Variance in response of pole-size trees and seedlings of Douglas-fir and western hemlock to nitrogen and phosphorus fertilizers

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Three experiments were conducted to determine effects of N and P fertilizers on growth and levels of plant-tissue nutrients of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Both pole-size trees in closed-canopy stands and potted seedlings were used. Soil series were Bunker for Douglas-fir and Klone for western hemlock in experiments 1 and 3, and Vesta in experiment 2. For each species in experiments 1 and 2, P and N fertilizers were tested in six or eight treatments using factorial design. In experiment 3, N and P fertilizers were individually tested on seedlings, at one rate of application each. Nitrogen fertilizers used were urea in experiment 1 and ammonium nitrate in the other two experiments; P was applied as triple superphosphate in all three experiments. In general, fertilization changed levels of some plant-tissue nutrients of the pole-size trees and potted seedlings. Neither height nor basal-area growth of the trees was significantly affected by any of the fertilization treatments in the first two experiments. Seedling growth of both Douglas-fir and western hemlock was dramatically improved by the P fertilizer, but was negatively affected by the N fertilizer. Results clearly show differences between pole-size trees and seedlings in response to N and P fertilizers. They also suggest that N not be applied where soils are high in N and low in P and that P applications be confined to sites with low-P soils, when trees are young, before canopy closure.

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Trois expériences ont été conduites afin de déterminer les effets des fertilisants N et P sur la croissance et les niveaux des nutriments dans les tissus du sapin de Douglas (*Pseudotsuga menziesii* (Mirb.) Franco) et de la pruche de l'Ouest (*Tsuga heterophylla* (Raf.) Sarg.). Des gaulis croissant en peuplements fermés et des semis cultivés en pot ont été utilisés. Pour les expériences 1 et 3 avec le sapin de Douglas et la pruche de l'Ouest, les séries de sol étaient Bunker et Klone respectivement, et pour l'expérience 2, la série était Vesta. Pour chacune des espèces dans les expériences 1 et 2, les fertilisants N et P ont été évalués dans six ou huit traitements avec un dispositif expérimental de type factoriel. Dans l'expérience 3, les fertilisants N et P ont été individuellement évalués sur des semis, à un seul niveau d'application chacun. L'urée a été utilisé dans l'expérience 1 et le nitrate d'ammonium dans les deux autres expériences; P a été appliqué sous forme de superphosphate triple dans les trois expériences. En général, la fertilisation a changé les niveaux de certains nutriments des tissus des gaulis et des semis cultivés en pot. Ni la croissance en hauteur, ni la croissance en surface terrière n'a été significativement affectée par aucun des traitements de fertilisation dans les deux premières expériences. La croissance des semis de sapin de Douglas et de pruche de l'Ouest a été considérablement augmentée par l'ajout de P mais négativement affectée par l'ajout de N. Les résultats indiquent clairement des différences entre les gaulis et les semis en réponse à l'ajout de N et de P. Ces résultats suggèrent de ne pas appliquer le N là où les sols ont une teneur élevée en N et faible en P et que les applications de P doivent être confinées aux stations avec les sols pauvres en P, et aux jeunes arbres avant la fermeture du couvert.

[Traduit par la rédaction]

Introduction

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) are major coniferous tree species in the forests of western Oregon, Washington, and coastal British Columbia. To increase timber production, N fertilizer, usually as urea, has been applied to young and middle-aged stands of Douglas-fir and, occasionally, to stands of western hemlock. However, growth response to N fertilizer has not been consistent. For example, although Douglas-fir responds well to N fertilization, about 30% of the unthinned stands do not respond positively to such treatment (University of Washington 1975). Also, response of western hemlock to application of N fertilizer has been extremely variable, and success has been generally less in coastal hemlock than in stands on the west slopes of the Cascade Mountains (Webster et al. 1976).

Various reasons have been proposed to explain the variability in growth response of Douglas-fir and western hemlock to N fertilizers. Factors believed to influence response of Douglas-fir include level of soil mineralizable

TABLE 1. Details of Douglas-fir and western hemlock sites

	Experiment 1		Experiment 2: western hemlock
	Douglas-fir	Western hemlock	
Location in western Washington	Central coast	Northwest coast	Southwest coast
Elevation (m)	460	90	90
Annual precipitation (cm)	200	270	250
Tree dbh (cm)	29.7	19.8	26.4
Tree height (m)	20.1	15.2	21.0
Tree age (years)	25	25	34
Site index (m)	36	32	34
Soil parent material	Basalt	Glacial	Basalt
Soil series	Bunker	Klone	Vesta
Soil texture	Silt loam	Gravelly loam	Silt loam
Soil drainage	Well drained	Well drained	Well drained

NOTE: Tree dbh, height, and age were determined before fertilization. Age is total tree age estimated from measured breast-high age. Site index is based on height at 50 years.

or total N (Shumway and Atkinson 1978; Radwan and Shumway 1984), forest floor C/N ratio and N content of the forest floor (Peterson et al. 1984), site index (Radwan and Shumway 1984), and stand density (Strand and DeBell 1981; Miller et al. 1989). Reasons postulated for general lack of success with N fertilizer in hemlock include high native soil N or low supplies of P (Radwan and DeBell 1980; Radwan and Shumway 1983*a*), damage of surface roots and mycorrhizae by urea N (Gill and Lavender 1983), and potentially harmful high levels of fertilizer ammonium N (Radwan and DeBell 1989).

In addition to, and perhaps more important than, the suggested response factors just listed, is the actual growth response of both Douglas-fir and western hemlock to application of P fertilizers, with and without N. For example, studies with potted seedlings showed excellent P response of both Douglas-fir (Strand 1964; Heilman and Ekuan 1980*a*; Radwan and Shumway 1985) and western hemlock (Heilman and Ekuan 1980*b*; Anderson et al. 1982; Radwan and Shumway 1983*b*). Similarly, substantial increase in growth was obtained in field tests with P or N + P applied to seedlings and young trees of both Douglas-fir (Austin and Strand 1960; Porada and Zasoski 1986) and western hemlock (Zasoski and Gessel 1982; Weetman et al. 1989). There are no reports, however, of successful use of P or N + P fertilizers on Douglas-fir or western hemlock pole-size trees in closed-canopy stands.

This study is a follow-up to our previous laboratory and greenhouse investigations. It was conducted to study the comparative effects of N, P, and N + P fertilizers on plant-tissue nutrients and growth of potted seedlings and pole-size trees of Douglas-fir and western hemlock.

Materials and methods

The study consisted of three experiments: (*i*) a main experiment with pole-size trees at two locations, one for Douglas-fir and another for western hemlock; (*ii*) a satellite test with pole-size western hemlock trees at a location different from that in the first experiment; and (*iii*) another satellite test with potted Douglas-fir and western hemlock seedlings grown in a lathhouse.

Experiment 1

The sites

The Douglas-fir site is located on Washington Department of Natural Resources Capitol Forest, 15 km west of Olympia, Washington. The site was planted in 1957, and the stand was precommercially thinned to 600–800 stems/ha in 1970.

The western hemlock site is located about 16 km north of Kalaloch in northwestern Washington. The site was occupied with a 25-year-old natural stand. The stand was precommercially thinned to about 1800 stems/ha in 1975.

Canopies were closed at both sites, and understory vegetation was negligible. Other pertinent information about the sites is given in Table 1.

Plot installation and sample-tree selection

At each site, 24 plots, arranged in three blocks of eight treatments each, were installed in winter 1982. Blocking was based on basal area, and blocks were reasonably uniform in stocking, site index, topography, and soil conditions. Treatment plots were about 0.04 ha, and plot edges were separated by buffers at least 10 m wide. Measurement plots, about 0.02 ha, were established within the treatment plots. In each of these plots, eight well-formed and healthy dominant and codominant trees were selected. All eight trees were used for height and diameter measurements, and at least six of these trees, chosen at random, were used to collect foliage for chemical analysis.

Sampling and chemical analysis of forest floor and mineral soil

To characterize the soils of each site, representative samples of the forest floor and mineral soil were collected. Each sample consisted of material obtained from two randomly selected spots within each plot. Forest floor was obtained using templates and cutting knives, and the underlying soil was sampled to a depth of about 15 cm. Samples of forest floor and mineral soil were composited separately for each site.

Representative subsamples were air dried and thoroughly mixed after roots and rocks were removed. Subsamples of mineral soil were passed through a 2-mm sieve, and sieved material was used for analysis. Soil subsamples used to determine N and all forest floor samples were ground to a fine powder before analysis.

Soils and forest floor were characterized by determining pH on 1:1 mixtures with water by glass electrode, total N by the Kjeldahl method (Bremner and Mulvaney 1982), total S by the turbidimetric method (Butters and Chenery 1959), and Bray 2 extractable P according to Bray and Kurtz (1945). Mineral soil was also analyzed for cation exchange capacity by NH_4OAc extraction (Chapman and Pratt 1961), and for exchangeable K, Ca, and Mg (NH_4OAc extraction) by atomic absorption (Perkin-Elmer Corporation 1976). Additional analyses of forest floor included P by the molybdenum blue technique (Chapman and Pratt 1961) and K, Ca, and Mg by atomic absorption (Perkin-Elmer Corporation 1976).

TABLE 2. Selected characteristics of study soils

	Bunker		Klone	
	Mineral soil	Forest floor	Mineral soil	Forest floor
pH	4.70	4.65	4.45	4.15
Cation exchange capacity (mequiv./100 g)	44.75	—	40.40	—
Exchangeable (NH_4OAc) K (mequiv./100 g)	0.38	—	0.25	—
Exchangeable (NH_4OAc) Ca (mequiv./100 g)	1.73	—	0.40	—
Exchangeable (NH_4OAc) Mg (mequiv./100 g)	0.59	—	0.46	—
Kjeldahl N (%)	0.46	0.94	0.41	0.71
S (%)	0.06	0.10	0.05	0.08
P (%)	—	0.07	—	0.08
Bray 2 extractable P (ppm)	6.50	30.15	5.15	36.90
K (%)	—	0.16	—	0.16
Ca (%)	—	0.40	—	0.28
Mg (%)	—	0.10	—	0.08

NOTE: Bunker and Klone soils were collected beneath Douglas-fir and western hemlock stands, respectively. Percents of K, Ca, and Mg in the forest floor are total concentrations.

Fertilization treatments

For both species, P and N fertilizers were tested in eight treatments, using a 4 × 2 factorial design. Phosphorus was applied as triple superphosphate (20% P) at rates of 0, 100, 300, and 500 kg P/ha. Nitrogen was applied as urea (46% N) at dosages of 0 and 224 kg N/ha. All fertilizers were commercial agricultural grade. Treatments were assigned at random to the eight plots within each block. Fertilizers were uniformly applied to the treatment plots by hand in March 1982.

Sampling and chemical analysis of foliage

Current year's foliage was collected during October 1982 and December 1983 at the end of the first and second growing seasons after fertilization, respectively. Collections were made from at least six of the eight measurement trees, and the same trees were used in both sampling years. Samples were obtained by climbing the trees and cutting one vigorous branch from the upper third of the crown. Tips of secondary laterals, approximately 5 cm long, were cut from the branches at random, and tips were composited by plot. Samples were collected in precooled jars and transported to the laboratory in portable coolers. In the laboratory, needles were separated from stems and buds. Needles were dried to constant weight in a forced-air oven at 65°C. The ovendried tissue was ground to 40 mesh and stored in sealed containers at −15°C until analyzed.

Foliar analyses were carried out as follows: total N by the micro-Kjeldahl procedure (Bremner and Mulvaney 1982), P by the molybdenum blue technique (Chapman and Pratt 1961), S by the turbidimetric method of Butters and Chenery (1959), and K, Ca, Mg, Mn, Fe, Cu, and Zn by atomic absorpton (Perkin-Elmer Corporation 1976).

Growth measurements

Height and diameter at breast height (dbh) were measured before fertilization and at the end of the study (i.e., 5 years for Douglas-fir and 4 years for hemlock). Height and basal-area growth and percent growth response over the unfertilized controls were calculated. All computations were based upon averages of the eight measurement trees in each plot.

Statistical analysis

For each species, data resulting from chemical analysis of foliage were subjected to analysis of variance, and means of each sampling were separated by Tukey's test (Snedecor 1961). For the growth data, increment means were adjusted by covariance analysis for differences in initial height. Differences were considered significant at $p < 0.05$ for the foliar-nutrient data and $p < 0.10$ for the growth data. The latter probability value was chosen because inherent variation within the stands was high, number of replications was small, and we wanted to decrease the chances of making a type II error (i.e., concluding that fertilizers had no effect on growth when in effect they did).

Experiment 2

This was a satellite field test on a site located in the southwestern coastal hemlock zone, near Raymond, Washington. The site was occupied by a natural 34-year-old stand of western hemlock. The stand was precommercially thinned to about 800 stems/ha in 1975. The canopy was closed, and understory vegetation was negligible. Soil is of the Vesta series. Other pertinent information is in Table 1.

Fertilization treatments and experimental design were the same as those of experiment 1, except that we used ammonium nitriate (34% N) at 112 kg N/ha instead of urea at 224 kg N/ha and eliminated the highest P treatment (500 kg P/ha). We thought that the N treatment of this experiment would be less likely to damage hemlock's surface roots than the N treatment used in experiment 1.

Fertilizers were applied in March 1985. Growth and growth response to fertilizer were assessed as in experiment 1, and annual measurements after fertilization continued for 3 years. Foliage was not analyzed, and soil analysis was not as extensive as in experiment 1.

Experiment 3

This was another satellite test to assess effects of P and N fertilizers on growth of Douglas-fir and western hemlock seedlings in soils collected from the two sites of experiment 1 (i.e., Bunker soil for Douglas-fir and Klone soil for western hemlock). The test was designed to compare pot and field results using the same tree species, soils, and kinds of fertilizers.

Test seedlings were 9 months old, individually potted in 7.6-L plastic pots containing the different soils. Mineral soil in each pot was covered with about 70 g of the appropriate forest floor to simulate field conditions. Three groups of three seedlings each (nine individually potted seedlings divided into three replications) were used for each soil-fertilizer treatment of each species. Seedlings were placed, in groups of three, at random in a roofed lathhouse.

TABLE 3. Foliar nutrient concentrations (%) of Douglas-fir and western hemlock trees at the end of the first growing season after fertilization

Species and treatment	N	P	K	Ca	Mg	S
Douglas-fir						
Control	1.30*a*	0.12*bc*	0.71*a*	0.30*ab*	0.11*a*	0.11*a*
N	1.28*a*	0.11*c*	0.72*a*	0.32*ab*	0.11*a*	0.11*a*
P_1	1.24*a*	0.14*abc*	0.72*a*	0.24*b*	0.11*a*	0.11*a*
P_2	1.31*a*	0.15*ab*	0.78*a*	0.42*a*	0.12*a*	0.10*a*
P_3	1.25*a*	0.17*a*	0.78*a*	0.36*ab*	0.12*a*	0.11*a*
$N+P_1$	1.38*a*	0.13*bc*	0.79*a*	0.28*ab*	0.12*a*	0.11*a*
$N+P_2$	1.36*a*	0.13*bc*	0.71*a*	0.28*ab*	0.12*a*	0.10*a*
$N+P_3$	1.38*a*	0.13*bc*	0.69*a*	0.31*ab*	0.12*a*	0.11*a*
Western hemlock						
Control	1.13*c*	0.13*c*	0.71*a*	0.23*ab*	0.14*a*	0.09*a*
N	1.48*a*	0.13*c*	0.64*a*	0.19*b*	0.11*ab*	0.08*a*
P_1	1.16*bc*	0.17*abc*	0.60*a*	0.27*a*	0.14*a*	0.09*a*
P_2	1.11*c*	0.16*abc*	0.55*a*	0.23*ab*	0.13*ab*	0.08*a*
P_3	1.18*bc*	0.20*a*	0.62*a*	0.24*ab*	0.12*ab*	0.09*a*
$N+P_1$	1.35*ab*	0.15*bc*	0.56*a*	0.18*b*	0.11*ab*	0.08*a*
$N+P_2$	1.50*a*	0.17*abc*	0.59*a*	0.19*b*	0.10*b*	0.09*a*
$N+P_3$	1.41*a*	0.17*abc*	0.55*a*	0.19*b*	0.12*ab*	0.08*a*

NOTE: Control, untreated; N, urea at 224 kg N/ha; P_1, P_2, and P_3, triple superphosphate at 100, 300, and 500 kg P/ha, respectively. Within species, values in the same column followed by the same letter are not significantly different at $p < 0.05$.

Fertilization treatments were as follows: (*i*) unfertilized control; (*ii*) ammonium nitrate (34% N) at 100 kg N/ha; and (*iii*) triple superphosphate (20% P) at 226 kg P/ha. As in experiment 2, ammonium nitrate was used instead of urea to avoid the appreciable rise in pH associated with urea use. A 100 kg N/ha rate was selected over the 224 kg N/ha rate used in the field because the lower rate is more suited to the limited amount of soil in the pots. Also, a mixed application of N + P was not included in the test because our unpublished results show no advantage of N + P over P when soils are high in N and low in P, as with the test soils used here.

Fertilization treatments were assigned to seedlings of each species at random. In spring 1985, fertilizers were placed around the potted seedlings on top of the forest floor without mixing to simulate field fertilization. Seedlings were watered immediately after fertilization. Seedlings were grown under natural temperature and light conditions in the lathhouse for 2 years.

Height and diameter of the seedlings were measured prior to and at the end of the experiment. At harvest, roots were washed free of soil, and seedling shoots and roots were dried to constant weight at 65°C. Height and diameter growth, dry weight of seedlings, and percent response to treatment were calculated. Seedling shoots were ground and analyzed for N, P, K, Ca, and Mg as with foliage of experiment 1. Also, growth and shoot-nutrients data were statistically treated by analysis of variance and Tukey's test (Snedecor 1961). Differences were considered significant at $p < 0.05$.

Results and discussion

Experiment 1

Site, stand, and soil properties

The two sites used in this experiment, separated by nearly 200 km, are located in western Washington. Basic properties of the sites and the tree stands are shown in Table 1. Both stands, 25 years old, were within the age considered economically suitable for fertilization by most forest managers.

The mineral soil and forest floor differed by site in many of their characteristics (Table 2). Parent material was basalt and glacial for the Bunker and Klone soils, respectively. The Bunker soil was especially higher in exchangeable Ca, Mg, and K than the Klone soil. There were only small differences between the two soils in pH, N, S, and extractable P. Extractable P of both soils was particularly low, as is often found in coastal Washington. The stands, with such low-P mineral soils, were especially selected to test for growth response to application of P fertilizer.

The forest floor of the Bunker soil was higher in N and Ca than the forest floor of the Klone soil. At both sites, extractable P was much higher in the forest floor than in the mineral soil.

Foliar nutrients

Concentrations of the macronutrients N, P, K, Ca, Mg, and S in foliage of the Douglas-fir and hemlock trees at the end of the first growing season after fertilization are presented in Table 3. Results for the same elements at the end of the second growing season and for micronutrients Mn, Fe, Cu, and Zn are not tabulated to save space, but are discussed briefly in the text below.

For both species and sampling years (1982 and 1983), concentrations of all macronutrients were within the ranges reported in the literature (Beaton et al. 1965; Lavender and Carmichael 1966; Radwan and DeBell 1980, 1989).

(i) Douglas-fir

Without fertilization, foliar N concentration (1.30%) was not particularly low, indicating that the trees might not respond positively to N application. Addition of N fertilizer alone or in combination with P did not significantly increase N concentration in the foliage of the fertilized trees. This was unexpected; N application usually increases foliar N, even by luxury consumption, during the 1st year after fertilization. There are instances in the literature, however, where uptake of fertilizer N was not detected in foliage of Douglas-fir (Heilman 1971) and other conifers (Powers and Jackson 1978). The exact reason for such a phenomenon is not known, although it could be related to dilution by increase of foliage mass or fixation of N by soil microorganisms.

Application of P fertilizer increased P levels in the foliage, and the increase was statistically significant at the highest rate of application. Still, even the highest foliar P concentration obtained (0.17%) was not proportionate to the large amount of P fertilizer applied (500 kg P/ha). This was probably caused by high capacity of the soil to fix P.

Fertilization with N, P, or N + P did not affect foliar concentrations of K, Mg, or S. Treatment caused only one significant difference in foliar Ca concentrations; the reason for that difference is not known.

(ii) Western hemlock

Unlike Douglas-fir, application of N and N + P to hemlock increased foliar N of the fertilized trees. Similarly, the P fertilizer alone and N + P enhanced foliar P. Some of the applied N and P, therefore, was taken up by the trees. As with Douglas-fir, however, the increases in foliar P were not proportionate to the large amounts of P fertilizer applied and, except for the highest application of P alone, were not statistically significant.

The fertilizers did not influence foliar levels of K or S, but the N fertilizer tended to depress Ca and Mg.

For both Douglas-fir and western hemlock, concentration of foliar nutrients did not change much the 2nd year after fertilization. In general, N concentrations were mostly lower, especially with hemlock, and other macronutrients showed little change and no definite trends compared with results of the 1st year after fertilization.

Within species, results of analyses of the micronutrients (Mn, Fe, Cu, and Zn) showed some differences in foliar concentrations among fertilization treatments and between harvests. Concentration ranges (ppm) were as follows: Mn = 450–760, Fe = 23–43, Cu = 3–6, and Zn = 16–27 for Douglas-fir; Mn = 450–720, Fe = 27–35, Cu = 2–5, and Zn = 12–22 for western hemlock. All values were within levels reported in the literature, and the data do not seem useful to understanding nutrition of either species or their response to fertilization. Similar findings with western hemlock were reported previously (Radwan et al. 1984; Radwan and DeBell 1989).

Tree growth

Trends of height and basal-area results were similar, but the height data showed more variability. To save space, therefore, the following discussion is limited to basal area.

Basal-area growth of unfertilized trees averaged 0.019 and 0.010 m^2/tree for Douglas-fir and western hemlock, respectively (Table 4). These growth rates were expected on such productive sites.

Responses to fertilizer addition ranged from −7.0 to 9.2% for Douglas-fir and from −10.6 to 6.7% for hemlock; over all treatments, average responses were 2.3 and 0.7% for Douglas-fir and western hemlock, respectively. None of the fertilizers produced a significant ($p > 0.10$) increase in basal-area growth over the controls with either species. The stands, therefore, did not respond positively to additions of N, P, or N + P fertilizers after 5 years with Douglas-fir and 4 years with hemlock.

Lack of growth response to N fertilizer is understandable because soils of both sites had relatively high N concentrations (Table 2). Under such conditions, positive growth response to N fertilizer is not likely. For both Douglas-fir and western hemlock, level of total N in mineral soil was found to be negatively correlated with growth response to N fertilizer (Radwan and Shumway 1984).

TABLE 4. Basal-area growth response of Douglas-fir and western hemlock pole-size trees to application of different fertilizers

	Douglas-fir		Western hemlock	
Treatment	Increment per tree ($m^2 \times 10^{-2}$)	Response (%)	Increment per tree ($m^2 \times 10^{-2}$)	Response (%)
Control	1.85*a*	—	1.04*a*	—
N	1.86*a*	0.5	1.03*a*	−1.0
P_1	1.81*a*	−2.2	1.09*a*	4.8
P_2	2.02*a*	9.2	0.93*a*	−10.6
P_3	1.95*a*	5.4	1.06*a*	1.9
$N+P_1$	1.72*a*	−7.0	1.07*a*	2.9
$N+P_2$	1.98*a*	7.0	1.11*a*	6.7
$N+P_3$	1.91*a*	3.2	1.04*a*	0.0

NOTE: Control, untreated; N, urea at 224 kg N/ha; P_1, P_2, and P_3, triple superphosphate at 100, 300, and 500 kg P/ha, respectively. Increment means were adjusted by covariance analysis for differences in initial height. Douglas-fir and hemlock data are for 5 and 4 years after fertilization, respectively. Response is calculated as percent of the different fertilization treatments over the unfertilized control. For each species, values in the same column followed by the same letter are not significantly different at $p < 0.10$.

The situation with P fertilizer was quite different from that with N fertilizer. We were expecting, but did not obtain, a positive response by the trees to additions of P, with or without N. Our expectation was based upon the fact that at both sites, extractable P was very low in mineral soil and low in the forest floor (Table 2). Also, our previous studies and research by others had shown very good response to P by Douglas-fir and western hemlock seedlings potted or outplanted in low-P soil (e.g., Heilman and Ekuan 1980*a* and 1980*b*; Radwan and Shumway 1983*b*, 1985; Porada and Zasoski 1986). Clearly, response to P fertilization by Douglas-fir and western hemlock (and probably other conifers) is a complex phenomenon. The minimum level of extractable P in mineral soil and (or) forest floor required before response to added P occurs is still not known. Extractable P may be judged "low," but mycorrhizal associations may be able to make enough organic P available to the trees for normal growth and development, especially if the P requirement is low. On the other hand, pole-size trees in closed stands should not be expected to respond to P (or other nutrients) like potted seedlings or young trees in open stands. Requirement for P by the seedlings and pole-size trees may be different; moreover, as the trees become older and gradually accumulate P, internal and external nutrient cycling may be sufficient to satisfy their annual P requirements.

The lack of response of our Douglas-fir trees to P and N + P is in agreement with results of a previous study in southwestern Washington in which 20-year-old trees were repeatedly fertilized with P and N + P over a 15-year period (Steinbrenner 1981). There is no literature on response of pole-size western hemlock trees in closed stands to P or N + P fertilizers.

Experiment 2

The Vesta soil at this site is derived from basalt. Limited chemical characterization revealed the following properties for the mineral soil and forest floor, respectively: pH = 4.5

TABLE 5. Effect of nitrogen and phosphorus fertilizers on growth and growth response of Douglas-fir and western hemlock seedlings

Species and treatment	Soil	Height growth: Increment (cm)	Height growth: Response (%)	Seedling dry weight: Quantity (g)	Seedling dry weight: Response (%)
Douglas-fir	Bunker				
Control		25.9*a*	—	28.3*b*	—
N		17.3*b*	−33.2	16.5*c*	−41.7
P		31.5*a*	21.6	44.4*a*	56.9
Western hemlock	Klone				
Control		35.4*a*	—	39.1*b*	—
N		12.7*b*	−64.1	7.0*c*	−82.1
P		38.1*a*	7.6	55.3*a*	41.4

NOTE: Control, untreated; N, ammonium nitrate at 100 kg N/ha; P, triple superphosphate at 226 kg P/ha. Individual treatments consist of three replications of three seedlings each. Response is calculated as percent of the different fertilization treatments over the unfertilized control. For each species, values in the same column followed by the same letter are not significantly different at $p < 0.05$.

and 4.1; N = 0.57 and 0.88%; Bray 2 extractable P = 4.0 and 18.0 ppm. Thus, both the soil and forest floor of this site were higher in N and lower in P than the soil and forest floor at the hemlock site of experiment 1.

Basal-area growth per year of the unfertilized control trees averaged 0.0022 m^2/tree during the 3-year experiment. This rate of growth is similar to that obtained at the hemlock site of experiment 1 (0.0026 $m^2 \cdot tree^{-1} \cdot year^{-1}$).

Basal-area growth per year of the fertilized trees ranged from 0.0020 to 0.0025 m^2/tree; height-growth data were much more variable. As in experiment 1, fertilization with N, P, or N + P did not significantly ($p > 0.10$) affect height or basal-area growth. Clearly, using ammonium nitrate instead of the urea fertilizer used in experiment 1 did not affect the results. Also, as in experiment 1, there was no response to the P fertilizer, with or without N, even though values of Bray 2 extractable P for mineral soil and forest floor were lower at this site than at the site of experiment 1.

Experiment 3

Seedling growth

Without fertilization, seedlings of both Douglas-fir and western hemlock grew reasonably well (Table 5), and harvested seedlings were free of disease and insect damage. The P fertilizer did not significantly ($p > 0.05$) affect height growth of either Douglas-fir or hemlock. Height growth of both species, however, was negatively affected by the N fertilizer. Average height-growth response to ammonium nitrate was −33.2% for Douglas-fir and −64.1% for western hemlock. Also, seedling dry weights were even more depressed by the N fertilizer than seedling heights. Average weight responses were −41.7 and −82.1% for Douglas-fir and western hemlock, respectively. Negative response to N fertilizer has been observed before with potted seedlings of Douglas-fir (Radwan and Shumway 1985) and western hemlock (Radwan and Shumway 1983*b*), when the soil is low in extractable P. Also, severe depression of growth has been previously observed after N fertilization of Douglas-fir on sites with low-P soils in coastal Washington. As with seedlings, these growth depressions may be attributed to stimulation of soil organisms by the applied N and the resultant reduction in available P by immobilization.

Unlike height growth, seedling dry weight was dramatically increased by application of P fertilizer to the Douglas-fir and western hemlock seedlings. Average weight responses to P were 56.9 and 41.4% with Douglas-fir and western hemlock, respectively. These responses agree with previous results with seedlings grown in pots (e.g., Heilman and Ekuan 1980*a*; Anderson et al. 1982; Radwan and Shumway 1985) and in the field (Zasoski and Gessel 1982; Porada and Zasoski 1986).

Clearly, significant response to the P fertilizer occurred only with potted seedlings and not with pole-size trees in closed stands. This discrepancy may be the result of differences between seedlings and trees in age and growth environment. For example, mycorrhizae probably have greater influence on P absorption by older trees under field conditions than by seedlings in pots. Similarly, root systems of older trees occupy the soil space more fully than do seedlings; they thus have greater ability to extract native P. Also, external and internal P cycling have much greater influence on tree P status in older trees under field conditions than in young, potted seedlings.

Shoot nutrients

Concentrations of the macronutrients in the shoots of the unfertilized seedlings of Douglas-fir and western hemlock (Table 6) were generally within the range of values in the literature (Radwan and Shumway 1985; Radwan et al. 1990). Fertilization affected concentrations of some nutrients in seedling shoots. With both species, the N fertilizer increased concentrations of N and K, and the P treatment apparently increased percent P, although some of the apparent increases were not significant. Those increases reflect uptake of fertilizer N and P by the seedlings.

Fertilization affected content of all shoot nutrients in both species. The P fertilizer increased weights of all nutrients. These gains most probably resulted from parallel increases in dry-matter production (Table 5) and nutrient uptake and utilization. Fertilization with N, however, reduced amounts of all nutrients in shoots of both species. These reductions must have resulted mostly from reductions of seedling growth in biomass by the N fertilizer (Table 5).

Conclusions and recommendations

In this study, N fertilizers did not improve growth of pole-size trees in closed-canopy stands and negatively affected growth of potted seedlings of both Douglas-fir and western hemlock. Phosphorus fertilizer, with or without N fertilizer,

TABLE 6. Effect of nitrogen and phosphorus fertilizers on nutrients in ovendried shoots of Douglas-fir and western hemlock seedlings

Species and treatment	P	N	K	Ca	Mg
	Concentration*				
Douglas-fir					
Control	464*b*	1.52*a*	0.33*a*	0.22*a*	0.08*a*
N	472*b*	2.02*b*	0.44*a*	0.24*b*	0.11*b*
P	651*a*	1.11*c*	0.36*a*	0.26*c*	0.10*c*
Western hemlock					
Control	573*a*	1.27*b*	0.43*b*	0.19*a*	0.09*a*
N	658*a*	2.16*a*	1.08*a*	0.24*b*	0.10*b*
P	671*a*	1.04*b*	0.33*b*	0.22*c*	0.12*c*
	Content (mg/seedling)				
Douglas-fir					
Control	2.8*b*	91.0*ab*	19.5*b*	13.0*a*	4.7*b*
N	1.5*b*	65.7*b*	13.2*b*	7.9*b*	3.4*b*
P	5.9*a*	101.5*a*	32.9*a*	24.1*c*	9.1*a*
Western hemlock					
Control	4.7*a*	105.4*a*	35.3*a*	15.8*a*	7.7*a*
N	0.9*b*	29.5*b*	14.9*b*	3.3*b*	1.4*b*
P	7.4*c*	111.9*a*	35.9*a*	24.3*c*	12.9*c*

NOTE: Control, untreated; N, ammonium nitrate at 100 kg N/ha; P, triple superphosphate at 226 kg P/ha. Values are averages of three replications each. For each species, within the concentration and content sections, values in the same column followed by the same letter are not significantly different at $p < 0.05$.

*Concentrations are given in percents, except for those of P, which are given in parts per million.

was also ineffective with both species in closed-canopy stands, but significantly improved growth of potted trees. These results are in agreement with some published and unpublished results by others.

Our findings, therefore, indicate that fertilization with P or N + P is unlikely to improve growth of Douglas-fir and western hemlock stands that do not respond to N fertilizer. Also, the results, together with work by others, offer two suggestions. First, sites high in soil N and low in available soil P should not be fertilized with N. Application of N fertilizers to such sites would most likely be ineffective or could result in negative growth response. Second, application of P fertilizer should be confined to sites with low-P soils when trees are young, before canopy closure. Application of P fertilizer to such stands would probably accelerate canopy closure and nutrient cycling.

Our work and recent literature point out the necessity for increased research on the fundamental aspects of tree nutrition and nutrient cycling in managed forests. Work is particularly needed on nutrient requirements of species at different stages of tree and stand development, the ability of trees to acquire nutrients, and the nutrient-supplying capacity of the soil and forest floor.

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