Review of Western Hemlock Growth Response to Forest Fertilization and Proposals for New Studies

ISSN 0835 0752

JANUARY 1993
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by

Holger Brix

4566 Markham Street
Victoria, B.C.
V6Z 5N3

January 1993
Funding for this publication was provided by the Canada-British Columbia Partnership Agreement on Forest Resource Development: FRDA II – a four year (1991-95) $200 million program cost-shared equally by the federal and provincial governments.

Canadian Cataloguing in Publication Data

Brix, H.
Review of western hemlock growth response to forest fertilization and proposals for new studies

(FRDA report. ISSN 0835-0752 : 201)

"Canada-British Columbia Partnership Agreement on Forest Resource Development: FRDA II, "
Co-published by B.C. Ministry of Forests.
Includes bibliographical references: p.


SD397.W45B74 1993 634.9'753'09795 C93-092087-2

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This is a joint publication of Forestry Canada and the British Columbia Ministry of Forests.

For additional copies and/or further information about the Canada-British Columbia Partnership Agreement on Forest Resource Development: FRDA II, contact:

Forestry Canada
Pacific Forestry Centre
506 West Burnside Road
Victoria, B.C. V8Z 1M5
(604) 363-0600

or

B.C. Ministry of Forests
Research Branch
31 Bastion Square
Victoria, B.C. V8W 3E7
(604) 367-6719
ABSTRACT

Western hemlock growth response to nitrogen fertilization is reviewed. Specifically, the effects of nitrogen source, nitrogen rate, other nutrient elements, stand thinning, stand age, and site influence are discussed. Studies of the response mechanism, limited to fertilizer effects on foliar nutrient concentrations and damage to roots and mycorrhizae, are also reviewed. They offer general guidelines, but no site-specific recommendations. A number of new studies are proposed, based on this review. They include examinations of fertilization with different rates and sources of nitrogen and phosphorus, and investigations of fertilization effects on stem growth, foliar nutrient concentrations, rate of photosynthesis, production of foliage, branch extension, biomass allocation, and damage to roots and mycorrhizae. Also proposed is a comparison of the response to fertilization of hemlock and Douglas-fir in mixed stands.
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INTRODUCTION

The growth response of western hemlock (Tsuga heterophylla (Raf.) Sarg.) to nitrogen (N) fertilization has been studied in many locations in British Columbia, Washington, and Oregon. Major project installations were initiated in 1969 by the co-operative Regional Forest Nutrition Research Project (RFNRP) in Oregon and Washington, and in 1971 by the British Columbia Ministry of Forests Experimental Project 703 (EP 703). Installations covered a wide range of site and stand conditions, including different age classes and thinned and unthinned stands (Chappell et al. 1992). Other programs have been undertaken by the USDA Forest Service Pacific Northwest Research Station, the Washington Department of Natural Resources, Forestry Canada, the University of British Columbia, and the forest industry.

Whereas the growth response of coastal Douglas-fir to fertilization has been significant in 75% or more of the RFNRP trials (Miller et al. 1986), the response of western hemlock has been inconsistent and in many cases negative (Chappell et al. 1992).

The 9-year net basal area growth response of hemlock to thinning and N fertilization in the EP 703 trials was reported by Omule and Britton (1991) for 16 installations with 220 plots in pure, naturally regenerated, and immature stands on northern Vancouver Island. The responses of unthinned stands to N fertilization were insignificant, but a 7–28% increase in basal area growth was obtained in thinned stands compared to unfertilized stands.

Given the commercial importance of western hemlock in coastal British Columbia, and the fact that the species has shown some good growth responses to N fertilization, forest managers could benefit from site-specific guidelines for applying this silvicultural tool. To develop such guidelines, however, more research is needed to clarify the inconsistent results obtained so far.

An earlier report reviewed the potential reasons for the inconsistent and poor responses recorded. This report updates that work and identifies areas where new research trials are needed. Mensurational aspects of the research are not reviewed here, as they have not changed since the 1987 review.

The growth response of western hemlock to N fertilization is reviewed in terms of how the treatment is influenced by (1) nitrogen source, (2) nitrogen rate, (3) other nutrient elements, (4) stand thinning, (5) stand age, and (6) site influences. The mechanism of the growth response is evaluated in relation to foliar nutrient status and the toxic effects of fertilization on primary roots. Also presented is an approach for comparing the nutrition of hemlock to that of Douglas-fir. The state of response prediction is discussed and general recommendations for new research are made.

GROWTH RESPONSE RELATIONSHIPS

Nitrogen Source

The source of N fertilizer can affect the availability of N to trees and the rate and duration of N uptake. Sand culture experiments with hemlock seedlings showed that seedling preference for ammonium or nitrate as an N source depended on soil pH (van den Driessche 1976). In other trials, a high concentration of available N and drastic changes in soil pH were found to have harmful effects on the primary roots and mycorrhizae of hemlock, thereby limiting root growth and nutrient uptake (Gill and Lavender 1983a). Such effects could be more important for the shallow-rooted western hemlock than for the deeper-rooted Douglas-fir.

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In a study by Radwan et al. (1984) five different N sources—ammonium nitrate, ammonium sulfate, calcium nitrate, urea, and urea-ammonium sulfate—were applied to hemlock seedlings at a rate of 224 kg N/ha on three different sites. Height and dbh of the trees were measured for 4 years; soil and foliar nutrient analyses were done for 2 years. Fertilization reduced the foliar content of other nutrients, especially phosphorus (P). At the coastal site, only basal area and volume growth were increased with fertilization, and urea resulted in the best response. At the Cascade site, height growth was also increased. The authors concluded that response to N fertilization could not be improved by applying an N source other than urea, but they called for experiments with adding other nutrients.

In another study, different formulations of urea—urea, urea treated with N-Serve, and sulfur-coated urea—were applied at 224 kg N/ha in a thinned 24-year-old stand (Radwan and DeBell 1989). The N-Serve inhibits nitrification and the sulfur-coated urea is a slow-release fertilizer that may prolong the N supply and prevent harmful, high N concentrations and drastic soil pH changes. All sources increased foliar N and decreased concentrations of other macronutrients, but the decrease was less with sulfur-coated urea. The height growth was not affected by any of the urea sources, but the basal area and volume growth responses were best with sulfur-coated urea. This was believed to result from the slow release of N, but the supply of sulfur (S) may also have had some effect. Radwan and DeBell (1989) recommended that more research be done with slow-release N fertilizers without sulfur, and with soluble N sources applied at frequent and low rates.

Miller et al. (1991) compared seedling growth response to foliar spray and prill application for different rates of N supply. This was done in four stands of mixed western hemlock and Douglas-fir. The response was best with prill application, but effects on growth were not distinguished for the two species.

**Nitrogen Rate**

Several studies have included different rates of N fertilization in unthinned and thinned stands. Under the RFNRP trials, in which rates of 224 and 448 kg N/ha were applied, unthinned stands on the Cascade sites showed the same basal area increases over 10 years for the two rates, but on coastal sites the high rate had a negative effect on height growth. In thinned stands there was no significant difference between the effect on growth of the two rates.

Omule and Britton (1991) reported on the 9-year net basal area response to thinning and N fertilization of hemlock in the EP 703 trials. They reported no benefit of urea application in unthinned stands. In thinned stands (20% basal area removed), a response to 225 kg N/ha was obtained, but no additional effect was found with higher rates (450, 675, and 900 kg N/ha).

**Other Nutrient Elements**

Growth response to N fertilization has been shown in several studies to be limited by deficiencies in other elements, particularly phosphorus (Heilman and Ekuan 1980; Radwan and DeBell 1989; Radwan and Shumway 1983; Chappell et al. 1992). Nitrogen fertilization has also induced foliar deficiencies in P and other essential nutrients (Gill and Lavender 1983b; Radwan and DeBell 1989). Using soils from a field trial site, P application alone produced growth response in seedlings, while N reduced growth (Radwan et al. 1991). Pole-sized trees on the site, however, did not respond to P or N, alone or combined. The authors pointed out that seedlings and pole-sized trees in closed stands would likely respond differently to P because of their different requirements for, and storage of, the element. Nevertheless, they expected a stand response to P on the basis of low extractable soil P, but no such response was obtained. Also, foliar N and P were increased from low to adequate levels, which further obscured the lack of response to fertilization.

Hemlock on two coastal sites grew best with lime and P added, but N fertilization had little or no effect, either alone or in combination with P (Anderson et al. 1982). Using seedlings growing in Mopang soil and fertilized with N, P, and S, Zasoski and Gessel (1985) found no effect on height growth of N alone, but a considerable increase in growth with N plus P.
Stegemoeller (1989) reported on the 6-year growth response of thinned hemlock stands on the coast to N, P, and N plus P fertilization. Because of great growth variability, the response to N and P could not be established.

A foliar vector analysis in young regeneration of hemlock, 0.5–1.6 m tall, on northern Vancouver Island indicated a deficiency of N and P (Weetman et al. 1989). This was confirmed by a 3-year height growth response to these elements, and P increased the increment obtained with N fertilization alone.

**Stand Thinning**

If part of the stem growth response to fertilization is caused by an expansion of crowns and an increase in foliar mass, it is to be expected that thinned stands and young stands before crown closure will benefit the most from fertilization.

Both the RFNRP (Peterson 1982; Chappell et al. 1992) and EP 703 (Ormule and Britton 1991) included fertilizer trials in thinned and unthinned stands. In general, the thinned stands exhibit a better fertilizer response—a conclusion also reached by Webster et al. (1976) in summarizing other trials. In unthinned stands, N fertilization has been shown to increase mortality, thus reducing the net gain from fertilization (Miller 1976).

**Stand Age**

In EP 703, Omule and Britton (1991) found that stand age had no effect on fertilizer response. The stand ages ranged from 31 to 65 years at the time of treatments, age classes that may have been too old for a maximum response. The RFNRP trials have generally shown a better response in the 12- to 23-year than in the 24- to 35-year age classes (Peterson 1982). This is to be expected if the response is related to degree of crown closure, as mentioned above.

**Site Influence**

The effect of N fertilization on growth of hemlock has been investigated in coastal British Columbia and in many coastal and inland locations in Oregon and Washington. Several studies have explored the relationship of growth response to site characteristics.

Results from the RFNRP have generally shown a better growth increment as a result of N fertilizer in the Cascade than in the coastal plots (Peterson 1982; Zasoski and Porada 1985). It has been suggested that deficiency of other elements on the coast, particularly P, contributes to the lower response to N in that region (Radwan et al. 1984; Zasoski and Porada 1984). Radwan and Shumway (1983) and Radwan et al. (1984) also found a higher level of native soil N in forest floor and mineral soil on the coast than on the Cascade sites.

Peterson and Zasoski (1987) reported that growth of hemlock in untreated plots in 30 installations was linearly related to several soil variables of forest floor and surface soil (%N, %C, C/N, base saturation). Fertilizer response was also related to these soil properties. The relationship of the N fertilization growth response to soil N, P, and S was investigated on 16 sites in the coastal and Cascade zones in western Washington (Radwan and Shumway 1983). The closest relationship was found with extractable P in the forest floor. In the mineral soil, the ratio of extractable P to mineralized or total N was best related to N fertilization response.

The response of hemlock to N fertilization has not been closely related to site index (Radwan and Shumway 1983; Omule and Britton 1991; Chappell et al. 1992).

Another approach to studying soil influences has been to grow seedlings in soils collected from different sites and to apply different fertilizer treatments to them. However, as mentioned before, seedlings and trees have reacted differently to nutrient amendments when grown on the same soils. In the EP 703 trials, Omule and Britton (1991) found that the best 9-year basal area response was found in ‘the fresh and moist sites’ and the poorest in unthinned stands in moderately dry sites.
At present, site characteristics cannot provide a reliable guide to fertilizer prescriptions.

**MECHANISM OF RESPONSE**

Most studies in hemlock fertilization have concentrated on establishing the empirical relationship between growth response and fertilizer treatment, and on determining the influences of stand and site conditions. Studies of the mechanism by which this response is achieved have been confined mainly to analyses of the effect of these treatments on foliar nutrient concentrations resulting from nutrient uptake and utilization. Studies of seedling response have included those by van den Driessche (1976), Hellman and Ekuan (1980), Anderson et al. (1982), and Zasoski and Gessel (1985); and of tree response, Radwan et al. (1984), Radwan and DeBell (1989), and Radwan et al. (1991). The foliar nutrient analysis has been limited to the first year or two after fertilization, so the long-term effects are not known.

Relationships between foliar nutrient concentrations of hemlock trees and important physiological processes (such as rates of photosynthesis and respiration) and foliage and branch growth have not been investigated. As a result, there is little information for explaining fertilization effects on tree growth. Such information is needed to clarify what now appear to be inconsistent responses in the studies conducted to date.

The growth response to N fertilization may be influenced by site and tree water stress. The possibility of an increase in tree water stress of hemlock as a consequence of an increase in foliar mass by N fertilization has been investigated. This could result in a decrease in growth response but no increase in water stress was detected.

The effect of urea fertilization on primary root mortality and mycorrhizal development was studied by Gill and Lavender (1983a). They found both mycorrhizae mortality and changes in types of mycorrhizae populations following fertilization. These effects could limit nutrient uptake (of P in particular) and therefore growth. Soil conditions also play a part, influencing root distribution and thus the degree of root damage by fertilization. To reduce such detrimental effects, slow-release fertilizers may be the answer, such as sulfur-coated urea and sources that have minimal effects on soil pH.

Fertilizer-induced mycorrhizae mortality may not only affect nutrient absorption, but will also require a carbohydrate supply to reconstitute the root system and thereby reduce tree growth. No published studies have followed up Gill and Lavender (1983a) to evaluate the importance of fertilizer root damage, although one is now in progress on northern Vancouver Island (R. Carter, Fletcher Challenge Canada, Vancouver, B.C., pers. comm.).

**HEMLOCK VERSUS DOUGLAS-FIR GROWTH RESPONSE**

The generally better response of Douglas-fir to N fertilization than hemlock may be caused by differences in (1) habitats occupied by the two species, (2) rooting habit, (3) limitations imposed by other nutrient elements, and (4) N requirement for growth. Different nutrient requirements may result from different growth rates, different productivity per unit of nutrients, and different efficiency in internal nutrient cycling. The first three aspects have received some research attention, as discussed previously, but we know little about differences in nutrient requirements.

One experimental approach is to study growth and nutrition of the two species growing on the same site. For example, van den Driessche (1976) compared the nutrient content and total dry matter of three pairs of 13-year-old hemlock and Douglas-fir trees growing side by side. The mean dry weight of Douglas-fir (9.58 kg) was nearly twice that of hemlock (5.10 kg), and the Douglas-fir had greatly higher branch dry weight than did the hemlock (2.29 vs 0.97 kg). No significant differences in foliar nutrient

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concentrations were detected. The N efficiency in stem production was highest for hemlock, with 44% more stem weight per unit of total tree N content produced by hemlock than by Douglas-fir. Litterfall could not be determined, but was probably small in these young trees, so total nutrient uptake could not be compared. These findings suggest that these differences in growth rate under similar site and tree nutrient conditions were caused by slower early crown development in hemlock than in Douglas-fir, and not by a lower foliar efficiency. On a stand basis, a high stem density during early stand development would therefore be more beneficial to the growth of hemlock than to the growth of Douglas-fir. Only a few trees were sampled and fertilization was not involved, but the experiment shows the kind of information that can be obtained with this approach.

Experiments on how nutrient cycling in hemlock ecosystems affect biomass production are lacking, but would be useful for evaluating nutrient requirements, internal cycling, and nutrient efficiency in growth of hemlock.

RESPONSE PREDICTIONS

Relationships between fertilizer growth response and site characteristics, including site index, have not been well established and site-specific fertilizer recommendations cannot be given. Only very general guidelines for hemlock fertilization can be drawn from past work, and these include applying urea or sulfur-coated urea as a source at a rate of 224 kg N/ha to young stands before crown closure or to young, thinned stands. For best response, P may be required in addition to N.

It appears that the foliar vector analysis (screening trial) has some promise in stand selection (Weetman et al. 1989). This is currently being further explored in 44 trials on the northern Vancouver Island coast on a wide variety of sites (R. Carter, Fletcher Challenge Canada, Vancouver, B.C., pers. comm.). The 1-year foliar response to N, P, S, and a mixture of micronutrients will be followed up with a 3-year growth response analysis.

RESEARCH PROPOSALS

Plans for studies in hemlock fertilization should be developed through consultation with all interested organizations—Forestry Canada, B.C. Ministry of Forests, the forest industry, and the University of British Columbia. Detailed plans and determination of priorities are therefore not provided at this time and proposals are only discussed in general terms.

Screening Trials

The contract proposal included fertilizer screening trials in the EP 703 hemlock installations where growth response is already known, as well as on other sites. The purpose of these trials was to assess the usefulness of this technique for predicting growth response of hemlock to fertilization. Since a similar project is in progress in 44 installations using spaced stands (R. Carter, Fletcher Challenge Canada, Vancouver, B.C., pers. comm.), no further studies of this technique are needed now.

Fertilizer Elements and Sources

Sulfur-coated urea was the best N source in the study by Radwan and Debell (1989) and more trials with this source on different sites should be established. The contribution of S to the growth response was not tested, and trials should include urea, urea plus sulfur, and sulfur-coated urea. The single rate of 224 kg N/ha would suffice in this test.

A deficiency of P has been shown to limit hemlock growth on many sites and also appears to limit growth response to N fertilization. Further studies with N, P, and N plus P should be undertaken. The P source used in most studies has been triple superphosphate. A less soluble phosphate source should be
tried to avoid possible harmful fertilizer effects on roots and to provide a more sustained long-term effect on P availability. Rock phosphate may be a suitable source to test, particularly on acid soils with low P retention.

Mechanisms of Response

The main factors affecting tree and stand productivity are rates of net photosynthesis per unit of foliage (foliage efficiency), quantity and distribution of foliage, and, with regard to stem productivity, the allocation of total production to stems. Each of these factors should be studied in relation to foliar nutrient status as affected by fertilization. The short-term growth response to fertilization will likely depend on how foliar efficiency is affected during the period of elevated nutrient status. The long-term effect, however, particularly in thinned stands, will likely depend on how production of foliage and branch extension are affected (Brix 1991).

Field trials should be established with N and P applied alone and in combination, at different rates, to establish a wide range of foliar nutrient conditions. The trials should be established on a site where foliar analysis has shown severe nutrient deficiency and good nutrient uptake in a screening trial.

Foliar nutrient concentrations Except for analyses of foliar nutrient concentrations, only a few studies have dealt with the response mechanism. These analyses have been limited to the first or second year after fertilization; long-term effects, therefore, are not known. In connection with other fertilizer trials, the foliar analysis should include the entire foliar response period in order to explain the magnitude and duration of the growth response. Sampling should not only be done in the dormant season, but also in the growing season to evaluate nutrient deficiency during growth, as discussed by Waring and Youngberg (1972).

As resources become available, studies of foliar nutrient status should be extended to include investigations of fertilizer effects on soil nutrient availability, nutrient uptake, and nutrient utilization. This would be the case, for instance, if fertilization showed no effect on foliar nutrient concentrations.

Photosynthesis Initial tree growth response to fertilization is likely to depend on its effect on the rate of photosynthesis (Brix 1991). The relationship between foliar nutrient concentration and rate of photosynthesis should therefore be studied. Branches with different foliar N and P concentrations should be collected from a field trial in which a wide range of N and P fertilizer rates are applied. Rates of photosynthesis should be measured under controlled light and temperature conditions in the laboratory. Studies may be extended to investigate the effects of light intensity and temperature on the relationship of rates of photosynthesis to foliar nutrient concentrations.

Production of foliage and branch extension Fertilizer effects on these properties will be particularly important for a growth response before crown closure. Increased production of foliage could also increase growth in closed stands (Brix 1991). Studies should include different crown positions for a period of 3 or more years using a fertilization trial in which different rates of N and P were applied.

Biomass allocation Part of the fertilizer effect on stem growth may be caused by an increased allocation of the total production to stem wood (Brix 1991). A study should therefore investigate biomass allocation to foliage, branches, stems, and roots. A growth response period of at least 6 years may be needed to detect a fertilizer effect on biomass allocation. Nutrient contents of these tree components should be analyzed if studies of nutrient utilization and nutrient cycling are contemplated.

Roots and mycorrhizae Fertilizer-induced mortality to primary roots and mycorrhizae could significantly reduce growth response to fertilization, as indicated in the study by Gill and Lavender (1983a). Further studies of this aspect are needed. The studies could be incorporated in field trials that use different N and P sources and in a trial with high rates of N and P.
Hemlock versus Douglas-fir response  To assist in explaining possible species differences in growth response to fertilization, pairs of adjacent hemlock and Douglas-fir trees of similar sizes should be studied in young stands. Treatments could include N as urea, N plus a P source, and a control. An analysis should be made of foliar nutrient concentrations, foliar mass, and branch extension, as well as of dbh and height increments over a 6-year response period. The biomass and nutrient contents for various tree components should be determined at the end of this period and for separate pairs at the beginning of the experiment. The biomass and nutrient contents of litterfall during the same period must be known. Any growth response difference between the two species could be analyzed in terms of differences in nutrient uptake and utilization, foliar efficiency, production of foliar mass, and biomass allocation to different tree components.

Selection of Research Sites

Field sites for hemlock fertilization trials could be selected on a contract basis. The initial selection criteria should include:

- uniform site and stand conditions over an area of 10 ha or more for large-scale trials. Smaller areas are also needed.
- young stands 10–15 years old for immediate use, but younger stands should be identified for future use.
- thinned or unthinned stands.
- mainly pure hemlock stands, but mixed stands of hemlock and Douglas-fir will also be needed.
- a variety of nutrient and moisture site conditions.
- easy access, particularly for experiments with an intensive sampling schedule.

Following the initial stand selection, which should include an ecological site classification, screening trials should be established in each stand to identify possible nutrient deficiencies.

Other Suggestions

Additional studies have been suggested by Rob Brockley (B.C. Ministry of Forests, Kalamalka Forestry Centre) who reviewed this report. They address: 1) different P rates and different sources in addition to rock phosphate, such as mono- and di-ammonium phosphate; 2) other slow-release N sources (e.g., Osmocote and Nutricote) in addition to sulfur-coated urea; 3) foliar sulfur manipulation; and 4) also establish studies on sites that have been unresponsive; this may identify important factors controlling fertilizer growth response.
CONCLUSION

Nitrogen fertilization of western hemlock has resulted in some positive growth responses that show promise for the use of this technique as an effective forest management tool. Additional studies are needed, however, to clarify the reasons for the generally unpredictable results. Root injury from N fertilization and a deficiency of other elements, particularly P, may have limited the response in some trials. Studies of P plus N applications, application of slow-release N and P sources, and determination of root injury are therefore needed.

The mechanism of the growth response of hemlock to fertilization is poorly understood and has received little attention. Studies are also needed of the relationship of N and P fertilization to foliar nutrient status, rates of photosynthesis, production of foliage, branch extension, and dry matter partitioning.

Mixed stands of western hemlock and Douglas-fir offer an excellent opportunity for comparing growth responses of the two species to fertilization under the same environmental conditions. Also, processes associated with differences in growth response of the two species to fertilization can be investigated, such as nutrient uptake, nutrient utilization, growth partitioning, foliage production, foliage efficiency, and branch extension.

An inventory of potential research sites should be prepared. A preliminary evaluation of nutrient deficiencies can be done through screening trials.

Consultation with all interested agencies must be made before more detailed plans are developed.
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