Foliar analysis and response of fertilized chlorotic Sitka spruce plantations on salal-dominated cedar–hemlock cutovers on Vancouver Island

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A series of microplot and conventional plot trials were used to determine the nutritional status and required nutrient additions to bring young chlorotic Sitka spruce (*Picea sitchensis* (Bong.) Carr) plantations out of "check." Check occurs on clear-cut and burned old-growth western red cedar (*Thuja plicata* Donn ex D. Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) stands in the Coastal Western Hemlock biogeoclimatic zone growing on deep mor-humus Podzols invaded by dense salal (*Gaultheria shallon*). Microplot trials identified the requirement for N and P. Checked trees responded to fertilization immediately with a 4- to 8-year temporary increase in leader length. Grubbing out of aboveground salal did not improve tree nutrition. There is a close parallel to "heather check" noted with Sitka spruce in British and Irish moorlands; a possible allelopathic effect of salal is suspected. It is concluded that one or more N and P additions are required to establish crown closure. Fertilized Sitka spruce show a high incidence of spruce weevil attack. The deficient and optimum foliar nutrient concentrations developed in Britain for the diagnosis of Sitka spruce appear to be applicable.

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Une série d'expérimentations avec des microparcelles et des parcelles conventionnelles ont été effectuées afin de déterminer le statut nutritif et les ajouts d'éléments requis afin d'amener de jeunes plantations chlorotiques d'Épinette de Sitka (*Picea sitchensis* (Bong.) Carr) à un niveau de suffisance. Des déficiences s'observent après coupe à blanc et après feu dans des vieux peuplements de Cèdre rouge de l'ouest (*Thuja plicata* Donn ex D. Don) et de pruche de l'ouest (*Tsuga heterophylla* (Raf.) Sarg.) dans la zone biogéoclimatique « Coastal Western Hemlock » croissant sur des Podzols coiffés d'un humus mor épais, envahi par un couvert dense de *Gaultheria shallon*. Les essais avec des microparcelles ont permis d'identifier les besoins en N et P. Les arbres déficients ont réagi immédiatement à la fertilisation avec un accroissement de la flèche terminale pendant 4 à 8 ans. L'enlèvement de la partie aérienne du *Gaultheria* n'a pas amélioré la nutrition des arbres. Il y a un parallèle étroit avec les déficiences observées sur l'Épinette de Sitka sur les landes de Grande-Bretagne et d'Irlande. Nous en concluons qu'un ou plusieurs ajouts de N et P sont requis pour en arriver à la fermeture du couvert. Les Épinettes de Sitka fertilisées montrent une forte incidence à l'attaque par le charançon de l'épinette. Les niveaux de déficience et de concentration foliaire optimale en éléments nutritifs déterminés en Grande-Bretagne pour le diagnose sur l'Épinette de Sitka apparaissent applicables pour la présente étude.

[Traduit par la revue]

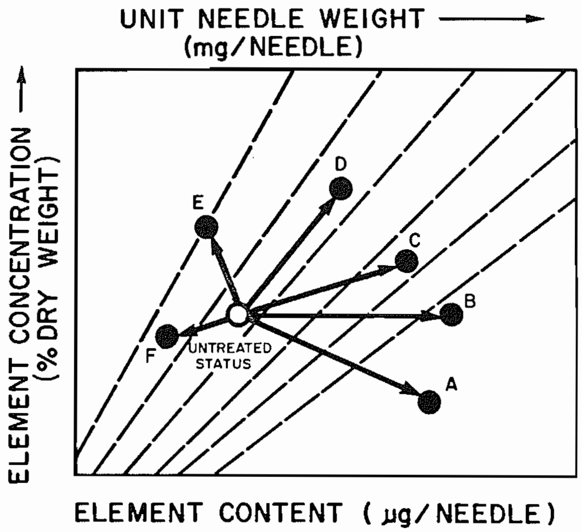
Introduction

In the wetter Coastal Western Hemlock biogeoclimatic zone (CHWb) (Pojar *et al.* 1987) of coastal British Columbia, salal (*Gaultheria shallon* Pursh.) tends to invade the cutovers following clear-cutting of old-growth western red cedar (*Thuja plicata* Donn ex D. Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forest.

During the late 1960s, 1900 ha of cutovers were planted with Sitka spruce (*Picea sitchensis* (Bong.) Carr) by Western Forest Products on tree farm licence No. 25. Initially, the trees planted on the cutovers grew well, but as the salal, an ericaceous evergreen shrub, spread vegetatively on the sites, the 8- to 14-year-old plantations went into "check." The annual leader growth was 5–10 cm (Fig. 5*a*) and the needles displayed chlorosis suggestive of N and P deficiencies (Binns *et al.* 1980). Chlorosis was also evident in natural regeneration of cedar and hemlock in the cutovers. Trees planted on roadsides or landings not dominated by salal had no growth check, were dark green, had 0.5-m leaders or longer, and were often attacked by spruce weevil (*Pissodes strobi* Peck). The plantation check is limited to cedar–hemlock (CH) sites characterized by deep ligno mor-humus Podzols that have developed under cedar and hemlock forests. These ligno mors have C/N ratios of 50–60:1, total N of 0.90%, pH 3–4, and are 22 to 30 cm deep. Trees in these forests have grown to great sizes for up to 1000 years without fire disturbance (Lewis 1982). Pacific silver fir (*Abies amabilis* (Dougl.) Forbes) and western hemlock stands grow on adjacent hemlock – *A. amabilis* (HA) sites, on the same parent materials, and are characterized by shallow mor-humus over Ferric-Humic Podzols (Agriculture Canada Expert Committee on Soil Survey 1987), and have developed following uprooting by windthrow. The HA sites do not display growth check. The sites equivalent to CH and HA are CWHb1(3) and CWHb1(4), respectively, as classified by Green *et al.* (1984).

This paper reports on three sets of fertilization experiments conducted between 1983 and 1987. These were designed to identify the limiting nutrients and the appropriate fertilizer prescription to restore the growth rate in the Sitka spruce plantations.

The protocol was to first use a microplot fertilizer screening trial to test the null hypothesis that fertilization would not restore growth in these checked plantations. This trial



Direction of shift	Response in: Needle weight	Nutrient: Concn.	Nutrient: Content	Change in: Nutrient status	Possible diagnosis
A	+	−	+	Dilution	Nonlimiting
B	+	o	+	Unchanged	Nonlimiting
C	+	+	+	Deficiency	Limiting
D	o	+	+	Luxury consumption	Nontoxic
E	−	++	±	Excess	Toxic
F	−	−	−	Excess	Antagonistic

FIG. 1. Interpretation of directional relationships among nutrient concentration, absolute nutrient content, and dry weight of needles following fertilizer treatment (adapted from Timmer and Ray 1988).

was used to identify the nutritional status of the plantations, and to predict response, based on current-year foliar analyses at the end of the first growing season following fertilization. These screening trials were followed the next year by conventional plot fertilizer trials to test the best treatments and to determine the duration of response. A third experiment was established to test the null hypothesis that salal does not directly compete with plantation trees for available nutrients. A manual aboveground removal of salal in combination with fertilization was tested.

The results of parallel studies on the fertilization of natural cedar and hemlock regeneration will be reported separately. The conduct of the research was strongly influenced by problems experienced by British and Irish foresters during the last 25 years with the use of fertilization to relieve Sitka spruce plantation check on *Calluna* heathlands (Carey 1977; Carey and Griffin 1983; McIntosh 1980, 1983; Taylor 1986).

Methods

Microplot fertilizer screening trial

The Sitka spruce microplot fertilizer screening trial was established during April 1983 in a 1975 plantation exhibiting severe chlorosis and growth check.

A 4 × 2 × 2 ((N0, N1, N2, N3) × (P0,P1) × (K0,K1)) factorial experiment in a completely randomized design was used with seven replications of each treatment (where N0 = control, N1 = 200 kg $N \cdot ha^{-1}$, N2 = 300 kg $N \cdot ha^{-1}$, N3 = 400 kg $N \cdot ha^{-1}$, P1 = 50 kg $P \cdot ha^{-1}$, and K1 = 50 kg $K \cdot ha^{-1}$); N was applied as ammonium nitrate, P as triple superphosphate, and K as muriate of potash. An additional micronutrient mix treatment was also tested on seven replication microplots. The commercial micronutrient mix designed by the British Columbia Ministry of Forests and Lands was added at 1000 $kg \cdot ha^{-1}$ to deliver (in $kg \cdot ha^{-1}$) 38 P, 91 K, 56 Ca, 48 Mg, 31 S, 1.8 Fe, 0.3 B, 0.72 Zn, 0.3 Cu, 0.75 Mn, and 0.2 Mo. Nitrogen was also added at 300 kg $N \cdot ha^{-1}$ as ammonium nitrate.

Circular 0.008-ha microplots were used with plot centers chosen for stand and site uniformity. Each fertilized plot contained five to seven trees. A dominant tree was the plot-centre tree and an adjacent dominant tree was chosen as off-center tree for foliar sampling.

At the end of the first growing season following fertilization, current-year needles were sampled from the two identified trees in each plot. Five lateral shoots from the upper crown were removed from each of the two trees and bulked for each plot.

Samples were kept in cool storage until oven-drying at 70°C. The needles were removed from the twigs. Subsamples were counted and weighed to determine weight in grams per 1000 needles, prior to grinding to pass through a 1-mm screen, and analyzed for N, P, K, Ca, Mg, Fe, B, Zn, Cu, and Mn. Total N and P were analyzed using the H_2SO_4–H_2O_2 digestion method with determination on a Technicon autoanalyzer. Potassium, Ca, and Mg were analyzed from the same digest with determination on an atomic absorption spectrophotometer (AAS). Micronutrients (Fe, Zn, Cu, and Mn) were analyzed using an AAS following dry ashing at 520°C, whereas B was determined using the azomethine-H method.

First-year needle weight and macronutrient foliar concentrations and contents for N, P, and K were fitted to polynomial response functions using the BMDP statistical package. The interpretation of changes in needle weight, concentration, and content used the graphical vector analysis technique (Weetman and Fournier 1982; Timmer and Morrow 1984; Timmer and Ray 1988) (Fig. 1).

Initial height in April 1983 and annual height growth in November 1983, 1984, 1985, 1986, and 1987 were measured for the two trees per plot to the nearest centimetre using a height pole.

In April of 1986, after three growing seasons, the plantation was partially refertilized to determine the response to a second fertilizer application; K1P0 plots were refertilized with N alone, K1P1 plots were refertilized with N and P (50 kg $P \cdot ha^{-1}$). Plots treated in 1983 with N and (or) P were not refertilized.

After the second growing season, spruce weevil attacked up to 40% of the leaders of the sample trees. Competing laterals developed in all cases (McMullen *et al.* 1987). Second attacks on the same trees were rare. Trees that had suffered attack during the 5-year period were removed from the experimental data base.

Annual height growth of single and repeated N and P fertilizer doses were plotted. Covariance adjusted mean treatment values with initial height as covariate were used.

The annual height growth of vigorous Sitka spruce planted on HA sites (Fig. 4) matches the height over age curve for site index at 50 years (SI_{50}) = 28 m using values developed by Western Forest Products.

Conventional plot fertilizer trial

To confirm the responses from the most successful treatments found in the 1st-year screening trials, a conventional plot fertilizer trial was established in spring 1984 in the 1975 plantation. The design used six randomized treatments replicated in three blocks. The treatments were N0 (control), N100P50, N200P50, N300P50, N300P150, N300P50K91 (where N, P, and K represent the nutrient supplied, and the numbers represent the concentrations at which they were applied in $kg \cdot ha^{-1}$), and M1 (addition of micronutrients; 1000 $kg \cdot ha^{-1}$), with one treatment plot per block. Nitrogen was added as ammonium nitrate and P as triple superphosphate. The micronutrient treatment used the same custom fertilizer mixture used for the screening trial. Triple superphosphate was added to deliver an extra 12 kg $P \cdot ha^{-1}$ above the 38 $kg \cdot ha^{-1}$ contained in the micronutrient mixture.

Each plot consisted of a square outer gross plot of 0.09 ha and an inner net plot of 0.0625 ha. Each inner plot contained 30 to 40 planted Sitka spruce, 1 to 2 m tall.

TABLE 1. Sitka spruce single-tree fertilizer screening trial: analysis of current-year foliage for main effects and interactions at the end of the first growing season

Main effects and interactions	Needle weight (g/1000 needles)	% ovendry weight		
		N	P	K
N				
N0	3.95 (100)	0.82 (100)	0.17 (100)	0.71 (100)
N1	5.38 (136)	3.52 (429)	0.17 (100)	0.38 (54)
N2	5.27 (133)	4.21 (513)	0.16 (94)	0.31 (44)
N3	5.17 (131)	4.43 (540)	0.17 (100)	0.31 (44)
P				
P0	4.52 (100)	3.24 (100)	0.13 (100)	0.41 (100)
P1	5.37 (119)	3.25 (100)	0.20 (154)	0.45 (110)
K				
K0	4.93 (100)	3.32 (100)	0.17 (100)	0.39 (100)
K1	4.95 (100)	3.17 (95)	0.17 (100)	0.46 (118)
N×P				
N0P0	3.77 (100)	0.72 (100)	0.12 (100)	0.71 (100)
N0P1	4.14 (110)	0.91 (126)	0.23 (192)	0.71 (100)
N1P0	4.45 (118)	3.65 (507)	0.14 (117)	0.36 (51)
N1P1	6.32 (168)	3.39 (471)	0.20 (167)	0.41 (58)
N2P0	4.91 (130)	4.17 (579)	0.14 (117)	0.28 (39)
N2P1	5.65 (150)	4.24 (589)	0.19 (158)	0.35 (49)
N3P0	4.94 (131)	4.42 (614)	0.14 (117)	0.30 (42)
N3P1	5.39 (143)	4.45 (618)	0.19 (158)	0.32 (45)
N×K				
N0K0	4.11 (100)	0.80 (100)	0.17 (100)	0.60 (100)
N0K1	3.80 (92)	0.83 (105)	0.18 (106)	0.83 (138)
N1K0	5.12 (125)	3.59 (449)	0.17 (100)	0.35 (58)
N1K1	5.65 (137)	3.45 (431)	0.17 (100)	0.42 (70)
N2K0	5.08 (124)	4.37 (546)	0.16 (94)	0.32 (53)
N2K1	5.43 (132)	4.05 (506)	0.17 (100)	0.31 (52)
N3K0	5.44 (132)	4.52 (565)	0.17 (100)	0.31 (52)
N3K1	4.90 (119)	4.34 (543)	0.16 (94)	0.31 (52)
P×K				
P0K0	4.47 (100)	3.29 (100)	0.13 (100)	0.38 (100)
P0K1	4.57 (102)	3.19 (97)	0.13 (100)	0.44 (116)
P1K0	5.42 (121)	3.35 (102)	0.20 (154)	0.41 (108)
P1K1	5.32 (119)	3.15 (96)	0.20 (154)	0.49 (129)

NOTE: Values in parentheses are relative to 100.

In November of the subsequent 4 years, a foliage sample was collected from a top lateral shoot from each of 10 trees per plot and bulked to produce one sample per plot. Chemical analyses used the same techniques as used for the screening trials.

All net plot trees were measured for initial 1984 (April) height and height increment (to the nearest cm) in November 1984, 1985, 1986, and 1987. In April 1984 and November 1986, all net plot trees were measured for diameter at stump height (DSH; to the nearest mm). A two-way analysis of covariance, with 1984 initial height (or 1984 basal area per tree) as covariate, was used to analyze the 4-year height increment and 3-year basal area increment at DSH. The experimental error (blocks × treatments) was used as the error term to determine the F-value for 4-year height increment.

Adjusted means were used when covariance was significant. Tukey's multiple comparisons were used to determine treatment differences. Any trees that were attacked by spruce weevil (35% of the trees) during the 4-year period were analyzed separately to determine the reduction in response due to weevil attack.

Using first growing season unit needle weight, percent N, percent P, and N content (mg/1000 needles) as independent variables, linear and multiple regressions were run against log 3-year height increment and log basal area increment. This was to assess the predictive value of current first season foliage analysis on subsequent growth response.

Salal grubbing and fertilization

During July–August 1984, the aboveground portions of salal were manually grubbed out from thirty, 0.0625-ha plots using Pulaski axes. The grubbed aboveground salal was left *in situ*. Sprouting of the salal from the intact roots was kept in check by a single herbicide application using Garlon 4E at 3.5 kg active ingredient/ha at the end of the second growing season.

The experimental design was 2 × 3 × 2 factorial: (S0, S1) × (N0, N1, N2) × (P0, P1), where S0 = intact salal, S1 = salal removed, N0 = control, N1 = 250 kg $N \cdot ha^{-1}$ as ammonium nitrate, N2 = 250 kg $N \cdot ha^{-1}$ as urea, P0 = control, and P1 = 100 kg $P \cdot ha^{-1}$ as triple superphosphate. The design was replicated in five Sitka spruce plantations established in 1969, 1971, 1973 (2), and 1975. Fertilizers were applied in April 1985.

In November, foliage samples were collected annually from 10 trees per plot and bulked. Chemical analyses were similar to those in the other experiments.

All plot trees (30–40/plot) were measured for initial 1985 (April) height and height increment (nearest cm) in November 1985, 1986, and 1987. In April 1985 and November 1987, all trees were measured for dbh (to the nearest mm).

Three-way analysis of covariance with 1985 initial height (or 1985 basal area per tree) as covariate was used to analyze the height increment and 3-year basal area increment at dbh. Adjusted means

TABLE 2. Sitka spruce fertilizer screening trial, first-growing season following fertilization: analysis of variance table for needle weight and N, P, K concentration and content

		Needle weight (g/1000 needles)		Concentration (% dry weight)						Content (mg/1000 needles)					
				N		P		K		N		P		K	
Source	df	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
N	3														
Linear (L)	1	14.87	<0.001	1547.66	<0.001	2.83	0.096	385.78	<0.001	333.63	<0.001	5.48	0.021	75.51	<0.001
Quadratic (Q)	1	13.89	<0.001	347.42	<0.001	1.46	0.230	125.28	<0.001	96.74	<0.001	9.00	0.003	9.73	
Cubic (C), lack of fit	1	3.04	0.084	27.98	<0.001	0.14	0.712	10.16	0.002	8.34	0.005	4.60	0.035	4.60	0.035
P (L)	1	17.19	<0.001	0.02	0.8942	252.28	<0.001	5.73	0.019	16.63	<0.001	141.96	<0.001	23.38	<0.001
K (L)	1	0.001	0.962	5.34	0.023	0.01	0.908	23.43	<0.001	0.65	0.423	0.03	0.869	6.89	0.010
N×P	3														
L	1	0.25	0.619	0.11	0.746	19.51	<0.001	0.50	0.481	0.02	0.895	3.05	0.084	0.13	0.718
Q	1	4.63	0.034	2.43	0.122	4.95	0.028	2.06	0.154	3.35	0.070	2.53	0.115	6.01	0.016
C	1	3.82	0.054	3.84	0.053	0.28	0.598	0.02	0.895	1.17	0.282	2.86	0.094	1.16	0.284
N×K	3														
L	1	0.22	0.643	1.84	0.179	1.32	0.254	36.51	<0.001	2.53	0.115	0.79	0.377	11.85	0.001
Q	1	4.61	0.034	1.33	0.252	0.18	0.674	8.34	0.005	1.84	0.177	3.88	0.052	0.08	0.783
C	1	0.03	0.867	0.30	0.586	1.82	0.180	0.02	0.885	0.005	0.816	0.32	0.574	0.28	0.599
P×K	1	0.22	0.643	0.56	0.456	0.22	0.6383	0.17	0.682	1.28	0.261	0.07	0.799	0.03	0.855
N×P×K	3														
L	1	0.24	0.627	1.01	0.318	3.41	0.068	22.02	<0.001	0.02	0.890	1.34	0.250	13.91	<0.001
Q	1	0.89	0.347	0.09	0.767	0.08	0.779	10.71	0.002	0.63	0.431	0.14	0.711	6.55	0.012
C	1	0.48	0.489	0.05	0.832	0.34	0.560	10.05	0.002	0.25	0.619	0.85	0.360	6.88	0.010
Error	96														
Error MS		0.01164		0.1205		0.00522		0.00592		0.1601		0.00444		0.0295	

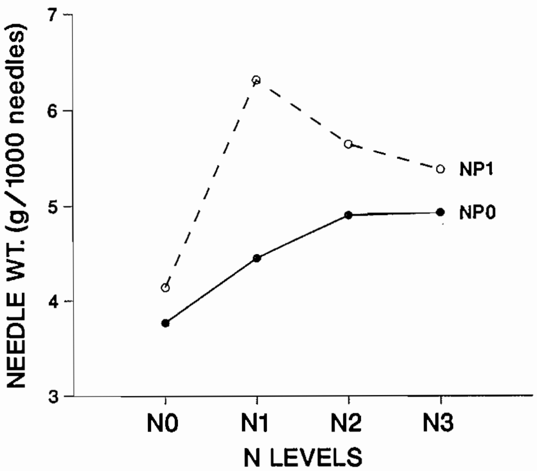


FIG. 2. Sitka spruce screening trial: first growing season current needle weight (g/1000 needles) for N levels with and without P.

were used when covariance was significant. Tukey's multiple comparisons were used to compare treatments.

Results

Microplot fertilization screening trials

First growing season foliar analysis

First-season foliar analyses for main effects and interactions are shown in Table 1 and in the ANOVA Table 2.

Needle weight increased with N application but was not significantly different beyond the N1 level. A trend for increased needle weight occurred when N and P were added together (Fig. 2). Nitrogen concentration followed a similar trend to that found for needle weight. Phosphorus uptake was greater when N was applied with P. Potassium uptake decreased with increasing N applications. The mean foliar N concentration for control plots was 0.64%, indicating a severe N deficiency for Sitka spruce (Binns *et al.* 1980).

The shifts in relative N, P, and K nutrient concentration relative nutrient content of needles and relative needle dry weight due to treatment are presented in Figs. 3A, 3B, and 3C. Sets and subsets indicate significant main factor and interaction effects for relative nutrient content (relative needle weight × relative nutrient concentration). The interpretation of the shifts follows Timmer and Ray (1988). The addition of N alone or P alone resulted in a significant increase in relative concentration with no significant increase in relative needle weight, indicating luxury consumption. When N and P were added together a significant increase in relative concentration with a corresponding significant increase in relative needle weight occurred, indicating a deficiency uptake for both elements. The trees were deficient in both N and P. Their ability to respond required both nutrients.

The mean foliar K concentration of control trees was marginally deficient (Binns *et al.* 1980), and when K was added alone a shift suggesting luxury consumption occurred (Fig. 3C). Additions of N alone or N and K significantly decreased percent K (Table 1) and K content, suggesting that an excess of N was antagonistic to K uptake. Visual evidence of scorching or bronzing (Binns *et al.* 1980) on current-year needles was seen. The bronzing was not apparent in subsequent years.

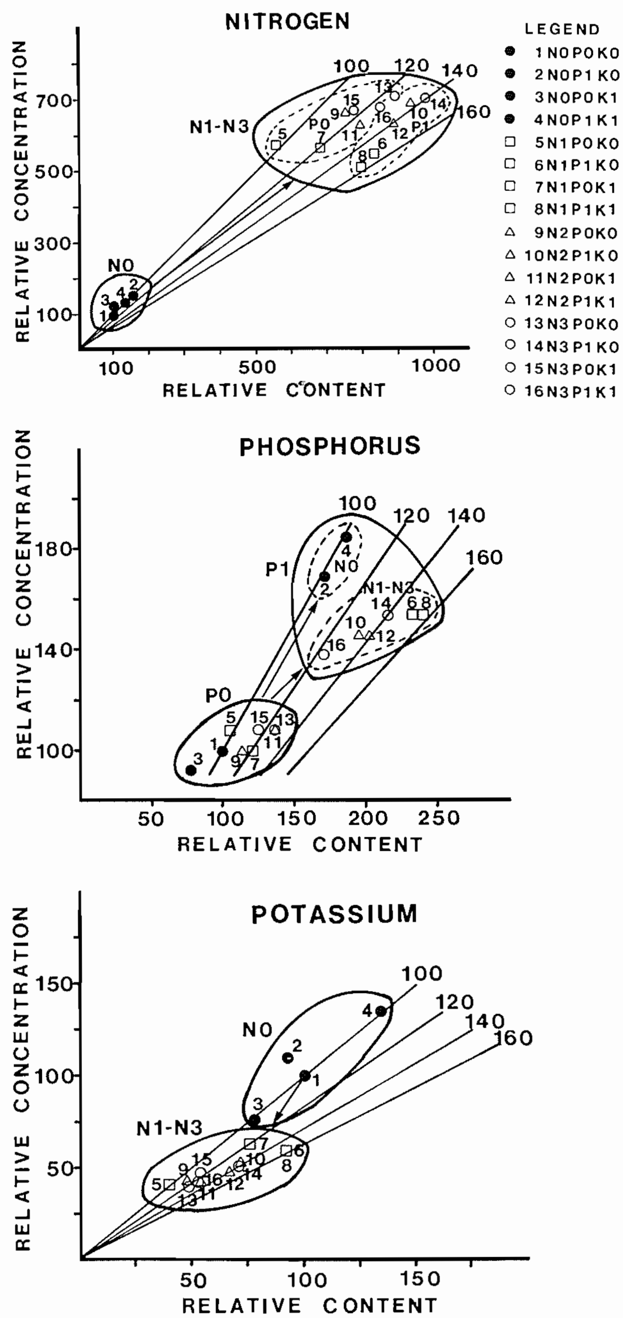


FIG. 3. The directional relationships for Sitka spruce between relative nutrient concentration, relative nutrient content, and relative dry weight of needles for N, P, and K at the end of the first growing season. Values relative to control: N = 0.64, P = 0.13, K = 0.68, and needle weight = 4.0 g/1000 needles. Values at the top end of the isobars represent relative needle weight.

Some trees in the N1K1 treatment showed curling of leaders. This was suggestive of a Cu deficiency based on similar curling noted in Sitka spruce in Ireland and Britain (Miller and Miller 1987). Control foliar Cu concentrations wee 2.3 ppm; the addition of N2P1K1 plus micronutrients raised the Cu concentration to 0.47 ppm with a corresponding needle weight of 6.75 g/1000 needles, indicating a deficiency uptake for Cu. The curling was not seen in subsequent years.

The Ca and Mg shifts did not show any consistent response to treatment and are not presented. Following these

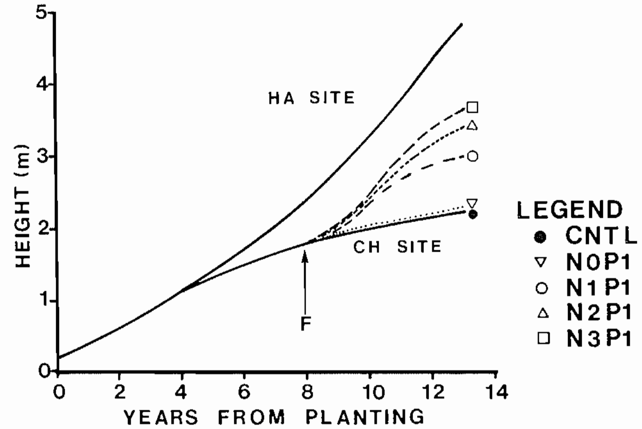


FIG. 4. Sitka spruce plantation tree height over age development for an unfertilized HA site and a fertilized CH site. F, year of fertilization; cntl, control.

1st-year foliar analyses, combinations of N and P with and without micronutrient additions were chosen for further formal testing using conventional fixed-area fertilizer plots.

Five-year height growth

Figure 4 compares the height development of plantation Sitka spruce on an unfertilized HA site and a fertilized CH site. The response in leader length was immediate in fertilized trees. The annual height growth recovered to match the spruce growing on the salal free HA sites, but after 3 years, the leader growth tended to decline unless refertilized.

The effects of a single and a repeated dose of N and N + P fertilizer on annual leader growth are shown in Fig. 5. The fertilizer effect is temporary. By the end of the fifth growing season, leader lengths had almost returned to control values. Refertilization with N alone did not restore response. Refertilization with N and P did cause some recovery in leader growth in N1 and N2 treatments. The repeated dose of N3P1K0 showed the slowest decline in leader growth.

Conventional plot fertilizer trials

Foliar analyses

Applications of N and P combinations, together with micronutrients at the highest dosage, as in screening trials, also produced greening of the chlorotic foliage and larger needles. Table 3 shows that unit needle weight has remained significantly higher for four growing seasons. Nitrogen concentrations were initially increased to 3–4% N from the deficient value of 0.69 (Binns *et al.* 1980) and then declined steadily. Phosphorus concentrations were increased from the deficient 0.13% to over 0.20%, but by the end of the fourth growing season had declined to 0.15% or less. Potassium values remained above the deficient values of 0.5 suggested by Binns *et al.* (1980).

Height growth and basal area response

Table 4 shows that weevil-damaged trees grew less than undamaged trees and also showed fewer significant differences in fertilizer response. The N300P150 and N300P50K91M1 treatments produced the greatest 4-year growth response. Higher responses were found with N200 or N300 plus P applications for 3-year basal area increment per hectare at stump height for all trees, weevil-damaged trees, and undamaged trees.

Linear and multiple regressions were used to test if 1st-year foliar parameters (particularly needle weight) were good predictors of subsequent growth response expressed as log 3-year height growth. Log unit needle weight explained 42% of the response. Log percent N and log percent P both explained 87% of the variation and log N content (mg/1000 needles), 90% of the variation, using linear regression; when multiple regression was used the R^2 value was 0.92. Tests of the same variables against log basal area increment gave an R^2 value of 0.86. The p-value for all regressions was <0.001.

The conventional plots also displayed dense and very high fireweed (*Epilobium angustifolium* L.) growth among the fast growing Sitka spruce. Salal also showed increased vigour due to fertilization. Neither species threatened the free-growing status of the spruce trees.

Salal grubbing and fertilization experiment

Neither salal grubbing followed by a herbicide application nor the addition of P alone increased needle weight significantly by the end of the third growing season or improved N uptake (Tables 5 and 6). Only the combined effect of N and P additions gave a significant response in needle weight during the first growing season; by the third growing season both N and P concentrations had declined, as occurred in the other experiments. There were no significant differences between urea and ammonium nitrate as N sources in increasing needle weight and leader length.

After three growing seasons, height growth was superior on N- and P-treated plots (Fig. 6). There was no evidence that salal grubbing further improved growth. The response in basal area matched the height growth changes.

Discussion

The screening trial confirmed that the Sitka spruce plantations growing in dense salal, an ericaceous shrub, are deficient in N and P. These deficiencies and visual foliar symptoms are analogous to the well-known "heather check" and associated N and P supply problems found in Sitka spruce plantations on ericacious British heathlands dominated by a heather (*Calluna vulgaris* (L.) Hull) sward. The reasons for the nutritional problems associated with heather have been reviewed by several authors (Handley 1963; Malcolm 1975; Read 1984; and Taylor and Tabbush 1989). Allelopathic substances produced by heather roots appear to be inhibiting mycorrhizal development. A similar situation also occurs with *Kalmia angustifolia* in Newfoundland (Meades 1983*a*, 1983*b*). Whether or not salal is producing allelopathic substances on the coast of British Columbia is now being investigated and will be reported on separately. Del Moral and Cates (1971) found some weak evidence for allelopathy in salal. Rose *et al.* (1983) have shown that allelochemicals in litter may inhibit seedling growth.

The CH sites display nutrient supply problems for not only Sitka spruce, but also western hemlock and western red cedar. The ancient cedar–hemlock forests are primarily rooted in ligno-mor humus overlaying well-drained soils. These ecosystems are found on an estimated 100 000 ha throughout the wetter portions of the Coastal Western Hemlock biogeoclimatic zone on Vancouver Island, the coastal mainland, and the Queen Charlotte Islands. They experience no seasonal moisture deficits, with 1730 mm of

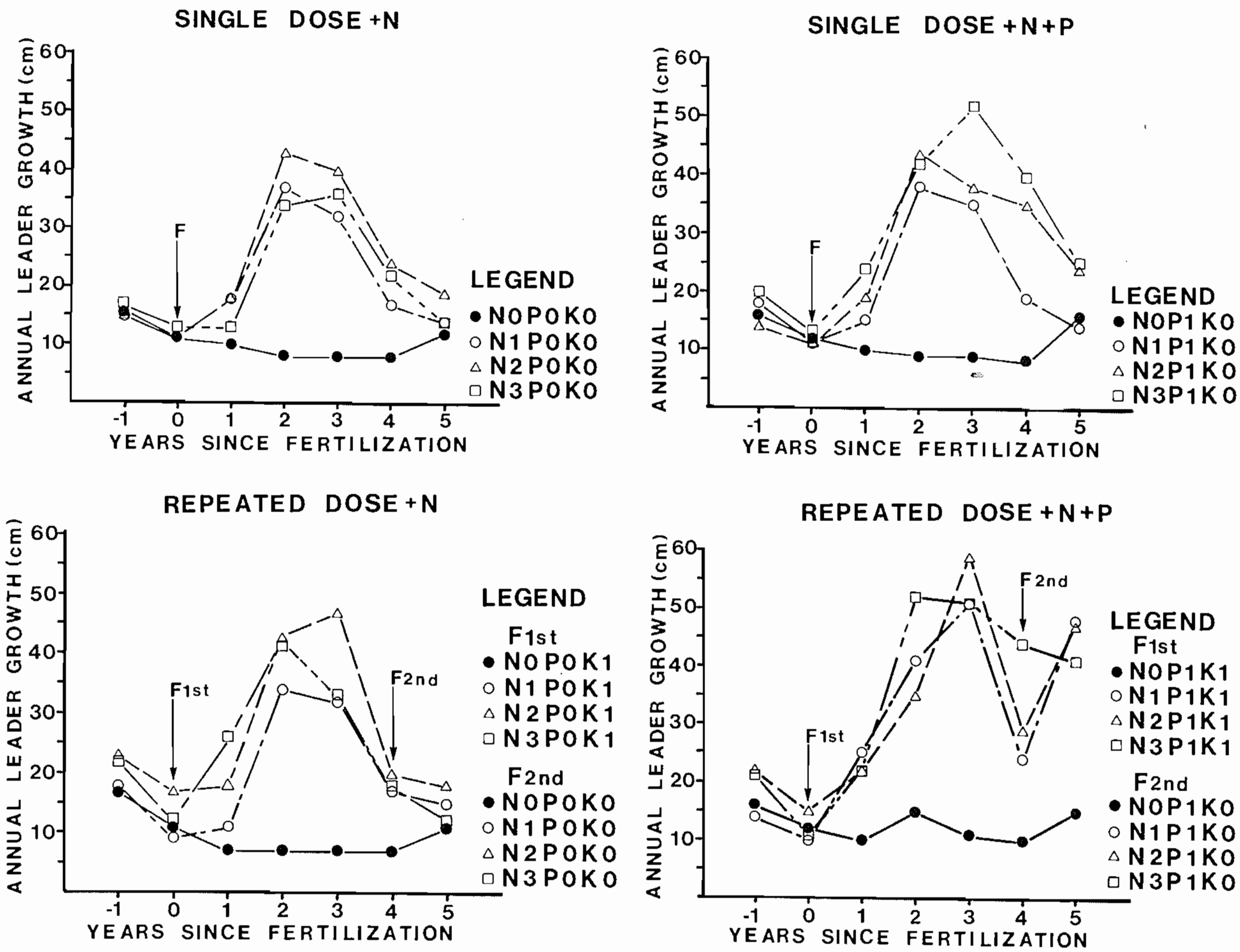


FIG. 5. Annual leader growth before and after single and repeated fertilizer applications in the single-tree screening trial. F, year of fertilization.

mean annual precipitation. Salal is a normal understory component in the old-growth forests. The salal cover expands rapidly by rhizomes following clear-cutting and burning; burning is considered to be a requirement for planting in order to remove up to 300 $m^3 \cdot ha^{-1}$ of woody debris and slash. Additional experiments are underway to test for the effects of total salal eradication, rather than salal grubbing as described in this report.

The rapid, but temporary, restoration of growth in the checked plantations agrees with the responses noted by McIntosh (1980) and Taylor (1987), i.e., response increases with N and P application, and there are no differences between urea and ammonium nitrate. The following Sitka spruce deficient and optimum foliar nutrient concentrations have been suggested by Binns *et al.* (1980) and would appear to apply to the Port McNeill plantations:

	%N	%P	%K
Deficient	<1.2	<0.14	<0.5
Optimum	>1.5	>0.18	>0.7

Miller (1981) has suggested that response to N is directly related to 1st-year N uptake. This has not been tested in this study, but would appear to be applicable. First year N concentrations in the needles reached 4% with an application of 400 kg $N \cdot ha^{-1}$. Whether the response will last long enough for the plantations to close canopy, smother the salal, and establish an improved N cycle based on litter fall appears to be uncertain. At 1100 stems/ha and after 4 years of response, crown closure is still several years away with 3 to 4 m tall trees. One or more refertilizations may be required.

Unfertilized checked plantations, while meeting current provincial "free growing" requirements, which are based on light as a limiting factor, are unlikely to produce marketable timber. The natural ingress of hemlock and cedar regeneration that is filling in the plantation is also chlorotic and slow growing; the estimated mean annual increment is 5 $m^3 \cdot ha^{-1} \cdot year^{-1}$ and SI_{50} = 15 m.

No evidence was found of the "nurse crop" effect noted by Malcolm (1987) and others in which mixed spruce–pine and spruce–larch forests overcame N supply problems noted in pure spruce forests planted in *Calluna*. Natural mixes of spruce – shore pine (*Pinus contorta* var. *contorta* Loud), spruce–hemlock, and spruce–cedar all show check on these CH sites on the coast of British Columbia.

The essential requirement for N and P in the Pacific Northwest has been demonstrated by Heilman and Ekuan (1980) and Porada and Zasoski (1986) for Douglas-fir and western hemlock. Heilman and Ekuan (1980) found that whereas P additions increased mycorrhizal development, mycorrhizal deficiencies did not appear to be the cause of the low availability and uptake of P by Douglas-fir seedlings. The low phosphorus availability found in northern Vancouver Island may be due to P fixation on these low

TABLE 3. Sitka spruce conventional plot fertilizer trials: current-year foliar analyses for the 4 years following fertilization (treatment df = 5; error df = 12)

Year	Control	N100P50	N200P50	N300P50	N300P150	N300P50 K91M1*	ANOVA p-value	Treatment MS	Error MS
				Needle weight (g/1000 needles)					
1	3.79	5.21	4.86	4.63	4.92	5.91	0.05	1.454	0.304
2	4.22	5.92	5.76	6.35	6.20	6.83	0.01	2.380	0.453
3	3.79	3.69	4.55	6.02	5.65	5.35	0.01	0.116	0.011
4	3.98	4.72	4.50	6.50	6.98	5.75	0.01	4.30	0.034
				%N					
1	0.69	2.96	3.51	3.93	3.99	2.98	0.01	4.458	0.157
2	0.56	0.98	1.19	1.44	1.48	1.47	0.01	0.399	0.005
3	0.66	0.70	0.95	1.43	1.36	1.37	0.01	0.373	0.011
4	0.50	0.42	0.50	0.91	0.73	0.58	0.01	0.102	0.005
				%P					
1	0.13	0.21	0.21	0.22	0.24	0.21	0.01	0.0041	0.000 26
2	0.10	0.15	0.14	0.16	0.18	0.16	0.01	0.002	0.000 07
3	0.13	0.19	0.17	0.20	0.20	0.18	0.01	0.002	0.000 3
4	0.11	0.12	0.14	0.13	0.15	0.13	ns	0.0004	0.000 5
				%K					
1	0.70	0.52	0.43	0.45	0.48	0.74	0.01	0.052	0.008
2	0.63	0.50	0.47	0.40	0.48	0.55	0.01	0.019	0.002
3	0.66	0.78	0.73	0.66	0.66	0.76	ns	0.009	0.009
4	0.57	0.55	0.51	0.51	0.53	0.39	ns	0.012	0.010
				%Ca					
1	0.43	0.45	0.46	0.44	0.49	0.40	ns	0.0027	0.004 2
2	0.42	0.34	0.40	0.35	0.40	0.45	ns	0.005	0.002
3	0.44	0.27	0.36	0.38	0.48	0.46	ns	0.018	0.007
4	0.63	0.34	0.32	0.32	0.32	0.25	0.05	0.052	0.016
				%Mg					
1	0.12	0.12	0.12	0.12	0.11	0.11	ns	0.00002	0.000 2
2	0.08	0.08	0.08	0.07	0.08	0.08	ns	0.00005	0.000 1
3	0.11	0.11	0.12	0.11	0.13	0.13	ns	0.0003	0.000 3
4	0.12	0.14	0.11	0.09	0.10	0.09	0.01	0.00103	0.000 18
				Cu (ppm)					
1	2	—	—	—	—	5	—	—	—
3	8	5	7	8	10	9	ns	6.77	10.06
				Zn (ppm)					
1	21	—	—	—	—	18	—	—	—
3	18	14	14	13	16	17	ns	11.6	6.0
				Mn (ppm)					
1	1143	—	—	—	—	1297	—	—	—
3	1310	920	1080	1290	1260	870	ns	113 210	112 000
				Fe (ppm)					
1	14	—	—	—	—	35	—	—	—
3	17	17	24	33	31	30	0.05	160.9	37.0
				B (ppm)					
1	15	—	—	—	—	23	—	—	—
3	20	18	15	14	30	19	ns	99.39	38.94

*Micronutrients include Fe, B, Cu, Zn, Mn, and Ma.

pH soils. Possible problems with Sitka spruce mycorrhizae caused by salal may be a symptom of low P availability in these soils.

Heavy single doses of N alone reduce foliar P concentrations down to 0.07% by the end of the third growing season, well below the deficient level of 0.14%; an addition of 50 kg $P \cdot ha^{-1}$ was enough to keep P concentrations in the 0.14 to 0.20% range. For Sitka spruce seedlings, the proportion by weight of P (where N = 100) at optimum steady state nutrition and maximum growth is 16, according to Ingestad

TABLE 4

A. Sitka spruce conventional plot fertilizer trials: 4-year height growth for undamaged and weevil-damaged trees, and 3-year basal area growth at stump height

	4-year height growth (cm)				3-year basal area growth at stump height ($m^2 \cdot ha^{-1}$)	
	Undamaged		Weevil-damaged			
Treatment	Mean	SD	Mean	SD	Mean	SD
Control	22*a*	18	34*a*	10	0.16*a*	0.14
N100P50	89*b*	32	92*b*	22	1.24*b*	0.26
N200P50	136*c*	46	113*c*	36	1.44*c*	0.45
N300P50	136*c*	43	121*c*	41	1.51*cd*	0.21
N300P150	166*d*	43	122*c*	41	1.65*de*	0.15
N300P50K91M1	163*d*	59	129*c*	33	1.72*e*	0.51

NOTE: Values are covariance adjusted for initial 1983 height and basal area. Values followed by the same letters are not significantly different at $p = 0.05$.

B. Analysis of covariance

	4-year height growth					
	Undamaged			Weevil-damaged		
Source	df	MS	*p*	df	MS	*p*
Treatments (T)	5	219 890.0	<0.001	5	10 358.0	0.003
Blocks (B)	2	813.2	0.752	2	737.8	0.750
B×T*	10	1 520.4	—	9	1 358.2	—
Covariate (initial 1983 height)	1	61 081.0	<0.001	1	16 223.0	<0.001
Sampling error	399	1 426.4	—	199	1 193.0	—

	3-year basal area growth		
Source	df	MS	*p*
Treatments	5	0.991	<0.001
Covariate (initial 1985 basal area)	1	0.890	<0.001
Sampling error	11	0.029	—

*Blocks × treatments (experimental error) was used as error term to determine *p*-value.

TABLE 5. Salal grubbing (S) and fertilization experiment: current needle foliage analysis for Sitka spruce first and third growing seasons following treatment

	Needle weight (g/1000 needles)		%N		%P	
Treatment	Year 1	Year 3	Year 1	Year 3	Year 1	Year 3
S0N0P0	4.75 (0.95)	3.81 (0.35)	0.64 (0.07)	0.74 (0.14)	0.09 (0.01)	0.10 (0.02)
S0N0P1	4.01 (0.19)	4.01 (0.12)	0.69 (0.06)	0.70 (0.8)	0.23 (0.05)	0.13 (0.03)
S0N1P0	5.00 (0.88)	4.20 (0.75)	1.96 (0.28)	0.78 (0.15)	0.10 (0.01)	0.10 (0.04)
S0N1P1	5.93 (0.80)	4.50 (0.80)	2.11 (0.41)	0.81 (0.16)	0.22 (0.07)	0.15 (0.04)
S0N2P0	4.47 (0.51)	4.21 (0.86)	1.87 (0.37)	0.78 (0.09)	0.09 (0.01)	0.10 (0.06)
S0N2P1	5.83 (0.92)	4.77 (0.85)	2.01 (0.22)	0.82 (0.23)	0.20 (0.02)	0.14 (0.04)
S1N0P0	4.58 (0.43)	4.71 (0.63)	0.74 (0.06)	0.88 (0.10)	0.11 (0.02)	0.11 (0.01)
S1N0P1	4.07 (0.92)	4.72 (0.87)	0.86 (0.10)	0.79 (0.18)	0.31 (0.07)	0.15 (0.03)
S1N1P0	4.39 (0.37)	4.83 (0.69)	2.50 (0.38)	1.13 (0.29)	0.13 (0.02)	0.09 (0.02)
S1N1P1	6.19 (0.84)	5.36 (0.92)	2.52 (0.27)	0.89 (0.03)	0.20 (0.03)	0.10 (0.03)
S1N2P0	5.17 (0.55)	4.31 (0.43)	2.16 (0.24)	0.87 (0.09)	0.12 (0.01)	0.08 (0.01)
S1N2P1	6.63 (1.16)	5.58 (1.09)	2.17 (0.15)	0.94 (0.26)	0.21 (0.03)	0.12 (0.02)

NOTE: SD is given in parentheses.

TABLE 6. Salal (S) grubbing and fertilization experiment: current needle weight, %N, and %P analysis of variance table for Sitka spruce first and third growing seasons following treatment

	1st growing season			3rd growing season		
Source	df	MS	p	df	MS	p
			Needle weight (g/1000 needles)			
S	1	0.451	0.387	1	6.666	0.001
N	2	8.176	<0.001	2	1.103	0.145
P	1	7.719	<0.001	1	3.418	0.016
S×N	2	1.256	0.125	2	0.174	0.736
S×P	1	0.616	0.310	1	0.226	0.533
N×P	2	6.750	<0.001	2	0.834	0.231
S×N×P	2	0.210	0.704	2	0.248	0.647
Error	48	0.582		48	0.554	
			%N			
S	1	1.170	<0.001	1	0.315	0.002
N	2	13.801	<0.001	2	0.076	0.075
P	1	0.103	0.203	1	0.021	0.391
S×N	2	0.159	0.087	2	0.018	0.535
S×P	1	0.147	0.634	1	0.034	0.274
N×P	2	0.0002	0.986	2	0.037	0.272
S×N×P	2	0.002	0.776	2	0.030	0.345
Error	48	0.062		48	0.028	
			%P			
S	1	0.0099	0.008	1	0.0017	0.221
N	2	0.0045	0.039	2	0.0008	0.500
P	1	0.217	<0.001	1	0.0202	<0.001
S×N	2	0.0029	0.117	2	0.0029	0.083
S×P	1	0.00004	0.836	1	0.0004	0.548
N×P	2	0.0072	0.007	2	0.0002	0.829
S×N×P	2	0.0042	0.046	2	0.0012	0.379
Error	48	0.0013		48	0.0011	

(1987). Values of 11 to 20 for P were found in the 2nd and 3rd year following N and P fertilization at rates of 100 to 300 kg N·ha^{-1} and 50 to 150 kg P·ha^{-1} (Table 3). In the first growing season, P values were diluted to 6 or 7 by the immediate N uptake. It appears that 50 kg P·ha^{-1} application satisfies the P requirement for these young plantations.

Since a long-lasting N effect was required, 300 kg N·ha^{-1} and 100 kg P·ha^{-1} were chosen for an operational aerial fertilization trial on these S1 CH sites in December 1986 and for routine fertilization in 1989.

A projected total response period of 8 years seems reasonable. The 1986 cost was $500/ha. If this single fertilization restores site productivity to match HA sites and results in crown closure and subsequent shading out of salal, then a SI_{50} of 28 m and a mean annual increment of 11 m^3·ha^{-1}·year^{-1} should be attainable. Owing to the widespread occurrence of chlorotic reproduction on salal-dominated sites in this wet climatic zone, fertilization may be an essential requirement for restoration of site productivity. It should be noted that salal growing as an understory in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) ecosystems in drier climatic zones of the coast of British Columbia does not appear to influence tree nutrition; under these circumstances, it does compete for moisture (Price *et al.* 1986). Vales (1986) has reviewed the current literature on salal.

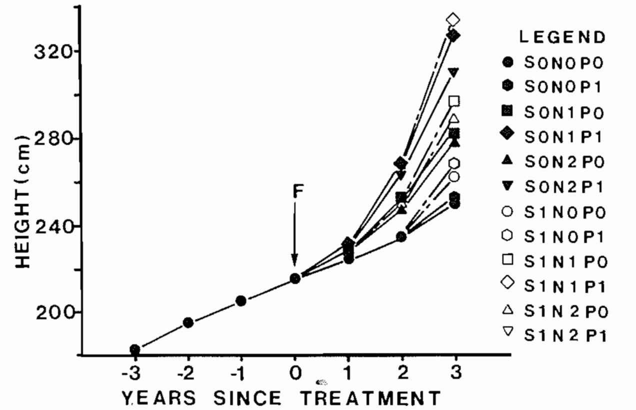


FIG. 6. Height over age curves for Sitka spruce treated with salal grubbing (S1), N as ammonium nitrate (N1) or urea (N2) at 250 kg·ha^{-1}, and P (P1) at 100 kg·ha^{-1}. F, year of fertilization.

Sitka spruce is currently little used for reforestation on Vancouver Island because of lack of control over weevil damage to leaders. Weevils are attracted to the most vigorous leaders (a 30% incidence of attack noted in this study) and fertilization stimulates vigour of leaders. The probability of attack increases as leaders attain 70 cm length (McMullen *et al.* 1987). Hemlock and cedar are currently planted in all CH cutovers. All three species are components of the old-growth forest. On the Queen Charlotte Islands where weevils are absent, Sitka spruce is planted. Cedar regeneration is usually eaten by excessive deer populations on the Queen Charlottes. Deer tend not to eat Sitka spruce; they rely on salal for winter forage, but do not remove it completely from cutovers. Three fertilizer screening trials conducted by MacMillan Bloedel Limited (Kumi 1987) on the Queen Charlottes in three chlorotic Sitka spruce plantations growing in dense salal produced 1st-year foliar analysis vector shifts indicative of N and P deficiencies. Elsewhere in the Coastal Western Hemlock biogeoclimatic zone chlorotic conifer reproduction has also been found growing on cutovers dominated by dense Alaskan blueberry (*Vaccinium alaskaense* Howell), an ericaceous shrub.

Of interest is the side by side occurrence, on the same parent material, of ancient old-growth cedar–hemlock forests characterized by salal, deep mor humus, low N mineralization rates, and adjacent windthrow origin Pacific silver fir and hemlock stands with thin humus layers and high N mineralization rates. This occurrence has led to the hypothesis that windthrow, which results in mixing of organic and mineral soil, is an essential requirement for revitalizing ecosystem productivity and avoiding the immobilization of N in deep mor humus soils. Managers are currently trying backhoes to mix humus and mineral soil on planting spots on CH cutovers. In this way, it is hoped that chlorosis and fertilizer requirement noted in this study might be avoided.

It does appear that N and P fertilizer applications are required to establish successful Sitka spruce plantations following clear-cutting of old-growth western red cedar and western hemlock forests growing on CH site deep humus soils in the wetter portions on the Coastal Western Hemlock biogeoclimatic zone. For diagnostic purposes, the foliar analysis values for Sitka spruce published by Binns *et al.* (1980) seem applicable and 1-year microplot screening trials using vector foliar analysis appear to accurately diagnose nutritional status and predict responses.

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