of vascular plant species present in macroplots over six sample periods where 1 = 22–31, 2 = 32–36, 3 = 37–40, 4 = 41–44, 5 = 45–48. NR, species not recorded in macroplots.

‡Planted seedlings excluded.

Cham. & Schltdl. (trailing blackberry), provide a good example of the early results. Both are common shrubs throughout the Western Hemlock Zone of Washington and Oregon (Franklin and Dyrness 1973). Information about preharvest vegetation of the forest was limited to a map of root rot induced canopy gaps and a coarse estimate of dominant shrub cover in 0.1-ha grid cells. *Gaultheria shallon* cover ranged from 70 to 100% on over half of the study site. Ingersoll et al. (1996)

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Table 2. Total plant cover (%, SE in parentheses, $n = 192$) in all stump-centered plots by treatment for spring and fall 1991 samples with overall ANOVA p-values.

		Chloropicrin (% of labeled dosage)		
Season*	Control	20	100	p
Spring	46.8 (1.7)*a*	37.6 (1.7)*b*	36.6 (1.7)*b*	0.0001
Fall	51.6 (1.5)*a*	45.9 (1.5)*b*	48.0 (1.7)*ab*	0.0192
p	0.0126	0.0001	0.0001	

Note: Levels of statistical significance were determined from transformed data values.

*Values within a season followed by a different letter are significantly different by Fisher's protected LSD ($p \leq 0.05$).

Table 3. Individual species mean cover change (%, SE in parentheses, maximum $n = 192$) in stump-centered plots, spring to fall 1991, by treatment with overall ANOVA p-values.

		Chloropicrin (% of labeled dosage)		
Species*	Control	20	100	p
MOSS	–7.2 (1.0)	–3.8 (0.5)	–4.1 (0.6)	0.7555
GASH	4.0 (0.5)	4.6 (0.4)	4.7 (0.5)	0.1380
RUUR	7.7 (0.8)*a*	5.2 (0.7)*b*	8.1 (0.8)*a*	0.0150
HYRA	–1.0 (0.3)*a*	–0.4 (0.2)*ab*	–0.2 (0.2)*b*	0.0606
CRNI	0.7 (0.2)*a*	0.2 (0.1)*b*	0.3 (0.1)*b*	0.0865
SESY	0.2 (0.1)	0.1 (0.1)	0.2 (0.1)	0.1694
EPAN	0.8 (0.3)	1.2 (0.3)	1.2 (0.3)	0.3545
EPPA	0.2 (0.1)	0.2 (0.1)	0.4 (0.1)	0.5889
TRLA	–0.3 (0.1)	–0.2 (0.1)	–0.2 (0.1)	0.6794
EPWA	0.2 (0.1)	0.1 (0.1)	0.3 (0.1)	0.2292
LUCA	–0.4 (0.1)*a*	–0.5 (0.1)*ab*	–1.0 (0.2)*b*	0.0069
LIBO	0.6 (0.3)*a*	3.0 (0.8)*b*	1.9 (0.5)*b*	0.0450
CIVU	0.0 (0.1)	0.0 (0.1)	0.0 (0.1)	0.8081
FEOC	–3.4 (1.0)*a*	–1.3 (1.0)*b*	–0.6 (0.4)*b*	0.0485
VEOF	1.3 (0.4)	1.7 (0.8)	1.0 (0.3)	0.7536

Note: Levels of statistical significance were determined from transformed data values.

*Values within a species followed by a different letter are significantly different by Fisher's protected LSD ($p \leq 0.05$).

Table 4. Individual species mean cover (%, SE in parentheses, maximum $n = 192$) in stump-centered plots for spring and fall 1991 by treatment with overall ANOVA p-values.

			Chloropicrin (% of labeled dosage)		
Species*	Season	Control	20	100	p
MOSS	Spring	9.5 (1.2)*a*	5.1 (0.7)*b*	5.8 (0.7)*ab*	0.0065
	Fall	1.8 (0.3)	1.1 (0.2)	1.6 (0.3)	0.2664
GASH	Spring	7.4 (0.7)*a*	8.5 (0.7)*b*	7.7 (0.5)*b*	0.0001
	Fall	12.1 (1.1)*a*	13.0 (0.9)*b*	12.3 (0.8)*b*	0.0006
RUUR	Spring	4.0 (0.4)*a*	2.9 (0.2)*b*	3.0 (0.2)*ab*	0.0796
	Fall	11.4 (1.0)*ab*	8.2 (0.8)*a*	11.8 (1.0)*b*	0.0539
HYRA	Spring	3.7 (0.5)*a*	2.5 (0.2)*ab*	2.2 (0.3)*b*	0.0432
	Fall	2.7 (0.3)*a*	2.1 (0.2)*ab*	2.0 (0.2)*b*	0.0212
CRNI	Spring	1.5 (0.2)*a*	1.1 (0.2)*b*	0.8 (0.1)*b*	0.0026
	Fall	2.2 (0.2)*a*	1.3 (0.2)*b*	1.1 (0.2)*b*	0.0117
SESY	Spring	0.3 (0.1)*a*	0.2 (0.1)*b*	0.2 (0.1)*ab*	0.0646
	Fall	0.6 (0.1)*a*	0.3 (0.1)*b*	0.4 (0.1)*ab*	0.0757
EPAN	Spring	2.9 (0.4)	3.1 (0.3)	3.3 (0.4)	0.2641
	Fall	3.6 (0.5)	4.3 (0.5)	4.3 (0.5)	0.3158
EPPA	Spring	0.3 (0.1)	0.4 (0.1)	0.4 (0.1)	0.4931
	Fall	0.5 (0.1)*a*	0.6 (0.1)*ab*	0.8 (0.1)*b*	0.0969
TRLA	Spring	0.5 (0.1)	0.4 (0.1)	0.4 (0.1)	0.7327
	Fall	0.3 (0.1)*a*	0.1 (0.1)*b*	0.2 (0.1)*ab*	0.0650
EPWA	Spring	0.6 (0.1)	0.5 (0.1)	0.6 (0.1)	0.6585
	Fall	0.9 (0.1)	0.7 (0.1)	1.0 (0.2)	0.2186
LUCA	Spring	1.0 (0.2)	1.1 (0.1)	1.6 (0.3)	0.1495
	Fall	0.6 (0.1)	0.7 (0.1)	0.6 (0.1)	0.6468
LIBO	Spring	2.6 (0.6)*a*	8.4 (1.1)*b*	6.4 (1.1)*b*	0.0001
	Fall	3.4 (0.8)*a*	11.4 (1.5)*b*	8.0 (1.1)*b*	0.0001
CIVU	Spring	0.3 (0.1)*a*	0.3 (0.1)*ab*	0.4 (0.1)*b*	0.0516
	Fall	0.4 (0.1)*a*	0.4 (0.1)*ab*	0.6 (0.1)*b*	0.0324
FEOC	Spring	8.7 (1.7)*a*	5.1 (2.1)*b*	5.0 (2.2)*b*	0.0001
	Fall	5.3 (1.0)*a*	3.9 (1.2)*b*	3.6 (1.7)*b*	0.0031
VEOF	Spring	9.9 (1.2)*a*	11.0 (2.2)*a*	4.4 (0.6)*b*	0.0075
	Fall	10.8 (1.3)*a*	11.9 (2.4)*a*	5.2 (0.8)*b*	0.0763

Note: Levels of statistical significance were determined from transformed data values.

*Values within a species followed by a different letter are significantly different by Fisher's protected LSD ($p \leq 0.05$).

estimated a 60% mean *G. shallon* cover for the study site prior to harvest. At the beginning of the first growing season post-harvest, mean *G. shallon* cover was reduced to 4% in the macroplots. Observations of dead leaves and stems showed that the logging operation produced an initial decrease in cover of *R. ursinus*, but the range of decrease could not be quantified because of the lack of precut data. Postharvest, mean *R. ursinus* cover was 1% in the macroplots. At the end of the first growing season (1989), microplots showed a significantly ($p \leq 0.001$) greater increase in the cover of these two species than the miniplots, regardless of treatment. This growth response can be attributed to the physically protected nature of the microplots relative to the impacts of the logging operation. The location of the 1×1 m microplots in contact with stumps and their smaller size made them less susceptible to being disturbed by the logging equipment than the miniplots that were intentionally placed to avoid proximity to other stumps (Fig. 2). Most of the area of the miniplots was in the open and subject to scarification and compaction.

For the purposes of this paper, data from the third growing season (1991) serve to exemplify the analysis and results from the first two seasons during which the vegetation exhibited similar responses to those found in the third year. At the beginning of the third growing season, total plant cover was highest in nonfumigated plots, regardless of plot distance from stump (Table 2). At the end of the third growing season, total plant cover was greater in microplots (those placed between stumps) than in open-site miniplots, regardless of treatment ($p = 0.0009$). The higher total cover on the microplots is primarily attributable to continuing greater growth of *G. shallon* and *R. ursinus* and from a much lower decline in moss cover during the season ($p = 0.0001$).

Generally, statistical interactions between fumigation treatment and plot distance to stump class (potential intensity of exposure) were lacking, thus providing little indication that the surrounding vegetation had been affected by chloropicrin. There was one exception; at the end of the third growing season, *Trientalis latifolia* Hook. had significantly greater ground cover in the nonfumigated microplots than those microplots

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Table 5. Adjusted correlation coefficients of macroplot species richness versus square root of macroplot distance from original stand edge with associated *p*-values ($n = 24$).

Sample period	Adj. R^2	*p*
Spring 1989	0.52	0.0001
Fall 1989	0.27	0.0052
Spring 1990	0.48	0.0001
Fall 1990	0.37	0.0009
Spring 1991	0.33	0.0019
Fall 1991	0.22	0.0118

Table 6. Mean cumulative species richness in macroplots (SE in parentheses, $n = 24$) for 1989–1990, shown by treatment.

Treatment*	Richness
Control	37.3 (1.4)*a*
Chloropicrin (20% of labeled dosage)	34.1 (1.0)*b*
Chloropicrin (100% of labeled dosage)	34.0 (1.2)*b*

*Values followed by a different letter are significantly different by Fisher's protected LSD ($p = 0.07$).

treated with chloropicrin ($p < 0.01$). *Trientalis latifolia* did not differ in abundance among treatments in the miniplots ($p > 0.33$). This may be attributable to so little area of the class A miniplots being in a zone of maximum exposure comparable with that of the microplots.

Trientalis latifolia had markedly higher mean cover in the microplots than in the miniplots ($p < 0.003$), leading to the conclusion that these microsites afforded protection of the soil that was important for this rhizomatous species. The reduced mean ground cover of this species in fumigated microplots suggests that *Trientalis* may be sensitive and act as an early indicator of chloropicrin effects in the clearcut habitat of this study. These results build on those of Luoma and Thies (1994) where, using plots that extended out 1 m from the base of live trees, effects were found on the vegetation 10 years after chloropicrin fumigation. In that forest study, which had substantially different light and moisture regimes, the shrub *B. nervosa* decreased around treated trees while the low vine *R. ursinus* increased in cover. *Trientalis latifolia* did not differ in abundance around fumigated and control trees, potentially because of a general suppression of its growth by competition for light. Additionally, the Luoma and Thies (1994) plots covered considerable area >0.5 m from the tree base and thus were more comparable with the class A miniplots in terms of fumigant exposure potential.

Our finding of fumigation effects on *T. latifolia* only in plots with the greatest potential exposure is similar to the pattern found on the same site 1 year after treatment by Moldenke and Thies (1996*b*) with soil arthropods. In stump-centered samples (greatest potential exposure), six of eight functional guilds were significantly different in control plots whereas area-wide random samples from the macroplots revealed only one significant shift in abundance. Ingham and Thies' (1996) study of soil foodweb organism responses on the same site 1 year after treatment showed little contrast between stump-centered and area-wide samples. Using stump-centered points, three fumigant treatment soil samples out of 180 had significant decreases in all organism numbers as compared with soil samples from around control stumps. Area-wide random samples from macroplots showed decreased soil foodweb organisms in one out of 45 soil cores in chloropicrin-treated areas. They concluded that their data showed little evidence of significant chloropicrin effects in the first year following stump fumigation (Ingham and Thies 1996).

Table 7. Mean distance from macroplot to preharvest stand edge and nearest canopy gap (m, $n = 8$).

Treatment	Edge distance	Gap distance
Control	108.8	13.9
Chloropicrin (20% of labeled dosage)	143.2	31.9
Chloropicrin (100% of labeled dosage)	154.5	48.3

We found a general trend of greater seasonal growth in the microplots than in miniplots when significant ($p \leq 0.05$) growth differences were detected. *Festuca occidentalis* Hook. had lower initial values on microplots but increased mean cover over the season compared with decreases on miniplots. The exception was *T. latifolia*, which had maximum cover in spring. Its cover declined more in microplots over the summer, but started from a greater initial value.

Individual species mean cover change varied significantly ($p \leq 0.05$) among treatments for six of the 15 examined species (Table 3; species are ordered according to overall constancy in Tables 3 and 4). No consistent pattern emerged, however. Half of these species had less growth in the control plots and half demonstrated more growth or smaller decreases in control plots. Similarly, species' mean percent cover in spring and fall (Table 4) showed no consistent differences with respect to the fumigation treatment.

An important aspect of this study is the size of the LSD in the cover data. The intensity of sampling relative to the variation in the data produced a Fisher's protected LSD that ranged from about 0.5 to 2% ground cover. The sampling intensity of this study resulted in statistically significant differences that are biologically meaningful. The study design was successful in matching sampling effort with the ability to make biological interpretations.

An unexpected result of this study was the detection of a species richness gradient from the former edge of the stand toward the interior (Fig. 1). This phenomenon was detected at the macroplot level and is distinct from the stump-centered investigation of fumigant effects on plant cover. Species richness tended to be greater when macroplots were closer to the preharvest stand edge (a long-established road with an adjacent clearcut), particularly in the first spring following harvest (Table 5). Control macroplots had higher mean species richness (Table 6) but were closer to the previous stand edge than treated macroplots (Table 7). Control plots were also closer to root rot induced gaps (Table 7), which increase edge effects, but those distances did not make a significant ($p \leq 0.05$) contribution to a stepwise regression model that already contained distance to former stand edge (Table 5). The distance from edge effect on species richness decreased with time (but was still significant in 1991) after the entire area was opened up to propagule dispersal (Table 5). The gradual lessening of the

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Table 8. Mean species richness shown by year and season with overall ANOVA *p*-values (SE in parentheses, $n = 24$).

Season*	1989	1990	1991	*p*
Spring	28.4 (1.6)*a*	36.8 (1.9)*b*	39.9 (1.6)*b*	0.0001
Fall	34.3 (1.6)	36.5 (1.6)	34.8 (1.1)	0.5023
p	0.0112	0.9074	0.0120	

*Values within a season followed by a different letter are significantly different by Fisher's protected LSD ($p \leq 0.05$).

residual edge effect was further evidenced by overall mean species richness, which reached a maximum in the third spring after clear-cutting (Table 8). Fumigant effects on individual plant species cover and change in cover were not confounded by the closeness of control plots to the previous forest edge because those effects were evaluated using measurements from stump-centered small plots that differed by proximity to the fumigant source.

It is particularly useful to compare richness group 1 ($n = 8$) with pooled groups 4 and 5 ($n = 7$) to examine the association of particular species with lower or higher macroplot species richness (Table 1). Response to the increased light levels of the edges and the ruderal habit of many species (Ingersoll et al. 1996) seemed to contribute most to higher species richness. Other factors such as propagule dispersal (prevailing westerly winds) and soil conditions would need to be considered in any extensive investigation of this phenomenon.

The species that contributed most to the species richness gradient were *Acer macrophyllum* Pursh, *Achlys triphylla* (Sm.) DC., *Adenocaulon bicolor* Hook., *Agrostis tenuis* Sibth., *Campanula scouleri* Hook., *Chrysanthemum leucanthemum* L., *Crepis nicaeensis* Balb. ex Pers., *Disporum smithii* (Hook.) Piper, *Festuca occidentalis* Hook., *Holodiscus discolor* (Pursh) Maxim., *Holcus lanatus* L., *Lactuca muralis* (L.) Fresen., *Lonicera ciliosa* (Pursh) DC., *Lotus crassifolius* (Benth.) Greene var. *subglaber* (Ottley) C.L. Hitchc., *Oemleria cerasiformis* (Torr. & A. Gray ex Hook. & Arn.) J.W. Landon, *Melica smithii* (Porter ex A. Gray) Vasey, *Prunella vulgaris* L., *Ranunculus uncinatus* D. Don var. *parviflorus* (Torr.), *Rumex acetosella* L., *Rubus parviflorus* Nutt., *Senecio sylvaticus* L., *Trisetum cernuum* Trin., and *Veronica officinalis* L. (Table 1).

Conclusions

Assessment of vegetational change during the first 3 years following clear-cut logging is important because of rapidly changing species abundance in early succession (Halpern et al. 1997). To test for fumigation effects, we augmented simple comparisons of plant cover among treatments with the examination of seasonal growth differences. This approach and the use of interaction tests between treatment and distance to stump main effects allowed us to more clearly interpret the results in light of the dominant impacts of the logging operation. We found that *T. latifolia* may be sensitive and act as an early indicator of chloropicrin effects in the clearcut habitat of this study. However, the general lack of statistical interaction between distance of plot to stump (chloropicrin exposure potential) and fumigation treatment leads us to conclude that the chloropicrin had little other effect on surrounding vegetation in the first 3 years following application. We hypothesize that the chloropicrin was not released at a great enough rate during the 3 years following treatment to affect most of the surrounding vegetation. Effects that may be attributed to harvest methods, study layout, and pretreatment conditions were detected. Since Luoma and Thies (1994) found that chloropicrin fumigation reduced total plant ground cover 10 years after treatment of live trees, we anticipate that chloropicrin can be expected to have increasingly detectable effects sometime between years 4 and 9 posttreatment. The results also demonstrate the magnitude of edge effects on species richness over a considerable distance (100 m) in forest stands and the legacy of edge effects over time. We emphasize the need to consider those effects in study planning.

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