
Salal Cedar Hemlock

Integrated Research Program:

A Synthesis

Edited by

C.E. Prescott and G.F. Weetman

Canada

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We hope that SCHIRP will serve as an exampleof cooperation between industry, government, and universities in conducting research that addresses both fundamental questions and applied problems.

Summary

This report presents a synthesis of the Salal cedar Hemlock Integrated Research Program (SCHIRP). The objective of this decade-long research effort was to understand the underlying causes of poor growth of conifer regeneration on northern Vancouver Island, British Columbia, and to recommend the most effective methods of improving tree growth. The problem occurred on sites formerly occupied by old-growth cedar-hemlock (CH) forests, 5-8 years after clearcutting and slashburning. Symptoms included chlorotic foliage and a near cessation of growth of Sitka spruce, western hemlock, western red cedar and amabilis fir, coincident with the expansion of the ericaceous shrub, salal, on the cutovers.

A series of fertilization trials identified deficiencies of nitrogen and phosphorus as the cause of the growth check of conifers, and determined that additions of 200-300 kg N ha⁻¹ and 50-100 kg P ha⁻¹ would provide an effective means of improving tree growth rates. Equivalent tree growth responses were achieved through additions of organic wastes such as sewage sludge and fish silage. Other silvicultural practices such as burning, cultivating, liming, higher planting densities or herbicide application, were less effective in promoting conifer growth.

The nutrient deficiencies in conifers on CH cutovers were the result of two main factors: low nutrient availability in soil and humus, and competition and interference from salal. Salal immobilized substantial amounts of N in biomass and an in vitro study suggested it was able to use organic forms of N through its mycorrhizal fungi, which would reduce the amount of N available to trees. The mycorrhizae of salal also interfered with those of hemlock, which further reduced their ability to take up nutrients. High concentrations of phenolic acids were associated with salal, which interfere with mineralization of N.

The low availability of N and P in CH cutovers originated in forest floors of the old-growth forests prior to clearcutting. Nutrient availability was low in all layers of the forest floor in CH forests; and this appeared to result from three main factors. First, cedar litter contains little N and more material resistant to decomposition than other species, and produces forest floors with low rates of N mineralization. Second, the forest floors in CH forests are wetter and have less soil fauna, leading to incomplete decomposition and mineralization of N. Third, the salal understorey in CH forests interferes with mineralization of N through the production of tannins and the activities of its mycorrhizal fungi.

The most effective procedure for regenerating CH cutovers is planting hemlock and cedar, and fertilizing at five years with at least 200 kg N ha⁻¹ and 50 kg P ha⁻¹, or organic wastes. A second fertilization may be necessary to achieve crown closure and thus shade out the salal. Continued monitoring of established long-term trials of these procedures is needed to test these predictions.

Introduction

Overview

This report presents a synthesis of the findings of the Salal Cedar Hemlock Integrated Research Program (SCHIRP). The objective of this decade-long research effort was to determine the underlying causes of poor growth of regenerating cedar, hemlock, amabilis fir and Sitka spruce on cutovers of old-growth cedar-hemlock forests invaded by salal. The project developed in responses to concerns raised by staff of Western Forest Products about the poor conifer regeneration on Tree Farm Licence #25 on northern Vancouver Island. Research was conducted to determine silvicultural practices to alleviate the growth problem, and to understand the fundamental cause of the poor nutrition of trees. Initial field trials demonstrated deficiencies of N and P as the cause of poor growth. Subsequent studies examined the decline in N and P availability following clearcutting and burning, and the role of salal in contributing to poor conifer growth. The origin of poor N and P supply were investigated in studies comparing nutrient cycling in old-growth cedar-hemlock forests with second-growth forests of hemlock-amabilis which do not have low nutrient supply.

The studies were conducted by an interdisciplinary team of scientists and included investigations of soil fauna, microbial biomass, mycorrhizae, structure and dynamics, nutrient cycling, allelopathy, competition, nutrition, plantation yield forecasting, humus chemistry, and economics. Studies were conducted within a framework of field experiments that examined the effects of fertilization, organic fertilizers, mechanical site preparation, plantation densities, vegetation control and different plantation species. The results of these investigations are integrated into chapters describing the forests, response to clearcutting and silvicultural trials.

The Setting

The natural landscape along the west coast of North America, from northern California to the top of the Alaskan panhandle, is dominated by coniferous forests of globally unsurpassed form and stature. Most of the genera composing these forests differentiated from earlier gymnosperms during the Jurassic period from 140-160 million years ago (Scagel et al. 1965). The ranges of individual species along the Pacific coast have shifted continuously over geological time

in response to glaciations and other climatic fluctuations. Northern Vancouver Island in British Columbia is located in the center of this band of Pacific coastal forest. The most recent glaciation retreated from this area about 14,000 years ago. Over the last 3,000 years, the forest vegetation has become dominated by western red cedar (*Thuja plicata* Donn.), western hemlock (*Tsuga heterophylla* (Raf. Sarge) and amabilis fir (*Abies amabilis* Dougl.) (Hebda 1983).

The study area is on northern Vancouver Island, between the towns of Port Hardy and Port McNeill, B.C. (Figure 1). The area is within the very wet maritime subzone of the Coastal Western Hemlock (CWH) biogeoclimatic zone (Pojar et al. 1991), and has a maritime climate with mild winters and cool moist summers. Mean annual precipitation is about 1700 mm, 65% of which occurs between October and February, and almost all is rain. Mean annual temperature is 7.9C, and daily averages range from 2.4C in January to 13.8C in August. The surface geological material is deep unconsolidated morainal and fluvial outwash material overlying three types of bedrock: gently dipping sedimentary rocks of the Cretaceous Nanaimo formation, relatively soft volcanics of the Bonanza group, and a small area of harder Karmutsen formation basalt which protrudes through the morainal cover.

The distribution of forest vegetation across this area varies with topography, geological substrate, and the type and frequency of natural disturbance. Wildfire is uncommon, and the predominant natural disturbance is withthrow. The forests are largely composed of western red cedar, western hemlock and amabilis fir, with occasional Sitka spruce (*Picea sitchensis* (Bong.) Carr.) on the outer coast, and lodgepole pine (*Pinus contorta* var. *contorta*) on poorly drained sites. On well-drained to somewhat imperfectly-drained middle or upper slope situations, the forests occur in two distinct types (Plate 1):

1. old-growth forests dominated by western red cedar with a smaller component of western hemlock (CH), and

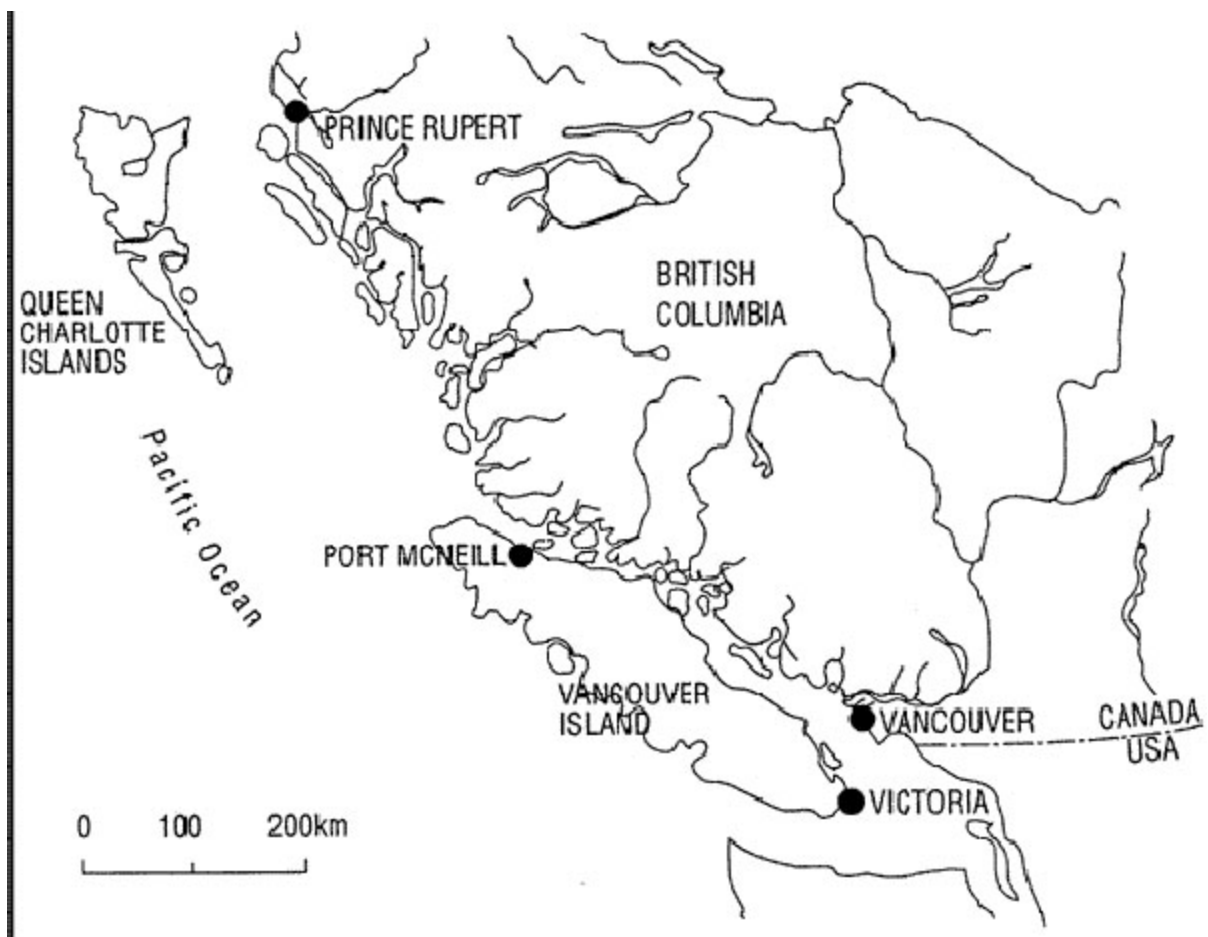


Figure 1. Location of study area near Port McNeill on northern Vancouver Island, British Columbia.



Plate 1. Aerial view of northern Vancouver Island, showing HA forests (dark green), CH forests (light green with dead tops), and cutovers

2. second-growth forests dominated by western hemlock and amabilis fir, that are even aged and originated following a widespread wind-storm in 1906 (HA).

The forest floors of both types are deep mor humus, generally of greater depth in the CH than the HA type (Germain 1985). Mineral soils are duric or orthic Humo-Ferric Podzols. Lewis (1982) could not distinguish between the two forest types on the basis of topography or mineral soil characteristics, and included them in the same ecosystem association. He further hypothesized that they were different stages (or phases) of a successional sequence, i.e. that HA forests were a seral stage of CH forests.

The Problem

During the 1960's, logging of old-growth CH forests generated substantial areas of cutovers which regenerated very slowly with cedar and hemlock. To achieve more rapid regeneration, sites were slashburned to reduce slash accumulations and the heavy cover of the ericaceous shrub, salal (*Gaultheria shallon* Pursh), and planted with Sitka spruce. Only Sitka spruce and Douglas-fir seedlings were available, and the sites were not suitable for Dou-

glas-fir. The spruce plantations grew well initially, but by age 6 to 8 years, they showed signs of severe nutrient deficiency and growth rates declined markedly. Cedar appeared to be less influenced by the nutritional problems on these sites and consequently cedar was planted thereafter.

In 1982, Lewis suggested the possibility of converting CH sites to HA by silvicultural treatments such as physical site preparation to simulate windthrow. Since then, a large experimental effort has been directed towards testing whether conversion of CH sites to more productive HA conditions can be achieved. Fundamental to this experimental effort has been the need to understand the origin of the differences between the two forest types.

The Approach

Over the 1983 to 1993 period a series of studies were conducted to:

1. Establish if the low nutrient supply in CH forests existed prior to harvesting.

2. Determine the origin of the low nutrient supply in CH forests by comparing stand structure, humus forms, soils, cycling of N and P, organic matter decomposition, and soil fauna in CH and HA forests.
3. Document the post-harvest decline in nutrient availability in CH cutovers.
4. Determine the extent to which salal contributes to growth check of conifers through competition and mycorrhizal interactions.
5. Establish field trials to test the effectiveness of silvicultural treatments for promoting conifer growth on CH sites, including:
 - (a) fertilization: single-tree screening, conventional plot, and operational trials;
 - (b) organic fertilizers, including sewage sludge, fish silage and pulp sludge;
 - (c) fertilization, scarification and variations in planting density;
 - (d) mechanical site preparation and burning;
 - (e) salal eradication (manual and herbicides);
 - (f) starch or lime amendments

These studies were undertaken by a team of scientists from the University of British Columbia, the Canadian Forest Service, the B.C. Ministry of Forests, and the staff of Western Forest Products at Port McNeill, B.C. All the experimental areas are situated on Tree Farm Licence #25 of Western Forest Products Ltd. near Port McNeill, B.C. Corporate support was also provided by MacMillan Bloedel Ltd. and Fletcher Challenge Canada Ltd. (now Timberwest Ltd.). Financial support was also received from the Natural Sciences and Engineering Research Council of Canada, the South Moresby Replacement Fund, the Science Council of British Columbia, and the Canada-B.C. Forest Resource Development Agreement.

The Hypothesis

To explain the differences between CH and HA sites, four general hypotheses were developed.

1. The "disturbance hypothesis"

It was argued that areas frequently disturbed by catastrophic windstorms will regenerate to western hemlock and amabilis fir, as is observed on HA sites (Figure 2). The resulting treefalls mix the soil, promoting well-drained and aerated conditions, and active organic matter decomposition and nutrient cycling (Ugolini et al. 1990). Improved soils increase the growth rate of trees and help to produce dense stands that exclude salal through shading. In areas that are not affected by the windstorms, western hemlock and amabilis fir stands open up, allowing the regeneration of western red cedar. The open stands with cedar are better able to withstand windstorms and so become less prone to disturbance. In the absence of catastrophic windstorms, the stand, soil structure and nutrient cycling become characteristic of CH forests. According to this hypothesis, practices such as clearcutting and mechanical site preparation that simulate windthrow should promote growth on CH sites similar to that on HA sites.

2. The "salal hypothesis"

It was argued that salal inhibits the growth of conifer seedlings. There are two theories which are relevant (Figure 3). One theory proposes that salal suppresses the growth of conifer seedlings through allelopathic interference, which inhibits either mycorrhizal development, root development, or both (deMontigny and Weetman 1990). These chemicals may also impede organic matter decomposition and nutrient mineralization. This theory is related to observations of growth problems of planted conifer seedlings in association with other ericaceous species in eastern Canada (Titus et al., in press) and in the heathlands of Europe (Malcolm 1975). The second theory suggests that salal is simply a better competitor than the conifer seedlings for soil nutrients in CH clearcuts. In either case, the reason for high productivity in HA sites following a major disturbance is that the dense regeneration of hemlock and fir excludes salal. By contrast, the CH stands are more open so salal maintains a dense understorey, spreads quickly after clearcutting, and inhibits growth of conifer seedlings. According to this hypothesis, removal of salal from CH sites should promote growth rates similar to HA sites, unless there is a persistent residual allelopathic effect of salal.

3. The "western red cedar hypothesis"

Western red cedar wood, unlike western hemlock and amabilis fir, is highly resistant to decay due to the presence of a fungitoxic chemical, thujaplycin and thujic acid which repels a variety of insects. Consequently, a forest-floor dominated by decomposing western red cedar wood will have a low mineralization potential with low rates of nutrient cycling and low nutrient availability (Figure 4). It has also been hypothesized that western red cedar can more readily obtain N and compete with salal. These conditions make CH sites more suitable for western red cedar than for hemlock or fir. Conditions in windthrown HA sites are suitable for cedar, but it does not become established because of the speed and density of hemlock and fir regeneration. According to this hypothesis, removal of cedar logs and humus and exposure of mineral soil are necessary to promote regeneration of hemlock and fir on CH sites.

4. The "site-difference hypothesis"

This hypothesis proposes that HA and CH sites are not different seral stages in the same succession, but rather are two different plant associations determined by topography (Figure 5). HA sites are situated on knolls and upper slopes and are more exposed to wind and better drained than the CH sites which are situated in lower areas. Differences between the two forest types arise from these initial site differences, and cannot be modified by management practices.

These four initial hypotheses about the two forest types were expanded and modified as new information and ideas became available. The hypotheses were examined in a series of studies in CH and HA forests and cutovers. The results of these studies are presented in the following chapters that describe the forests, the responses to clearcutting, and the silvicultural trials that were conducted as part of SCHIRP.

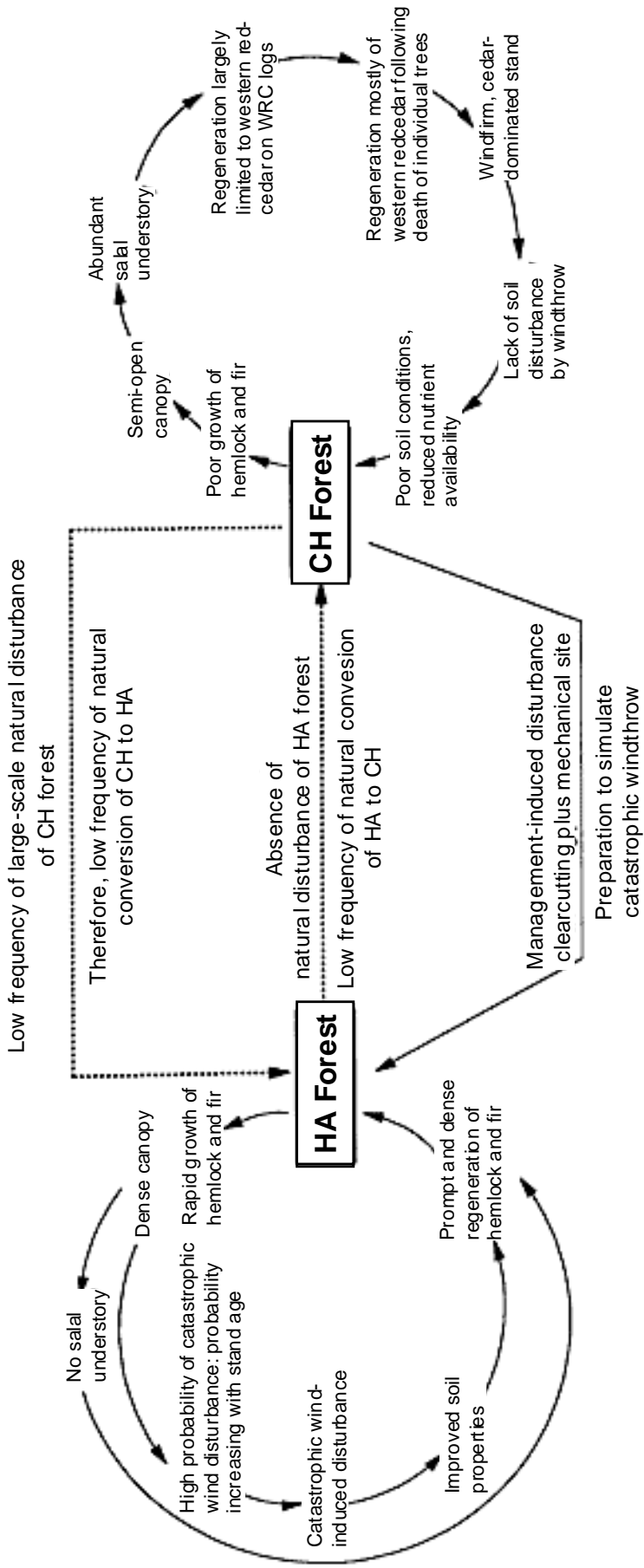


Figure 2. The disturbance hypothesis.

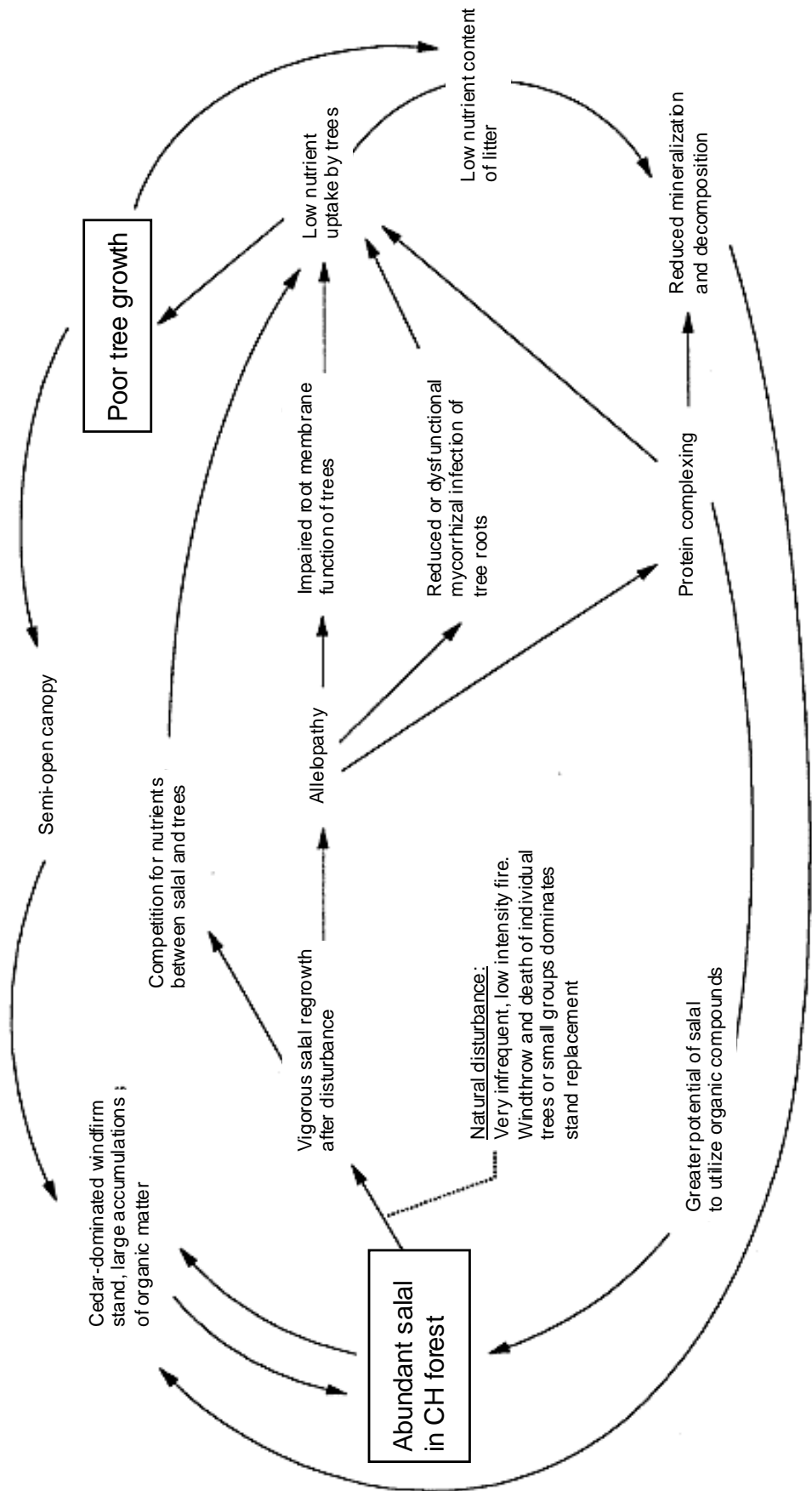


Figure 3. The salal hypothesis.

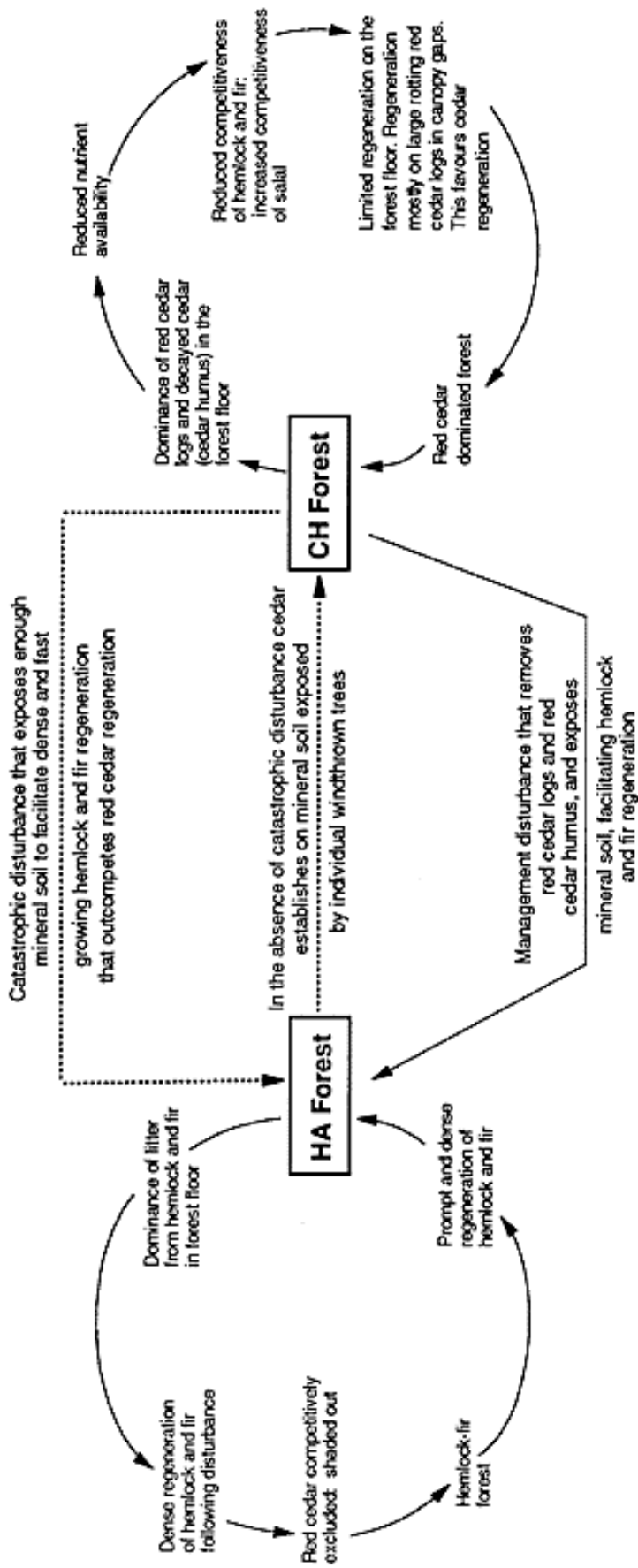
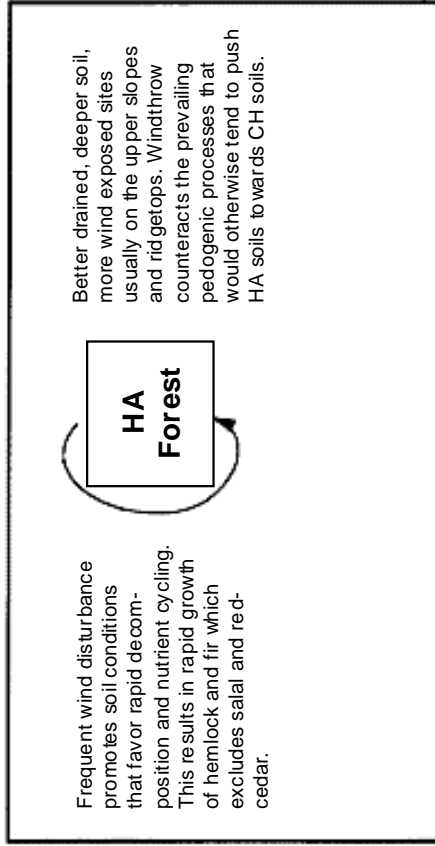


Figure 4. The western red cedar hypothesis

HA SITES



CH SITES

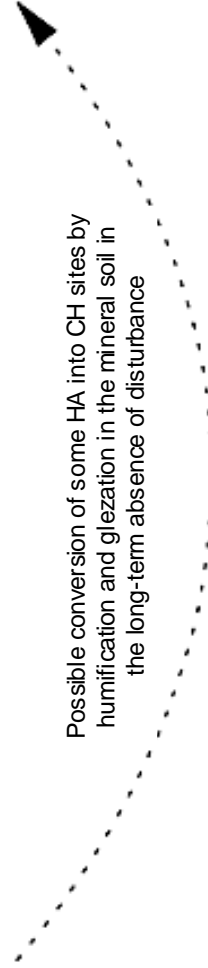
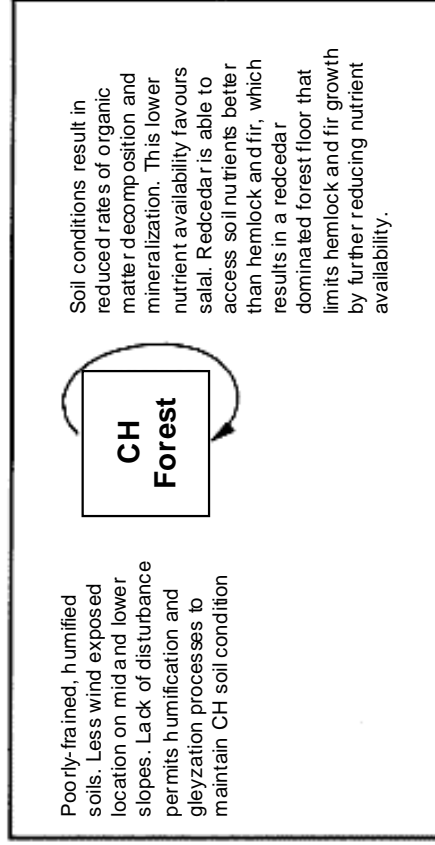


Figure 5. The site difference hypothesis.

The Forests

Studies of the two forest types, cedar-hemlock (CH) and hemlock-amabilis fir (HA) were undertaken to determine:

1. if the low N and P supply in CH cutovers was present in old-growth CH forests;
2. the origins of differences in N and P availability between the two forest types.

Possible origins of the differences in N availability that were investigated were:

1. more N is tied up in humus and woody debris in CH forest floors so that less N is cycling and available;
2. decomposition of litter is slower in CH forests, resulting in slow rates of N mineralization;
3. the lack of disturbance by windthrow in CH forests has led to the development of conditions such as poor soil drainage and aeration which inhibit mineralization of N;
4. the forests occupy different sites with respect to soil, climate and topography, which create differences in N and P cycling.

These hypotheses were addressed by comparing adjacent CH and HA forests in terms of stand structure, humus and soil characteristics, litter quality and input, mass and nutrient content of forest floor layers, rates of decomposition and N mineralization, and soil fauna. The results presented here are summaries of investigations in CH and HA forests by Battigelli (1992), deMontigny (1992), Cade-Menun (1995), deMontigny et al. (1993), Keenan (1993), Keenan et al. (1993), (1994a, b), (in review), Prescott and Preston (in press), and Prescott et al. (1993), (1994).

Stand Structure

Information on stand structure was collected in adjacent CH and HA forests on three different sites (Keenan 1993). The height, diameter and species of all trees greater than 4 m in height were measured in one 50 x 50 m plot in each CH and HA forest. Tree ages were estimated from diameter-age relationships determined from stumps in nearby cutovers. Saplings and seedlings less than 4 m tall were surveyed on 100 1m² subplots in each plot.

The old-growth CH forests were composed of western red cedar up to 1000 years old and 260 cm in diameter, and western hemlock up to 400 years old and 90 cm in diameter. Of the trees more than 4

m in height, hemlock were the most abundant, averaging 388 st ha⁻¹, followed by cedar (120) and amabilis fir (60). The average basal area of cedar (84.3 m² 2ha⁻¹) was greater than that of hemlock (21.6) and fir (2.5). The diameter distribution of hemlock (Figure 6) was a reverse-J, with large numbers of seedlings (13,000 ha⁻¹). The diameter distribution of cedar was flat with gaps, and the estimated number of established seedlings was 4,100 ha⁻¹. This diameter-class distribution is indicative of a self-replacing, climax community. Seedling establishment was restricted to upturned root mounds and decaying logs.

The second-growth HA forests originated from a catastrophic windstorm in 1906. They were composed of hemlock and amabilis fir, mostly between 70 and 100 years old, but ranging from 30 to 160 years. Of the trees greater than 4 m in height, hemlock were more abundant (467 st ha⁻¹) than fir (99). The average basal area was 63.0 m² ha⁻¹ for hemlock and 13.9 for amabilis fir. The diameter class distribution of HA stands (Figure 6) was unimodal, and there were very large numbers of seedlings in the understorey. The diameter class distribution of the previous stand, reconstructed from remaining stumps, was similar to the current stand (i.e. unimodal and of similar diameters) only at one of the three sites studied. At the others, the previous stand had a reverse J-shaped distribution and the trees were much larger than those in the current stand, suggesting that some of the previous stands were much older than the current stands.

The understorey vegetation in CH forests was dense, dominated by salal (49% cover), deer fern (*Blechnum spicant*) (8%) and blueberry (*Vaccinium* spp.) (3%), with lesser amounts of bunchberry (*Cornus canadensis*), and salmonberry (*Rubus spectabilis*) (deMontigny 1992). The moss layer was comprised of *Hylocomium splendens* (39% cover), *Kindbergia oregana* (33%), and *Rhytidiadelphus loreus* (22%). The understorey vegetation in HA forests was sparse, consisting mostly of mosses, *K. oregana* (24% cover), *H. splendens* (22%), and *R. loreus* (20%), with small amounts of blueberry (*Vaccinium* spp.) (4%), deer fern (*Blechnum spicant*) (4%) and salal (1%).

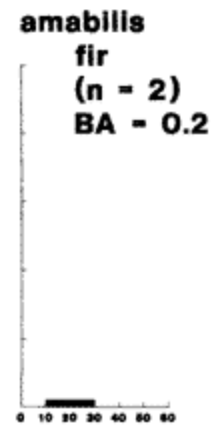
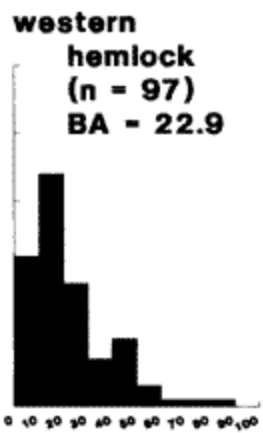
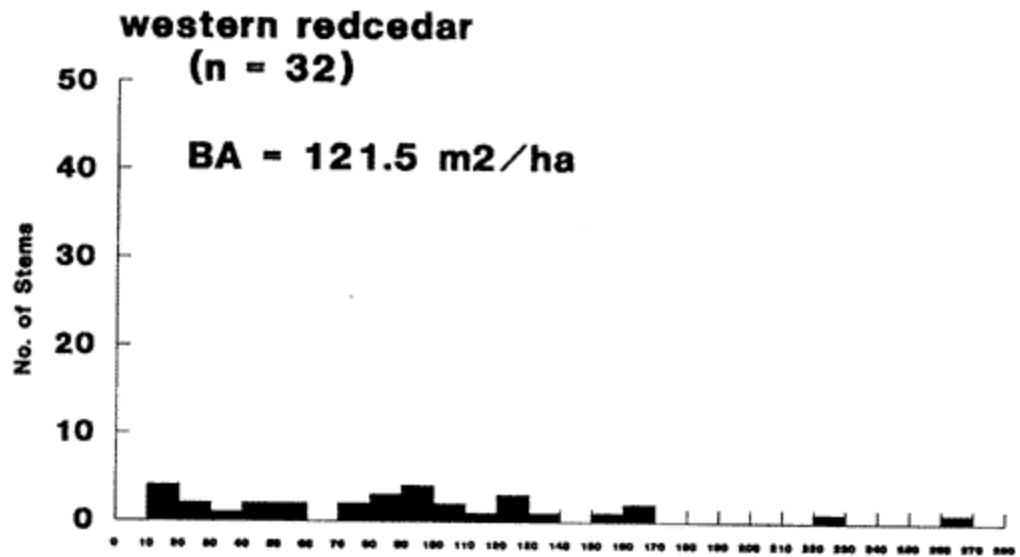


Plate 2. Old-growth cedar-hemlock (CH) forest with salal understory.



Plate 3. Second-growth hemlock-amabilis fir (HA) forest.

CH



HA

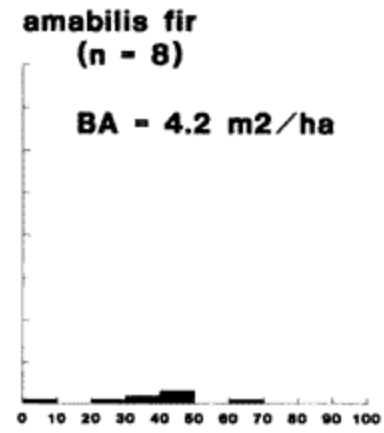
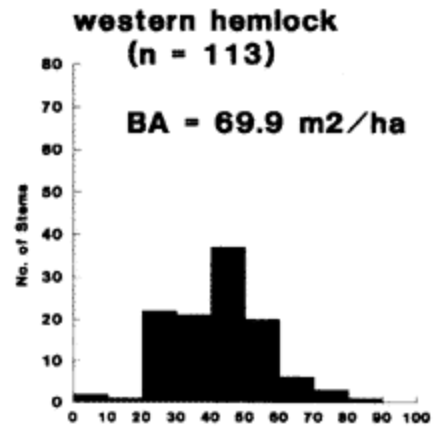


Figure 6. Diameter distribution of cedar, hemlock and amabilis fir in CH and HA forests.

Soils

Forest floor and mineral soil horizons were classified in 10 pits located along 30 m transects in 5 CH and 5 HA forests (deMontigny 1992). Forest floor horizons (humus forms) were classified according to Green et al. (1991), based on the apparent degree of decomposition (Table 1). In later studies, a simplified classification scheme was used, in which L, F, and H designated litter, fragmentation and humus layers, and “w” designated woody material. Humus profiles were also mapped along a trench from CH to HA forests (deMontigny 1992).

The humus forms in CH forests (Figure 7) were mostly humimors, with well developed H horizons, and lignomors, with a large proportion of Hw horizons of old wood. Hydromors, which develop under the influence of excessive moisture on poorly-drained soils were also common in CH forests. Mineral soils in CH forests were compact with hu-

mus-enriched Bf layers over a continuous thin pan. Root restricting layers, such as cemented or compacted layers or standing water, were found in 98% of the 50 plots surveyed. The average rooting depth was 21 cm, and most roots were in the forest floor. Soils were humoferric podzols and predominantly loams. Mineral soils in CH forests had lower N concentrations and greater C:N ratios than those in HA forests (Table 2).

The humus in HA forests were largely of lignomors with equal proportions of young and old woody horizons, hemimors, characterized by thin F horizons over disturbed mineral mounds, and humimors (Figure 8). Mineral soils in HA forests were friable, well-aerated and well-drained. Pans were found under the humimors, but were thin and discontinuous. Root restricting layers were found in 78% of the 50 plots surveyed. The average rooting depth was 29 cm, and most roots were in the forest floor. Soils were humoferric podzols and predominantly loams.

Table 1. Physical description of organic horizons in CH and HA forests.

Horizon	Composition	Color	Structure	Rooting
Fm	>60% plant	10R 3-4/4-6	compact, matted	abundant, fine to coarse
	<20% amorphous	2.5YR 3/4/4-6		
	>20% fungi	5YR 2.5-3		
Fw	>90% wood	10R 3/4	woody structure holds	few
		2.5YR 3/4-6		
		5YR 3/4-6		
Hrw	<80% wood	10R 2.5-3	crumbly, greasy	plentiful to abundant
	>20% amorphous	2.5YR 1-2 5YR 1-2		
Hw	<20% wood >80% amorphous	10R 2.5-3		
		2.5 YR 1-2		
		5YR 1-2		
Hh	no wood	10R 2.5-3	massive, blocky, greasy	plentiful to abundant
	>80% amorphous	2.5YR 1-2		
		5YR 1-2		
Hhi	>95% amorphous	5YR 2.5-5	massive, very greasy blocky to fine granular	very few
		7.5YR 0-1		

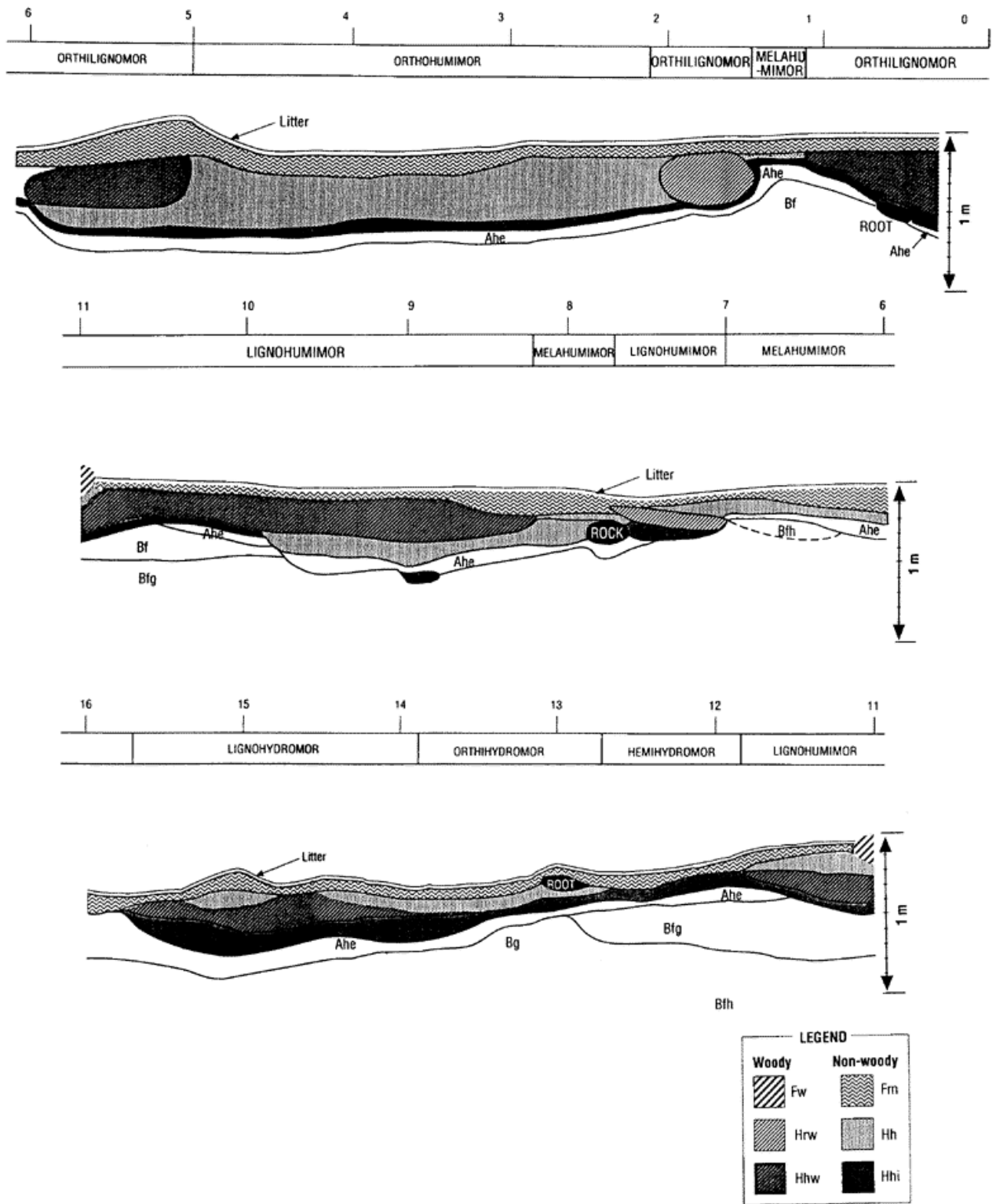


Figure 7. Humus profile along a trench in a CH forest.

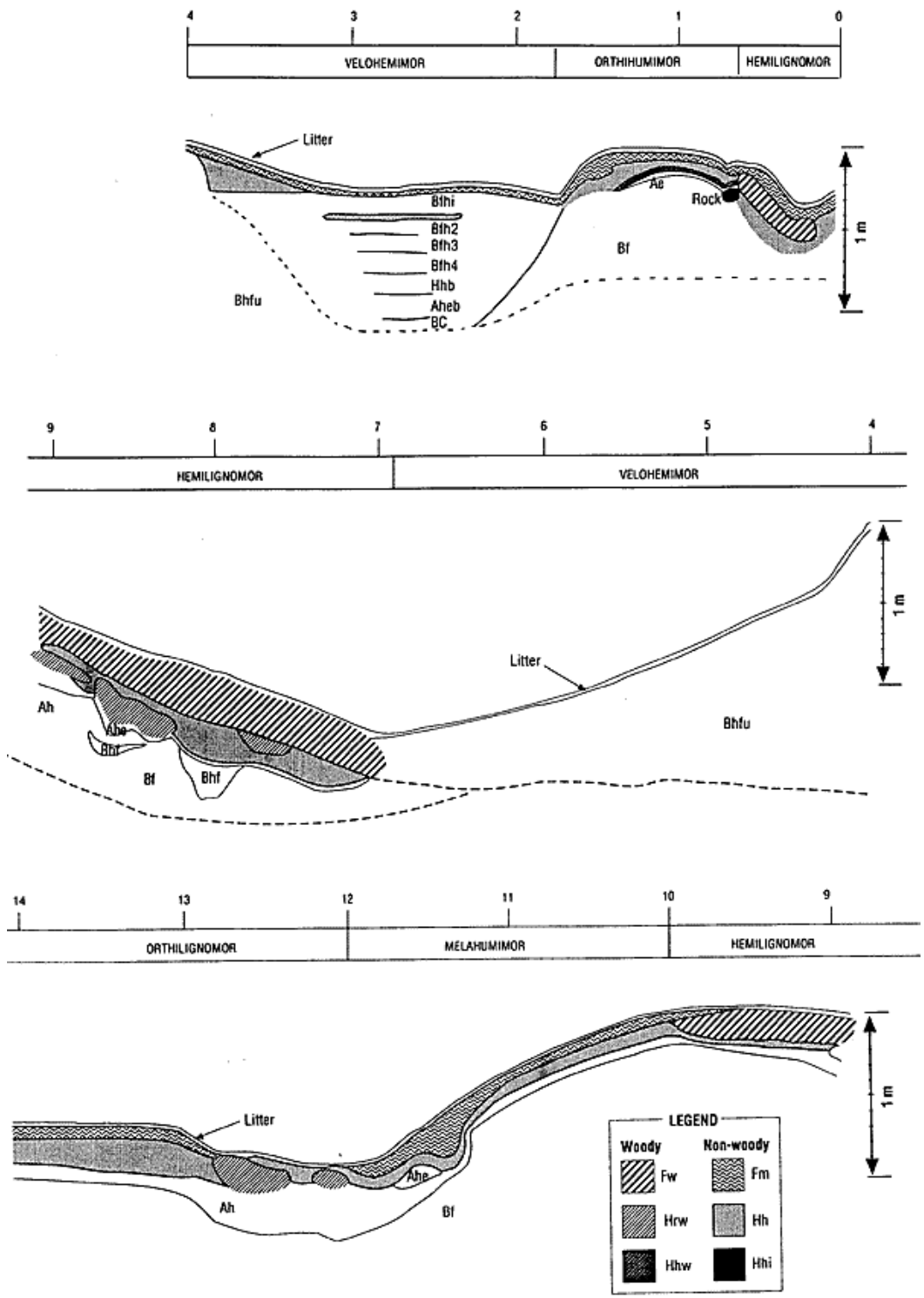


Figure 8. Humus profile along a trench in a HA forest.

Table 2. Physical and chemical properties of mineral soils in CH and HA forests.

Type	Depth (cm)	Bulk Density (g cm ³)	Coarse fragment (% mass)	Sand (%)	Silt (%)	Clay (%)
CH	0-30	0.71 (0.06)†	34 (6.6)	41 (2.8)	37 (2.0)	22 (1.0)
	30-60	0.69 (0.12)	43 (4.2)	42 (2.9)	35 (0.4)	23 (2.7)
HA	0-30	0.71 (0.12)	43 (1.7)	39 (1.7)	38 (2.4)	23 (1.1)
	30-60‡	0.68	43 (0.8)	37	40	23

† Each value is the mean and standard errors (in parentheses) of 3 samples per site and 3 sites per forest type.

‡ Average of 2 HA sites.

Type	Depth (cm)	Organic C (mg g ⁻¹)	Total N (mg g ⁻¹)	C:N	Available P (mg kg ⁻¹)	Fe (mg g ⁻¹)	Al (mg g ⁻¹)
CH	0-15	141†	2.7*	52.2	4.34	9.0*	6.1
	15-30	50	1.3	38.5	1.96		
	30-60	34	1.2	28.3	2.06		
HA	0-15	152	3.8	40.0	2.71	12.1	8.7
	15-30	36	3.0	12.0	1.25		
	30-60	37	1.3	28.4	1.77		

† Values for the 0-15cm depth are the mean of 10 samples per site, 3 sites per forest type. Values for the lower horizons are the mean of 3 samples per site, 3 sites per forest type. Asterisks indicate significant differences ($p < 0.05$) between the forest types based on Student's t-test.

Coarse Woody Debris

The length, diameter, species, and decay class of all standing dead and downed logs were measured on 50 x 50 m plots in three CH and three HA forests (Keenan et al. 1993). Densities were estimated from 4-6 samples of logs of each species and decay class. Estimates of the mass of buried wood in each plot were obtained from eight 30 x 30 cm samples of the forest floor.

There was a very large amount of coarse woody debris (CWD) in CH forests; 80 Mg ha⁻¹ of standing dead trees and stumps, 283 Mg ha⁻¹ of downed wood on the surface, and 166 Mg ha⁻¹ of buried wood. About 298 Mg C ha⁻¹ 1101 kg N ha⁻¹ and 83 kg P ha⁻¹ ha were stored in CWD. There was also a considerable mass of CWD in HA forests; 21 Mg ha⁻¹ of standing dead trees and stumps, 205 Mg ha⁻¹

of downed wood on the surface, and 134 Mg ha⁻¹ of buried wood. About 240 Mg C ha⁻¹ 1210 kg N ha⁻¹ and 72 kg P ha⁻¹ were stored in CWD in HA forests.

Forest Floors

Forest floor mass was estimated from eight 30 x 30 cm samples of the forest floor from the three CH and three HA forests (Keenan et al. 1993). The forest floor mass (non-woody LFH) in CH forests was 114 Mg ha⁻¹ which contained about 60 Mg C ha⁻¹ 1077 kg N ha⁻¹ and 59 kg P ha⁻¹ (Table 3). The average mass of forest floor (non-woody LFH) in HA forests was 77 Mg ha⁻¹ which stored about 41 Mg C ha⁻¹ 839 kg N ha⁻¹ and 46 kg P ha⁻¹. Compared with HA forests, CH forest floors had a larger total mass, but smaller amounts of F layer material and larger masses of humus (Table 3).

Table 3. Mass and nutrient content of forest floors and woody detritus in CH and HA forest. Asterisks indicate significant differences in mass between the two forest types.

Layer	Type	Mass (Mg ha ⁻¹)	N (kg ha ⁻¹)	P (kg ha ⁻¹)
L	CH	4.3	28.81	2.58
	HA	4.1	34.03	3.28
Lw	CH	1.7*	1.36	0.09
	HA	3.7	2.29	0.22
F	CH	18.1*	162.9	10.86
	HA	30.1	298.0	21.07
Fw	CH	29.7	95.04	5.94
	HA	25.9	101.0	7.70
H	CH	91.3*	885.6	45.7
	HA	43.0	507.4	21.5
Hw	CH	134.6	673.0	40.4
	HA	104.1	812.0	41.6
Forest floor (non-woody)	CH	113.7 (12.5)*	1077.3	59.1
	HA	77.2 (9.9)	839.4	45.9
Forest floor (woody)	CH	166.1 (14.3)	769.4	46.4
	HA	133.7 (14.9)	915.3	49.5
Surface woody	CH	362.9 (28.8)*	331.9	36.2
	HA	225.5 (33.9)	294.7	22.9
Total	CH	642.5 (36.4)*	2178.6	141.7
	HA	436.4 (39.4)	2049.4	118.3

Solid-state C-13 NMR spectra of CH and HA forest floors were similar to each other, and to spectra of coniferous forest-floors reported elsewhere (Figure 9) (deMontigny et al. 1993). There was a slightly higher ratio of carbohydrate to lignin moieties in the CH forest floor, indicative of less complete decomposition and consistent with the chemical analysis. Compared with HA forests, forest floors in CH forests had higher concentrations of lipids and polysaccharides, and generated a smaller ratio of acid:aldehyde (vanillic acid:vanillin) on CuO oxidation, indicative of a smaller degree of lignin biodegradation. In addition, there was evidence for tannins in the CH forest floor spectrum, as indicated by a peak at 145 ppm. The dipolar-dephased CH spectrum also had higher intensity at

108 ppm, another feature diagnostic of tannins. This tannin may be associated with salal; C-13 NMR spectra of salal components indicate high levels of tannin (Figure 10).

Nutrient Availability

Availability of N and P were compared in five samples of each forest floor layer (litter, fermentation (woody and non-woody), and humus (woody and non-woody)) collected from three forests of each type (CH and HA) (Prescott et al. 1993a). All layers of CH forest floors had smaller concentrations of total and extractable N (Table 4 and Figure 11) and mineralized less N during 40-day aerobic incubations in the laboratory (Figure 11). Total and extractable P was lower in the litter layer of CH forest floors (Table 4 and Figure 11). Seedlings of western red cedar, Sitka spruce, western hemlock, and amabilis fir grown from seed in forest floor

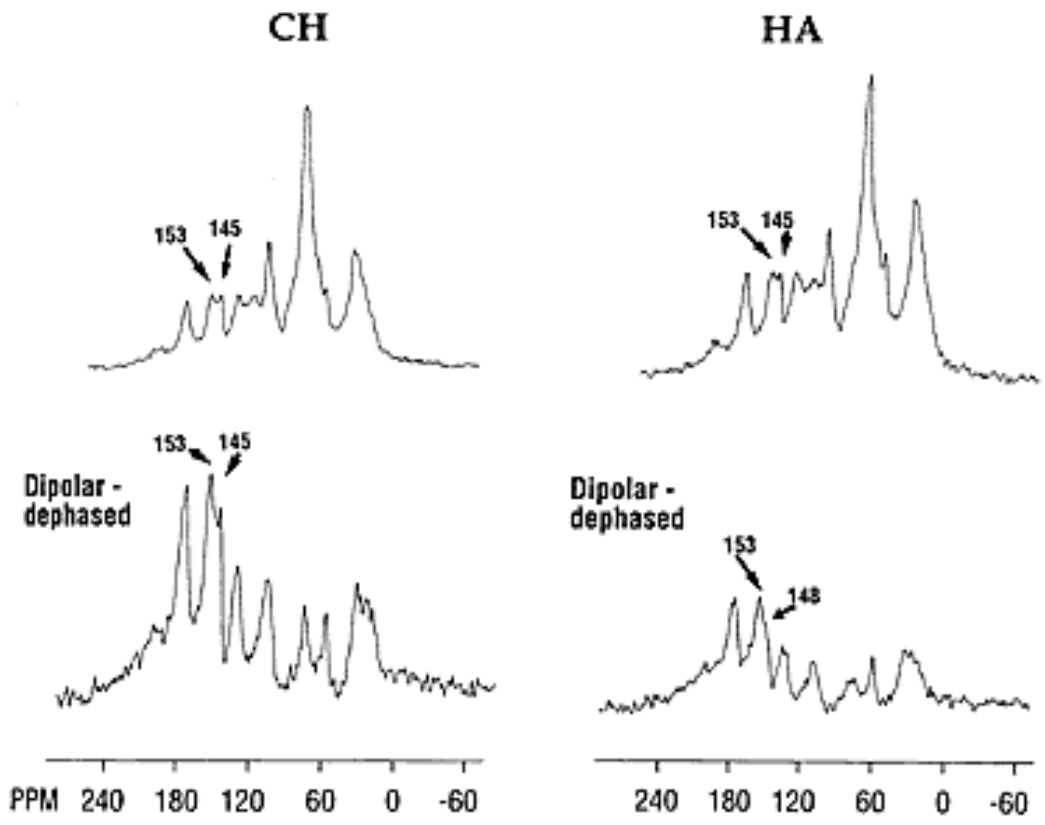


Figure 9. C-13 NMR spectra of forest floor F layers from CH and HA forests showing tannin peaks at 145 ppm.

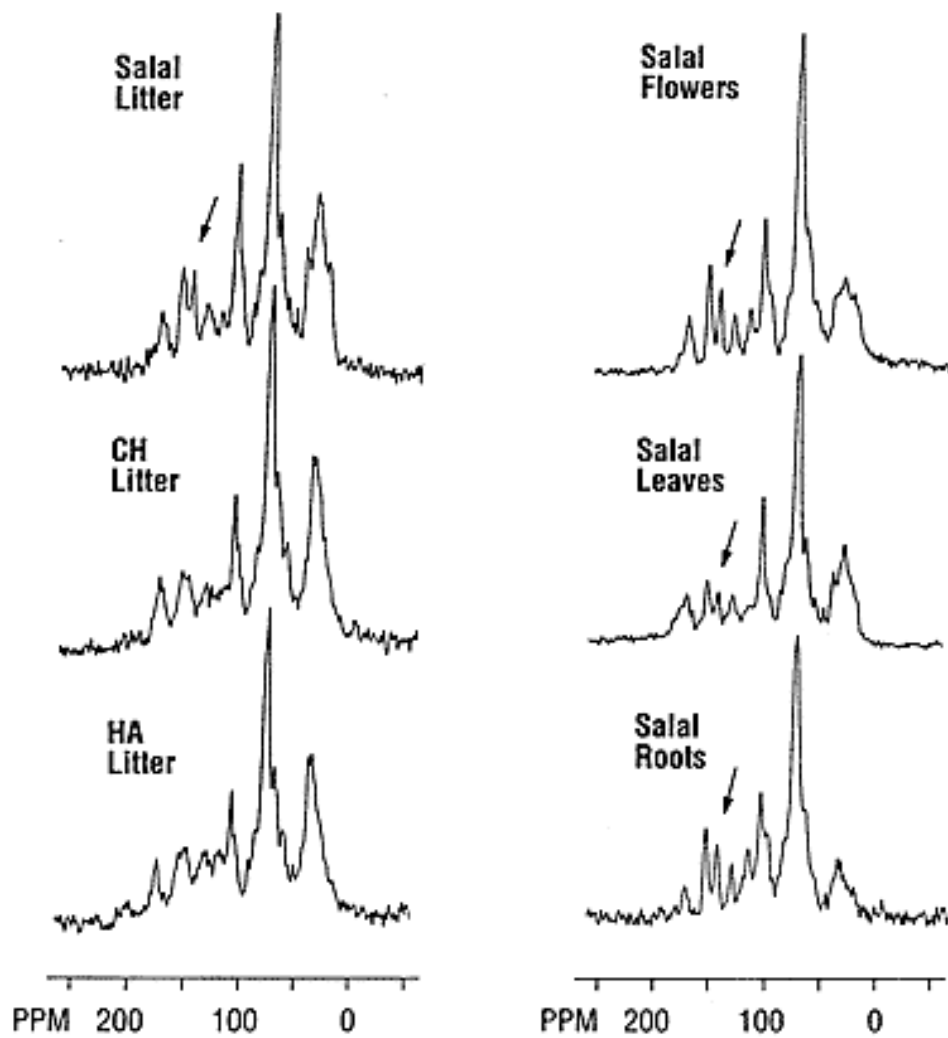


Figure 10. C-13 NMR spectra of litter from CH and HA forests, and of leaf litter, flowers, leaves and roots of salal.

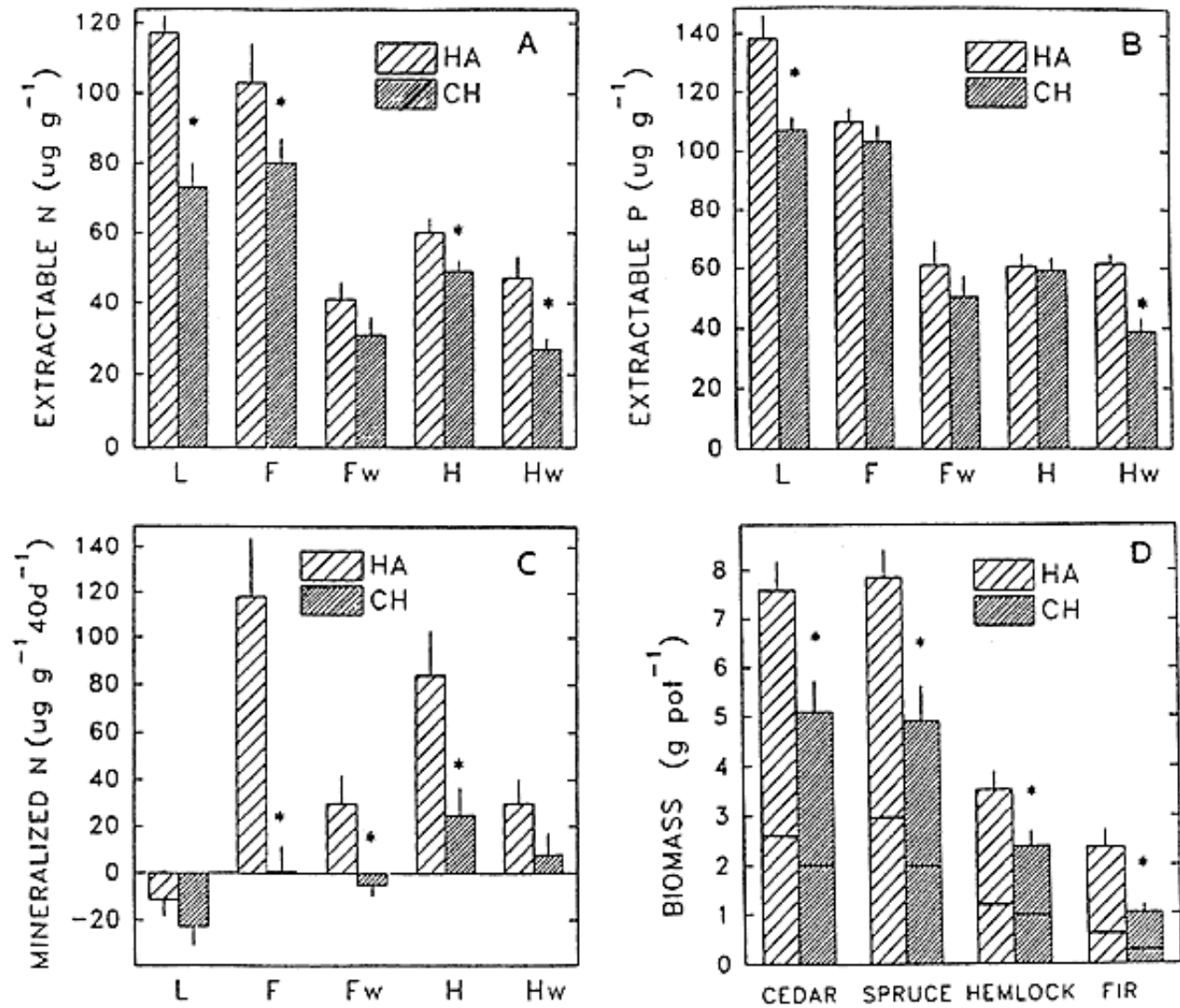


Figure 11. Availability of nutrients in each forest floor layer of CH and HA forests, measured as concentrations of KCl-extractable N (A), Bray-extractable P (B), amounts of N mineralized during a 40-day aerobic lab incubation (C), and biomass production by tree seedlings of four species grown in F layer material from each forest type (D). Each value is the mean (+s.e.) of 15 samples; asterisks indicate significant differences between 2 forest types. Horizontal lines separate values for shoots (above) and roots (below).

Table 4. Concentrations of N, P and C and pH of each forest floor layer from CH and HA forests. The mean and standard deviations of 15 samples are presented; asterisks indicate significant differences between the two forest types.

Layer†	Type	N (mg g ⁻¹)	P (mg g ⁻¹)	C (mg g ⁻¹)	pH
L	CH	6.7 (0.5)*	0.6 (0.1)*	543 (19)	4.75 (0.28)*
	HA	8.3 (0.5)	0.8 (0.1)	534 (23)	3.96 (0.11)
F	CH	9.0 (1.1)*	0.6 (0.1)	529 (28)	4.21 (0.31)*
	HA	9.9 (1.0)	0.7 (0.1)	531 (18)	3.45 (0.20)
Fw	CH	3.2 (1.6)	0.2 (0.1)	626 (35)	3.57 (0.15)
	HA	4.0 (2.1)	0.3 (0.1)	628 (45)	3.58 (0.02)
H	CH	9.7 (1.2)*	0.5 (0.1)	523 (17)	3.65 (0.24)*
	HA	11.7 (1.8)	0.6 (0.1)	517 (23)	3.19 (0.14)
Hw	CH	5.0 (1.5)*	0.2 (0.1)*	534 (43)	3.41 (0.23)
	HA	8.0 (3.3)	0.4 (0.1)	558 (36)	3.23 (0.14)

†L=litter, F=fermentation, H=humus, w=woody.

material from CH forests grew more slowly and took up less N and P than did seedlings grown in HA forest floor material during a one-year greenhouse experiment (Figure 11). Analysis of phosphorus forms by P-31 solution NMR indicated that concentrations of total and available P were lower in CH forest floors, or there was less polyphosphate and more of the phosphate in CH forest floors (Cade-Menun 1995). The pH of non-woody forest floor layers was greater in CH forests (Table 4).

Rates of CO₂ evolution from CH forest floors during the lab incubations, indicative of rates of breakdown of organic matter, were equal to or greater than those in HA forest floors (Prescott et al. 1994). Decomposition rates of a standard litter substrate (pine needles) was the same in CH and HA forests. During a 2-year incubation in CH forests, foliar litter of cedar lost about 50% of its original mass and salal lost 75%. During 2 years of decomposition in HA forests, hemlock foliar litter lost about 60% of its original mass, which was similar to the rate in CH forests. Forest floor F-layer material from HA forests decomposed more slowly during three years incubation in HA forests than did CH material in CH forests.

The composition and biomass of soil fauna were surveyed in forest floor and mineral soil from CH and HA forests (Battigelli et al. 1994). Macrofauna were collected by handsorting, Oligochaeta using the Formalin method, nematodes and enchytraeid worms using Baermann funnels, and microarthropods with a high gradient extractor. The biomass of soil fauna was less in CH forests than in HA forests, and was dominated by millipedes and potworms. Nematodes and aquatic animals such as Copepods and Brachiopods were also more abundant in CH forests. Higher moisture levels were generally found in samples of forest floor and soil from CH forests. In HA forests, the biomass of soil fauna was more evenly distributed among the dominant groups, Diplopods, Enchytraeids, mites and Dipteran larvae.

Litterfall & Internal Nutrient Cycling

Aboveground litterfall was collected for 2 years in twenty 0.25 m² traps located in one 50 x 50 m plot in three CH and three HA forests (Keenan et al. in review). Green foliage was collected from five upper crown branches of each species in the three CH and three HA forests in February 1992. N and P concentrations were measured in green needles and

needle litter of each species, and resorption of N and P (i.e. withdrawal during senescence) was estimated as the difference between concentrations in green and senesced foliage.

The annual mass of aboveground litterfall in CH forests was 3094 kg ha⁻¹, half of which was conifer foliar litter. The N and P concentrations in litterfall were 0.46% and 0.03%, respectively, and the amounts returned annually were 14.2 kg N ha⁻¹ and 0.9 kg P ha⁻¹. Nitrogen concentrations in green foliage and foliar litter of cedar were less than in hemlock. Cedar resorbed a greater proportion of N during senescence (76.4%) than hemlock (64%).

The annual mass of aboveground litterfall in HA forests was 4173 kg ha⁻¹, of which half was conifer foliar litter. Concentrations of N and P in litterfall were 0.86% and 0.06%, and the amounts returned annually were 35.9 kg N ha⁻¹ and 2.29 kg P ha⁻¹. Nitrogen concentrations in foliar litter were 0.83% in hemlock and 1.11% in amabilis fir. N concentrations in green foliage were 1.4% in hemlock and 1.29% in amabilis fir. Hemlock resorbed a greater proportion of N during senescence (50.9%) than fir (17.9%). Hemlock in HA forests had higher N concentrations in green foliage and foliar litter than hemlock on CH sites, and resorbed a greater amount of N. Litter in HA forests had greater proportions of carbohydrate and lower proportions of lignin than litter in CH forests (Prescott et al. 1994).

At a stand level (Table 5), more than twice as much N was returned in foliar litterfall in HA forests (18.5 kg ha⁻¹) compared to CH forests (7.15 kg ha⁻¹). More of the tree 'demand' for N was met through resorption in CH forests. Nitrogen use efficiency was higher in cedar than in hemlock in CH forests, and was greater in hemlock in CH forests than in HA forests. During the first year of decomposition, foliar litter in CH forests released 0.46 kg N ha⁻¹, compared to 1.41 kg N ha⁻¹ in HA forests (Keenan et al., in review). Using the ecosystem model, LINKAGES, Keenan et al. (1994) showed that the lower N content of litter in CH forests and slower decomposition of cedar litter contributes to low rates of N mineralization, as measured in CH forest floors.

Discussion

Measurements of nutrient availability in CH and HA forest floors demonstrated that lower N and P availability in CH forest floors existed prior to clearcutting.

There was not much evidence to support the hypothesis that more N and P were immobilized in detritus in CH forests, since the total amounts of N and P in CWD and forest floors were similar in the two forest types. However, there was relatively more N in the humus (H) layer in CH forests and less in

Table 5. Foliar litter mass, litter N mass, green foliage mass equivalent, green foliage N content, amount of nutrient resorbed, percentage of green foliage N content, and N use efficiency in CH and HA forests. All values are kg ha⁻¹.

	CH		HA	
	Cedar	Hemlock	Hemlock	Fir
Foliar litterfall	1212	303	1674	419
Foliar litterfall N	5.21	1.94	13.89	4.65
Green equivalent of litterfall mass	2376	433	2041	440
Green N content ('demand')	22.10	5.46	28.58	5.68
Amount resorbed	16.89	3.56	14.69	1.03
% of 'demand'	76	65	51	18
N use efficiency	233	156	121	23

the F layer, so the N may be less available in CH forests. The greater mass of humus in CH forests may be the result of their greater age, or less complete decomposition, as discussed below.

Less N was returned in aboveground litter in CH forests, and there was greater internal recycling within the trees. This resulted from very efficient use of N by cedar, and from more efficient use of N by hemlock growing in CH forests. This is probably a response to low N availability and could also create a positive feed-back that would exacerbate the low N availability in CH forest floors.

Decomposition rates of standard litter substrates were similar in the two forest types, and rates of CO₂ evolution from each forest floor layer during lab incubations were similar to or greater than those in HA forests. These findings suggest that the decomposition potential of the two sites is similar. The lower N availability despite similar rates of litter decay may be attributable to the tannins from salal, which bind proteins and immobilize N. Nitrogen may be more rapidly immobilized in microbial biomass in CH forest floors, resulting in less available N despite similar microbial activity. The presence of cedar in CH forests could also contribute to low N availability. In a modeling study (Keenan et al. 1994), there was lower N availability in forest floors in simulated cedar forests, than in hemlock forests. In trials at the UBC Research Forest (Prescott and Preston 1995), and in Ireland (Prescott et al. 1995), low rates of N mineralization were measured in forest floors in cedar plantations, compared with adjacent plantations of other species including hemlock and firs. The relatively low concentrations of N and high concentrations of lignin, waxes and lipids in cedar litter may be responsible for slower N mineralization in cedar forests.

There was evidence that moisture levels in CH forest floors and soil were greater than in HA forests, and this may have resulted in conditions that inhibit decomposition and nutrient cycling in CH forests. Moisture contents of samples of forest floors and mineral soils were usually greater in CH forests, and sensors placed in the humus recorded consistently higher moisture levels in CH forests. Mineral soil in many of the CH forests studied was more compacted and cemented layers were continuous and shallower. This could lead to poorer drainage

of humus, as indicated by the occurrence of hydromors in CH forests. The lower abundance of fauna and the greater representation by aquatic animals such as copepods and brachiopods in CH forest floors also indicate wetter conditions. The high moisture and smaller faunal biomass could result in less complete decomposition in CH humus. This was suggested by the higher concentrations of lipids and carbohydrates and the poorer lignin biodegradation in CH forest floors. The poorer drainage in CH forest floors may be attributed to the lack of soil disturbance by windthrow, or the tendency for the CH forests studied to be on lower topographic positions.

Conclusion

- N and P availability was lower in CH forests than HA forests prior to harvesting, so the low nutrient supply in CH cutovers is not created by clearcutting.
- There was not more N tied up in humus and woody debris in CH forests than in HA forests. There was less N cycling in CH forests, as evident in the lower N content of litter and N mineralization rates in CH forests. This resulted from higher efficiency of N use in trees in CH forests.
- Decomposition was less complete in CH forests, leading to larger amounts of humus with higher concentrations of lipids and carbohydrates.
- Incomplete decomposition in CH forests may be a consequence of poorer drainage of the humus, and may be mediated through effects on the soil fauna.
- Tannins are present in CH forest floors, apparently associated with salal, and may interfere with decomposition and N mineralization in CH forest floors.
- Lower rates of net N mineralization in CH forest floors, despite high rates of decomposition and C mineralization, may indicate greater immobilization of N in microbial biomass in CH forest floors.
- Cedar litter may contribute to low N and P availability in CH forest floors.

Response to Clearcutting

Introduction

The origin of the SCHIRP study of the CH/HA phenomenon was the observation that Sitka spruce planted on clearcut and slashburned CH sites exhibit growth check after a few years, coincident with expansion of salal on the cutovers. By contrast, cedar and hemlock trees on clearcut HA sites grew well. The initial focus of studies was on the proximal cause of this growth decline of planted spruce on CH cutovers. This was shown to be related to inadequate nitrogen nutrition of the spruce, and, to a lesser extent, to lack of phosphorus. The first question was: How does the availability of soil nutrients change over time on sites that exhibit the growth decline (CH sites), and secondly, how does this temporal pattern compare with that on HA sites that exhibit sustained good tree growth? These questions were addressed by comparing nutrient availability on CH and HA sites and over a chronosequence of CH sites. The role of salal as a competitor for nitrogen was also investigated, by comparing the growth and nutrition of conifers in the presence and absence of salal. Allelopathic effects and mycorrhizal interactions of salal and conifers were examined to determine if they played a role in the dominance of salal on CH sites.

Temporal Pattern of Nutrient Availability

Following Harvesting and Burning

Two approaches to this question were used: 1. analytical measures of soil nutrient availability and, 2. bioassays of nutrient availability, including seedling growth and nutrition in field, pot and greenhouse trials, and analysis of the nutrition of competing vegetation and microbial biomass.

Analytical measures of nutrient availability

Weetman et al. (1990) examined nutrient availability on an 8-year post-burning chronosequence of CH sites. Extractable N generally declined from year 1 to year 8 (Table 6). The 5th year increase may relate to initial site differences not to a real temporal characteristic of these disturbed ecosystems. Mineralizable N and net mineralizable N showed the same pattern. Extractable P was highest in year 1, but declined in year 2. There was no statistically significant trend in total forest floor mass or total N, suggesting that the temporal pattern of nutrient availability was the consequence of dynamics of a small component of the forest floor: the upper, active humus form.

Messier (1993) compared CH sites 2 and 8 years after burning (Table 7), and reported declines in total N and extractable P, and a decrease in P retained in ion-exchange resin bags. HA sites 2 years after burning had higher rates of cellulose decomposition than 2-year post-burning CH sites, but lower total N. Cade-Menun (1995) examined P availability in soil from CH cutovers immediately, 5 years and 10 years after clearcutting and burning. There was a flush of available (Bray-extractable) P immediately after burning, which declined during the next 10 years, and a decline in total P during the 10 years (Figure 12). P-31 NMR spectroscopy as used to determine the distribution of organic forms of P. Most of the P was in organic forms in the surface horizons. Deeper in the profile, there was less organic P and more inorganic P. Immediately after burning, almost all of the P was converted to inorganic forms in the LF horizon, but the forms were unchanged in the lower horizons.

Table 6. N and P availability over an 8-year post-burning chronosequence of CH sites. Within a row, values followed by the same letter are not significantly different.

	Years since burning					
	1	2	3	4	5	8
Total N (%)	1.02 ^b	0.92 ^b	0.95 ^b	0.91 ^b	0.91 ^b	0.81 ^a
Total P (%)	0.076 ^c	0.057 ^b	0.059 ^b	0.049 ^a	0.064 ^b	0.052 ^a
Extractable N (µg/g)	412 ^c	205 ^b	84 ^a	101 ^a	152 ^{ab}	67 ^a
Mineralizable N (µg/g)	512 ^d	312 ^c	230 ^b	172 ^{ab}	222 ^b	113 ^a
Net Mineralizable N (µg/g)	100 ^b	107 ^b	146 ^c	71 ^a	70 ^a	46 ^a



Plate 4. Six-year old cedar tree on a CH cutover.



Plate 5. Six-year old hemlock tree on a HA cutover.

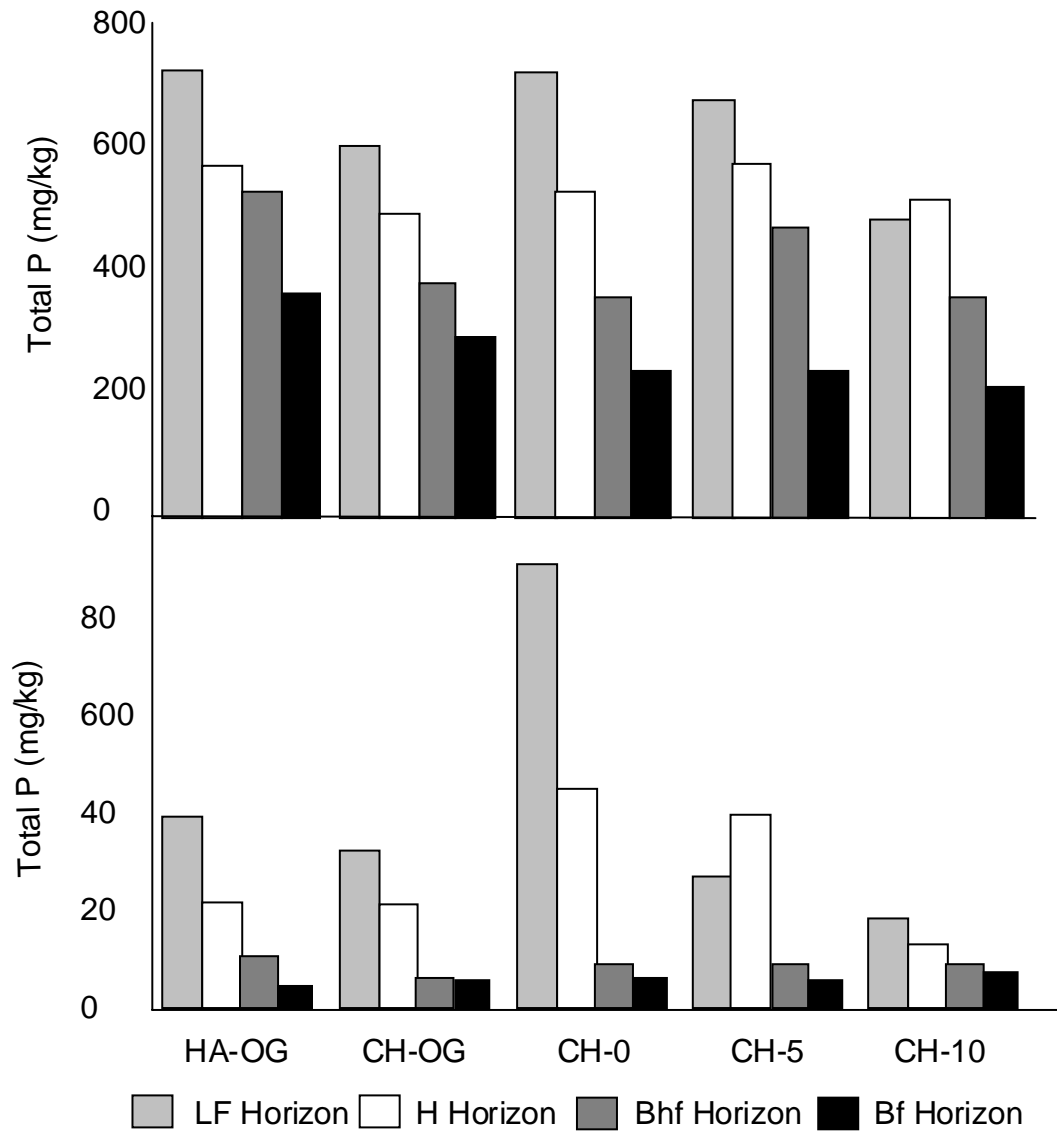


Figure 12. Concentrations of total P and Bray-extractable P in humus and soil from old-growth HA and CH forests and from CH cutovers 0, 5 and 10 years after burning.

Table 7. Soil variables in 2- and 8-year post-burning CH sites and a 2-year HA site. Within a row, values with the same letter are not significantly different.

	Years since burning		
	CH sites		HA site
	2	8	2
Forest floor thickness (cm)	20-70	20-70	10-40
Total N (%)	1.25 ^b	1.10 ^a	1.05 ^a
Extractable P (µg/g)	0.22 ^b	0.005 ^a	0.20 ^b
Mineralizable N (µg/g)	0.37 ^b	0.28 ^a	0.37 ^b
Cellulose decomposition (%)	25.9 ^a	27.3 ^a	65.0 ^b
Resin bag NH ₄ ⁺ (mg/g)	0.472 ^a	0.580 ^a	0.873 ^b
Resin bag P (mg/g)	0.160 ^b	0.053 ^a	0.124 ^b

Bioassays of nutrient availability

(a) Foliar nutrient concentrations of salal and fireweed

Foliar concentrations of macronutrients can be a useful indicator of soil nutrient availability. Weetman et al. (1990) measured foliar concentrations of N, P and K in foliage of salal and fireweed (Table 8). Nutrient concentrations of salal generally declined with time; N declined steadily over the chronosequence, whereas P and K reached minimum values within 2 or 3 years. Fireweed was not present on the one-year-old CH site. Fireweed foliar N concentrations showed a pattern similar to that of salal (Table 8). Fireweed P and K showed no trend, matching the salal data for comparable site ages.

(b) Field seedling bioassay

Seedling growth performance was used as a bioassay of soil fertility on different aged cutovers and different site types (CH and HA) in several experiments. Messier (1993) planted 1-year-old nursery-grown seedlings of western hemlock, western red cedar, and Sitka spruce on HA sites 2 years after burning, and on CH sites 2 and 8 years after burning. Light competition was prevented by clipping back the competing vegetation. Height and diameter growth of western red cedar was not affected by time since burning on the CH site (2-8 years), or by differences between CH and HA sites

on the 2-year post-burning sites. In contrast, height and diameter increments of hemlock and Sitka spruce were greatest on the HA site, followed by the young CH site, and least on the oldest CH site (Figure 13). Height increment of all three species increased over the second and third growing seasons on the HA site. In contrast, there was either little change (cedar) or a declining trend (spruce and hemlock) in height increment on the oldest CH site.

(c) Pot seedling bioassay

Spruce and cedar, representing responsive and unresponsive species, were examined in this study (Messier 1993). Seedlings were grown for two growing seasons in pots containing forest floor material from the same sites used in the field bioassay (Figure 14). The greatest height and diameter growth during the two growing seasons was in forest floors from 2-year HA sites. These results confirmed the field seedling bioassay results, suggesting that nutrient availability is in the order 2-year post-burning HA > 2-year CH > 8-year CH, and that cedar is insensitive to nutrient availability. Interestingly, the greatest increase in growth from year 1 to year 2 of the pot trial was in cedar in the 8-year CH forest floor material. Apparently, cedar was able to access nutrients despite their low availability in the CH forest floor.

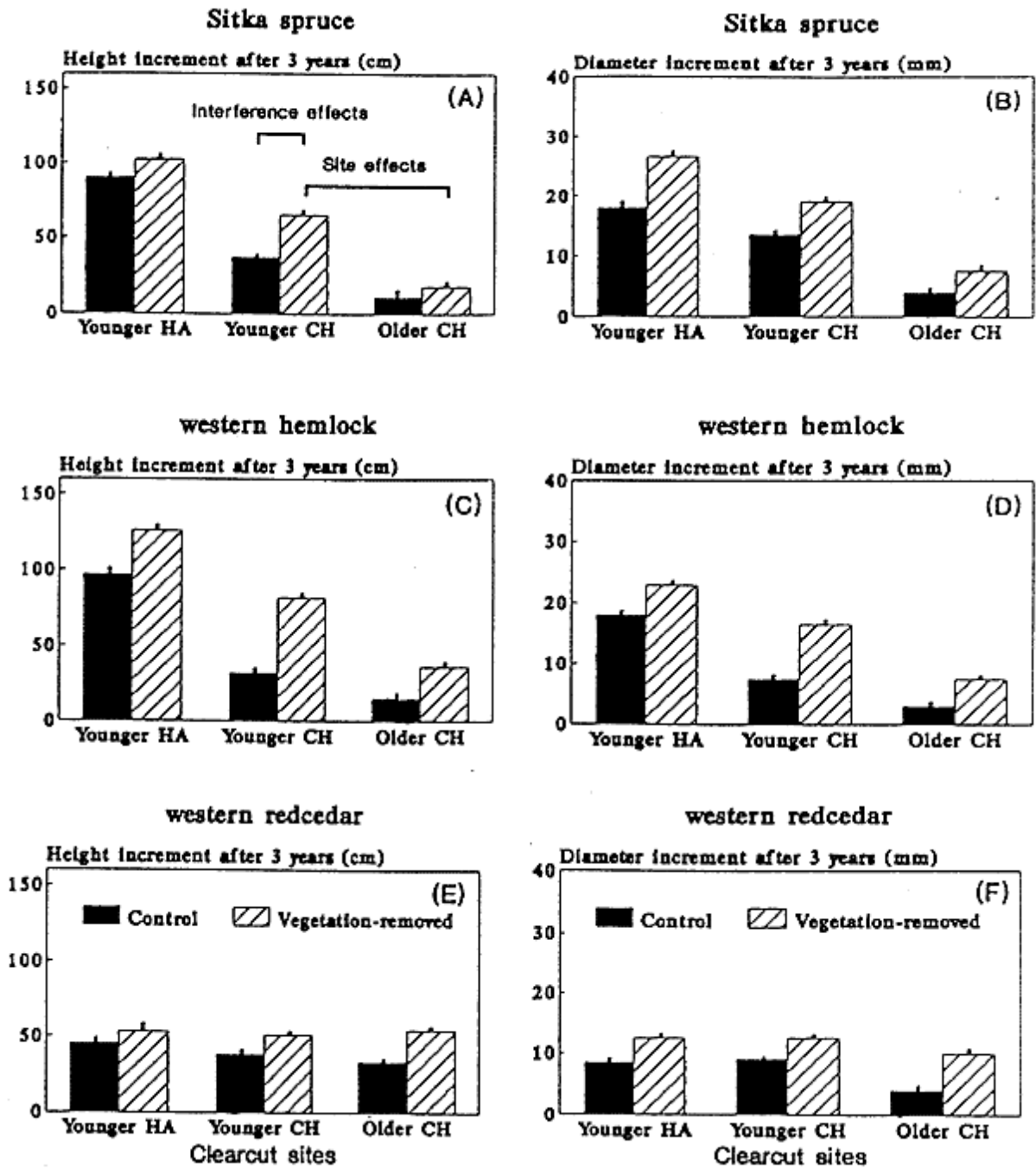


Figure 13. Height and diameter increments of conifer seedlings after three growing seasons in 2-year post-burning HA and 2- and 8-year CH cutovers, with and without removal of competing vegetation.

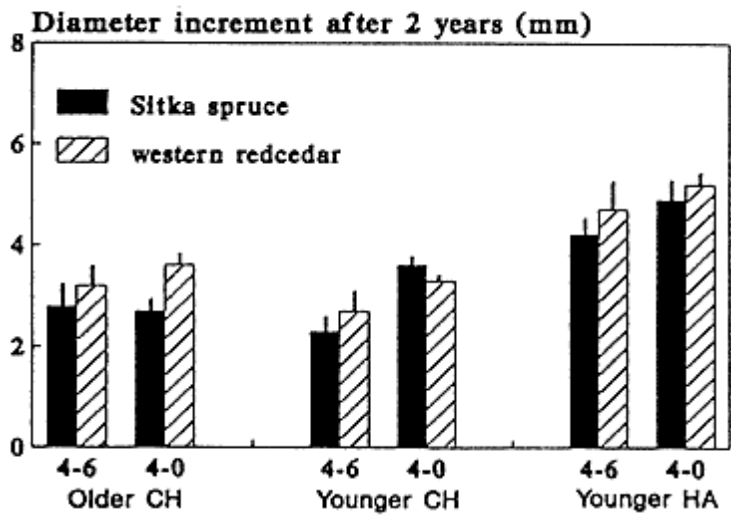
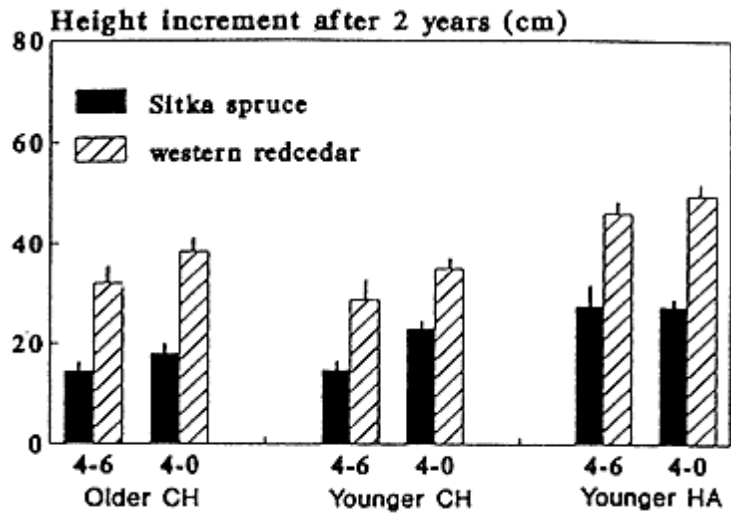


Figure 14. Height and diameter increments after two growing seasons of spruce and cedar seedlings grown in forest floors from 2-year post-burning HA sites and 2- and 8-year CH sites, with conifer:salal ratios of 4:6 and 4:0.

Table 8. Foliar concentrations (%) of N, P and K in salal and fireweed over an 8-year post-burning chronosequence of CH sites. Within a row, values with the same letter are not significantly different.

		Years since burning					
		1	2	3	4	5	8
Salal							
N		1.41 ^d	1.04 ^c	0.86 ^b	0.87 ^b	0.72 ^a	0.75 ^a
P		0.12 ^c	0.09 ^b	0.07 ^a	0.08 ^b	0.06 ^a	0.06 ^a
K		0.92 ^c	0.71 ^{ab}	0.69 ^{ab}	0.80 ^{bc}	0.62 ^a	0.76 ^{ab}
Fireweed							
N		np	2.06 ^a	1.77 ^c	1.62 ^b	1.58 ^b	1.44 ^a
P		np	0.13 ^a	0.19 ^c	0.16 ^b	0.16 ^b	0.15 ^a
K		np	1.23 ^b	1.04 ^b	1.01 ^b	1.18 ^b	0.64 ^a

np = not present

(d) Greenhouse seedling bioassay

A greenhouse trial was conducted to monitor soil P availability in a CH chronosequence, measuring seedling biomass production, P-32 uptake, isotopically exchangeable P and P-retention capacity of the soil (McDonald, unpublished). Seedlings (1+0) of Sitka spruce and western red cedar were transplanted into pots containing soils from a chronosequence of CH cutovers, 1 year, 4 years and 8 years after burning, and from an old-growth CH forest. The seedlings were grown for one year in a greenhouse. After one year, P-32 was added as a drench to all pots and seedlings were harvested over the next 4 weeks. The above and belowground biomass, nutrient concentrations and P-32 uptake of each seedling were measured. Estimates of the size of the labile P pool were made by isotopically exchangeable P (IEP). The P-retention capacity of the soil was estimated by adding P solutions. The results are summarized in Figure 15 and Figure 16. Seedlings grown in the 1- and 4-year post-burning soils took up the most P-32. Seedlings grown in the 8-year post-burning soils took up the least 32-P, in spite of a greater demand, as reflected in lower foliar P concentrations and less biomass production. The 8-year post-burning soil also had the greatest

capacity to fix phosphorus and the smallest labile pool. This suggests the P deficiency in CH cutovers arises at least partly through immobilization of P in these soils.

(e) Nutrient content of microbial biomass

The C and N contents of the microbial biomass in a chronosequence of CH sites (3 and 10 years after burning, and old-growth) were measured in fumigation experiments in the laboratory (Chang et al., in review). Microbial C and N content and moisture content of the forest floor were greater in the old-growth forest than in the cutovers. The least extractable N and the greatest microbial C:N ratio were in the 10-year cutover, confirming the decline in N availability during the first decade after clearcutting and burning CH sites.

The results of the above studies support the hypothesis that a significant component of the growth problem on CH sites is a rapid decline in soil nutrient availability during the decade following harvesting and burning.

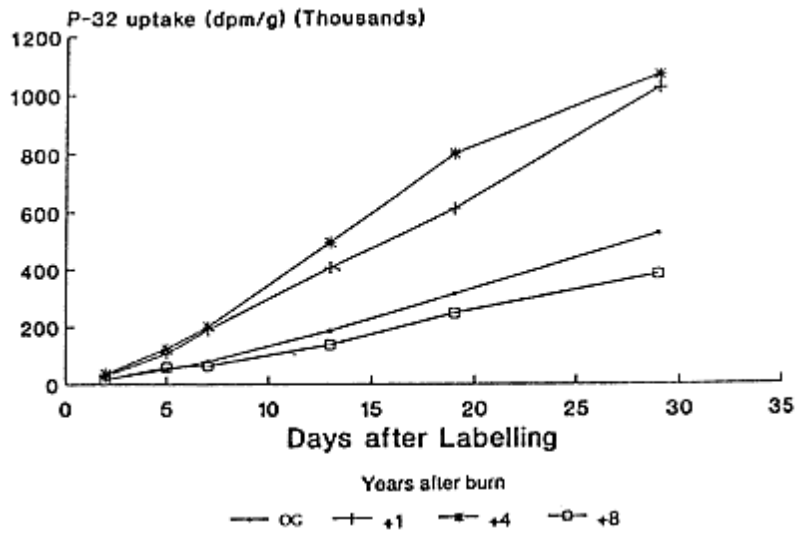


Figure 15. P-32 uptake by seedlings grown in soils from an old-growth CH forest and from 1-, 4- and 8-year post-burning CH sites.

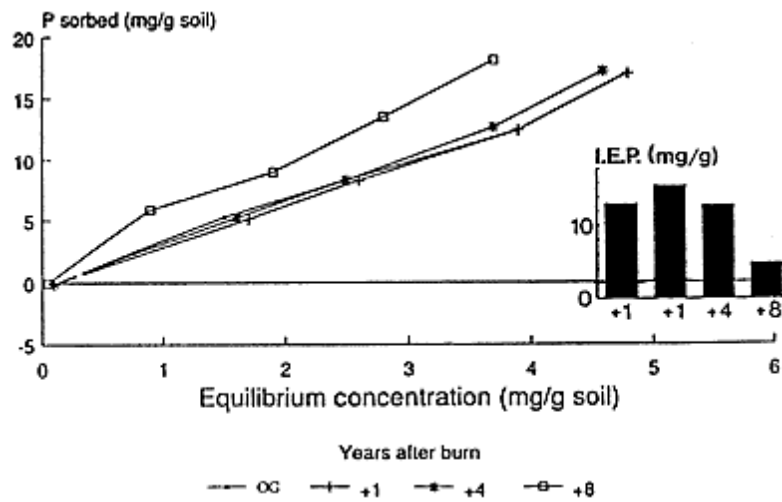


Figure 16. P sorption and isotopically exchangeable P (I.E.P.) in soils from an old-growth CH forest and from 1-, 4- and 8-year post-burning CH sites.



Plate 6. Seedling bioassay in greenhouse at UBC.

The Role of Salal

Several experiments were conducted to determine the role of salal in contributing to growth check of conifers on CH cutovers.

Biomass of competing vegetation

Messier and Kimmins (1990, 1991) estimated the biomass and nutrient content of competing vegetation in a CH chronosequence 2, 4 and 8 years after clearcutting and slashburning. Between 2 and 8 years, the above and belowground biomass and N and P contents of competing vegetation increased exponentially (Figure 17). At least 70% of the biomass at each time was salal. By 8 years, the biomass of competing vegetation averaged about 17,000 kg ha⁻¹, which contained about 70 kg N ha⁻¹ and 7 kg P ha⁻¹.

Correlations between salal abundance and tree growth

The influence of salal on planted hemlock and cedar saplings was examined through correlation analyses between the growth performance of 2 and 4-year-old hemlock and cedar saplings and salal leaf area index on CH and HA cutovers (Fraser 1993). The growth of western hemlock was negatively correlated with abundance of salal, more so

than was growth of western red cedar. When growing with western hemlock, salal appeared to be strongly competitive in control and fertilized CH and HA sites, and the negative influence increased over time. When growing with cedar, salal appeared to be weakly competitive in fertilized plots on CH sites, and in control plots on HA sites. The negative influence of salal on western red cedar only occurred in 2-year-old trees, and not in 4-year-old trees, suggesting that the influence was temporary.

Removal of competing vegetation

In the field trial with cedar, hemlock and spruce seedlings on 2-year HA and 2- and 8-year CH sites, Messier (1993) included a vegetation-removal treatment. A 200 cm patch around each seedling was kept free of competing vegetation by continuously clipping aboveground parts and trenching to 40 cm around the perimeter. After three growing seasons, the height and diameter of seedlings of all three species on all sites were greater in the vegetation-removed plots. Western red cedar grew more slowly and was less affected by removal of competing vegetation than were spruce and hemlock. Removal of competing vegetation also increased soil

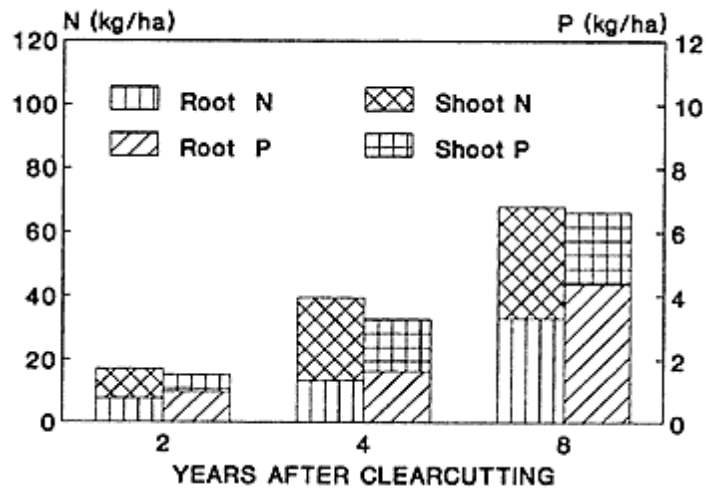
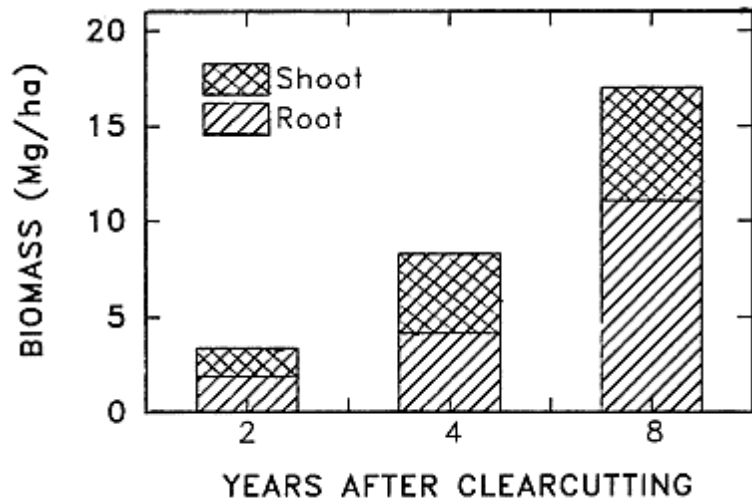


Figure 17. Above- and belowground biomass and nutrient content of competing vegetation on CH sites 2, 4 and 8 years after burning.

temperatures by 1-3°C and the availability of N and P in resin bags. P-32 uptake by seedlings of all three species was greater in the clipped plots, especially for hemlock (Figure 18) .

In the field pot trial with cedar and spruce seedlings, Messier (1993) included treatments with and without salal. Soil was collected from 2-year post-burning HA and 2- and 8-year CH cutovers. Height and diameter of seedlings were measured for two growing seasons. There were no significant differences in growth of seedlings with and without salal.

A greenhouse study was conducted to determine if salal competed with conifer seedlings for P (McDonald, unpublished). Seedlings of Sitka spruce, western red cedar and western hemlock were grown in pots with salal seedlings for one growing season. After this period, in half of the pots, the salal was clipped away at soil level, and P-32 added as a drench to all the pots. P-32 uptake by the trees was measured two weeks later. If there was direct competition for P, removing salal should increase uptake by the tree seedlings. Figure 19 shows that only with spruce was there a significant increase in P-32 uptake upon removal of salal. Cedar was unaffected, and hemlock showed a slight increase.

Allelopathic effects of salal

Tannins, thought to be either a procyanidin or a procyanidin and prodelfphinidin mix, were identified in the leaves, roots, flowers, berries and litter of salal using C-13 NMR. Salal flowers and berries, which are extremely abundant in cutovers, could be a large source of readily leachable tannins, and decomposition of salal litter may also release tannins. Tannins are known to reduce the biodegradability and humification of organic matter by three processes: the production of protein-tannin complexes which are much more resistant to microbial decomposition than unaltered proteins; the permeation and coating of non-proteins such as cellulose and hemicellulose by the protein-tannin complexes, giving them considerable resistance to microbial attack; and by the inactivation of enzymes important in the process of decomposition (deMontigny and Weetman 1990). The high ratio of total carbohydrate to lignin C (as found by C-13 NMR) and the low concentrations of lipids, polysaccharides and cellulose in CH humus may be the effects of tannins.

Phenolic acid concentrations in humus from CH forests were significantly higher in syringic, p-coumaric and ferulic acids, all of which have been shown to inhibit root ion uptake in laboratory experiments. Concentrations of free phenolic acids under salal on cutovers were higher in non-woody horizons than in woody horizons. Concentrations of vanillic, protocatechuic and p-hydroxybenzoic acids originating from conifers, were significantly higher in the colder, wetter months. Concentrations of syringic and p-coumaric acids were significantly higher in warmer drier months. These high concentrations are coincident with physiological activity of salal, particularly flower and fruit production in the summer months.

In a laboratory bioassay, phenolic acid solutions at field concentrations, and a 5% solution of salal flower and berry (unbuffered) significantly reduced the germination value of Sitka spruce and western red cedar seeds (deMontigny 1992). Seedlings of spruce, cedar and hemlock watered with the salal leachate solution had significantly lower biomass than the control seedlings after 12 weeks. The phenolic acids solution resulted in total biomass of the seedlings being lower than controls, but only the spruce seedlings were significantly lower. The results indicated that the salal leachate and soil phenolic acid solutions can significantly affect the growth of seedlings. Root samples of mature cedar and hemlock were placed into the treatment solutions augmented with a P-32 labelled phosphorus solution (unbuffered). The phenolic acid solution reduced P uptake by cedar and hemlock to 36% and 69% (respectively) of that of controls. The salal leachate solution had an even more pronounced effect, reducing P uptake by cedar and hemlock to 15% and 9% (respectively) of that of controls.

When the roots of seedlings which had been watered with the treatment solutions were placed into a P-32 labelled phosphorus solution, the short-term uptake was significantly lower for the phenolic acid treatment in cedar only, indicating possible root damage. The total inorganic P uptakes in spruce and hemlock were actually higher in the treated seedlings than in the control seedlings. This suggests that the seedlings were deficient in P, and given the new conditions of higher P concentrations, hemlock and spruce were able to respond by increasing short-term P uptake. The P deficiency may have resulted

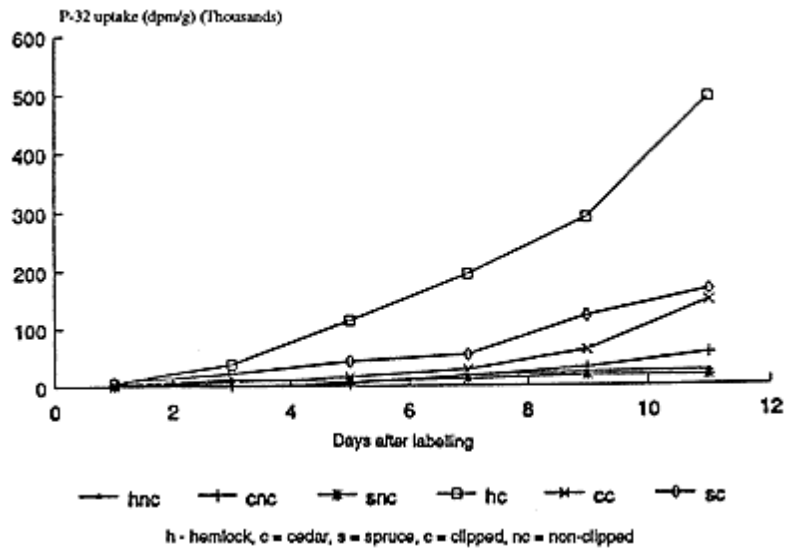


Figure 18. P-32 uptake by cedar, hemlock and spruce seedlings in control and clipped plots on CH cutovers.

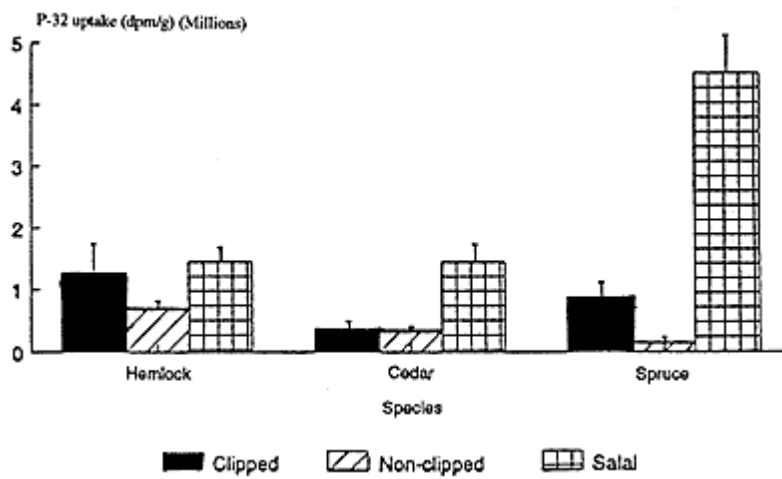


Figure 19. P-32 uptake by cedar, hemlock and spruce seedlings grown with and without salal.

from reduced ion uptake either directly at the root by phenolic acids or tannin leachates (as was found in the mature root bioassay), or indirectly by inhibition of P mineralization in soils containing tannins (as was found in CH humus). Removing the roots from the inhibiting conditions reversed the effects at least for spruce and hemlock.

Mycorrhizae of salal, cedar and hemlock

A greenhouse trial was conducted to examine the influence of salal on growth and mycorrhizal colonization of cedar seedlings (Husted; unpublished data). One-year-old nursery stock cedar seedlings were planted in pots containing humus from an 8-year post-burning CH cutover. The four treatments were: 1) one cedar per pot, 2) two cedars per pot, 3) one cedar and one salal seedling per pot, and 4) one cedar and one salal with root systems separated by a wooden divider.

After two growing seasons, relative growth rate and N and P contents were reduced in cedars grown in competition with cedar or salal. Colonization of roots with mycorrhizal (VAM) fungi was reduced by 10% in pots containing salal compared to pots

containing either one or two cedars. In partitioned pots, VAM colonization was similar in all treatments. These results suggested that the presence of salal roots reduced mycorrhizal colonization and nutrient uptake by cedar seedlings.

Additional studies were conducted to determine: 1) the forms of salal mycorrhizae, 2) if mycorrhizae enable salal to use organic N, and 3) if salal mycorrhizae are antagonistic to those of hemlock (Xiao 1994). Salal formed typical ericoid mycorrhizae, characterized by a weft of hyaline hyphae on the surfaces of root hairs and crowded hyphal complexes inside the outer layer of cortical cells. The ability of the four species of ericoid mycorrhizal fungi, isolated from salal roots, to use different forms of organic N was tested in pure culture or in association with salal. The organic forms of nitrogen applied were glutamine (an amino acid), glutathione (a peptide), and bovine serum albumin (BSA, a protein). The fungi tested were *Oidio dendron griseum*, *Acremonium strictum*, and two nonsporulating unknown fungi. There was considerable variation between fungal species, or the plants inoculated with those fungi in terms of using

Table 9. The cell percent colonization of salal plants inoculated with five root-associated fungi. Each value is the mean and (standard deviation) of 10 samples; values with the same letter are not significantly different.

Plants inoculated with	Nitrogen Sources				
	Ammonium	Glutamine	Glutathione	BSA	N-free
Unknown 1	18gh (3)	20g (3)	95a (2)	96a (2)	95a (2)
<i>Oidiodendron griseum</i>	20gh (6)	19gh (2)	80de (7)	94ab (3)	93abc (5)
<i>Acremonium strictum</i>	11h (2)	11gh (2)	83de (4)	63f (6)	86bcde (2)
Unknown 2	18gh (2)	17gh (2)	82de (5)	84cde (4)	90bcde (4)
<i>Hymenoscyphus ericae</i>	17gh (2)	20gh (3)	84cde (5)	81de (6)	79e (7)



Plate 7. A salal root showing cortical cells colonized by ericoid mycorrhizal fungi.

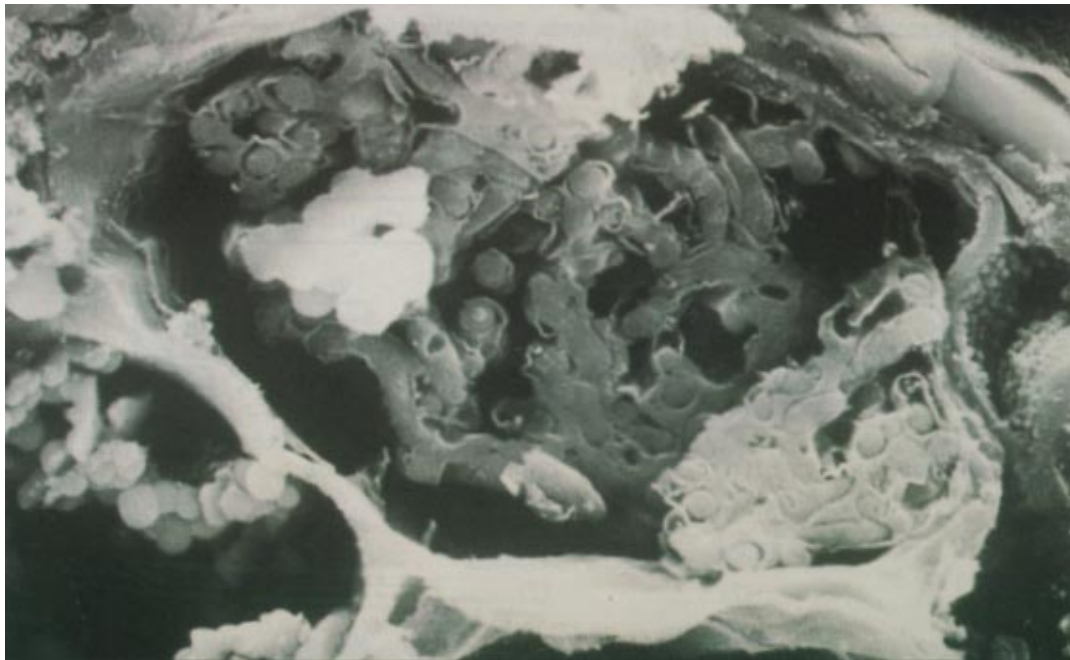


Plate 8. A colonized cortical cell of salal, showing hyphae separated from the host cytoplasm by a continuous root plasmalemma.

glutathione and BSA. *Oidiodendron griseum* on glutathione and *Acremonium strictum* on BSA produced significant yields in pure culture or as a mycorrhizal partner. The mycorrhizal plants of salal inoculated by all four fungi had higher colonization rate on glutathione or BSA than on ammonium or glutamine (Table 9) . The ericoid mycorrhiza formation of salal was suppressed by application of available N and simple organic N, and favoured by more complex organic N.

Interactions between species of four ericoid mycorrhizal fungi (*Acremonium strictum*, *Oidiodendron griseum* and two unknown species that were isolated from salal roots), and three ectomycorrhizal fungi proven to be mycorrhizal with western hemlock (*Pisolithus tinctorius*, *Rhizopogon semi-reticulatus* and *Suillus lakei*), were examined in vitro and characterized on buffered and unbuffered modified Melin Norkrans agar (MMN). Three interaction patterns were revealed: neutral intermingling, deadlock and inhibition. Inhibition, in which the growth of one mycelium was reduced by the other, was the predominant outcome of the pairing of ectomycorrhizal fungi and ericoid mycorrhizal fungi. All three ectomycorrhizal fungi were inhibited

by ericoid mycorrhizal fungi, but none of the four ericoid mycorrhizal fungi were inhibited by any of the ectomycorrhizal fungi. *Acremonium strictum* was the most aggressive of the ericoid mycorrhizal fungi, inhibiting all three ectomycorrhizal fungi in five of six interspecific pairings on both media. *Oidiodendron griseum* was the second most aggressive. *Suillus lakei* and *Rhizopogon semireticulatus* were kept in check by three of the four ericoid mycorrhizal fungi on both media. The results showed that the ericoid mycorrhizal fungi of salal were inhibitory to the ectomycorrhizal fungi of hemlock.

This study demonstrated that salal formed ericoid mycorrhizae with a number of fungi which can use organic forms of N in pure culture, and that the ericoid mycorrhizal fungi of salal were antagonistic to ectomycorrhizal fungi of western hemlock. Mycorrhizal fungi of salal contribute to the dominance of this ericaceous species on CH sites by providing access to organic forms of nitrogen, and by reducing the growth of western hemlock seedlings through inhibition of their mycorrhizal fungi.

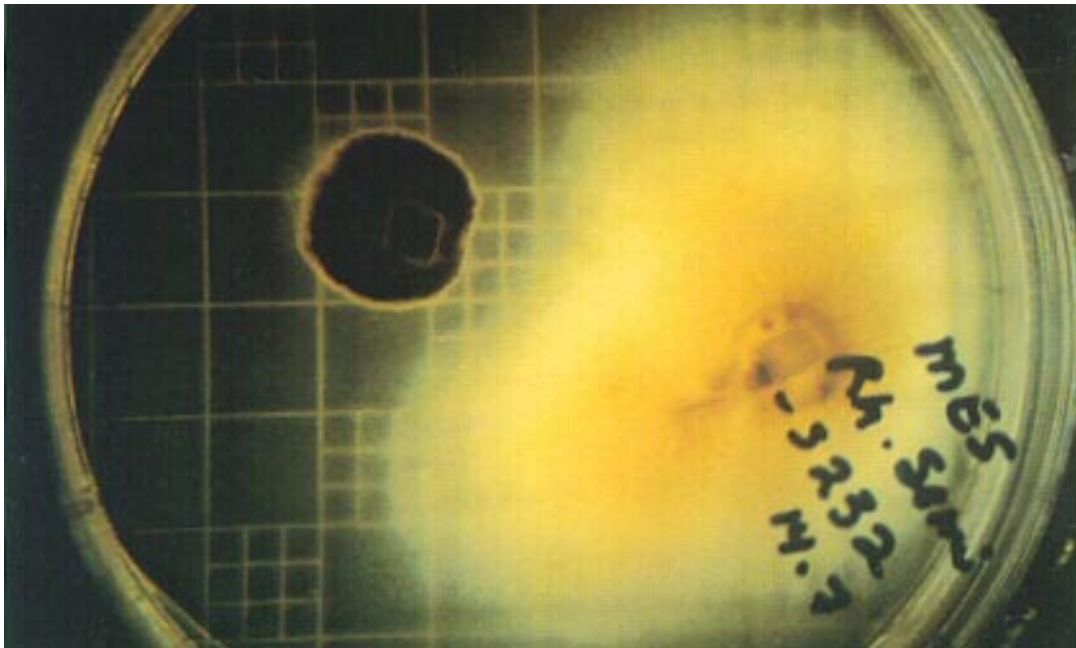


Plate 9. Inhibition of colony growth of *Rhizopogon semireticulatus* (black) by *Acremonium strictum* (yellow).

Conclusions

- A significant component of the growth problem of conifers on CH sites is the decline in availability of N and P during the first decade after clearcutting and burning.
- Salal re-establishes rapidly on CH cutovers and contributes to the slow growth of Sitka spruce and western hemlock by competing for N and P.
- Western red cedar grows more slowly than spruce and hemlock, but is less affected by low nutrient availability or salal abundance.
- The ericoid mycorrhizal fungi of salal inhibit the ectomycorrhizal fungi of hemlock.
- The ericoid mycorrhizae of salal utilize organic forms of N, and are suppressed by inorganic N and simple organic N.

Silvicultural Trials

Experiments were established in CH cutovers to test the effectiveness of a variety of treatments for improving the growth of conifers. Treatments included fertilization, scarification, weed control, planting density manipulation, and liming.

Fertilization Experiments

Three types of fertilization experiments were conducted to identify nutrient deficiencies of young, slow-growing conifers and to determine growth responses to fertilization as a function of fertilizer composition and dose. In plantations, the sample trees were all the planted trees within the measurement plot and all other conifers of breast height or greater. In natural regeneration, sample trees were all conifers of breast height or greater. Measurements were made of height and diameter of each sample tree in the spring prior to fertilization and every winter for up to eight years thereafter. Foliar samples were collected in the winter following fertilization. Needle weights and concentrations of macronutrients (N, P, K, Ca, Mg) were measured. In most experiments winter foliar samples were collected and analysed in succeeding years.

1. Single-tree screening trials

Trials were conducted on Sitka spruce and western red cedar on CH sites 5-8 years after planting. Numerous combinations of N, P and K were applied by hand in the spring to circular plots of 5 m radius centred on the test tree. Fertilizer combinations were

generally replicated five times. The first-year response data were analyzed using foliar vector analysis. The results indicated that the growth of both species was limited by N and P but not by K. The growth limitation of spruce was much greater than that of cedar. Fertilizer doses of 200 - 300 kg N ha⁻¹ and 50 - 100 kg P ha⁻¹ were identified as optimum treatments (Weetman et al. 1989a, 1989b).

2. Conventional plot trials

In these trials, square plots (25 or 30 m on a side) of pure spruce, cedar or western hemlock were hand fertilized 5-8 years after planting. All measured trees were within an inner measurement plot of 20 x 20 m or 25 x 25 m. Spruce plots received one of six treatments (all numbers are kg ha⁻¹): 0N, 0P (control); 100N+50P; 200N+50P; 300N+50P; 300N+150P; or 300N+50P+91K plus a micronutrient mix. Cedar and hemlock plots received one of 12 treatments; 0, 100, 200 or 300 N, combined with 0 P, 100 P, or 100 P plus micro-nutrients. Each treatment was replicated three times to give 18 plots of spruce and 36 plots each of cedar and hemlock. The results indicated that growth of all three species was limited by N and P deficiencies. The growth limitation was greatest for spruce and least for cedar (Table 10 and Table 11). For Spruce, the greatest growth rates were recorded in the 300N+150P and 300N+50P+micronutrient treatments. For cedar and hemlock, the greatest growth response was in the 200 or 300N plus 100 P (with or without

Table 10. Diameter increment (mm/5 years) of trees in conventional plot trials and operational fertilization. Significant treatment differences within species are indicated by different letters.

Species	Control	Conventional +N ¹	Conventional +N+P ²	Operational +N+P ³
Spruce	11.5 ^a	-	37.8 ^b	39.1 ^b
Hemlock	7.6 ^a	26.1 ^b	45.7 ^c	27.3 ^b
Cedar	28.0 ^a	35.1 ^b	53.7 ^d	43.1 ^c

¹300 kg N ha⁻¹.

² 300 kg N plus 100 kg P ha⁻¹ (mean of 50 P and 150 P for spruce).

³Combined results for plots at 300kg N plus 100 kg P ha⁻¹ and 225 kg N plus 75 kg P ha⁻¹.



Plate 10. Fertilized plantation on a CH cutover



Plate 11. Operational fertilization.

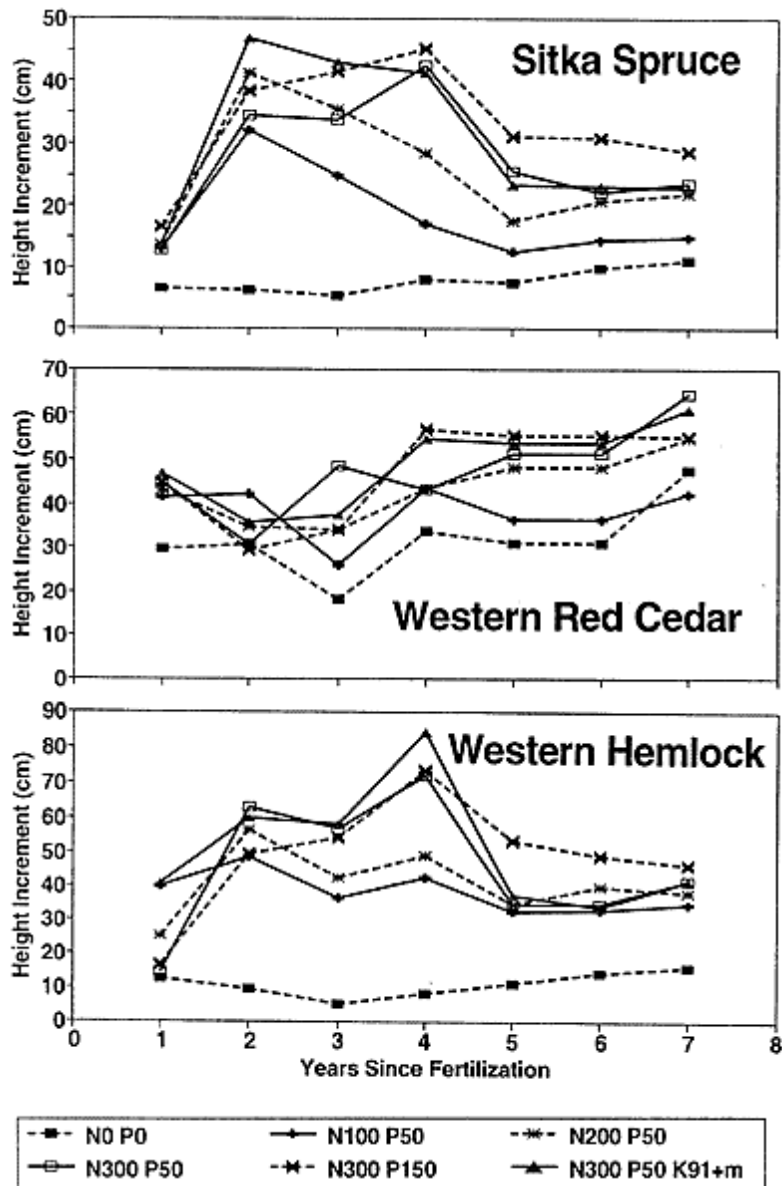


Figure 20. Height increment of spruce, cedar and hemlock after fertilization with N, P, K and micronutrients.

Table 11. height increment (cm/5 years) of trees in conventional plot trials and operational fertilization. Significant treatment differences within species are indicated by different letters.

Species	Control	Conventional +N ¹	Conventional +N+P ²	Operational +N+P ³
Spruce	33.0 ^a	-	153.0 ^b	223.9 ^c
Hemlock	62.4 ^a	236.4 ^b	358.7 ^c	240.6 ^b
Cedar	183.0 ^a	213.3 ^b	256.2 ^c	254.2 ^c

¹300 kg N ha⁻¹.

²300 kg N plus 100 kg P ha⁻¹ (mean of 50 P and 150 P for spruce).

³Combined results for plots at 300kg N plus 100 kg P ha⁻¹ and 225 kg N plus 75 kg P ha⁻¹.

micronutrients) treatments. The growth response was greatest in the second to fourth years following fertilization of spruce and hemlock, but it continued for at least seven years in all three species (Figure 20) (Weetman et al. 1989a, 1989b; Thompson and Weetman 1992a). Combined data from these experiments indicated a strong correlation between relative growth rate and foliar N concentrations (Figure 21). Fertilization with N and P significantly advanced stands toward crown closure (Figure 22). Six years following treatment with 300 kg N ha⁻¹ plus P (150 kg ha⁻¹ or 50 kg ha⁻¹ plus 91 kg K ha⁻¹ plus micronutrients), crown closure exceeded 70%, while in control plots crown closure averaged 30%.

3. Operational fertilization

Operational fertilization experiments were conducted in 1986 in four 50 ha trials in CH cutovers. The four trials were:

1. spruce planted in 1973;
2. spruce planted in 1975;
3. cedar naturally regenerated on a failed spruce plantation of 1975, and
4. cedar planted in 1981.

Fertilizer was applied by helicopter in doses of 300 kg N ha⁻¹ plus 100 kg P ha⁻¹ to the cedar, and 225 kg N ha⁻¹ plus 75 kg P ha⁻¹ to the spruce. Twenty-six circular plots were established, ranging in size from 4 to 12 metres radius (smaller plots located where stand density was higher). Most plots contained spruce, cedar and hemlock. All stems of breast height or greater were tagged, and their height and diameter were measured prior to, one year after, and five years after fertilization. Growth rates were compared with the control plots for the “conventional” trials to determine the effects of fertilization. For all three species, operational fertilization significantly increased growth rates (Table 10 and Table 11). The growth response to fertilization was greatest for spruce, very large for hemlock and modest for cedar (Thompson and Weetman 1992a).

Economics of Fertilization

Methods

An assessment of the economics of operational fertilization of CH cutovers was undertaken (Thompson and Weetman 1992b). The analytic design is summarized in Table 12.

For Cases I and III we assumed that fertilization produces no additional merchantable volume for a given crop dimension. It was assumed only that fertilization reduces the time from planting to harvest. Merchantable volumes of both fertilized and

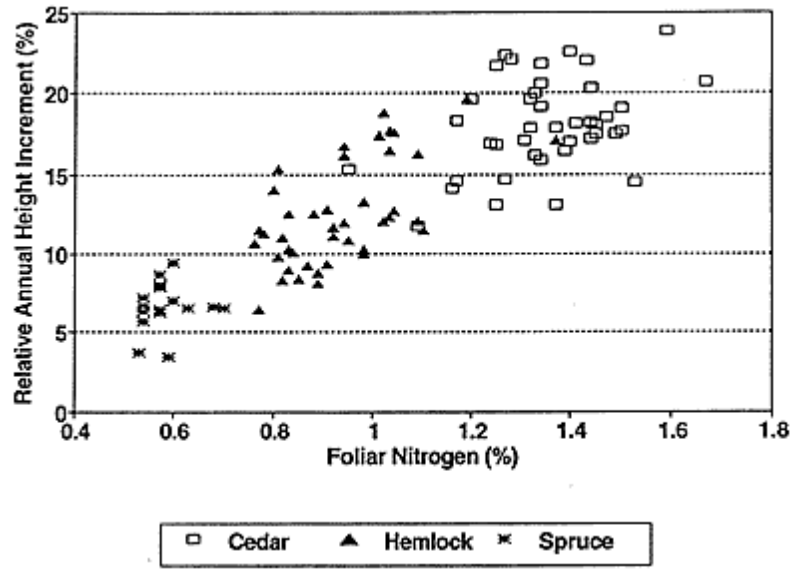


Figure 21. Relationship between height growth and foliar % N of conifers.

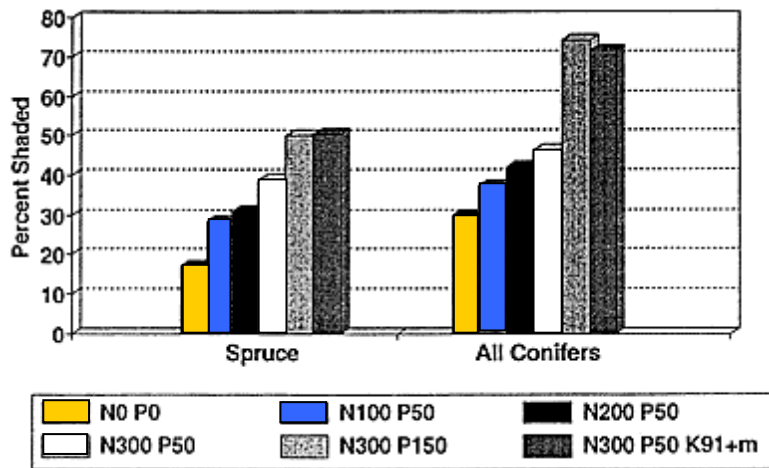


Figure 22. Crown closure (%) of conifers in fertilized plots.

Table 12. Analytic design of Cases I-IV.

Case	Additional merchantable volume?	Price trends equal?	Mixed species stands?	Single species stands?
I	no	yes	no	yes
II	yes	yes	yes	yes
III	no	no	no	yes
IV	yes	no	yes	yes

non-fertilized stands were projected using the same table, based upon mean stand height and dbh. Height and dbh were also projected using the same height over age and diameter over age curves to a rotation age equal to the maximum mean annual increment (MAI). For the non-fertilized stands, the chronological age was not used. Instead, use was made of these curves and the current height and dbh, to calculate an “effective” age (this is equivalent to a regeneration delay). The approach assumed that growth check would eventually be overcome following canopy closure. To date, there has been no firm empirical evidence to support (or refute) this assumption, although 7 year data are suggestive. This assumption is valid where initial stand density is high enough that one fertilizer application will be sufficient to overcome.

For Cases II and IV we assumed that fertilization of CH stands ‘converts’ them to HA stands, increasing the site index by 4 metres for plantations of each conifer species. Furthermore, by improving the growth rate of ingrown hemlock, fertilization was assumed to shift the species composition of mixed stands from 75% cedar, 20% hemlock and 5% spruce to 20% cedar, 75% hemlock and 5% spruce.

For Cases I and II we assumed that logs of all species would appreciate at an average real rate of 0.5% per annum. For Cases III and IV we assumed separate rates of 0.9%, 0.1% and 0.7% per annum for cedar, hemlock and spruce, respectively.

As fertilized and non-fertilized stands were assumed to have different rotations, financial returns from fertilization were calculated by comparing the soil expectation value (SEV) of fertilized and non-fertilized stands. The financial returns were calculated from:

1. costs of basic silviculture, fertilization, harvest and delivery, and administrative fees;
2. delivered value of logs at time of harvest;
3. times when costs and benefits accrue, and
4. discount rate.

All costs and benefits were calculated in real dollars (i.e., 1994 dollars). Economic data for the analysis were obtained from both published sources (primarily FRDA reports) and unpublished sources (WFP company data). The values used in the analysis are summarized in Table 13.

The costs in the analysis were: basic silviculture and planting, which takes place in the year after harvest; fertilization, which takes place five years after planting; delivered wood cost (tree-to-truck plus delivery to water); and annual carrying cost. Costs were estimated from published sources and discussions with WFP personnel. Historic data indicate that these costs have remained constant in real terms; that is, they have risen at the same rate as inflation.

Two classes of management costs which are small or unaffected by fertilization were excluded. The first were costs which are distributed over large

Table 13. Parameter values for financial analysis; average values, 1994.

COSTS	
Basic Silviculture	\$1350/ha
Fertilization (3N:1P)	\$0.50/ha
Delivered Wood Cost	\$40.00/ha
Annual Carrying Cost	\$8.00/ha/yr
BENEFITS	
Delivered Log Value	
Spruce	\$76.61/m ³
Cedar	\$56.14/m ³
Hemlock	\$71.25/m ³
CH log mix	\$60.18/m ³
HA log mix	\$68.49/m ³
Discount Rate	4.0%/yr
Rate of Cost Increase	0.0%/yr
Rate of Price Increase	0.5%/yr Cases I&II 0.7%/yr Cases III&IV
Spruce	0.9%/yr Cases III&IV
Cedar	0.1%/yr Cases III&IV
Hemlock	

areas, and hence are small on a hectare basis. These include road building and maintenance, which were excluded both for this reason and because we are considering second-growth stands, where a road network already exists. Additionally, this group of costs varies little with fertilization. The second group of excluded costs were those for other silvicultural treatments of individual stands, such as spacing, pruning and commercial thinning. To the extent that other silvicultural treatments might further enhance the benefits of fertilization, the conclusions of this study can be considered conservative.

Estimation of future delivered log values was broken down into three parts:

1. yield (m³/ha);
2. average price (\$/m³);
3. rate of price increase relative to inflation.

Yields were estimated using TIPSYS 2.0. An operational adjustment factor of 20% was assumed. Site indices for non-fertilized CH sites were 17, 20 and 21 for cedar, hemlock and spruce, respectively (WFP data). For fertilized stands in Cases I and III we assumed a reduced rotation length based upon the experimental work reported above (see Table 14). For fertilized stands in Cases II and IV we assumed an increase in site index of 4. Average log prices were estimated from Vancouver log market data and previous studies. Estimates of long-term log price trends range from 0 to 1.5% per annum. For Cases I and II we assumed a 0.5% per annum rate as a moderately conservative choice for coastal B.C. For Cases III and IV we adopted the estimates of 0.9%, 0.1% and 0.7% per annum for cedar, hemlock and spruce, respectively.

Case I & III Gains are expected because fertilization shortens the rotation; fertilization was not presumed to permanently change site quality or the relationship of volume to height and diameter. Site indices SI50 were 17m, 20m and 21m for cedar, hemlock and spruce respectively. Case I & III Gains are expected because fertilization was presumed to permanently change site quality or the relationship of volume to height and diameter. Site indices SI50 for not fertilized stands were 17m, 20m and 21m for cedar, hemlock and spruce, respectively. Site indices increased by 4m with fertilization. Fertilization of mixed stands was assumed to convert CH sites to HA sites, both increasing site index and shifting species mix at final harvest from 75% cedar, 20% hemlock and 5% spruce to 20% cedar, 75% hemlock and 5% spruce, CH and HA respectively.

Stumpage rate was not considered in this analysis. Also ignored was the allocation of costs between private and public sectors. While the division of benefits and costs does not affect the aggregated return, and hence does not affect the preferred management from a social perspective, the allocation of benefits and costs can be critical in determining the choice of management alternatives.

The choice of an appropriate discount rate for public forest investments is a subject of considerable contention. Four percent was chosen for this

Table 14. Effect of fertilization on wood supply for cedar, hemlock and Sitka spruce plantations.

Cases I&III. Gains are expected because fertilization shortens the rotation; fertilization was not presumed to permanently change site quality or the relationship of volume to height and diameter. Site indices SI₅₀ were 17m, 20m, and 21m for cedar, hemlock and spruce, respectively.

Plantation	Mean Annual Increment (MAI, m ³ /ha/yr) (merchantable volume, 12.5 cm diameter limit) and Rotation (years to culmination of MAI)				Additional wood
	Fertilized		Non-fertilized		
	MAI	rotation	MAI	rotation	
Cedar	4.7	130	4.5	135	0.2
Hemlock	8.0	100	6.1	130	1.9
Spruce	10.1	120	9.3	130	0.8

Cases II&IV. Gains are expected because fertilization was presumed to permanently change site quality or the relationship of volume to height and diameter. Site indices SI₅₀ for non-fertilized stands were 17m, 20m and 21m for cedar, hemlock, and spruce, respectively. Site indices increased by 4m with fertilization. Fertilization of mixed stands was assumed to convert CH sites to HA sites, both increasing site index and shifting species mix at final harvest from 75% cedar, 20% hemlock and 5% spruce to 20% cedar, 75% hemlock and 5% spruce, CH and HA respectively.

Plantation	Mean Annual Increment (m ³ /ha/yr) (merchantable volume, 12.5 cm diameter limit) and Rotation (years to culmination of MAI)				Additional wood
	Fertilized		Non-fertilized		
	MAI	rotation	MAI	rotation	
Cedar	6.4	105	4.5	135	1.9
Hemlock	8.3	100	6.1	130	2.2
Spruce	11.4	105	9.3	130	2.1
Mixed (CH->HA)	8.1	105	5.1	135	3.0

Table 15. Soil expectaiton values (SEV, \$/ha) of cedar, hemlock, spruce and mixed (Case II only) plantations with and without fertilization; log value trends the same for all species (other parameter values per Table 2).

Case I. Fertilization reduces length of rotation, but does not increase site index

Species	Treatment	3%	4%	5%
Cedar	+F	454	-120	-247
	-F	534	10	-103
	gain/loss from +F	-80	-130	-144
Hemlock	+F	3048	875	148
	-F	1433	267	-27
	gain/loss from +F	1615	608	175
Spruce	+F	3217	733	27
	-F	2614	591	66
	gain/loss from +F	603	142	-39

Case II. Fertilization increases site index; as a consequence, rotation length decreases

Species	Treatment	3%	4%	5%
Cedar	+F	1308	228	-106
	-F	534	10	-103
	gain/loss from +F	774	218	-3
Hemlock	+F	3214	934	170
	-F	1433	267	-27
	gain/loss from +F	1781	667	197
Spruce	+F	4776	1415	321
	-F	2614	591	66
	gain/loss from +F	2162	824	255
Mixed	HA	2665	693	62
	CH	741	64	-88
	CH->HA by +F	1924	629	150

Table 16. Soil expectation values (SEV, \$/ha) of cedar, hemlock, spruce and mixed (Case II only) plantations with and without fertilization; log value trends differing by species (other parameter values per Table 2).

Case III. Fertilization reduces length of rotation, but does not increase site index.

Species	Treatment	3%	4%	5%
Cedar	+F	1513	158	-169
	-F	1505	254	-37
	gain/loss from +F	8	-96	-132
Hemlock	+F	1192	231	-91
	-F	426	-7	-105
	gain/loss from +F	766	238	13
Spruce	+F	4701	1160	159
	-F	3851	920	159
	gain/loss from +F	850	240	0

Case IV. Fertilization increases site index; as a consequence, rotation length decreases

Species	Treatment	3%	4%	5%
Cedar	+F	3106	800	95
	-F	1505	254	-37
	gain/loss from +F	1601	546	132
Hemlock	+F	1271	260	-80
	-F	426	-7	-105
	gain/loss from +F	845	267	24
Spruce	+F	6707	2040	541
	-F	3851	920	159
	gain/loss from +F	2856	1120	382
Mixed	HA	1942	454	-22
	CH	1500	257	-36
	CH->HA by +F	442	198	14

analysis. It falls within the range of 2.5 to 5.0% recommended by recent Canadian studies. We also report many results for discount rates of 3.0% and 5.0%.

A second measure of return from fertilization is the cost of producing additional wood. This was computed as the fertilizer treatment cost divided by the additional wood produced over the rotation ($\$/\text{m}^3$). Since rotations differ with treatment, additional wood produced was computed as the difference in MAI between fertilized and non-fertilized stands (Table 14), times the rotation length for fertilized stands.

Results

Results of the financial analysis are presented in Table 15 and Table 16. For Case I (no volume response to +F and species price trends equal) fertilization of hemlock gave a positive financial return for discount rates from 3 to 5%; fertilization of spruce was financially justified for discount rates of 3 and 4%, while fertilization of cedar was not justified for discount rates of 3% or higher (Table 15). Under the assumption that fertilization does increase site quality (Case II, same financial assumptions), cedar gave positive returns for discount rates up to 4% and spruce gave positive returns up to 5% (Table 15). Analysis of returns for mixed stands (CH to HA conversion) indicated positive returns for discount rates up to 5%.

The prediction that cedar and spruce log prices will rise much faster than the average, while hemlock log prices will rise more slowly than the average has important implications for the analysis. Following this assumption of unequal price trends and assuming no increase in site quality from fertilization (Case III), we found that hemlock fertilization remained financially justified for discount rates up to 5%, while returns for fertilizing cedar and spruce increased (Table 16). Cedar fertilization gave positive returns at 3%, and spruce fertilization gave positive returns up to nearly 5%. Assuming both unequal log price trends and increased site quality from fertilization, we found positive returns from fertilization for all three species and for mixed CH stands for discount rates up to 5% or higher (Table 16).

Based on these results and sensitivity analysis (not shown), the following conclusions were drawn.

1. Hemlock fertilization is financially justified.
2. Spruce fertilization is also financially justified, provided that insect problems (not considered here) do not significantly reduce yield or wood quality.
3. Cedar fertilization is financially justified if:
(a) prices for cedar logs rise at a faster rate than prices for most other species;
(b) fertilization releases stands from growth check for longer than 5 years (data from some research experiments indicates a longer release than 5 years provided that P is included in the fertilizer); or
(c) cedar stands include at least 10% hemlock or 25% spruce.
4. Fertilization is financially justified at a discount rate of 3% when it reduces the rotation by 5 years and at a discount rate of 5% when it reduces the rotation by at least 10 years.

Since most plantations established on CH cutovers have a significant component of ingrown hemlock, fertilization of young plantations with 300 kg N ha⁻¹ and 100 kg P ha⁻¹ can be expected to yield significant financial gains.

A second measure of returns to fertilization considers gains in wood volume rather than wood value. As shown in Table 17, assuming no volume gain to fertilization (Cases I & III), additional fertilizer-grown wood costs about \$1 per cubic metre for hemlock, \$2 for spruce, and over \$7 for cedar. In sharp contrast, the assumption that fertilization increases site quality (Cases II & IV) implies that fertilizer-grown wood will cost \$1 per cubic metre or less for all three species.

As shown above, fertilization of young conifer plantations on CH cutovers with inorganic N plus P is economically justified. This is a robust conclusion as far as the fertilizer response is concerned. The analysis was conservative in estimating the length of the fertilizer response to be only five years. Data from a few older fertilizer experiments at Port McNeill suggest that the inclusion of P in the fertil-

Table 17. Calculated cost of fertilizer-grown wood over one rotation, assuming fertilization cost of \$200/ha.

	\$/m ³	rotation (yrs)
Case I and III		
Cedar	7.69	130
Hemlock	1.05	100
Spruce	2.08	120
Case I and III		
Cedar	1.00	105
Hemlock	0.91	100
Spruce	0.91	105
Mixed	0.63	105

izer results in a much longer fertilizer response, probably exceeding ten years. If that long a growth response occurs following operational fertilization, then fertilization with inorganic N plus P would be financially justified up to much higher discount rates. Finally, it should be noted that the analysis here is a stand level analysis of the benefits of fertilization. There is probably a real forest level (ACE) benefit which is not revealed in this analysis.

Efficiency of Fertilization

In a field trial, 15 N labelled ammonium sulphate fertilizer was applied to single tree plots of Sitka spruce, western red cedar and western hemlock on a CH cutover. Salal was manually removed from half of the plots. Total 15 N recovery in the plantsoil system after two growing seasons was 54-83%. Of this, most of the 15 N was immobilized in the soil (62-83%). In the plots with salal, 20-31% of the 15 N was immobilized in understory vegetation, and only 2-5% was in the trees. In the plots from which salal had been removed, 8-18% of the 15 N was in the trees and only 2-5% was in the understory. Control of salal prior to fertilization was recommended to increase the efficiency of fertilizer use by trees.

Fertilization, Scarification and Planting Density Trials

Two experiments with cedar and hemlock at the time of planting were conducted on both CH and HA cutovers at the "SCHIRP installation." The first

experiment compared hand fertilization with no treatment, for hemlock and cedar planted on CH and HA cutovers at densities of 500, 1500 and 2500 stems per hectare. Each treatment plot contained 64 seedlings (area varied with planting density). Treatments were replicated four times, for a total of 96 plots. On an area basis, the fertilizer dose varied with planting density; 25 kg N, 6.25 kg P and 12.5 kg K per hectare at 2500 stems per hectare, 60% as much at 1500 stems per hectare and 20% as much at 500 stems per hectare. In the second experiment, the treatments were fertilization and scarification, with density constant at 2500 stems per hectare. Each treatment combination replicated 4 times for a total of 64 plots. Unscarified plots planted at 2500 stems per hectare were included in both experiments (32 plots). The fertilizer dose was 10 g N, 2.5 g P and 5 g K per tree. Scarification was done to a depth of 0.5 m.

Growth response (height and diameter) after five years differed between species and between CH and HA sites (Figure 23 and Figure 24). Hemlock on HA sites was unaffected by treatment and grew more rapidly than hemlock on CH sites or cedar on either site type. Untreated hemlock on CH sites grew the least, particularly at the highest planting density. Hemlock on CH sites was very responsive to both fertilization and scarification. Cedar growth differed little between site type or planting density. Both scarification and fertilization resulted in modest increases in growth on either site. Foliar N concentration was strongly correlated with growth of both species (Figure 25). (Thompson and Weetman 1992a; Fraser 1993).

The second trial was also used to assess the influence of salal on planted hemlock and cedar saplings, and the influence of fertilization and scarification on this relationship. Correlation analyses were performed between the growth increment of 2- and 4-year-old hemlock and cedar saplings and salal leaf area index (Fraser 1993). There were 8 site x treatment combinations: 2 sites (CH and HA) and 4 treatments (control, fertilized, scarified, and fertilized plus scarified). The analyses suggested that the abundance of salal affected the growth of western hemlock more than that of western red cedar (Figure 26). Salal abundance was strongly ($p < 0.05$) correlated with hemlock growth in fertilized plots on CH sites, and in fertilized and control plots on HA sites. Salal abundance was weakly ($p > 0.1$)



Plate 12. Scarification of a CH cutover.



Plate 13. Application of sewage sludge to a CH cutover.

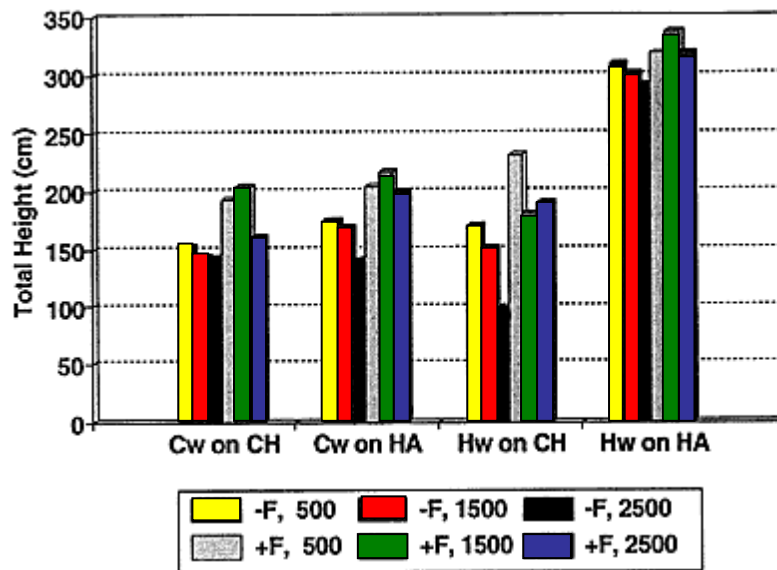


Figure 23. Mean height of cedar (Cw) and hemlock (Hw) trees on CH and HA sites planted at different densities (500, 1500 and 2500 st ha⁻¹) 5 years after fertilization (F) with N and P.

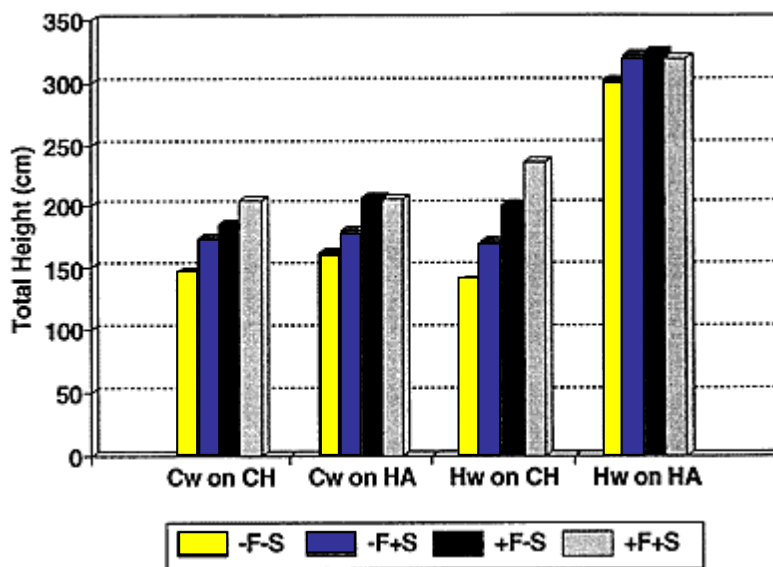


Figure 24. Mean height of cedar (Cw) and hemlock (Hw) trees on CH and HA sites 5 years after fertilization (F) with NPK and/or scarification (S).

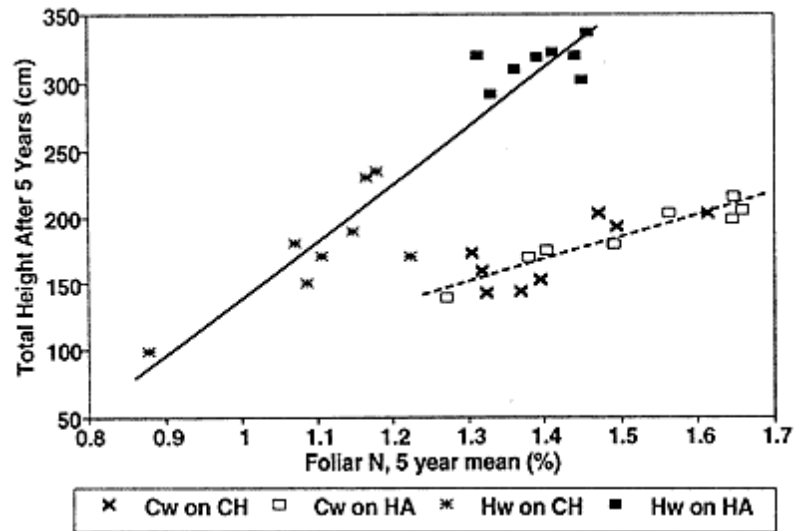


Figure 25. Relationship between height growth and foliar % N of conifers.

correlated with cedar growth in control plots on CH and HA sites. However, the apparent negative influence of salal on western red cedar only occurred in 2-year-old trees, and not in 4-year-old trees, suggesting that the influence was waning. For hemlock, the opposite occurred, suggesting that the influence of salal was increasing with time. Scarification appeared to reduce the influence of salal on hemlock, perhaps because the salal present in scarified plots had only recently become established.

Organic Fertilization Trials

Two trials were established in plantations on clearcut and burned CH sites to test the efficacy of a variety of organic wastes for improving the growth and nutrition of trees (McDonald et al. 1994, Brown 1994, Weetman et al. 1993) (Plate 13). In the first trial, the response of 9-year-old cedar, hemlock and amabilis fir in plots treated with municipal sewage sludge from Vancouver was compared with response in plots treated with N+P fertilizer and untreated controls. Sewage sludge was applied at 500 kg N/ha and 133 kg P/ha; fertilizer was applied at 225 kg N/ha as ammonium nitrate and 75 kg P/ha as triple super phosphate. The higher loadings of sewage sludge were designed to compensate for much of the N and P being bound in organic matter. The trial was replicated in 3 blocks, each of which contained four 15 x 15 m plots of each tree species. During the first growing season, height growth of trees in

plots of all three species treated with sludge or inorganic fertilizer was 2-3 times that in control plots. Nitrogen concentrations in foliage were also 2-3 times those in control plots, and were highest in inorganic fertilized plots. Phosphorus concentrations in hemlock were greater in fertilized trees, especially in trees that received sludge. S concentrations in hemlock foliage declined in trees fertilized with N+P, suggesting a possible S deficiency induced by N+P additions. Foliar S concentrations of all three species increased in sludge-amended plots. After three years, growth was still enhanced in trees of all three species fertilized with sewage sludge or N+P (Figure 27).

In the second trial in a 9-year-old cedar plantation on the same CH cutover, several organic wastes were applied: sewage sludge, sewage sludged mixed with pulp sludge, fish silage mixed with wood ash, silage and ash mixed with pulp sludge, wood ash alone, and inorganic N+P fertilizer. Organic wastes were applied at about 500 kg N/ha; N+P fertilizer was applied at 225 kg N/ha and 75 kg P/ha. All of the additions except wood ash increased height and diameter of cedar trees (Figure 28). The greatest height growth during the 3 years after treatment was in the N+P fertilized plots, followed by the plots treated with silage and sewage sludge. Mixing with pulp sludge reduced the response to sludge or silage. Wood ash alone suppressed tree growth. During

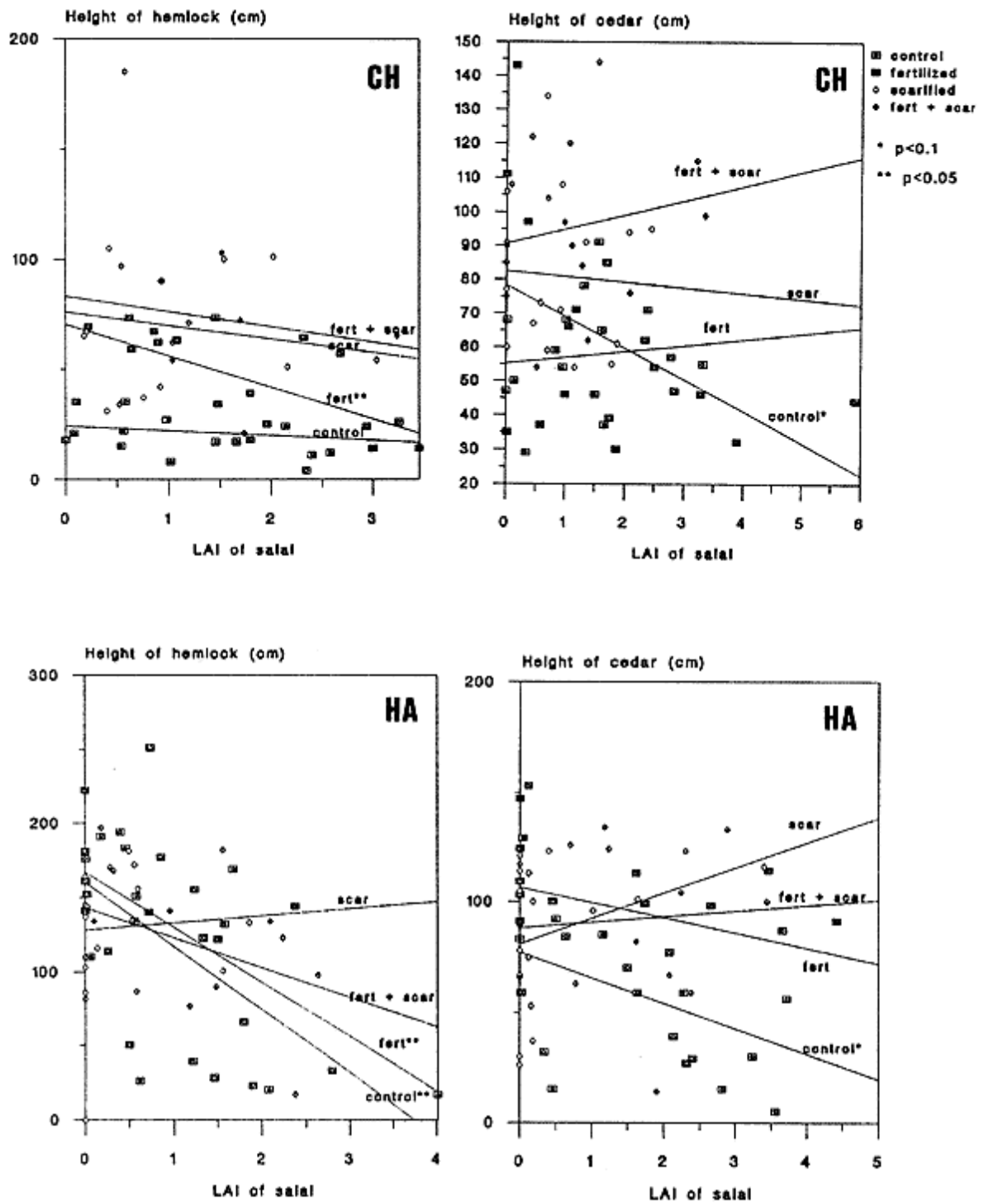


Figure 26. The relationship between salal area index and 2-year height increment of western hemlock and western red cedar on CH and HA sites, within four treatments (control, fertilized, scarified, fertilized plus scarified).

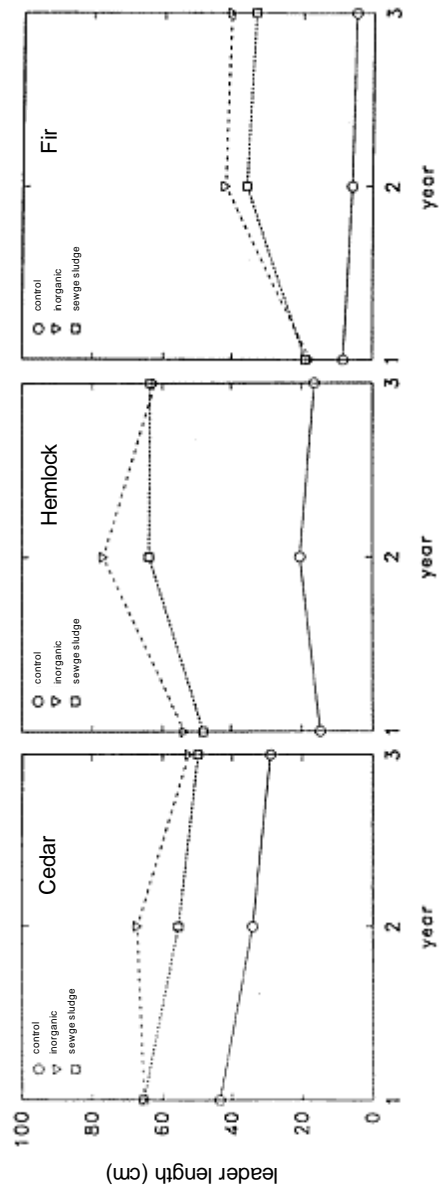


Figure 27. Leader length of cedar, hemlock and amabilis fir trees treated with sewage sludge or N+P fertilizer. Each value is the mean of 25 trees.

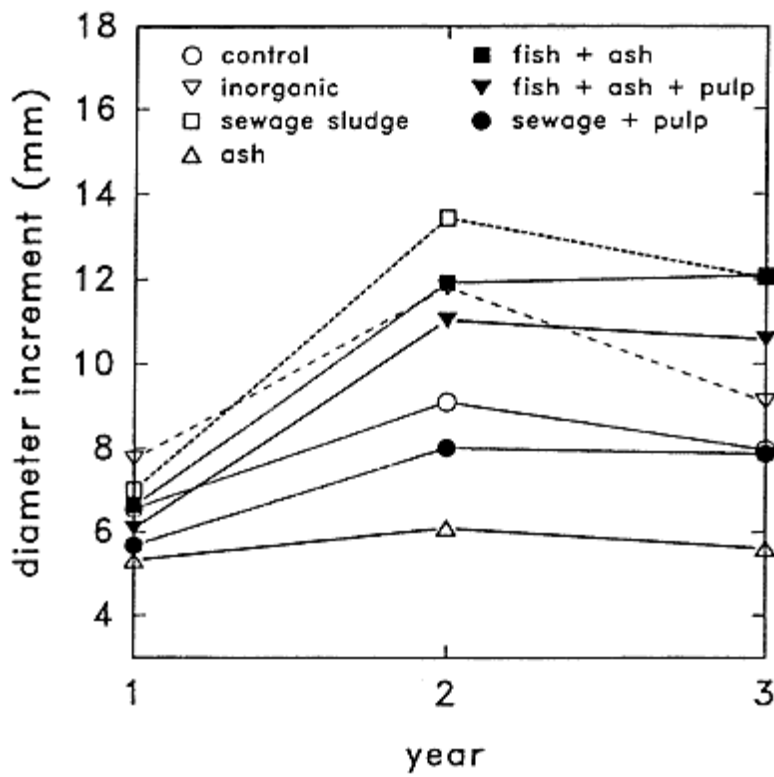
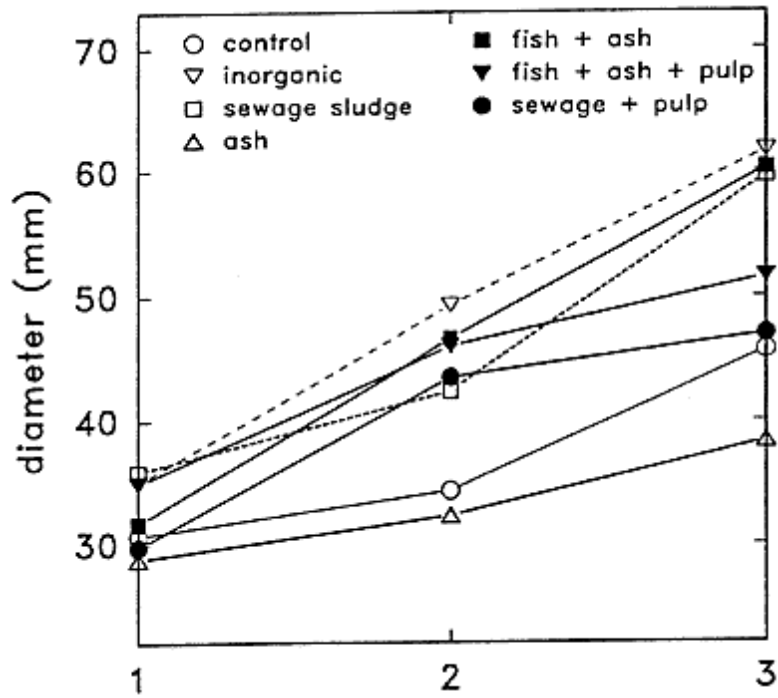


Figure 28. Diameter growth of cedar trees treated with organic wastes. Each value is the mean of 25 trees.



Plate 14. Slashburning on a CH cutover.

the third growing season, height and diameter increment remained high in the plots treated with fish silage (with and without pulp sludge), but declined in other treatments.

These trials demonstrated that tree growth on CH cutovers can be improved by application of organic wastes. Growth response will be monitored for several years to determine if organic wastes provide a longer-term response than inorganic fertilizers.

Burning, Cultivation and Weed Control

A trial was established in 1982 to evaluate the effects of burning, cultivation and weed control on growth of hemlock, amabilis fir and cedar on CH sites. One unburned site was compared with two burned sites. A split plot factorial design with three replications was used so that treatments could be evaluated individually and in combination to identify any interactions. Growth rates and foliar nutritional responses were monitored.

Treatments were burned, unburned x cultivated, uncultivated x weed control, no weed control. Plots were cultivated to 0.75 m depth using a rake attachment to a backhoe. Plots receiving weed control (salal suppression) were sprayed with Garlon 4E at 2.5 kg active ingredient ha⁻¹. Cedar, hemlock and amabilis fir were planted in 7 x 7 tree blocks at 2.8

m spacing. Measurements were confined to the inner 25-tree block. Foliar samples were collected three growing seasons after planting and concentrations of N and P were measured. Height and root collar diameter were measured after four growing seasons. Live salal cover was measured prior to treatment and after three growing seasons.

Foliar nitrogen concentrations were generally deficient on all sites three years after planting. However, cedar and amabilis fir both had significantly higher foliar N concentrations on burned sites, while hemlock had lower foliar N concentrations on burned sites. Foliar phosphorus concentrations were in the moderately deficient range. Burning resulted in elevated foliar P levels in all three species and significantly higher rates of growth and survival.

Cultivation did not significantly affect foliar N concentrations in cedar and hemlock but did increase them in amabilis fir. Cultivation did not affect foliar P concentrations in hemlock and amabilis fir but did cause a significant reduction in cedar. On unburned plots, cultivation increased tree growth, probably as a result of salal removal. On burned sites, cultivation had no impact on growth. Averaging all species and treatment combinations, relative growth rate was increased 42% by burning, 12% by cultivation and 2% by weed control. Garlon caused some damage to seedling foliage and did not kill salal rhizomes which resprouted following

treatment. All three treatments reduced salal cover: 31% to 19% by burning, 30% to 27% by cultivation, and 34% to 18% by Garlon application. As a consequence of pesticide regulations and the failure of Garlon to kill salal, there were no further trials with herbicides.

Soil Mixing

An investigation (Keenan et al. 1994b) of the effects of soil mixing (simulated windthrow) on soil properties was conducted on CH and HA cutovers. Soil samples were collected from: 1) uncut forest; 2) clearcut and burned sites with unmixed soil and 3) clearcut and burned sites with mixed soil. Samples from clearcut sites were collected 4.5 years after burning or burning plus mixing. Soil mixing was done with a large rake attached to an excavator (as part of an experiment on seedling growth). On HA sites, clearcutting and soil mixing had little effect on the rate of microbial activity measured as CO₂ evolved in laboratory incubations, or N and P measured after KCl extraction, anaerobic incubation, or using ion-exchange resin bags in situ. On CH sites, clearcutting and soil mixing decreased mineralizable N and phosphate-P held on resin bags, and the rates of cellulose decomposition and CO₂ evolution. Mixing markedly decreased the cover of salal compared to both the clearcut only and the uncut treatment. The anticipated benefits of increased soil nutrient availability brought about by the mixing of mineral and organic horizons were not realized. This was probably because the mixing treatment brought humus material from deeper in the soil profile to the surface. Decomposition of this material is limited more by its poorer quality as a substrate for decomposers (lower N concentration, and possibly higher lipids and tannins) than by soil micro-climate.

Salal Eradication

An experiment (Weetman et al. 1989a, 1989b) was initiated in 1984 to examine the effects of salal removal and fertilization on young spruce, cedar and hemlock trees. The plantations were established in 1969, 1971, 1973 (2) and 1975 on clearcut and slashburned CH sites. Salal was manually removed (grubbed) in 1985 from thirty 0.0625 ha plots and left in situ. Intact salal roots were treated with Garlon 4E (3.5 kg active ingredient ha⁻¹) at the end of the second growing season to prevent resprouting. The

experimental design was 2 x 3 x 2 factorial: (S0, S1) x (N0, N1, N2) x (P0, P1), where S0 = intact salal, S1 = salal removed, N0 = control, N1 = 250 kg N ha⁻¹ as ammonium nitrate, N2 = 250 kg N ha⁻¹ as urea, P0 = control and P1 = 100 kg P ha⁻¹ as triple superphosphate. Fertilizers were applied in April 1985. The effects of salal removal on conifer height and diameter increment were assessed after three growing seasons.

Foliar N concentrations for all three species in salal grubbed plots was significantly higher than in control plots. Foliar P concentrations were unaffected by salal removal in all three species. Three-year height increments for spruce, hemlock and cedar were greater in grubbed than non-grubbed plots (Figure 29). Cedar response was more closely related to grubbing while hemlock response was more closely related to fertilization. A greater response was observed to N+P than to N alone.

N Fertilization of Salal

Reductions in salal density have been reported in several field fertilization trials in B.C. and Washington, and have been attributed to shading from denser crowns in N-fertilized plots (Heilman 1961, Stanek et al. 1979). Other ericaceous shrubs such as *Kalmia*, *Vaccinium* and *Calluna* are also reduced in N-fertilized forests and heathlands. This study (Prescott et al. 1993b) was undertaken to quantify the changes in understorey vegetation in two fertilization trials, and to determine the rate and type of fertilizers that produce the changes.

In a trial at the Pack Forest in Washington, USA, salal was eliminated in a plot that had been fertilized with N alone (1540 kg N ha⁻¹ as ammonium nitrate and urea between 1950 and 1982), but was unchanged in a plot that received P and S in addition to N (1082 kg N ha⁻¹). In a trial near Parksville, B.C., salal cover was reduced with increasing amounts of nitrogen, and was eliminated in plots that received 600 kg N ha⁻¹ as urea in three applications (Figure 30). Reductions were less pronounced in plots that received S in addition to N. In the Pack Forest trial, the cover of snowberry (*Symphoricarpos albus* (L.) Blake) increased in the plot in which salal was eliminated; in the Parksville trial, no other species became more abundant in the absence of salal. The stem volume and the stem volume increment in each plot during the five years

Table 18. Soil chemical properties and microbial activity in old-growth, clearcut, and mixed treatments in the CH and HA forest types. Mean and (standard error). Within forest type values followed by different letters were significantly different ($\alpha \leq 0.05$) using orthogonal contrasts following the ANOVA. Log transformed values were compared for resin ammonium, but the untransformed mean and standard error are shown.

	CH			HA			p ¹
	Old growth	Clearcut	Mixed	Old growth	Clearcut	Mixed	
Extractable ($\mu\text{g g}^{-1}$)							
nitrate-N	12 (0.6)a	12 (0.3)a	11 (0.5)a	13 (0.4)x	12 (0.3)x	12 (0.2)x	0.175
ammonium-N	34 (2.3)a	39 (4.7)a	30 (3.0)a	44 (6.4)x	41 (1.8)x	46 (0.9)x	0.006
phosphate-P	6 (1.0)ab	14 (5.3)a	4 (1.1)b	9 (2.0)x	19 (1.2)y	13 (2.1)y	0.022
Mineralisable ($\mu\text{g g}^{-1}$)							
ammonium-N	48 (9.1)a	48 (7.5)a	20 (5.6)b	54 (3.8)x	49 (8.2)x	37 (4.3)x	0.171
Resin ($\mu\text{g g}^{-1}$)							
nitrate-N	36 (1.6)a	36 (3.5)a	45 (8.8)a	53 (19.9)x	49 (5.5)x	48 (4.9)x	0.124
ammonium-N	270 (37.8)a	262 (3.1)a	435 (67.0)a	536 (117.7)x	1370 (68.5)x	1010 (22.1)x	0.003
phosphate-P	312 (19.7)a	114 (27.3)ab	39 (17.8)b	89 (48.1)x	117 (19.6)x	157 (62.0)x	0.596
Evolved C ($\mu\text{g g}^{-1}$)	270 (24.3)a	197 (29.9)ab	98 (20.7)b	249 (14.8)x	196 (57.7)x	187 (17.2)x	0.430
Cellulose decomposition (% wt loss)	45 (5.2)ab	58 (5.9)a	26 (5.9)a	31 (7.2)x	33 (8.0)x	59 (5.5)y	z
pH	3.8 (0.12)a	4.1 (0.18)ab	4.6 (0.19)b	4.0 (0.23)x	3.9 (0.22)x	4.6 (0.18)y	0.795

¹ p values for differences between forest types using a two-way ANOVA

z Indicates a significant interaction ($\alpha \leq 0.001$) between site and treatment

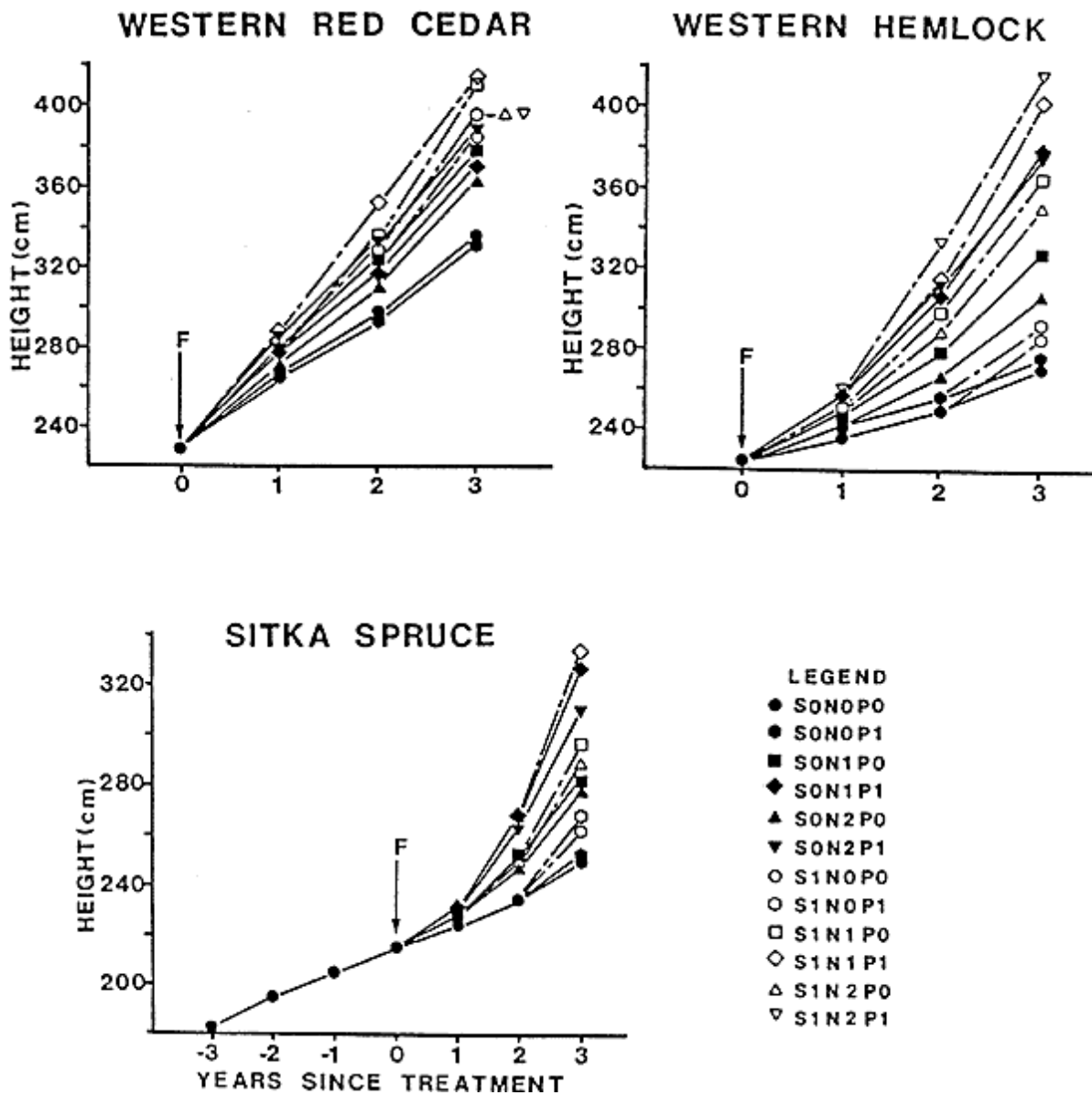


Figure 29. Height increment of conifers following salal removal (S1) and fertilization with ammonium nitrate (N1) or urea (N2) and triple superphosphate (P1).

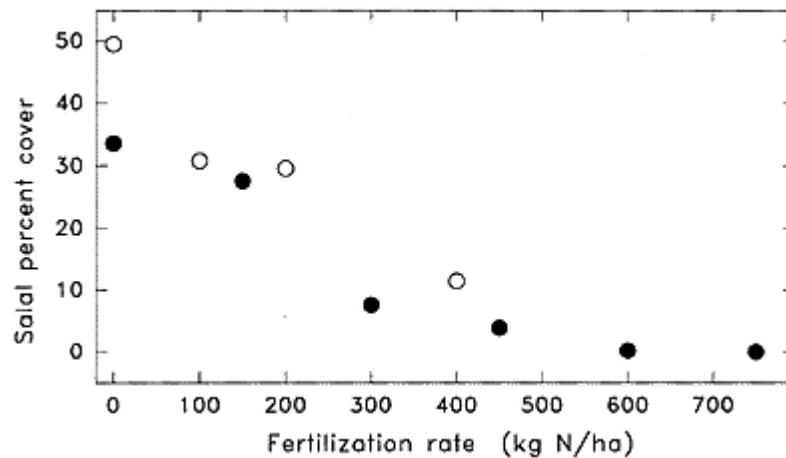


Figure 30. Average percent cover of salal in plots fertilized with N-only (●) and N+S (○) fertilizers in the Parksville trial.

after fertilization (an indirect measure of the amount of shading) was not related to salal cover in the plots. In the Parksville trial, concentrations of S in salal leaves in plots fertilized with at least 600 kg N ha⁻¹ were lower than in control plots. No nutrient imbalances were apparent in salal leaves in fertilized plots in the Pack Forest trial. High concentrations of ammonium and nitrate in the forest floors in fertilized plots may render salal less competitive, or may interfere with ericoid mycorrhizae, contributing to reduced cover of salal in forests receiving repeated applications of N. This suggestion is in keeping with the conclusion of Xiao (1994), that ericoid mycorrhizal formation of salal was suppressed by application of inorganic N forms and enhanced by more complex organic forms of N.

Field trials, with single large applications of N (1000 kg N/ha) alone or repeated smaller applications of N (300 kg N/ha in annual applications) were established on CH cutovers in 1993 to determine if large doses of N fertilizer reduce salal growth. An additional trial was established near Port Alberni in May 1994 to assess the effects of repeated additions of ammonium nitrate on growth of salal and Douglas-fir regeneration.

Effects of N concentration and source, and S concentrations, on growth and photosynthetic rates of salal were investigated in a greenhouse trial (Hawkins, unpublished). Salal germinants, from seeds collected at field sites, were grown in a peat-perlite mix. Seedlings were watered with one of 10 nutrient solutions, which differed in the N concentration (10 or 100 ppm), N source (NH₄, NO₃ or) and S concentrations (0 or 20 ppm). After 5 months, half of the seedlings were harvested, and the dry weight of shoots and roots were measured. After 8 months, rates of net photosynthesis were measured in the remaining seedlings.

Growth of salal seedlings was greatest in the high-N treatments, and there was little difference between seedlings given NH₄, NO₃, or 0 and 20 ppm S (Figure 31). Seedlings in the high N treatment had higher shoot:root ratios and slightly higher rates of net photosynthesis than seedlings in the low N treatment. The results of this short-term greenhouse experiment indicated no adverse effects of N addition on salal growth.

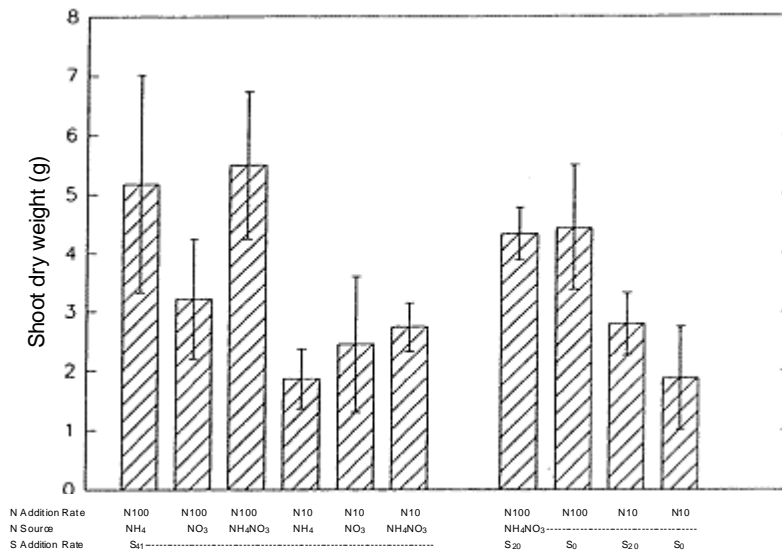


Figure 31. Biomass of salal shoots grown in a greenhouse and watered with nutrient solutions of different N concentrations, (10 and 100 ppm) N sources (NH₄, NO₃ or NH₄NO₃) and S concentrations (0 and 20 ppm).

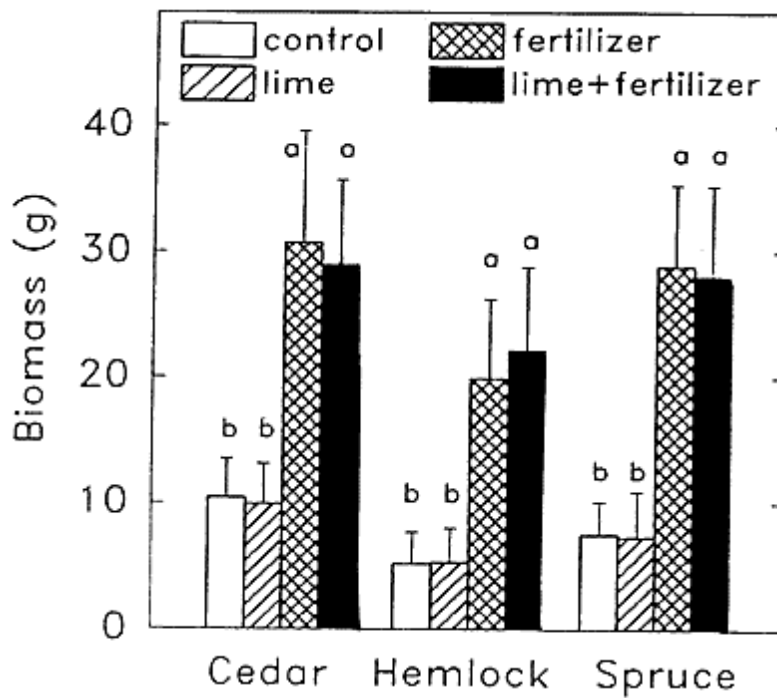


Figure 32. Aboveground biomass of conifer seedlings grown in a greenhouse for 18 months in humus from CH cutovers amended with lime or N+P fertilizer. Each value is the mean (+s.d.) of 15 trees. Within a species, treatments with different letters are significantly different.

Starch and Lime Amendments

The possibility that rates of N mineralization in CH humus could be stimulated by adding available carbon in potato starch or by raising the pH by adding lime, was addressed in field and laboratory experiments (Prescott and McDonald, in press). Lime was applied to a CH cutover at a rate of 2500 kg/ha, and fertilizer was applied at 275 kg N/ha as urea and 75 kg P/ha as triple superphosphate, in a randomized complete block design in 1989. There were three 30 x 30 m plots of each treatment: control, limed, fertilized, and limed plus fertilized. Four years after application, trees in fertilized plots had longer leaders and were greener in colour, but there were no visual effects of the lime additions. The effects of lime and N+P fertilizer were also tested in a greenhouse bioassay. Seedlings of cedar, hemlock and Sitka spruce were grown in pots of CH humus to which lime and fertilizer had been applied at rates approximating 5000 kg lime/ha, 225 kg N/ha and 75 kg P/ha. After 1.5 years, the biomass of seedlings of all three species was significantly greater in pots that received fertilizer (with or without lime), but there was no effect of lime (Figure 32).

In a field trial on a CH cutover, potato starch was added combined with N fertilizer. Four years later, the trees that received fertilizers had longer leaders and greener foliage, but there were no visual effects of starch addition. The effects of starch and glucose additions were also tested in a laboratory incubation. Five-gram samples of humus (H and Hw) from a CH cutover were amended with 354 mg of potato starch and incubated in the lab for 36 days. Amounts of extractable N were determined before and after the incubation, and rates of CO₂ evolution were measured weekly in amended and control samples. There was no effect of the starch addition on the rates of net N mineralization or CO₂ evolution in H or Hw samples (Figure 33). Addition of glucose, a simpler C compound stimulated microbial activity and decreased N availability in CH humus.

These experiments indicated that additions of starch or lime would not improve rates of N mineralization in humus in CH cutovers.

Conclusions

- Fertilization with N at 200-300 kg ha⁻¹ and P at 50-100 kg ha⁻¹ increased growth of conifers on CH cutovers, and significantly advanced stands towards crown closure.
- Growth response was correlated with foliar N concentrations.
- Sitka spruce and western hemlock were more responsive to fertilization than western red cedar.
- Fertilization of hemlock and spruce are financially viable; fertilization of cedar is financially questionable, unless the stands also have a significant component of spruce or hemlock.
- Efficiency of fertilizer uptake by trees can be improved by controlling salal.
- Organic fertilizers such as sewage sludge and fish silage at 500 kg N ha⁻¹ provided tree growth responses similar to those with inorganic (N+P) fertilizers at 225 kg N/ha
- Mixing sewage sludge and fish silage with pulp sludge reduced the growth response of trees.
- High planting densities did not improve tree growth but may hasten canopy closure.
- Site preparation treatments that mix the soil did not improve nutrient supply, but reduced salal competition, and provided modest increases in tree growth.
- Burning increased foliar nutrient concentrations and growth and survival of conifers.
- Manual removal of salal increased conifer growth; Garlon was not effective in killing salal.
- Salal may be suppressed by repeated applications of N in the field.
- Liming and starch amendments did not improve nutrient availability in CH cutovers.

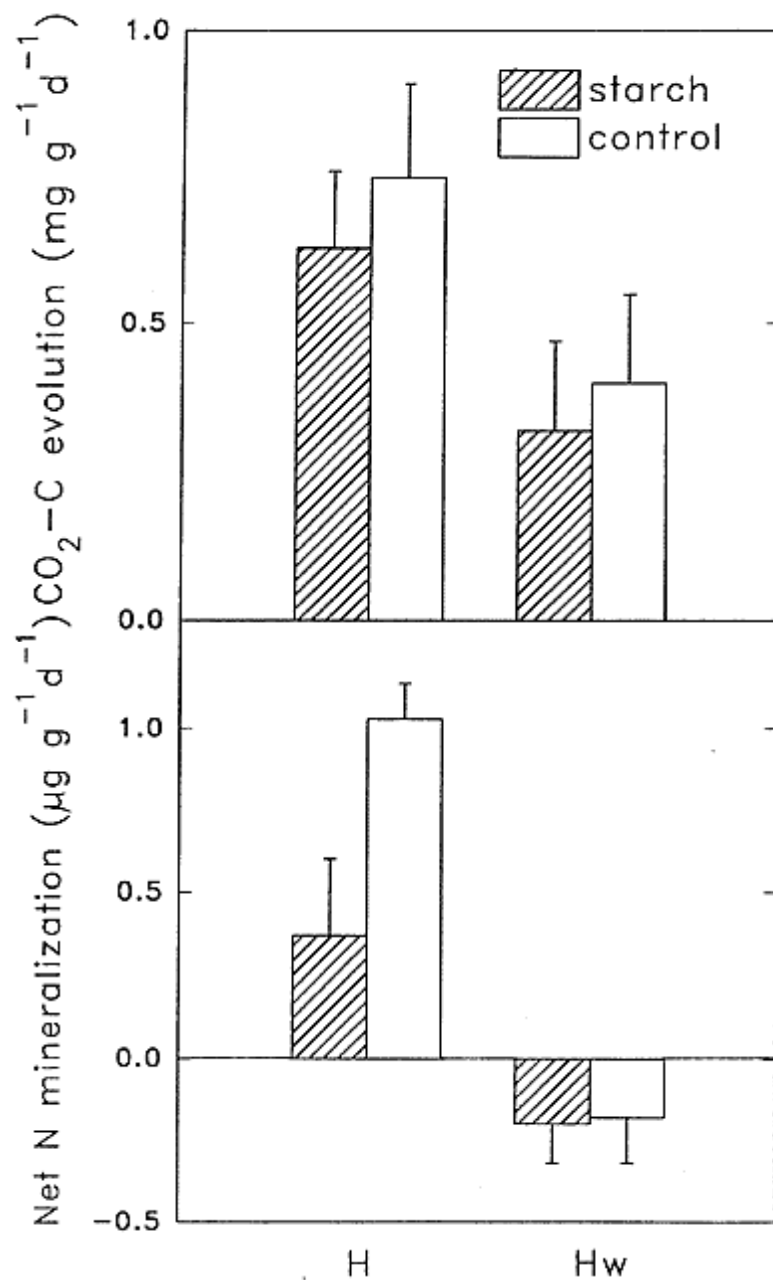


Figure 33. Respiration and N mineralization in CH humus amended with starch during a 36-day lab incubation. Each value is the mean (+s.d.) of 10 samples of humus (H) or 6 samples of woody humus (Hw). Within a humus type, there were no significant differences between treated and control samples.

Conclusions and Recommendations

The investigations described in this report provided evidence that supported some of the hypotheses regarding the origin of differences between CH and HA sites.

Disturbance

There was no evidence to suggest that sudden disturbance such as windthrow or mechanical site preparation would rapidly change nutritional conditions on CH sites in the short-term. Soil disturbance from repeated wind throw may contribute to better aeration and nutrient supply in HA soils.

Salal

There was evidence that salal interferes with conifer growth through competition for nutrients and interference with mycorrhizae. Phenolic acids and tannins were associated with salal in cutovers and old-growth cedar-hemlock forests, which may further interfere with N mineralization, although this was not conclusively demonstrated. Salal exacerbates the fundamental nutrient supply problem which originates in humus in CH forests.

Western Red Cedar

There was no evidence that large amounts of decaying cedar wood contributed to the low nutrient availability in CH forest floors. Similar amounts of N were present in woody debris in HA forests. The non-woody layers in CH forest floors had low nutrient availability, suggesting that cedar litter, rather than wood was responsible. The low N content and slower decay of cedar foliar litter contribute to low N availability in CH forest floors.

Site Difference

CH forest floors tended to be wetter than adjacent HA forest floors, which could lead to incomplete decomposition and low rates of N mineralization. This may be a consequence of less windthrow disturbance in CH forests, which would cause them to be more poorly drained, or may be because many of the CH forests studied were on lower slope positions.

The growth check in conifer regeneration in cutovers of cedar-hemlock forests is a consequence of inadequate supplies of N and P. The low nutrient supply originates in the forest floor of the old-growth cedar-hemlock forests, prior to cutting (Figure 34). Several factors appear to contribute to low nutrient availability in CH forest floors, and their relative importance is not clear. Cedar litter, tannins associated with salal, and greater soil moisture drainage lead to incomplete decomposition and low N availability in CH forest floors. Under these conditions, there is more efficient use of nutrients by trees, and less nutrients recycled in litter, which further reduces nutrient availability in the forest floor. These conditions develop over several centuries without severe disturbance, and may be most prevalent on lower slope positions.

After clearcutting there is an assart effect (Figure 35). causing a temporary improvement in N and P availability for growth of regeneration. During this period, salal resprouts from rhizomes, immobilizing nutrients in biomass and causing growth check in conifers through N and P competition, mycorrhizal antagonisms and release of tannins.

The growth check of the conifers can best be relieved by fertilization with additions of 300 kg N ha⁻¹ and 100 kg P ha⁻¹, or fish silage or sewage sludge. With this treatment crown closure will be reached after a few years, shading the salal and leading to sustained improvement in the growth rates of conifers.

Attempts to alleviate the growth check by mechanical site preparation or vegetation control have not been effective. Although cedar grows best on CH sites, it may perpetuate the N supply problem through its litter. Hemlock might provide a long-term improvement in N availability and should be encouraged on fertilized CH sites. Although slashburning helps to prepare planting spots and increases the assart flush of nutrients, it may reduce the available N capital of the site in the long term.

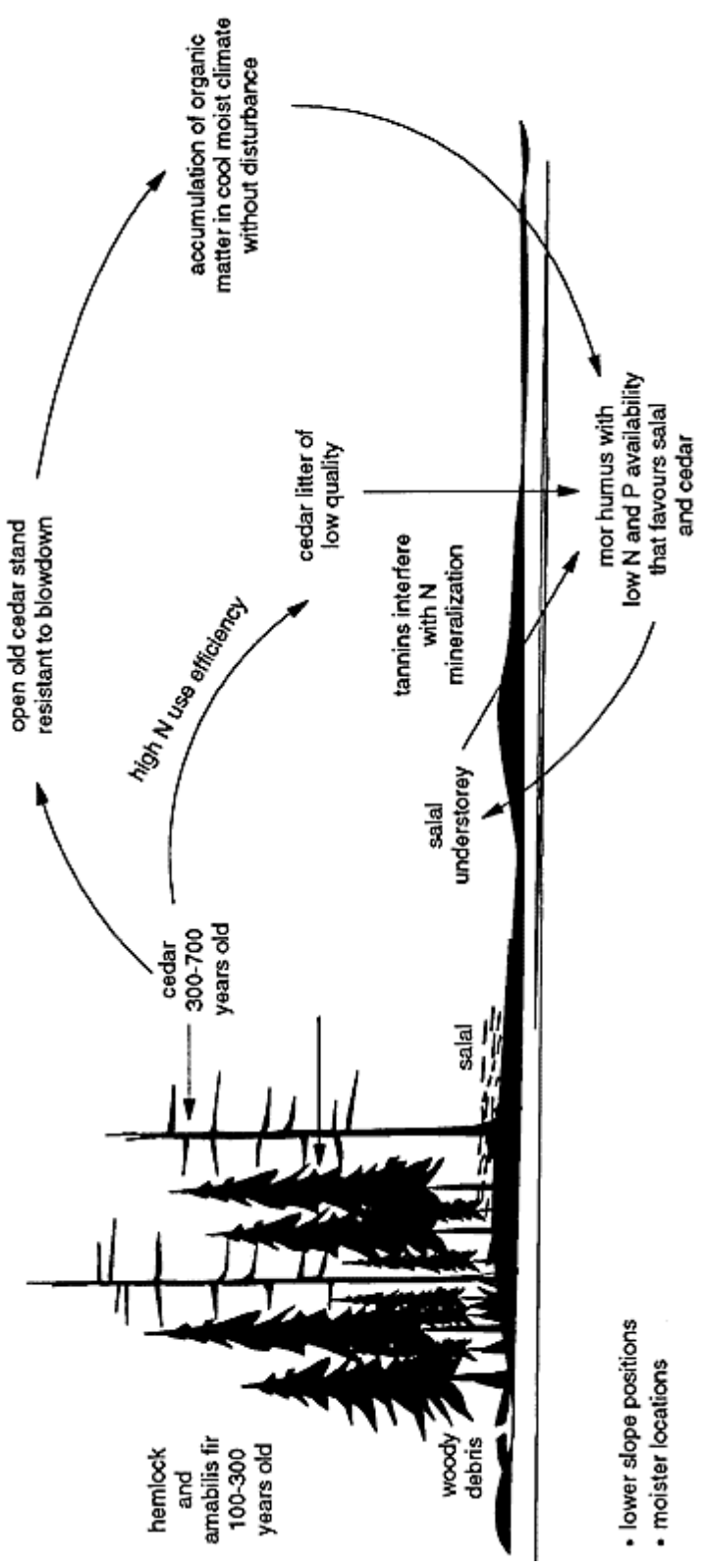


Figure 34. Development of low nitrogen supply in old-growth CH forests.

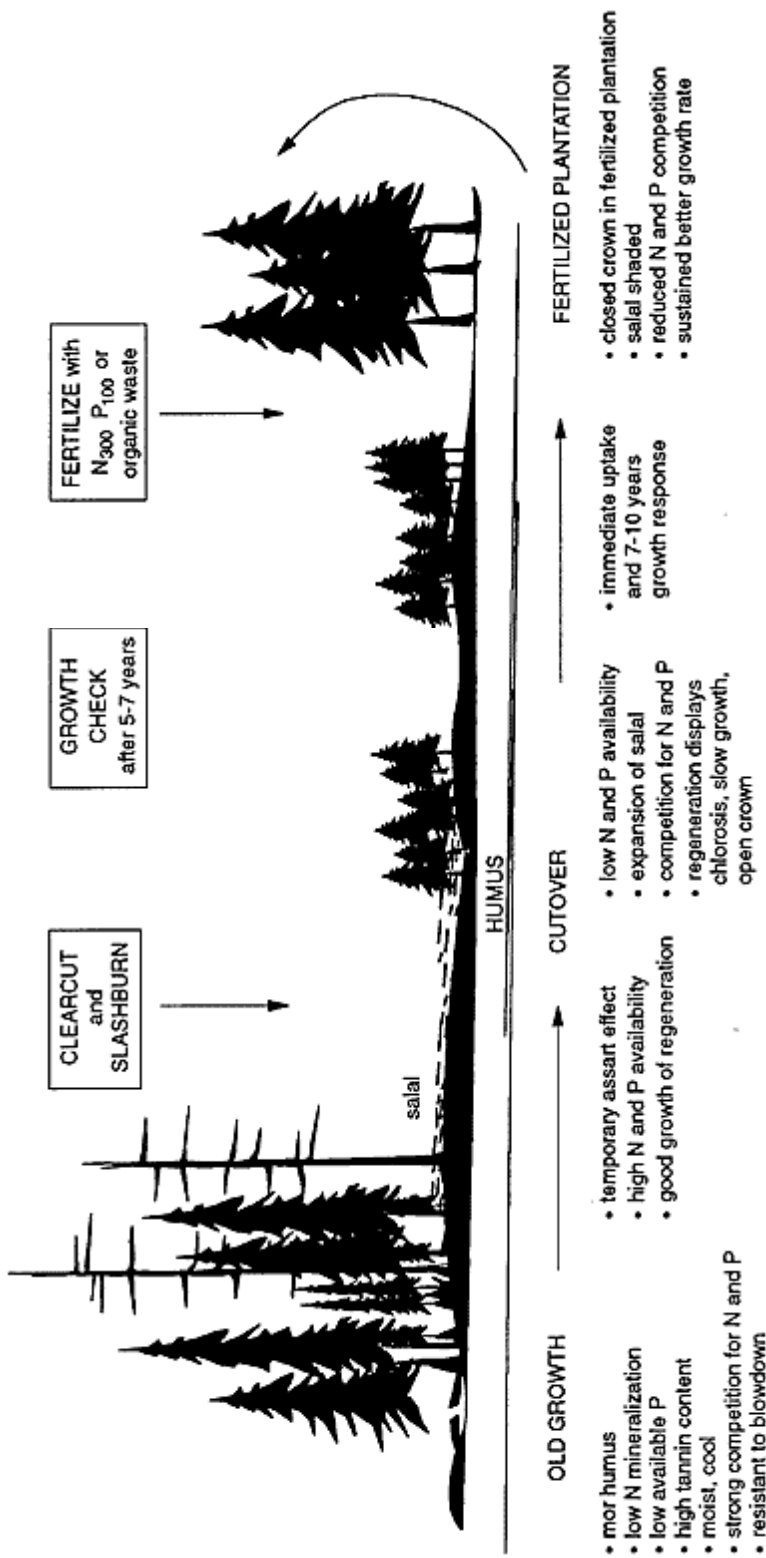


Figure 35. CH forests before and following clearcutting and fertilization.

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