Abstract: Western hemlock (Tsuga heterophylla) is one of the most important tree species in coastal management units facing reductions in wood supply. Forest fertilization is a proven method to enhance the productivity of many conifer species. However, operational fertilization of western hemlock is not currently an option as foresters lack the necessary tools to distinguish stands that will respond to fertilization from stands that will not respond. This FII project is part of a research program to determine if the isotopic composition of carbon (δ^{13}C values) within foliage and stemwood can be used by foresters to assess the nutritional status of this species and to predict response to fertilization. A set of eight fertilization trials installed in 1995 on the north end of Vancouver Island and on the Sunshine Coast were utilized. Six year basal area increment, and foliar sulfate concentration of current year foliage collected in the six growing season were assessed. The addition of N alone did not result in a growth response, supporting the hypothesis that the response of western hemlock following N fertilization is often limited by secondary deficiencies. Lack of response to N additions is thought to be due to induced S deficiency. The best response to fertilization was achieved with the addition of N + P (100 kg/ha) + blend. This may have been due to the addition of S that alleviated S deficiency. A companion study to evaluate possible effects of wood composition on apparent stable isotope discrimination was also conducted.

Key words: western hemlock, Tsuga heterophylla, fertilization, basal area increment, sulfur, nitrogen, carbon isotope discrimination, cellulose, lignin, reaction wood

Evaluation of project objectives: All project objectives were completed as detailed in the modified work plan as approved by the FII in a letter dated Dec 4, 2002. This included a presentation at the annual meeting of the Salal-Cedar-Hemlock Integrated Research Program (SCHIRP) on Feb 7, 2003.

Assessment of applicability: The results indicate that future fertilization prescriptions should include S in addition to N. Assessment of the use of foliar and wood δ^{13}C values to assess nutritional status and predict fertilization response awaits completion of the full NSERC-funded program in 2005.
Contribution to knowledge gap: See Final Report (attached). The importance of sulfur as a key secondary limiting nutrient (more so than phosphorous) is highlighted. Concerns surrounding differential contributions of cellulose and lignin to the $\delta^{13}$C of whole wood were allayed. Indeed, the common practice of isolating cellulose prior to isotopic analysis should in fact be avoided.

Key operational variances: No major variances. Isotopic analysis of wood fractions was delayed due to two equipment problems. In the first case a ball mill failed because of a broken timing belt. This took 3 weeks to replace. In the second case there were minor problems with the isotope ratio mass spectrometer in the stable isotope laboratory at Earth and Ocean Sciences, UBC.
(Towards) A Novel Method for Assessing the Nutritional Status of Western Hemlock

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FINAL REPORT
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**Introduction**

Western hemlock (*Tsuga heterophylla*) is one of the most important tree species in coastal management units facing reductions in wood supply. Forest fertilization is a proven method to increase the growth of many conifer species. However, operational fertilization of western hemlock is not currently an option as foresters lack the necessary tools to distinguish stands that will respond to fertilization from stands that will not respond. We report here on FII funded components of a longer term research program to determine if the isotopic composition of carbon within foliage and stem wood can be used by foresters to assess the nutritional status of this species and to predict response to fertilization.

The only tool available to professional foresters to actually increase an existing stand’s productivity, as measured by m³/ha, is fertilization. Operational fertilization programs have two essential requirements that pertain to the science of tree nutrition. Firstly, managers must be able to diagnose the nutritional status of a stand. This involves identifying the nutrient, or nutrients, that are the primary factors limiting productivity. Secondly, managers must be able to accurately predict the growth response of a stand when the nutrient deficiency is removed by fertilization. While research has indicated that the growth of western hemlock can be increased significantly with the addition of fertilizer, we still have no way to accurately distinguish stands that will respond to fertilization, from those that will not respond.

Since conventional foliar analysis offers little utility in distinguishing potentially responsive from non-responsive hemlock stands, researchers have focused on identifying alternative tools or approaches for this purpose. Foliar vector analysis is one such tool that is often used to diagnosis nutrient deficiencies and predict a stand’s responsiveness. However, Carter et al. (undated) reported that the first-year needle weight response, measured as the average weight of 100 needles, was not correlated with long-term basal area increment when applied to a study of 44 hemlock stands. Furthermore, vector analysis was developed only for species exhibiting a determinant growth pattern.
Consequently, the vector technique appears to hold little promise to addressing the problem of hemlock nutrition. Researchers have attempted to use soil chemical properties to understand the nature of nutrient deficiencies and predicting long-term response of hemlock to fertilization (e.g., Radwan & Shumway 1983). This research indicated that soil chemical variables are not an option in identifying responsive stands of hemlock.

Plants discriminate against $^{13}$CO$_2$ over the lighter and more abundant $^{12}$CO$_2$ during photosynthesis, resulting in $^{13}$C concentrations (expressed as $\delta^{13}$C values) in tissues that are lower than the CO$_2$ source. The magnitude of this discrimination depends, among other factors, on the photosynthetic type and rate, environment and genotype. In C3 plants this discrimination is determined largely by the ratio of the concentration of intercellular to atmospheric CO$_2$ (Farquhar et al. 1982, 1989), which, in turn, is directly affected by the balance between net assimilation rate ($A$) and stomatal conductance ($g_s$). Differences in $\delta^{13}$C occur as a result of variations in either stomatal conductance or photosynthetic capacity (Hubick et al. 1986, Condon et al. 1987, Ehleringer 1990). The effects of environmental or physiological factors on $A$ or $g_s$ are, therefore, reflected in tissue $\delta^{13}$C. A low $\delta^{13}$C caused by a low photosynthetic capacity, indicative of poor nutrition, should be negatively correlated with CO$_2$ assimilation rate and dry matter production. The relationship between carbon isotope discrimination and foliar nutrient concentrations, its applicability to assisting in the diagnosis of a stand’s nutritional status, and as a predictor of fertilization response, have received little or no attention within the field of tree nutrition.

A series of western hemlock fertilization experiments was carried out in the mid-1990's by researchers within the Department of Forest Sciences at the University of British Columbia (White 2000). In one of these experiments, eight immature western hemlock stands located on the coast of BC were fertilized in the spring of 1995. The three-year basal area increment following fertilization was compared to the three-year increment prior to treatment. The present study sought to revisit this experiment to analyze the six-year basal increment response, as well as to determine available sulfate-S in foliage.
collected the year after fertilization (i.e. 1996). These data are preliminary to an assessment of foliar and stem wood stable carbon isotope composition (separately funded by NSERC). We also sought to determine whether isotopic analysis of stem wood might be complicated by differing proportions of lignin relative to cellulose. We hypothesize that because lignin is depleted in $^{13}$C relative to the carbon source, any increase in its synthesis must be balanced by an isotopic enrichment of the remaining fractions, primarily cellulose.

**Methodology**

**Experimental approach**

Eight immature western hemlock stands were fertilized with a total of six treatments in the spring of 1995. Seven of the eight stands were located on northern Vancouver Island with the remaining stand located on the Sunshine Coast (Figure 1). Each of the eight pure hemlock stands had undergone pre-commercial thinning approximately twelve years prior to the commencement of this study. A total of thirty-six single-tree plots had been previously established at each of the eight installations (i.e. a total of 288 trees). Detailed site descriptions were provided in White (2000).

**Treatments**

The six treatments were: (1) control (no fertilizer applied); (2) N (224 kg/ha as urea); (3) N (224 kg/ha) + P (100 kg/ha); (4) N (224 kg/ha) + P (500 kg/ha); (5) N (224 kg/ha ) + P (100 kg/ha) + blend (230 kg/ha); and (6) N (224 kg/ha) + P (500 kg/ha) + blend (230 kg/ha). Phosphorus had been applied in the form of triple-super-phosphate. The blend addition included 60 kg/ha K applied as potassium sulfate, 40 kg/ha Mg applied as magnesium sulfate, 10 kg/ha Cu applied as copper sulfate, and 20 kg/ha Zn applied as zinc sulfate. This application resulted in the addition of approximately 100 kg/ha sulfur in the form of sulfate.
Measurement of 6-year basal area increment

In the winter of 2003 (i.e., eight growing seasons after fertilization), a minimum of two cores were extracted at breast height from each tree (a total of 4 cores were extracted when time permitted). Cores were collected from 270 trees. A total of 18 trees could not be sampled. In several cases, trees were wind blown or had died. A number of trees at one installation had been lost to road construction. Care was taken to avoid stem deformities and to ensure that the core passed through the center of the tree. Windendro (version 6.04) was used to measure ring increment during the '92, '93, '94 (i.e., three years prior to fertilization) and '95, '96, '97, '98, '99 and 2000 (i.e. 6 years following fertilization) growing seasons.

Foliar analysis

Current-year foliage that had been previously collected at the end of the second growing season (i.e. sampled in the fall of 1996) was re-analyzed for total S and sulfate concentrations. Pacific Soil Analysis of Richmond, British Columbia carried out the total-S and sulfate analysis. Total S was determined using a Leco sulfur analyzer. Available sulfate using a 1:20 tissue to 0.01 NCl boiled extract. Sulfate was determined by hydriotic acid bismuth reducible distillation method.

Analysis of wood fractions

The influence of wood composition on $\delta^{13}$C was examined by measuring the isotopic signatures of major wood components in reaction wood and adjacent normal wood, from the same tree rings. In conifers, reaction wood (i.e., compression wood) normally has high lignin and low cellulose content (Westing 1965, 1968). Two hemlock saplings (~10 cm dbh) with sharply curved stem butts were felled and sectioned into quarters at five positions within and above the zone of reaction wood formation (total = 40 wood samples). Sapwood rings covering the period 1993-2002 were collectively isolated from the disks quarters. Extractives were quantitatively prepared from large milled samples as
described by Green (1963). For lignin (Goering & Van Soest, 1970), milled wood samples (each sample ~250 mg) were soaked with 72% Sulfuric acid (4.35 mL) for 16 hours, then the acid concentration was adjusted to 3% and the mixture boiled for 4 hours. The lignin obtained was filtered using a glass fibre filter, washed with deionized water, dried at 105°C and weighed. For cellulose (Green, 1963), wood samples (each sample ~250 mg) were suspended in 5 mL of deionized water in a round-bottom flask (25 mL) with a glass stopper. The reaction was initiated by adding 1.25 mL of sodium chlorite/acetic acid solution. At 30-min intervals 1.25 mL of sodium chlorite/acetic acid solution was added to the reaction, for a total of 5 mL. At the end of 2 hr (total of 4 additions), the reaction was cooled and filtered using a glass fibre filter. The resulting cellulose was washed with deionized water, dried at 105°C, and weighed. δ¹³C values of wood fractions were determined for calculations of mass balance and comparison with δ¹³C values of whole wood.

**Statistical analysis**

Installation and treatment were each considered fixed variables, therefore, Zar’s (1984) ANOVA type I was used for the analysis of data. Basal area response was normalized by a log transformation prior to covariate analysis where the previous three-year basal area increment prior to fertilization was considered the covariate.
Figure 1. Location of eight installations on northern Vancouver Island and the Sunshine Coast.
Results

Growth Response

The six-year basal area increment was significantly affected by treatment (Table 1). However, no interaction between site and treatment was evident at this measurement period, owing perhaps to high between tree variation. The addition of N alone did not result in a growth response in these trees (Table 2). This is contrary to the three-year measurement reported by White (2000) that had detected a N response. The addition of P, at the 100 kg/ha application rate in combination with the addition of the elements contained within the blend fertilizer, had the greatest effect on the six-year increment. The addition of P at the high rate of 500 kg/ha had no effect on growth.

The six-year basal area increment was also significantly affected by installation (Table 1). The Port McNeill #2, Port Alice #1 and #2 installations were generally unresponsive. In contrast, the Nimpkish installation showed evidence of a strong response to the N + P100 + Blend treatment. These findings are in general agreement with earlier findings by Carter et al. (undated) with a few notable exceptions. The Port McNeill #1 installation had been previously reported as unresponsive by Carter et al. (undated) but was found to respond to similar treatments in this study.

Foliar analysis

Available SO₄-S of foliage collected at the end of the second growing season after fertilization is presented in Table 4. Some sites (Port McNeill #1 and Sechelt) were clearly deficient as indicated by control values of less than 75 ppm. By this criterion, S deficiencies were induced by fertilization with either N or N+P at all other sites. Blend treatments, however, had greatly elevated levels relative to controls reflecting the presence of sulfur in the fertilizer applied.
Analysis of wood fractions

The extractives content of wood samples removed from the two strongly "piped" hemlock sapling was ~3% (alcohol and water-soluble components combined). Mass spectrometric analysis of the extractives fraction showed that it was very close to whole wood in isotopic composition and could therefore safely be ignored.

Lignin to cellulose ratios did appear to vary with vertical position through the zone of reaction wood formation (Figure 2), but did not show any clear radial trends (not presented). Contrary to expectations, the lignin content through the curved part of the stem (disks 1-4) was actually somewhat lower than in samples taken above this zone (disk position 5) where reaction wood was absent.

As expected, lignin was depleted in $^{13}$C relative to whole wood, whereas cellulose was enriched. The $\delta^{13}$C values of the two fractions differed by 3.39‰ ±0.33 (mean ±SD; n=40). There were slight differences between the two trees, as expected, due to either genetic or environmental factors. Whole wood $\delta^{13}$C values from different disk positions were quite stable within each tree (Figure 3), as were $\delta^{13}$C values for the lignin fraction only (Figure 4). Cellulose, on the other hand, was much more variable (Figure 5).
Figure 2. Lignin/cellulose ratios of disks removed from two western hemlock saplings through zones of extensive reaction wood deposition. Disk position 1 is at the bottom of the stem, whereas position 5 is from above the zone of curvature. Maximum curvature is at positions 2 and 3. Reaction wood was essentially absent from disks collected at position 5. Each bar represents the mean (±SE) of four separately extracted and analyzed quarters from each disk.
Figure 3. Isotopic composition ($\delta^{13}$C value) of whole wood (years 1993-2002 combined) from disks removed from two western hemlock saplings. Other details as in Figure 2.
Figure 4. Isotopic composition ($\delta^{13}$C value) of lignin extracted from wood disks removed from two western hemlock saplings. Other details as in Figures 2 and 3.
Figure 5. Isotopic composition ($\delta^{13}C$ value) of cellulose extracted from wood disks removed from two western hemlock saplings. Other details as in Figures 2 and 3.
Discussion

The lack of a growth response to N fertilization is in general agreement with the hypothesis that the response of western hemlock following N fertilization is often limited by secondary deficiencies. In the present study, N additions significantly reduced foliar sulfate concentrations. Foliar standards for S adequacy have yet to be reliably developed for western hemlock. However, the low sulfate values in the present study, relative to that required in other conifer species indicate that the lack of N response was most likely due to induced S deficiencies.

It was hypothesized that the growth response of western hemlock following N additions was limited by P deficiency, where the latter is often not relieved by the addition of 100 kg/ha. This experiment attempted to address the latter half of this question by including treatments that applied P at the rate of 500 kg/ha. The six-year basal area response results, however, indicated that none of the eight stands responded to either of these treatments. This would seem to indicate that the P requirement in these trees was met from existing sources without the need of further P additions through fertilization. However, the strong response at some installations to the N + P (100kg/ha) + blend treatment may have been due to a condition of balanced nutrition. This is particularly relevant given the low P concentrations in current-year foliage of either the control or N treated plots at all installations (White 2000). Unfortunately, the blend was not tested without a P addition so conclusive statements regarding the role of P nutrition in these stands cannot be stated.

The six-year basal area increment is not in agreement with the three-year growth measurement reported in White (2000). In the latter, it was reported that the only growth response detected was that to N only additions. Since an increase in basal-area response must be preceded by one or more years of crown expansion, a six-year response data would be more sensitive in detecting not only the magnitude of a response but also the duration. It is possible that some of the stands that have been shown to have statistically responded to N additions over a three-year period may not show such evidence when
their growth response is measured over a six-year period. This would be caused if the duration of their response to N additions were of a short duration.

The effect of each treatment on foliar nutrients and various organic (amino acids) and inorganic (foliar Pi and P uptake) indicators in these eight installations had been previously reported (White 2000). This large nutritional data set is being complimented by current research into the photosynthetic response following fertilization as determined through carbon isotope discrimination. The six-year growth response data set, as reported here, will be invaluable to investigators and will allow the latter to better understand the physiological and nutritional variables that control productivity in these stands.

The isotopic analysis of whole wood, and cellulose and lignin fractions derived there from, revealed that bias is likely to be introduced by isolating cellulose prior to mass spectrometric analysis. Indeed, this practice may actually create the very problems it is meant to reduce. Because lignin and cellulose differ in isotopic composition, it has been commonly assumed that differences in the lignin/cellulose ratio might affect whole wood δ13C values. This notion is incorrect. Mass balance among different components of any one tissue derived from a common carbon source must be observed.

Conclusions

1. The addition of N alone did not result in a growth response in these trees supporting the hypothesis that the response of western hemlock following N fertilization is often limited by secondary deficiencies.

2. Lack of response to N additions was thought to be due to induced S deficiency. These results indicate that future fertilization prescriptions should include S in addition to N, which may be prohibitively expensive.
3. The best response to fertilization was achieved with the addition of N + P (100 kg/ha) + blend. This may have been due to the addition of S that alleviated S deficiency but may have also been due to a condition of balanced nutrition.

4. There is no need to complicate isotopic analysis of wood by first isolating the cellulose fraction prior to mass spectrometry. Indeed, contrary to common opinion, this practice likely introduces the very bias it was thought to remove.
Literature Cited


Table 1.  Covariate Analysis of basal area increment:  F ratios and level of significance for covariate, treatment, installation, and their interaction.

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Table 2 Basal areas response by treatment relative to control: means were adjusted for covariate.

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Table 3. Basal area response relative to control by treatment and installation. Installations are Eve River (EVE), Nimpkish (NIMP), Port Alice #1 (PA1), Port Alice #2 (PA2), Port McNeill #1 (PN1), Port McNeill #2 (PN2), Zebellos (ZEB), and Sechelt (SEC).

<table>
<thead>
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Table 4. \( \text{SO}_4^2- \) (ppm) in current year foliage of western hemlock at the end of the second growing season following treatment.

Values are means of six trees ± standard error (SE). Installations are Eve River (EVE), Nimpkish (NIMP), Port Alice #1 (PA1), Port Alice #2 (PA2), Port McNeill #1 (PN1), Port McNeill #2 (PN2), Zebellos (ZEB), and Sechelt (SEC).

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