Effects of live tree fumigation on nontarget vegetation

DANIEL L. LUOMA[1]
Department of Forest Science, Oregon State University, Corvallis, OR 97331, U.S.A.
AND
WALTER G. THIES
USDA Forest Service, Pacific Northwest Research Station, 3200 Jefferson Way, Corvallis, OR 97331, U.S.A.

Received March 31, 1994
Accepted August 15, 1994

LUOMA, D.L., and THIES, W.G. 1994. Effects of live tree fumigation on nontarget vegetation. Can. J. For. Res. **24**: 2384–2389.

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees, both healthy and infected by *Inonotus sulphurascens* (Pilát) M.J. Larsen, F.F. Lombard, & J.W. Clark (*Phellinus weirii* sensu lato), were fumigated with chloropicrin or methylisothiocyanate at a site in the Oregon Coast Range. Ten growing seasons later, vegetation cover on plots around treated and untreated individuals was evaluated to determine fumigant effects on nontarget plants. Total plant cover and individual species cover for *Berberis nervosa* Pursh and *Stokesiella oregana* (Sull.) Robins were significantly reduced in the chloropicrin treatment plots. The dominant shrub, *Gaultheria shallon* Pursh, was little affected in chloropicrin plots. Slightly greater species richness and *Rubus ursinus* Cham. & Schlecht. cover in chloropicrin plots were attributed to higher light levels and other factors associated with reduced shrub cover on the treated plots. Multivariate analysis showed little overlap in plant community structure between chloropicrin-treated and control plots. Detection of effects due to the methylisothiocyanate treatment was hindered by the lack of strictly paired control trees. The results are discussed in relation to the retrospective nature of the study.

LUOMA, D.L., et THIES, W.G. 1994. Effects of live tree fumigation on nontarget vegetation. Can. J. For. Res. **24** : 2384–2389.

Des sapins de Douglas (*Pseudotsuga menziesii* (Mirb.) Franco, sains et infectés par *Inonotus sulphurascens* (Pilát) M.J. Larsen, F.F. Lombard, & J.W. Clark (*Phellinus weirii* sensu lato), ont été fumigés avec la chloropicrine ou l'isothiocyanate de méthyl dans une station de la chaîne côtière de l'Orégon. Dix ans plus tard, le couvert végétal au sol présent dans les parcelles entourant les arbres traités et témoins a été évalué pour évaluer l'effet des fumigants sur les plantes non visés par le traitement. Le couvert total et le couvert d'espèces individuelles, comme *Berberis nervosa* Pursh et *Stokesiella oregana* (Sull.) Robins, furent significativement réduits dans les parcelles traitées avec la chloropicrine. L'arbuste dominant, *Gaultheria shallon* Pursh, a été peu affecté dans les parcelles traitées. La richesse en espèces et le couvert de *Rubus ursinus* Cham. & Schlecht. qui étaient légèrement plus élevés dans les parcelles traitées avec la chloropicrine furent attribués à des niveaux de lumière plus élevés et à d'autres facteurs associés au faible couvert d'arbustes dans les parcelles traitées. L'analyse multivariée a montré peu de recouvrement dans la structure de la communauté végétale entre les parcelles témoins et celles qui avaient été traitées avec la chloropicrine. La détection des effets dus au traitement avec l'isothiocyanate de méthyl a été rendue difficile à cause du mauvais pairage des arbres témoins. Les résultats sont discutés dans le contexte d'une étude rétrospective.

[Traduit par la Rédaction]

Introduction

Laminated root rot, caused by *Inonotus sulphurascens* (Pilát) M.J. Larsen, F.F. Lombard, & J.W. Clark, is widespread throughout the range of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). *Inonotus sulphurascens* primarily affects Douglas-fir, but many conifer species appear to be susceptible to some degree. The closely related *Inonotus weirii* (Murr.) Kot. & Pouzar is primarily a root and stem decay fungus of *Thuja plicata* Donn (Larsen et al. 1994). The disease caused by these organisms 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).

We accept and adopt the taxonomic and nomenclatural conclusions reached by Larsen et al. (1994). They have determined that the fungus previously known as the Douglas-fir form of *Phellinus weirii* (Murr.) Gilbertson is conspecific with *Phellinus sulphurascens* Pilát, originally described from Siberia. The fungus causing laminated root rot on Douglas-fir demonstrated mating incompatibility with *Phellinus weirii* sensu stricto. Both species are now properly placed in the genus *Inonotus* (Larsen et al. 1994).

Treatment of stumps with chloropicrin[2] has been shown to dramatically reduce the amount of laminated root-rot inoculum on a forest site (Thies and Nelson 1987*a*), and chloropicrin has been labeled by the U. S. Environmental Protection Agency for this use. Potentially widespread general use of this chemical to kill *I. sulphurascens* necessitates the gathering of information as to its effects on organisms other than those targeted.

Chloropicrin is a general biocide that has been used as a soil fumigant and studied for its effectiveness in reducing specific pests; however, information on effects on nontarget organisms is scanty. In laboratory and field experiments, chloropicrin (alone, or in combination with other biocides)

[1]Author to whom all correspondence should be addressed.

[2]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.

has killed organisms from several groups: vascular plants, fungi, nematodes, and bacteria (Jones and Hendrix 1987; Martin and Kemp 1986; Ono 1985; Peterson and Smith 1975; Rhoades 1983; Sumner et al. 1985; Trappe et al. 1984.) Direct assessment of the movement of chloropicrin in ecosystems has not been ascertained (Castellano et al. 1993).

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 stump fumigation as a means of eradicating *I. sulphurascens* from stumps (Thies and Nelson 1982). The maximum distance chloropicrin diffuses in a root system or the rate at which it leaves the root system is not known. Thies and Nelson (1987*a*) found that the odor of chloropicrin was commonly detected when roots from treated stumps were cut 1 m or less from that stump and occasionally was detected when roots were cut as far as 2.4 m from the stump two growing seasons after treatment. 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 temperatures reduce volatilization rates of chloropicrin (Tanagawa et al. 1985). Thus we anticipate that disappearance of chloropicrin from treated substrates may take many years in the Pacific Northwest.

A study was established in 1981 to determine if living Douglas-fir can tolerate levels of either chloropicrin or methylisothiocyanate (MITC) necessary to kill wood-inhabiting fungi in roots and stems (Thies and Nelson 1987*b*). Further results of that research (of which, the present paper is an extension) are in preparation (W. Thies, unpublished data). The fungicide MITC is a major component of commonly used wood fumigants (Morrell 1989). It is registered for use on wood utility poles. Research on this chemical has concentrated on its effectiveness as a fungicide and its diffusion and sorption in Douglas-fir heartwood (Zahora and Morrell 1988, 1989). MITC performs as well as chloropicrin at protecting utility poles from fungal decay (Morrell 1989). Our review of the literature did not find papers reporting the impacts of MITC on nontarget organisms. We would expect that the fumigants move through and escape from the roots of the treated live trees in much the same way they do in treated stumps.

In this paper, we discuss differences in the composition and species diversity of understory plant communities associated with application of chloropicrin or MITC to live Douglas-fir trees in an Oregon Coast Range forest ecosystem. Our evaluation of nontarget organisms at the site of this study parallels a 3-year effort of monitoring similarly fumigated stumps at a site in western Washington (Ingham et al. 1991; Thies et al. 1991). The combined data will provide a clearer picture than we currently have of the impact of chloropicrin in Pacific Northwest temperate forest ecosystems.

Study area description

The study area, in the Oregon Coast Range near Apiary, Oregon (46°01′N, 123°04′W), had the following characteristics: elevation 420 m, slope 0–35%, mean annual precipitation 145 cm, and Olympic silt loam soil. At the time of our observations (1991), the 57-year-old, naturally regenerated stand was strongly dominated by Douglas-fir. Stand growth characteristics indicated that the stand occupied land that should receive designation of site class II (McArdle et al. 1961). Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) constituted the remainder of the overstory and most of the natural tree reproduction. The understory was dominated by salal (*Gaultheria shallon* Pursh), sword-fern (*Polystichum munitum* (Kaulf.) Presl), and mountain Oregon-grape (*Berberis nervosa* Pursh).

Methods

Selection of trees

For the tree fumigation study (established 1981, Thies and Nelson 1987*b*), dominant and codominant Douglas-fir, with clearly visible crowns, were selected. Trees showing severe stress symptoms were rejected. Because tolerance of an individual tree to fumigants could depend on presence and causal organism of stem and root decay, trees in three classes of probable decay caused by *I. sulphurascens* were selected. Candidate trees were examined for the presence of *I. sulphurascens* by carefully exposing major lateral roots within 60 cm of the base of the tree, examining the root surface for characteristic ectotrophic mycelium, and occasionally boring with an increment borer to detect stained or decayed root wood. Each tree was tagged, measured, and then, based on examination results, assigned to one of three infection classes: I, *I. sulphurascens* infected; II, *I. sulphurascens* ectotrophic mycelium absent from subject tree, but probably infected (i.e., with crown symptoms and inoculum within 5 m); and III, probably uninfected, no symptoms and no identified inoculum source within 25 m of subject tree.

Each infection class contained 45 trees separated into five groups of nine based on diameter at breast height (DBH) and tree location. Selected trees ranged in diameter from 27.4 to 62.2 cm. Treatments were randomly assigned to trees within each group.

Fumigation

Test dosages were based on a dosage expected to kill *I. sulphurascens* in treated wood. Earlier work (Thies and Nelson 1982) suggested that a dose of 6.7 mL of either chloropicrin or Vorlex per kilogram of stump and root biomass was sufficient to eradicate *I. sulphurascens*. The active ingredient in Vorlex is MITC. In the initial fumigation study, a standard dosage (D) was 6.7 mL of chloropicrin or 1.5 g of MITC per kilogram of treated biomass. The dosage for MITC was based on the concentration of MITC in Vorlex. It was assumed that the dose tolerated by a tree would vary linearly with the estimated biomass of its major roots and lower bole (first 2.4 m of bole). The dose applied to each tree was based on biomass, as estimated from DBH. Fumigants were introduced through holes drilled near the base of the tree down toward the root collar. Chloropicrin and MITC treatments were applied in March 1982. Details of the study installation and the survival and appearance of the treated trees after three seasons have been reported (Thies and Nelson 1987*b*).

Treatments

This study examined treatment impact on the plant community immediately around treated trees. The study sampled a total of 24 trees. Vegetation cover was assessed around four trees in each of four chloropicrin categories: (1) known infected, untreated; (2) presumed healthy, untreated; (3) known infected, treated; and (4) presumed healthy, treated. Vegetation cover was also assessed around eight trees treated with MITC regardless of health category. The control (untreated) trees to be used were not necessarily those from the original study. During the 10 growing seasons following treatment, many trees were lost and salvaged from the test stand, thus changing the amount of light reaching the ground and influencing the associated plant cover. Control trees were selected to be those (infected or uninfected as appropriate to

TABLE 1. Plant species encountered in all plots (n = 24), acronyms, and abundance values

Species	Acronym	Constancy*	Cover†
Trees			
Acer circinatum	ACCI	46	7
Pseudotsuga menziesii‡	PSME	8	+
Tsuga heterophylla‡	TSHE	38	1
Shrubs			
Berberis nervosa	BENE	71	16
Gaultheria shallon	GASH	88	27
Ribes sp.	RIBES	4	+
Rosa gymnocarpa	ROGY	13	+
Rubus leucodermis	RULE	8	+
Rubus parviflorus	RUPA	8	+
Rubus ursinus	RUUR	83	2
Vaccinium alaskaense	VAAL	8	+
Vaccinium parvifolium	VAPA	54	4
Herbs			
Anemone deltoidea	ANDE	8	+
Athyrium filix-femina	ATFI	4	+
Blechnum spicant	BLSP	4	+
Campanula scouleri	CASC	17	+
Chimaphila menziesii	CHME	4	+
Chimaphila umbellata	CHUM	4	+
Cirsium vulgare	CIVU	8	+
Digitalis purpurea	DIPU	4	+
Disporum smithii	DISM	4	+
Festuca occidentalis	FEOC	4	+
Festuca subuliflora	FESU	8	+
Galium triflorum	GATR	71	1
Hieracium albiflorum	HIAL	4	+
Holcus lanatus	HOLA	4	+
Hypochaeris radicata	HYRA	4	+
Lotus crassifolius	LOCR	17	1
Lupinus rivularis	LURI	8	+
Luzula parviflora	LUPA	17	+
Osmorhiza chilensis	OSCH	21	+
Oxalis oregana	OXOR	8	+
Poaceae	GRASS	4	+
Polystichum munitum	POMU	88	19
Pteridium aquilinum	PTAQ	21	1
Pyrola picta	PYPI	4	+
Ranunculus uncinatus	RAUN	8	+
Stokesiella oregana	STOR	100	15
Trientalis latifolia	TRLA	46	+
Trilium ovatum	TROV	13	+
Veronica officinalis	VEOF	21	+
Viola sempervirens	VISE	67	1

*Percent of plots with the species present.
†Mean percent cover. +, <1.
‡Reproduction cover only; trees <3 m tall.

match treatment) nearest the chloropicrin-treated subject tree that exhibited a similar structural environment (diameter, crown position, stand density, proximity to skid roads, gaps and other species, especially hemlock and vine maple). This was done to standardize the light conditions of the pairs as much as possible. Plots were not located where soil disturbance was evident. Owing to the selection and grouping of trees in the original study, the MITC-treated trees were near the chloropicrin-treated trees. The new control trees were used in comparisons with both chloropicrin and MITC treatments. All chloropicrin-treated trees were from the 0.25D treatment group. MITC dosage levels varied, with three trees at 1.0D, two at 0.5D, and three at 0.25D.

Vegetation

Vegetation was measured as percent cover for each species in plots centered on treated and control trees. Each plot had a radius extending 1.5 m from the base of the treated bole to yield a sample area of about 10 m^2. Species richness was determined as the number of plant species in each plot. Moss cover was almost exclusively finger moss (*Stokesiella oregana* (Sull.) Robins), although minor amounts of other species were included within its cover values. The vegetation data were collected in July 1991.

Data values were transformed to more closely meet the assumptions of normal distribution and constant variance (Sabin and Stafford 1990). Comparisons of chloropicrin and control treatments for individual dominant or highly constant species and total vegetative cover were made by use of a paired t-test of cover values after a square-root transformation. Comparisons of MITC and control treatments were made by use of a nonpaired t-test because control trees were not paired with MITC treated trees. The number of individual species comparisons (8) was limited to species with constancy values ≥50% to reduce the likelihood of spurious significant results. Differences in species richness were tested (paired and nonpaired t-tests as above) after a square-root transformation. Analysis of the vegetation structure was accomplished by way of multivariate ordination of the vegetation in each tree-centered plot by using the program DECORANA (Hill 1979). Species cover values were converted to an octave scale prior to ordination. This is essentially a log base 2 transformation (Gauch 1982).

TABLE 2. Mean cover (%) and standard error (in parentheses) of variables that showed significant differences between treatments

Cover	Control (n = 8)	Chloropicrin (n = 8)	p value*
Total plant cover	102.8 (9.6)	85.1 (5.8)	0.06
Stokesiella oregana	19.6 (8.6)	8.3 (4.7)	0.03
Berberis nervosa	15.5 (5.1)	7.1 (4.4)	0.03
Rubus ursinus	0.8 (0.4)	2.0 (0.6)	0.01

*From t-test on transformed data.

Results and discussion

Data from all plots (Table 1) show that the vegetation represents a seral stage of a *T. heterophylla* / *G. shallon* – *P. munitum* plant association (Franklin and Dyrness 1973). There were no statistically significant differences in plant species cover (p = 0.71) or richness (p = 0.91) between the control plots and the MITC plots. The inability to detect treatment effects with MITC is not surprising because control trees were not specifically matched to the MITC treatment. In fact, field notes for three of the MITC trees state that the control trees were particularly poor matches in terms of stand structure. The lack of complete pairing necessitated the use of a less powerful, nonpaired statistical test (Snedecor and Cochran 1980). The problematic nature of the MITC data precludes further interpretation of that treatment and emphasizes the need for well-planned comparisons. Infection status of the test trees had no significant relationship with plant species cover (p = 0.88) or richness (p = 0.89).

Compared with chloropicrin-treated plots, total plant cover was greater on control plots (Table 2). Chloropicrin-treated plots had an average of 18% less total cover. Mean total plant cover of the chloropicrin plots included a 27% (statistically nonsignificant, p = 0.77) reduction in *P. munitum* cover. Control plots had 2.4 times greater mean cover for *S. oregana* and 2.2 times greater *B. nervosa* cover. Though low in relative abundance, *Rubus ursinus* Cham. & Schlecht. cover doubled in chloropicrin-treated plots. A total of 42 species were recorded; 27 were in chloropicrin plots and 22 in control

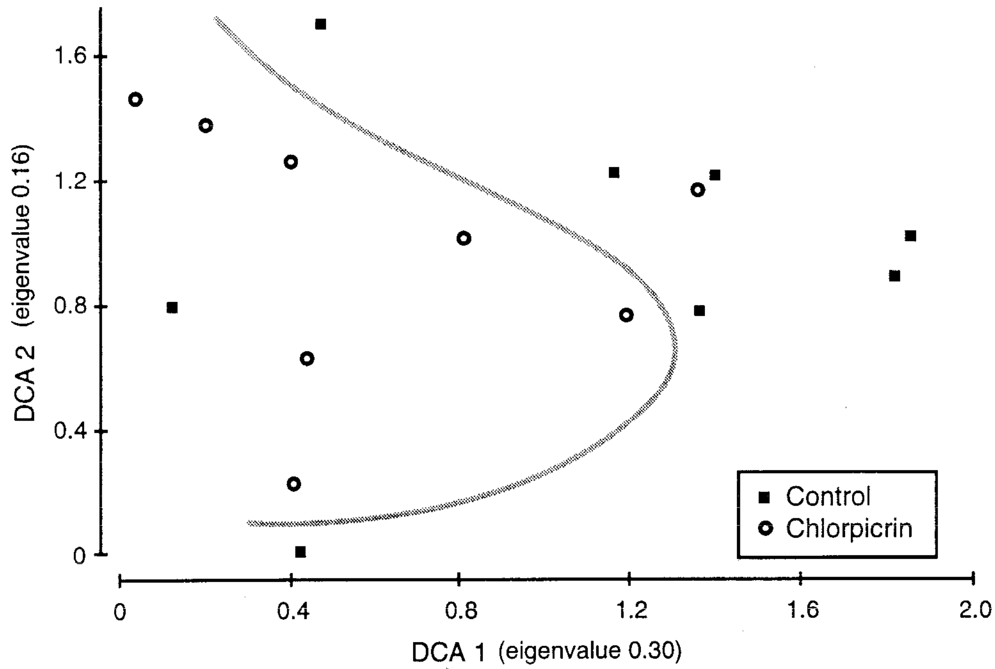

FIG. 1. Plot of control and chloropicrin plots in two-dimensional ordination space derived from detrended correspondence analysis (DCA). Axis scale is in standard deviation units.

plots. Mean species richness was 10.5 in chloropicrin plots and 9 in control plots ($p = 0.04$).

The slightly higher mean species richness and *R. ursinus* cover in the chloropicrin-treated plots is interpreted as a response to increased available light resulting from lower mean *B. nervosa* and *P. munitum* cover. The trailing growth form of *R. ursinus* is well adapted to exploiting areas of increased sunlight on the forest floor (D. Luoma and T. Spies (Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, OR 97331), personal observations) while allowing it to be rooted away from the treated trees. The ecological importance of a 1% change in the cover of *R. ursinus* is open to question. The apparent lack of chloropicrin treatment effect on *G. shallon* cover may indicate tolerance to the fumigant. *Gaultheria shallon* is strongly rhizomatous and may also be responding opportunistically to light gaps in a manner similar to *R. ursinus*. Growth responses of *G. shallon* to various light conditions have been demonstrated (Huffman et al. 1994; Smith 1991; Vales 1986).

Occupation of distinct areas in ordination space by control and treatment plots (Fig. 1) indicates that the chloropicrin treatment is associated with changes in plant community composition. The eigenvalues of DCA axes 1 and 2 are 0.30 and 0.16, respectively. The gray line in Fig. 1 is a visual borderline placed equidistant between chloropicrin and control plot points. It serves to separate two groups of plots; only one member of each treatment is in the ordination space of the other group. Although the plots are in the same vegetation association, enough divergence has occurred between treatments to be detectable by this multivariate approach. Table 3 provides the relative abundance of each species in each plot. Several differences in community structure between the control and chloropicrin treatments are evident in Table 3. Of the species with more than a single occurrence, *Campanula scouleri* Engelm., *Cirsium vulgare* (Savi) Ten., *Ranunculus uncinatus* D. Don, and *Vaccinium alaskaense* Howell were found only in the chloropicrin plots. *Vaccinium parvifolium* Smith and *Trientalis latifolia* Hook. occurred with greater constancy in the chloropicrin plots. *Oxalis oregana* Nutt. was found only in the control plots, and *Pteridium aquilinum* (L.) Kuhn and *Viola sempervirens* Greene were found with greater constancy in the control plots. These differences together with the changes in the major species already described provide for most of the differentiation in community structure.

Conclusions

This study shows that the chloropicrin treatment seems to have impacted nontarget organisms (i.e., the plant community surrounding treated trees), but there are several reasons to treat the results of this study as preliminary. There is a lack of base-line data: composition and structure of the pretreatment vegetation around each tree is not known. The forest is managed by the land owner, who harvests primarily dead and dying trees, thereby continually changing canopy structure. Many plots are located near skid trails. Current plot conditions are the result of changes across 10 years, and many impacts have not been accounted for. Knowledge of the differences in the trajectory of vegetation change from the pretreatment condition by periodic monitoring would give a better picture of the effects of fumigation. Direct measures of fumigant in the soil also are desirable. Although the effects associated with chloropicrin treatment are "real" statistically, the observed differences could have origins in pretreatment conditions and from cumulative land-use effects over time. The randomized block design of the original study is intended to ameliorate these considerations by distributing stand level influences across the treatments.

By pairing control trees with treated trees in a manner specifically addressing these concerns, we tried to eliminate land-use history as a source of bias. To the extent that we could determine, plots were located where the soil had not been disturbed at least since initial stand harvest 57 years previous. Control trees were those nearest the chloropicrin-treated subject tree that

TABLE 3. Relative abundance of plant species in each plot, by treatment

Species*	Chloropicrin	Control	MITC
ACCI	--633-6-	--65--1-	--425-2-
ANDE	-------1	--------	------1-
ATFI	--------	-2------	--------
BENE	53--26-2	56-62642	75--57-6
BLSP	--------	--------	------2-
CASC	--12----	--------	--1--2--
CHME	--------	--------	-------1
CHUM	--------	--------	--1-----
CIVU	---1-1--	--------	--------
DIPU	--------	--------	-------1
DISM	--------	-----1--	--------
FEOC	--------	--------	--1-----
FESU	---2----	---1----	--------
GASH	64646767	5262-757	-66666-3
GATR	1-22-112	-12--111	131--322
GRASS	--------	--------	-------1
HIAL	--------	--------	-1------
HOLA	--------	--------	---1----
HYRA	-----1--	--------	--------
LOCR	-1------	---2----	---5---2
LUPA	-------1	--------	-1-1---1
LURI	--------	---1----	---1----
OSCH	---1---1	--------	--2--11-
OXOR	--------	-2---1--	--------
POMU	62563265	77441561	454---76
PSME	--------	---1----	---1----
PTAQ	2-------	-3---3-3	------4-
PYPI	-1------	--------	--------
RAUN	------11	--------	--------
RIBES	-----1--	--------	--------
ROGY	---2----	--------	---1-3--
RULE	--2-----	--2-----	--------
RUPA	--------	-----2--	-------2
RUUR	21321233	112--232	322--332
STOR	13236235	16457225	23643566
TRLA	1-12---1	--1-----	-221-223
TROV	--------	---1----	--1----1
TSHE	-1-12---	--312---	-414----
VAAL	-2----2-	--------	--------
VAPA	-7-13212	--5-4---	-1-143-2
VEOF	-------1	--------	-1-1--11
VISE	-----113	-121-122	132-1434

NOTE: Abundance scale for ground cover: 1 = 0.1–1%; 2 = 2–3%; 3 = 4–6%; 4 = 7–12%; 5 = 13–24%; 6 = 25–48%; 7 > 48%. -, species absent.

*See Table 1 for list of species acronyms.

exhibited a similar structural environment (diameter, crown position, stand density, proximity to gaps and other species, especially hemlock and vine maple). By standardizing the light conditions of the pairs as much as possible, we sought to reduce the effects of other management activities on vegetation response or to equalize their influences across treatments. Because there is no obvious systematic bias to the results presented here, we conclude that if potential impacts on nontarget vegetation are to be considered, great caution is warranted before introducing chloropicrin into an ecosystem.

Acknowledgements

Our thanks are extended to K.C. VanNatta for providing the study site and personal contributions to the effort. We also thank NOR-AM Agricultural Products, Inc. (Naperville, Ill.) and Great Lakes Chemical Corporation (Fresno, Calif.) for supplying fumigants, advice, and financial assistance. Our appreciation goes to Elisa Pandolfi for technical support.

Castellano, M.A., Mckay, D., and Thies, W.G. 1993. Ecological impacts of using chloropicrin to control laminated root rot in northwest conifer forests: growth and mycorrhiza formation of planted Douglas-fir seedlings after two growing seasons. USDA For. Serv. Res. Pap. PNW-RP-464.

Filip, G.M. 1976. Chemical applications for control of *Armillaria* root rot of ponderosa pine. Ph.D. thesis, Oregon State University, Corvallis.

Filip, G.M., and Roth, L.F. 1977. Stump injections with soil fumigants to eradicate *Armillariella mellea* from young growth ponderosa pine killed by root rot. Can. J. For. Res. **7**: 226–231.

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

Gauch, H.G., Jr. 1982. Multivariate analysis in community ecology. Cambridge University Press, Cambridge.

Hill, M.O. 1979. DECORANA—A FORTRAN program for detrended correspondence analysis and reciprocal averaging. Cornell University, Ithaca, N.Y.

Huffman, D.W., Tappeiner, J.C., II, and Zasada, J.C. 1994. Regeneration of salal (*Gaultheria shallon*) in the central Coast Range forests of Oregon. Can. J. Bot. **72**: 39–51.

Ingham, E.R., Thies, W.G., Luoma, D.L., Moldenke, A.R., and Castellano, M.A. 1991. Bioresponse of nontarget organisms resulting from the use of chloropicrin to control laminated root rot in a Northwest conifer forest: part 2. *In* Pesticides in natural systems: How can their effects be monitored? *Edited by* M. Marsh. U.S. Environmental Protection Agency, Seattle, Wash. pp. 85–90.

Jones, K., and Hendrix, J.W. 1987. Inhibition of root extension in tobacco by the mycorrhizal fungus *Glomus macrocarpum* and its prevention by benomyl. Soil Biol. Biochem. **19**: 297–300.

Larsen, M.J., Lombard, F.F., and Clark, J.W. 1994. *Phellinus sulphurascens* and the closely related *P. weirii* in North America. Mycologia, **86**: 121–130.

Martin, J.K., and Kemp, J.R. 1986. The measurement of carbon transfer within the rhizosphere of wheat grown in field plots. Soil Biol. Biochem. **18**: 103–108.

McArdle, R.E., Meyer, W.H., and Bruce, D. 1961. The yield of Douglas-fir in the Pacific Northwest. Tech. Bull U.S. Dep. Agric. No. 201.

Morrell, J.J. 1989. The use of fumigants for controlling decay of wood: a review of their efficacy and safety. International Research Group on Wood Preservation, Stockholm. Doc. IRG/WP/3525.

Nelson, E.E., Martin, N.E., and Williams, R.E. 1981. Laminated root rot of western conifers. USDA For. Serv. For. Insect Dis. Leafl. 159.

Ono, K. 1985. The application of soil sterilants for controlling tobacco wildfire and angular leaf spot caused by *Pseudomonas syringae* pathovar *tabaci*. Bull. Okayma Tob. Exp. Stn. pp. 93–100.

Peterson, G.W., and Smith, R.S., Jr. 1975. Forest nursery diseases in the United States. U.S. Dep. Agric. Agric. Handb. 470.

Rhoades, H.L. 1983. Efficacy of soil fumigants and nonfumigants for controlling plant nematodes and increasing yield of snap beans (*Phaseolus vulgaris*). Nematropica, **13**: 239–244.

Sabin, T.E., and Stafford, S.G. 1990. Assessing the need for transformation of response variables. Oreg. State Univ. For. Res. Lab., Spec. Publ. 20.

Smith, N.J. 1991. Sun and shade leaves: clues to how salal (*Gaultheria shallon*) responds to overstory stand density. Can. J. For. Res. **21**: 300–305.

Snedecor, G.W., and Cochran, W.G. 1980. Statistical methods. The Iowa State University Press, Ames.

Sumner, D.R., Dowler, C.C., Johnson, A.W., Chalfant, R.B., Glaze, N.C., Phatak, S.C., and Epperson, J.E. 1985. Effect of root diseases and nematodes on yield of corn (*Zea mays*) in an irrigated multiple-cropping system with pest management. Plant Dis. **69**: 382–387.

Tanagawa, S., Irimajiri, T., and Oyamada, M. 1985. Persistence of chloropicrin in soil and environmental effect on it. J. Pestic. Sci. **10**: 205–210.

Thies, W.G., and Nelson, E.E. 1982. Control of *Phellinus weirii* in Douglas-fir stumps by the fumigants chloropicrin, allyl alcohol, Vapam, or Vorlex. Can. J. For. Res. **12**: 528–532.

Thies, W.G., and Nelson, E.E. 1987*a*. Reduction of *Phellinus weirii* inoculum in Douglas-fir stumps by the fumigants chloropicrin, Vorlex, or methylisothiocyanate. For. Sci. **33**: 316–329.

Thies, W.G., and Nelson, E.E. 1987*b*. Survival of Douglas-fir injected with the fumigants chloropicrin, methylisothiocyanate or Vorlex. Northwest Sci. **61**: 60–64.

Thies, W.G., Castellano, M.A., Ingham, E.R., Luoma, D.L., and Moldenke, A.R. 1991. Bioresponse of nontarget organisms resulting from the use of chloropicrin to control laminated root rot in a northwest conifer forest: Part 1. Installation of study. *In* Pesticides in natural systems: How can their effects be monitored? *Edited by* M. Marsh. United States Environmental Protection Agency, Seattle, Wash. pp. 81–84.

Trappe, J.M., Molina, R., and Castellano, M.A. 1984. Reactions of mycorrhizal fungi and mycorrhiza formation to pesticides. Annu. Rev. Phytopathol. **22**: 331–359.

Vales, D.J. 1986. Functional relationships between salal understory and forest overstory. MS thesis, University of British Columbia, Vancouver.

Zahora, A.R., and Morrell, J.J. 1988. Decomposition of methylisothiocyanate in Douglas-fir heartwood. For. Prod. J. **38**: 46–52.

Zahora, A.R., and Morrell, J.J. 1989. Diffusion and sorption of the fumigant methylisothiocyanate in Douglas-fir wood. Wood Fiber Sci. **21**: 55–66.