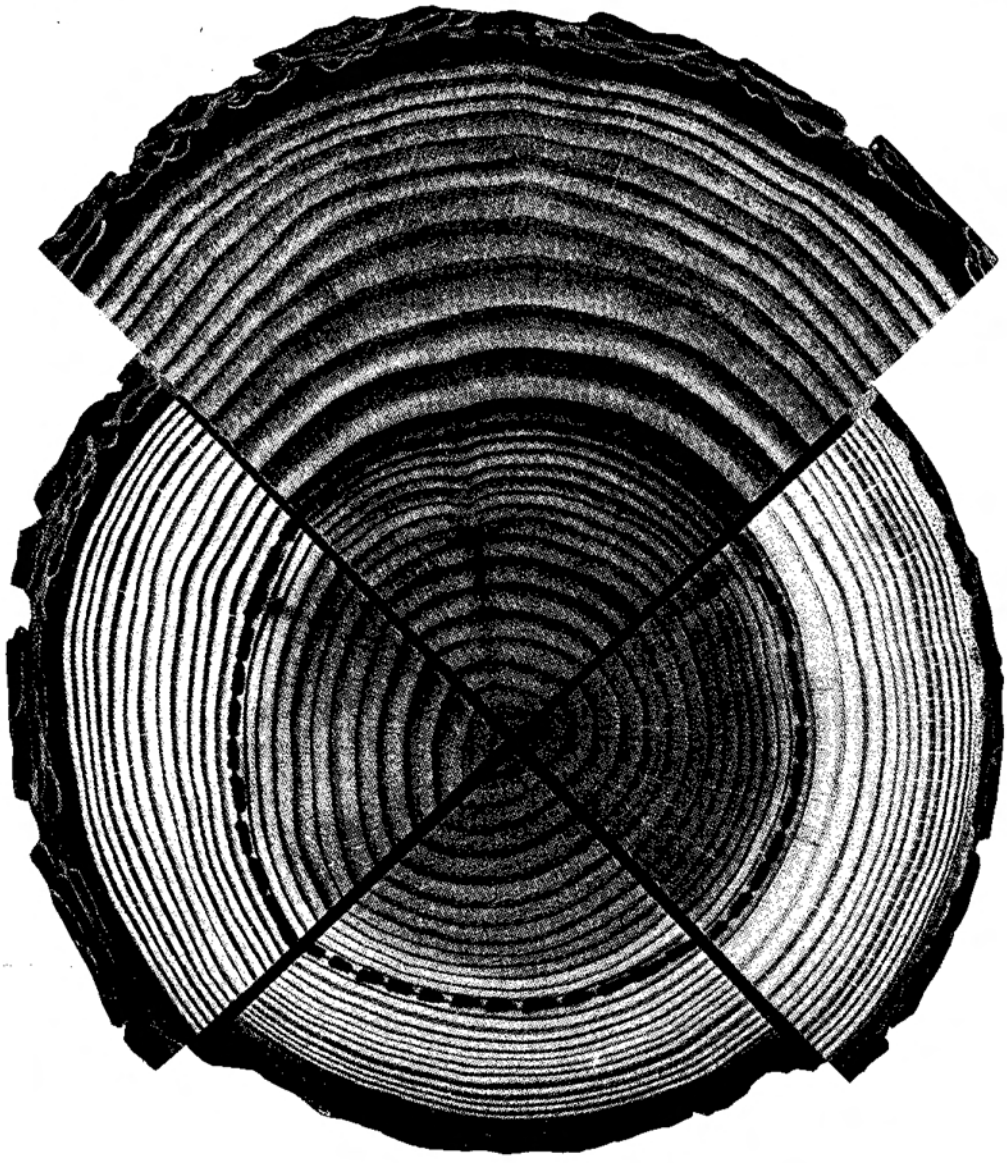
FORESTRY

FRDA REPORT 196

Fertilization and Thinning Effect on a Douglas-fir Ecosystem at Shawnigan Lake: A Synthesis of Project Results

ISSN 0835 0752

JANUARY 1993



CANADA-BRITISH COLUMBIA PARTNERSHIP AGREEMENT ON FOREST RESOURCE DEVELOPMENT: FRDA II

Canada

BC

Fertilization and Thinning Effect on a Douglas-fir Ecosystem at Shawnigan Lake: A Synthesis of Project Results

by

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November 1992

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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.
Fertilization and thinning effect on a Douglas-fir ecosystem at Shawnigan Lake

(FRDA report, ISSN 0835-0752 ; 196)

"Canada-British Columbia Partnership Agreement on Forest Resource Development: FRDA II."
Co-published by B.C. Ministry of Forests.
Includes bibliographical references: p.
ISBN 0-7726-1688-4

1. Douglas-fir - British Columbia - Shawnigan Lake Region - Fertilization. 2. Douglas-fir - British Columbia - Shawnigan Lake Region - Thinning. 3. Douglas-fir - British Columbia - Shawnigan Lake Region - Growth. I. Canada. Forestry Canada. II. Canada-British Columbia Partnership Agreement on Forest Resource Development: FRDA II. III. British Columbia. Ministry of Forests. IV. Title. V. Series.

SD397.D7B74 1993 634.9'7542'09711 C93-092055-4

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

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EXECUTIVE SUMMARY

This report describes a multidisciplinary research project on the effects of thinning and nitrogen (N) fertilization on growth and biology of a 24-year-old coastal Douglas-fir ecosystem near Shawnigan Lake on Vancouver Island, British Columbia.

The objectives of the project are to record short-term and long-term effects of thinning and nitrogen fertilization on growth and yield, and to explain growth responses through ecosystem changes both above and below the ground. A better understanding of growth response to stand tending will lay the foundation for predicting responses under different site and stand conditions.

Treatments were initiated in 1970–71 with the basic 3×3 factorial treatments of three levels of thinning (T0, T1, and T2, removing none, one-third, and two-thirds of the stand basal area, respectively) and three levels of urea fertilization (F0, F1, and F2, with rates of 0, 224, and 448 kg N/ha, respectively). Two replicate plots were installed in 1971 and two more were installed in 1972. The plots fertilized in 1972 (F1, F2) were refertilized at year 9 at the initial rates. The F1 plots received their second refertilization at year 18. New plots were installed in 1987 to study effects of phosphorus (P) and sulphur (S) on response to N. Subsidiary treatments included N fertilization with ammonium nitrate and urea fertilization with the high rates of 672, 896, and 1344 kg N/ha (F3, F4, and F6).

Growth and yield for the basic treatments were reported for 3-year periods until year 15 for height, diameter, basal area, and volume. Growth increments are given for total stand, merchantable trees, and the 250 and 500 per ha crop trees. Stand diameter distribution, crown size, and mortality are recorded. Effects of nitrogen source and high rates of nitrogen are given.

Growth responses continued to year 15. Over the 15-year period the yearly net volume increment was 15.3 m^3/ha per year in untreated plots (T0F0). The increment was decreased 4.2 m^3/ha per year (27%) by heavy thinning alone (T2F0) and increased 4.3 m^3/ha per year (28%) with the high rate of fertilization (T0F2) and 3.0 m^3/ha per year (20%) by a combination of thinning and fertilization (T2F2), thus showing a considerable interaction between these treatments. Height growth was increased 74% by both treatments and almost 100% by the combined treatments. Refertilization at year 9 was effective for 3 years at T0, and response continued to year 15 with T2. The growth response to ammonium nitrate was better than that to urea. The response increased with an increasing rate of urea to the F6 level, but with a diminishing effect above F2.

The aboveground biomass and its distribution to seven tree components and their nutrient contents at the time of treatment and at year 9 were determined. Treatment effect on understory biomass and nitrogen content was reported.

The effect of thinning and fertilization on wood quality was studied with regard to wood density, knots, ring width, and amount of juvenile wood. Increase in the amount of juvenile wood with thinning appears to be the most serious treatment effect.

The seasonal pattern of tree growth and tree growth processes is given. The length of the growing season is not affected by treatments. Increase in stem diameter growth after thinning and fertilization is caused mainly by an increase in the number rather than in the size of xylem cells. Crown development during the first 7 years was determined including foliage mass (area) and its distribution, branch elongation, crown size, and structure. Fertilization increased the leaf area by 50% in unthinned stands and by more than 100% in thinned stands.

The physiological mechanism of tree and stand growth response to treatments was investigated by determining changes in foliar nitrogen status, tree water stress, light regime in crowns, and their relationships to rates of photosynthesis and respiration. The foliar nitrogen concentration was increased for up to 4 years by fertilization, but thinning had little or no effect. Thinning decreased soil and tree water stress, but fertilization had no effect on water stress. The light regime in crowns of individual trees was improved by thinning. The relative importance of foliage quantity and foliage efficiency in growth response was determined. The foliar efficiency was improved the first 4–5 years by both treatments, but decreased thereafter because of increased mutual shading in the crowns. The growth response after this initial period was caused by the increased foliage

quantity for both treatments and provided for the long-term response and the greatest portion of the total response. This analysis provides an understanding of the duration and magnitude of growth responses and relationships to stand density (thinning) and refertilization.

The fate of the two nitrogen fertilizers, ammonium nitrate and urea, after application, was studied to determine losses (gaseous and leaching), movement and transformations in the soil, immobilization, and uptake by trees. The availability of nitrogen to trees was higher with ammonium nitrate than with urea; this was also evident from the analysis of foliar nitrogen status and resulting tree growth. Uptake of nitrogen was similar in thinned and unthinned stands over the first 9 years. Loss of nitrogen by trees in litterfall was determined as part of the nutrient cycling analysis.

The continuous availability of soil nutrients depends on the activity of soil fauna and flora in organic matter decomposition. Population changes were studied in relation to thinning and fertilization and only short-term effects were found. Rates of soil respiration are being measured to determine soil organism activity.

One study showed an increased response to nitrogen fertilization with increased soil moisture. Also, height growth response to fertilization at Shawnigan was best in years with above-normal rainfall. However, fertilization has generally given a good growth response on the very dry Shawnigan site.

Careful application of fertilizers will result in no adverse environmental impact. Thinning has increased understory growth greatly and thereby improved the habitat for deer browsing.

A mechanistic model at the ecosystem level, SHAWN, was developed to assist in setting research priorities.

An economic analysis showed that heavy thinning combined with fertilization (T2F2) ranked as the best treatment.

A general discussion deals with the issues of direct and indirect growth response to fertilization, the effect of thinning versus that of fertilization on growth, prediction of growth response to fertilization, monitoring the effect of fertilizer on growth and processes in new installations, and fertilization of low-density stands, which, although common practice, is in need of more research.

PREFACE

The aim of this project was to obtain a better understanding of the complex interconnected processes leading to Douglas-fir ecosystem responses to pre-commercial thinning and nitrogen fertilization. By identifying important processes and their relationships to site and stand conditions, it was anticipated that this would improve our prediction of growth responses to these stand treatments.

Throughout the 20-year duration of the project we have maintained close communication with other researchers and foresters from many parts of the world. Frequent tours of the Shawnigan installation have been conducted and up-to-date reporting of results has been emphasized. The feedback from these contacts has been of immense importance to our progress and has made our management staff more aware of the importance of continuous support for this long-term project.

More than 70 reports have been published and some results are still to come. With the volume of information distributed in so many different types of publications, it was felt that this synthesis of project findings was needed.

Many researchers at the Pacific Forestry Centre of Forestry Canada in Victoria, British Columbia, with specialties in different disciplines, have been involved with the project from time to time. Participants in the different fields of study were:

Silviculture and mensuration: Mr. C.P. Brett, Mr. M. Crown, Dr. R.V. Quenet, Dr. H.J. Barclay, Ms. E.R. Gardner (now Mrs. E.R.G. McWilliams), and Mr. R. de Jong

Soil chemistry: Dr. B.D. Webber, Dr. P.C. Pang, and Dr. C. Preston

Tree physiology: Dr. H. Brix, Dr. A.K. Mitchell, and Dr. D.F. Pollard

Soil fauna: Dr. V.G. Marshall

Soil microflora: Dr. J. Dangerfield, and Dr. T. Trofymow

Growth and process modelling: Dr. H.J. Barclay, Dr. T.H.J. Hall, and Dr. T. Trofymow

Several technicians have had a long association with the project and have provided a valuable service. They are Mr. H. Barker, Mrs. M. Clayton, Mr. K. McCullough, and Mr. C.R. Layton.

I had the privilege of being associated with the project from the planning stage in 1970 until my retirement in 1988, and during the last 11 years as project leader. This experience gave me some knowledge of all aspects of the project.

My gratitude for assistance in producing the report is expressed to Dr. M. Bonnor and Mrs. L. de Montigny (British Columbia Ministry of Forests) for arranging the FRDA contract, to Dr. H. Barclay, Dr. V.G. Marshall, Mrs. E.R.G. McWilliams, Dr. A.K. Mitchell, Dr. D.F. Pollard, Dr. C. Preston, and Dr. T. Trofymow for bringing me up-to-date on research progress since my retirement, and to Dr. Raj Prasad, who provided a valuable guide to the project research. The editorial comments given by Mrs. E.R.G. McWilliams and Mr. S. Glover were much needed and greatly appreciated.

Holger Brix

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1 INTRODUCTION

During the 1960s many trials in forest fertilization were initiated in coastal Douglas-fir forests (*Pseudotsuga menziesii* [Mirb.] Franco) in British Columbia as well as in Oregon and Washington. An account of the early history of research and operational nitrogen fertilization in British Columbia was given by Kumi *et al.* (1991). Good growth responses to nitrogen fertilization were demonstrated in the province by the forest industry (Crossin *et al.* 1966), by the University of British Columbia (Smith *et al.* 1968), and by the Canadian Forestry Service (Lee 1968). Trials in Oregon and Washington also showed promising results (Gessel *et al.* 1969; Miller and Pienaar 1973). Operational trials with urea spread by aircraft were initiated by the Pacific Logging Co. Ltd. in 1963. To coordinate operational and research efforts in coastal British Columbia, the Forest Fertilization Board was established in 1967 with representatives from coastal forest industries and government agencies.

Several major fertilization projects were initiated in the years 1969–71. The British Columbia Forest Service formed the Forest Productivity Committee in 1970 and in 1971 they began the establishment of a series of field installations to study growth and yield responses to nitrogen fertilization in thinned and unthinned stands (EP 703). By 1976, 85 permanent installations with 940 plots had been established over a wide range of sites and stand ages in coastal Douglas-fir and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). Similar growth and yield research was initiated in Oregon and Washington in 1969–70 under the cooperative Regional Forest Nutrition Research Project (RFNRP).

In the late 1960s the Pacific Forest Research Centre of the Canadian Forestry Service, Victoria, B.C. was urged by the Forest Fertilization Board to expand their research effort in forest fertilization. The objective of most existing projects was to provide growth and yield information from empirical field trials. It was decided to complement these projects with process-oriented research that would assist in explaining, and thereby predicting, responses to fertilization under different site and stand conditions. No explanation could be given for the wide range of responses obtained at that time due to a lack of understanding of the mechanism of the response and relationships to site and stand parameters. The need for knowledge of this nature was emphasized by Gessel (1968) in his review of forest fertilization problems. Furthermore, concerns were expressed about fertilization effects on environmental quality, and these aspects were included in the objectives.

In the late 1960s there was a growing interest in stand thinning (primarily juvenile spacing) as a management tool, and the questions of a possible interaction between thinning and fertilization and the optimum levels of treatment combinations were often raised. Studies of both treatments, separately and combined, were therefore undertaken.

To address these objectives a team of researchers was formed specializing in the appropriate disciplines of soil chemistry, soil fauna, soil flora, tree physiology, mensuration, and modelling. This enabled the study of changes in the forest ecosystem in soil, understory, trees, and microclimate as a result of treatments. Furthermore, analysis of these changes, their relationships, and their role in tree growth response and potential environmental impacts could be studied. Investigating these complex problems required a cooperative, interdisciplinary approach over a long time period.

A field installation in a 24-year-old Douglas-fir plantation near Shawnigan Lake on Vancouver Island was started in the winter of 1970–71 (Crown and Brett 1975). Treatments included different levels of thinning and rates and sources of nitrogen fertilization as described in Section 3. Field studies have been carried out mainly at the Shawnigan Lake site but they have been supplemented by studies in other field locations and also with laboratory studies under controlled environmental conditions such as temperature, light, and water. This will provide a basis for extrapolating results to environments other than those encountered at Shawnigan.

The main aspects studied and reported here are thinning and nitrogen fertilization effects on:

1. Growth and yield – three thinning levels; six rates and two sources of nitrogen; refertilization at year 9; effect of understory.
2. Wood quality – wood density; branch size.
3. Tree growth – seasonal pattern; xylem and sapwood development; crown development.

4. Tree physiology – mechanism of tree growth response; foliar nutrient status; tree–water relations; photosynthesis and respiration; foliage quantity and efficiency; and effect of these on growth.
5. Environmental changes – light regime in tree crowns; soil temperature; seasonal and yearly changes in soil water stress.
6. The fate of fertilizer applied and thinning effects; losses; movement and transformations in soil.
7. Nitrogen availability and uptake by trees and understory; relationship to thinning and rate and source of nitrogen.
8. Nutrient and carbon cycling – dry matter and nutrient content of tree components, understory, and litterfall; nutrient losses.
9. Soil biology – the role of soil fauna and microflora and changes in populations.
10. Environmental impacts – thinning and nitrogen fertilization effects on water quality and wildlife habitat.
11. Modelling of growth and processes.
12. Economics of thinning and fertilization.

Since the initiation of the Shawnigan Lake project, more than 70 reports have been produced; others are in preparation, and additional data have yet to be analyzed. This report will:

- review and integrate published and unpublished information,
- provide references for readers wishing more detailed information, and
- discuss information of relevance to forest managers and researchers.

2 THE SHAWNIGAN SITE AND STAND

The Shawnigan Lake experimental site covers an area of about 50 ha and is located approximately 5 km west of the north end of Shawnigan Lake on southeastern Vancouver Island. The site and stand characteristics are described briefly in an introductory report (Environment Canada 1978) and in detail in the establishment report (Crown and Brett 1975).

The installation is situated on top of a well-rounded knoll 305–350 m in elevation. The soils are shallow (45–60 cm to C1 horizon), well-drained coarse loamy and coarse silty glacial till underlain by impermeable basal till. No roots penetrate into this basal till. The soil is classified as Orthic Dystric Brunisol. The water holding capacity and percentage of carbon (C) and of N are low. The C/N ratio is approximately 15:1 except in the top mineral horizon where it is as much as 35:1. Amounts of exchangable cations are low except for hydrogen. There is essentially no Ae horizon and only a thin (usually less than 3 cm) organic mantle as a result of burning prior to planting.

The site is within the very dry maritime Coastal Western Hemlock biogeoclimatic subzone (CWHxm) and consists of very dry, nutrient-poor to medium ecotopes (Klinka *et al.* 1984). The Douglas-fir site index is 25 m at breast height age 50 (Bruce 1981). This is equivalent to Mitchell and Cameron's (1985) medium-poor site class. The soil characteristics and low precipitation during the summer months (120 mm June–September; 1075 mm yearly) result in a 24 month soil water deficit, with July and August being the driest months. The mean temperature is 8.8°C for the year and 15.6°C for the four months June–September.

Douglas-fir is the dominant species, mixed with a minor component of western hemlock, western redcedar (*Thuja plicata* Donn.), western white pine (*Pinus monticola* Dougl.), and lodgepole pine (*Pinus contorta* Dougl.). The most abundant understory species is salal (*Gaultheria shallon)*, followed by bracken fern (*Pteridium aquilinum*), feathermoss (*Kindbergia oregana*), and dull Oregon grape (*Mahonia nervosa*).

To date there has been no insect attacks of major consequence. The most common pest is the root rot *Phellinus weirii.* At the time of plot establishment, the scattered root rot centres were identified and plots were

relocated to exclude the disease areas. The spread of the disease is being monitored and studied in a separate area. There is no evidence that the spread is influenced by even high rates of nitrogen fertilization (G. Wallis, Research Scientist, retired, Pacific Forestry Centre, Victoria, B.C. pers. comm.).

Stand History The naturally occurring stand of Douglas-fir was burned by a wildfire in 1925. Following salvage logging, the site was naturally regenerated to Douglas-fir. Another fire in 1942 destroyed the young stand and left the site devoid of slash and with little humus. The area was planted with 2-0 Douglas-fir in the spring of 1948. The seed stock came from low elevations in the Courtenay–Campbell River area. The planting density averaged 2189 trees/ha, in addition to the 1164 trees/ha that came in naturally, for a total of 3353 trees/ha (A.H. Bamford, unpublished data, 1973, B.C. Forest Service, Victoria, B.C.). With additional fill-in after planting, the third year survival record showed a total of 3953 trees/ha. There was no stand tending treatment until the project was undertaken in 1970. At that time the stand was 24 years old for the planted stock and within 13 years for the naturals. The average tree was 7.6 cm in diameter and 8.6 m in height.

3 STAND TREATMENTS AND EXPERIMENTAL DESIGN

The experimental design can be divided into two components: 1) the basic experiment, and 2) the subsidiary experiments.

3.1 Basic Experiment

These trials were initially laid out as a completely randomized design with a 3×3 factorial treatment structure consisting of three levels each of thinning and nitrogen fertilization. Each of the nine treatment combinations was replicated twice in each of the years 1971 and 1972, for a total of 36 plots. The three levels of thinning were:

- T0 – no thinning (control)
- T1 – approximately 1/3 of basal area (ba) removed
- T2 – approximately 2/3 of basal area removed

The three levels of nitrogen fertilization were:

- F0 – no fertilization (control)
- F1 – 224 kg N/ha applied as forestry-grade urea
- F2 – 448 kg N/ha applied as forestry-grade urea

In 1981, 9 years after the first fertilization, the 1972 plots were refertilized at their original rates. This resulted in the basic experiment being divided into two smaller components, each consisting of 18 plots. In 1990, 18 years after the first fertilization and 9 years after refertilization, the 1972 F1 plots received their second refertilization.

3.2 Subsidiary Experiments

These trials were established in the springs of 1972, 1973, and 1987 in an attempt to answer the following questions:

1. What are the effects of high doses of urea?
2. How do ammonium nitrate and urea compare as nitrogen sources in ecosystem and growth responses?
3. How does the understory vegetation affect the tree growth response in thinned and fertilized stands?
4. Do P and S fertilization increase the growth response to N? (foliar analysis indicated a possible deficiency of P and S in nitrogen-fertilized stands).

High doses of urea were applied in the spring of 1973 in the treatment combinations T0F4, T1F4, T2F3, T2F4, and T2F6, where F3, F4, and F6 were applied in rates of 672, 896, and 1344 kg N/ha, respectively. The T0, T1, and T2 treatments were as described above. Each treatment combination was randomly applied to two plots.

Ammonium nitrate was applied at the rates of 224 kg N/ha (F1*)[1] and 448 kg N/ha (F2*). The following treatment combinations (T0F1*, T0F2*, and T2F2*) were applied randomly to two plots.

The first two treatments were applied in 1972. The T2F2* was established in 1973 along with a urea-fertilized T2F2. The latter also served as a comparison for the high urea treatments given in that year.

To study the role of understory vegetation, one T2F2 plot was established in 1973 in which the aboveground vegetation was repeatedly removed by clipping. The only understory species remaining is the moss *Kindbergia oregana*.

Two thinned plots (T2F0) were installed in 1983 to study the effect of thinning on water use and soil water balance during the growing season.

In 1987 eight new plots were established to investigate the growth response to P and S along with N. These "NPS" plots were all thinned to the T2 level and the following fertilizer treatments were randomly applied to two plots each:

- control,
- N alone (F1),
- N (F1) plus P, and
- N (F1) plus P, plus S.

Phosphorus was applied at the rate of 100 kg /ha as triple superphosphate (20% P) and S at 100 kg /ha as 90% pelleted elemental sulphur.

3.3 Plot Establishment

The plot layout is shown in Figure 1. The 1971 and 1972 plots were established as square ⅕ acre plots with 33 foot buffer strips on all sides. A square 1/10 acre core plot, from which the bulk of the mensurational data are taken, was then established in the centre of the ⅕ acre plot. The remaining 1/10 acre area surrounding the core plot was designated the measured buffer and the 33 foot wide strips surrounding this were designated the unmeasured buffer. Converting these measurements to metric units gives a central core plot of 0.04 ha surrounded on all sides by 4.2 m wide measured buffer strips. The reason for the measured buffer is to allow for the calculation of competition indices for the trees on the edge of the core plots. The 1973 plots differ from the 1971 and 1972 plots in that the unmeasured buffer is only 5.8 m wide compared to 10.1 m. In the remainder of this report, three different classes of trees will be referred to: 1) core plot trees – those located within the central 0.04 ha core plot; 2) buffer trees – those located within the measured buffer; and 3) volume trees – a subsample of the core plot trees on which more frequent and detailed measurements are taken to allow for accurate volume estimates.

Upon completion of plot layout, and before any treatment application, an inventory was taken of all core plot and buffer trees greater than 2.5 cm diameter at breast height (dbh). The variables recorded were species, crown class, height, dbh, height to live crown, and tree condition. In addition, each core plot and measured buffer were mapped. Therefore, a complete record of all trees, thinned and unthinned, exists today.

3.4 Thinning Criteria

Thinning criteria in order of importance were: 1) creation of a range in density from open-grown trees to closed canopy (the heavy thinning left about 900 stems/ha, considered heavy at that time but now regarded as moderate); 2) even spacing of residual trees; 3) maximum +5% difference in average plot basal area and dbh within each thinning level; 4) retention of the maximum number of potential crop trees; 5) adequate tree

[1] no asterisk = urea; asterisk = ammonium nitrate

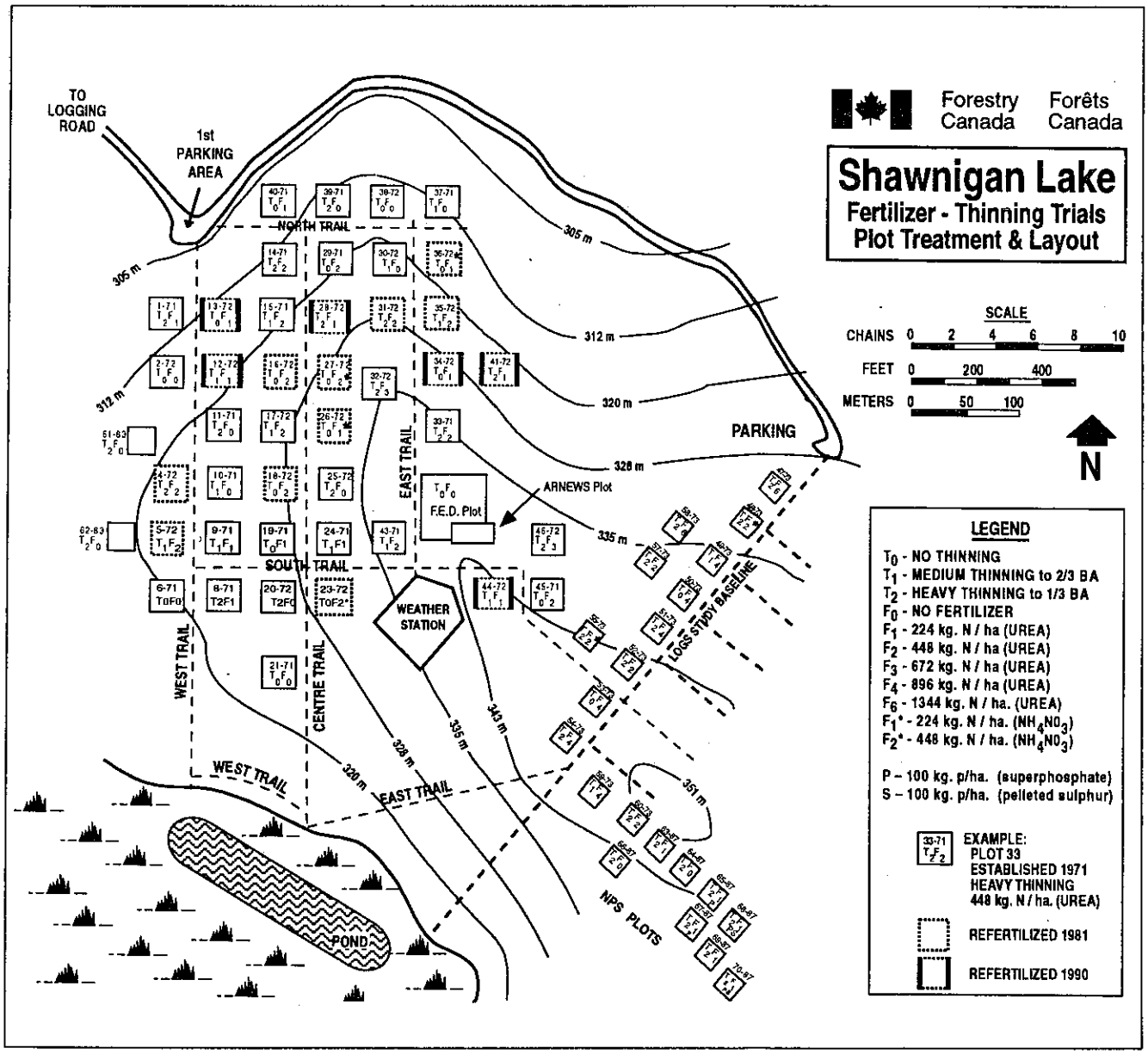

FIGURE 1. Shawnigan Lake, plot treatment and layout.

representation across a range of diameter classes to study responses of trees of different sizes; and 6) elimination of advanced natural regeneration or "wolf" trees, where possible. Thinning operations were carried out in the fall and winter of the years 1970, 1971, and 1972 for the 1971, 1972, and 1973 plots, respectively.

3.5 Fertilization Criteria

The criteria were: 1) even spread of the precise amount of the required fertilizer; 2) fertilizer to be spread during snow-free, cool, moist weather before the end of the wet winter season; and 3) all applications to be carried out in the shortest time possible. Fertilizations were done during March in 1971, 1972, 1973, 1981, 1987, and 1990, by hand with the use of a model 20 "Cyclone" spreader.

4 GROWTH AND YIELD

4.1 Basic Experiment

Growth and yield in the basic experiment have been reported for each 3-year period: year 3 (Crown *et al.* 1977), year 6 (Hall *et al.* 1980), year 9 (Barclay *et al.* 1982), year 12 (Barclay and Brix 1985a), and year 15 (Gardner 1990).

Tree measurements were done for different groups of trees and variables at different intervals, as shown in Appendix 1. Trees were grouped into core trees, volume trees, and extra-height trees (Gardner 1990). The core trees are those located within the central 0.04 ha core plots, the volume trees are a subsample of the core trees selected across a range of diameters and on which a more detailed and frequent sampling was performed, and the extra-height trees are a subsample of the core trees to cover a range of diameter classes after year 9. Heights were measured for all trees at years 0, 3, 6, and 9, but only for volume trees and extra-height trees thereafter.

The diameter at breast height, height, basal area, and their increments, as well as stem number, mortality, and crown length were reported for each 3-year period with the most recent for year 15 (Gardner 1990). Response to refertilization at year 9 was given in the 12-year (Barclay and Brix 1985a) and 15-year reports (Gardner 1990). Volume has been calculated as stand total volume per hectare and on an individual tree basis and as increments in net and merchantable volume per hectare (12.5 and 17.5 cm dbh limits). Volume losses during 3-year measurement periods and gross volume increments have been calculated for this report. Growth of the largest 250 and 500 crop trees per hectare has been presented in the 15-year report and growth for other crop tree numbers was used in earlier reports.

The stand data for different treatments at year 0 and for every 3-year period until year 15 are given for quadratic mean diameter, basal area, average height, total volume, and merchantable volume in Appendices 2–7, together with the 3-year periodic annual increments (PAI) for these properties (from Gardner 1990). A summary for the stand data at years 0 and 15 is presented in Table 1 and the increments for this period in Table 2. Detailed information can be obtained in the 15-year and earlier reports. The major findings are as follows.

TABLE 1. Stand data at year 0 (after thinning) and year 15 by treatment (data from Gardner 1990)

	Live stems per hectare		dbh (cm)		Basal area (m^2/ha)		Height (m)		Total volume (m^3/ha)		Merc volume[a] (m^3/ha)	
Treatment	0	15	0	15	0	15	0	15	0	15	0	15
T0F0	4852	4283	8.4	11.9	26.6	47.3	8.4	13.2	143	373	5	71
T0F1	3572	2979	9.0	14.0	22.7	46.1	8.7	15.8	124	387	6	122
T0F1-1	3684	2522	9.3	15.8	25.2	49.7	9.3	17.8	146	461	16	206
T0F2	4042	2855	7.8	14.2	19.1	45.0	7.9	15.4	92	386	0	114
T0F2-2	3226	2262	9.1	16.8	21.1	50.1	8.9	17.8	112	446	0	208
T1F0	1972	1922	10.0	15.3	15.6	35.4	9.8	15.4	88	300	2	101
T1F1	1817	1718	10.1	16.8	14.5	38.4	9.2	16.6	79	339	0	160
T1F1-1	1819	1805	10.5	17.6	16.3	43.7	10.4	18.5	95	405	4	207
T1F2	2015	1916	9.6	17.1	14.6	44.1	8.4	16.5	76	383	2	181
T1F2-2	2089	1768	10.1	18.7	16.8	48.6	10.2	19.9	101	490	2	272
T2F0	896	896	10.8	18.7	8.3	24.7	9.9	16.9	46	212	2	112
T2F1	939	915	10.8	20.6	8.6	30.4	10.6	19.5	49	290	0	186
T2F1-1	890	865	11.0	21.5	8.5	31.4	10.5	20.0	48	309	2	208
T2F2	915	915	10.8	22.0	8.4	34.8	9.8	19.4	45	319	0	221
T2F2-2	878	853	11.1	23.1	8.5	35.8	10.3	20.3	48	346	1	244

[a] Merchantable volume at 17.5 cm dbh limit.

TABLE 2. Periodic annual increments, 0–15 years, and percent of control for various stem parameters by treatment (data from Gardner 1990). Refertilization was done at year 9.

	dbh		Basal area		Height		Net volume		Merc volume [a]	
Treatment	(cm)	%	(m^2/ha)	%	(m)	%	m^3/ha	%	(m^3/ha)	%
T0F0	0.18	100	1.38	100	0.27	100	15.3	100	4.4	100
T0F1	0.26	144	1.56	113	0.41	152	17.5	114	7.7	175
T0F1-1	0.32	178	1.63	118	0.49	181	21.0	137	12.7	289
T0F2	0.34	189	1.73	125	0.47	174	19.6	128	7.6	173
T0F2-2	0.42	233	1.93	140	0.52	193	22.3	146	13.9	316
T1F0	0.33	183	1.32	96	0.38	141	14.1	92	6.6	150
T1F1	0.42	233	1.58	114	0.48	178	17.3	113	10.7	243
T1F1-1	0.44	244	1.83	133	0.51	189	20.7	135	13.5	307
T1F2	0.47	261	1.97	143	0.52	193	20.5	134	11.9	270
T1F2-2	0.51	283	2.12	154	0.61	226	25.9	169	18.0	409
T2F0	0.52	289	1.09	79	0.47	174	11.1	73	7.3	166
T2F1	0.64	356	1.45	105	0.59	219	16.1	106	12.4	282
T2F1-1	0.68	378	1.53	111	0.63	233	17.4	114	13.7	311
T2F2	0.74	411	1.76	128	0.64	237	18.3	120	14.7	334
T2F2-2	0.79	439	1.82	132	0.66	244	19.9	130	16.2	368

[a] Merchantable volume, 17.5 cm dbh limit, 10-cm top.

4.1.1 Height

The time trend for height growth response is shown in Figure 2 indicating a continuous response to both thinning and fertilization to year 12 (Barclay and Brix 1985a). This is still evident at year 15 (Gardner 1990).

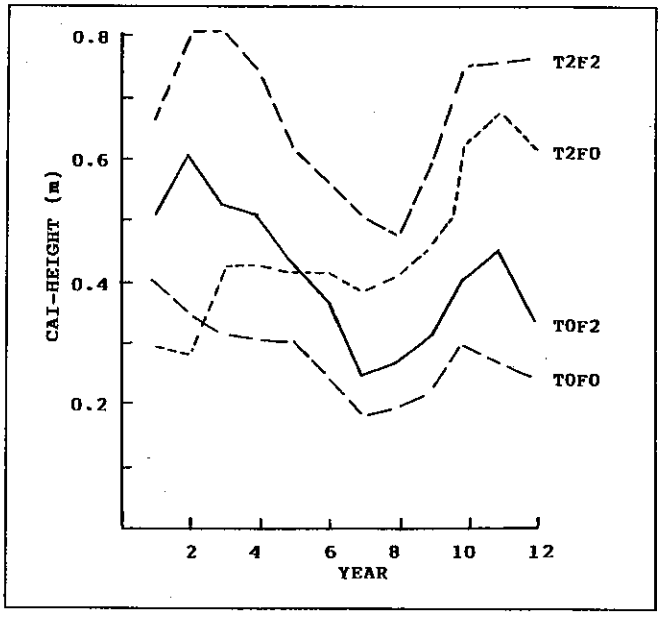

FIGURE 2. Height growth increments in years since treatments for 1971 plots (adapted from Barclay and Brix 1985a).

Thinning decreased height in growth the first 1–2 years. This so-called thinning shock has been commonly observed in coastal Douglas-fir. Shoot elongation in the crown is also reduced during this period (Brix 1981a). The sudden exposure of shade-grown foliage to higher light intensity and increased transpiration and respiration have been suggested as explanations. Although these factors may have had contributing effects, the shock does not appear to be associated with a reduced productivity because diameter and volume growth are increased. Experiments with stayed and free-swaying trees (Larson 1963) suggest that new bending stresses developed after thinning result in redistribution of growth (Brix 1983). It is noticeable that fertilization has increased height growth at all thinning levels, even in the first two years.

Early European research did not show any effect of thinning on height growth (Braathe 1957). This led to the general notion that height growth was independent of stand density and was reassuring for the use of height as an indicator of site quality. However, apart from the initial response to thinning, the overall increase in height was considerable, and this has implications for site index determination. Other thinning trials with Douglas-fir and trials with plantation spacing have shown similar effects (Smith and Reukema 1986). Thinning decreased tree and soil water stress during June when height growth takes place (see Section 8.2). This could be one explanation for the thinning effect on height growth. This influence would not occur on sites that do not suffer from a severe drought during height growth.

4.1.2 Diameter

Diameter increment with heavy thinning was greater than increment from fertilization but the average diameter of the 250 and 500 crop trees per hectare was similar for the two treatments. Over the 15-year period, dbh increment was almost doubled by F2, tripled by T2, and more than quadrupled by T2F2 (Table 2). Increments were greatest for the largest trees in all treatments, although when relative growth rates were considered, the smallest trees benefited the most from thinning.

4.1.3 Stem form

The effect of thinning and of fertilization on distribution of area increment along the stem was studied by Thomson and Barclay (1984). Thinning, but not fertilization, had an effect over the 9-year response period. A below-average area increase above the base of the live crown and an above-average increase below this point was noted. These responses increased the stem taper. The effect declined from the 4- to 6-year period to the 7- to 9-year period. As discussed above, tree swaying will initially affect this redistribution of growth and, subsequently, the deeper crowns resulting from thinning (Section 7.3) will have a contributing effect. As concluded by Smith and Reukema (1986) it seems likely that once crowns lift with progression of crown closure, the taper of the lower bole will be influenced little by spacing.

Form quotients for use in volume equations were calculated from diameter measurements at breast height and at 10, 30, 50, 70, and 90% of total height above breast height. Thinning but not fertilization reduced form quotients at years 9 and 12 and volume equations were derived on that basis (Barclay *et al.* 1982; Barclay and Brix 1985a).

4.1.4 Volume

The total and merchantable volume (17.5 cm dbh limit) at years 0 and 15 are given in Table 1 and the periodic annual increments (PAI) for this period in Table 2. The volume data for 3-year periods are shown in Appendices 5–7. Thinning decreased the total volume and net volume increments because of the reduction in growing stock but increased the merchantable volume and merchantable increments. Fertilization greatly increased total and merchantable volumes within all thinning levels and responses were still evident 15 years after treatments (Gardner 1990). Over the 15-year period the yearly net volume growth was decreased 4.2 m^3/ha per year by heavy thinning alone (T2F0) and increased 4.3 m^3/ha per year with the high rate of fertilization (T0F2) and 3.0 m^3/ha per year by a combination of thinning and fertilization (T2F2), thus showing a considerable interaction. For the 250 and 500 crop trees per hectare thinning increased rather than decreased the total volume per hectare (Fig. 3). Fertilization increased the total volume of crop trees considerably.

4.1.5 Refertilization

This treatment, applied at year 9, increased volume growth above that of plots fertilized only once. In the heavily thinned plots this increase was still evident 6 years after refertilization, but in the unthinned plots an increase in volume growth was only observed for the first 3 years (Appendix 2, page 62). There was little or no difference in volume growth resulting from one application of 448 kg N/ha (F2) and from two applications of 224 kg N/ha (F1-1) up to year 15. The net volume increment with 448 kg N/ha was approximately double the increment with 224 kg N/ha at the T0 and T1 levels and slightly less at T2. The efficiency of fertilization (volume response per kg N) was therefore similar for different N rates and refertilization.

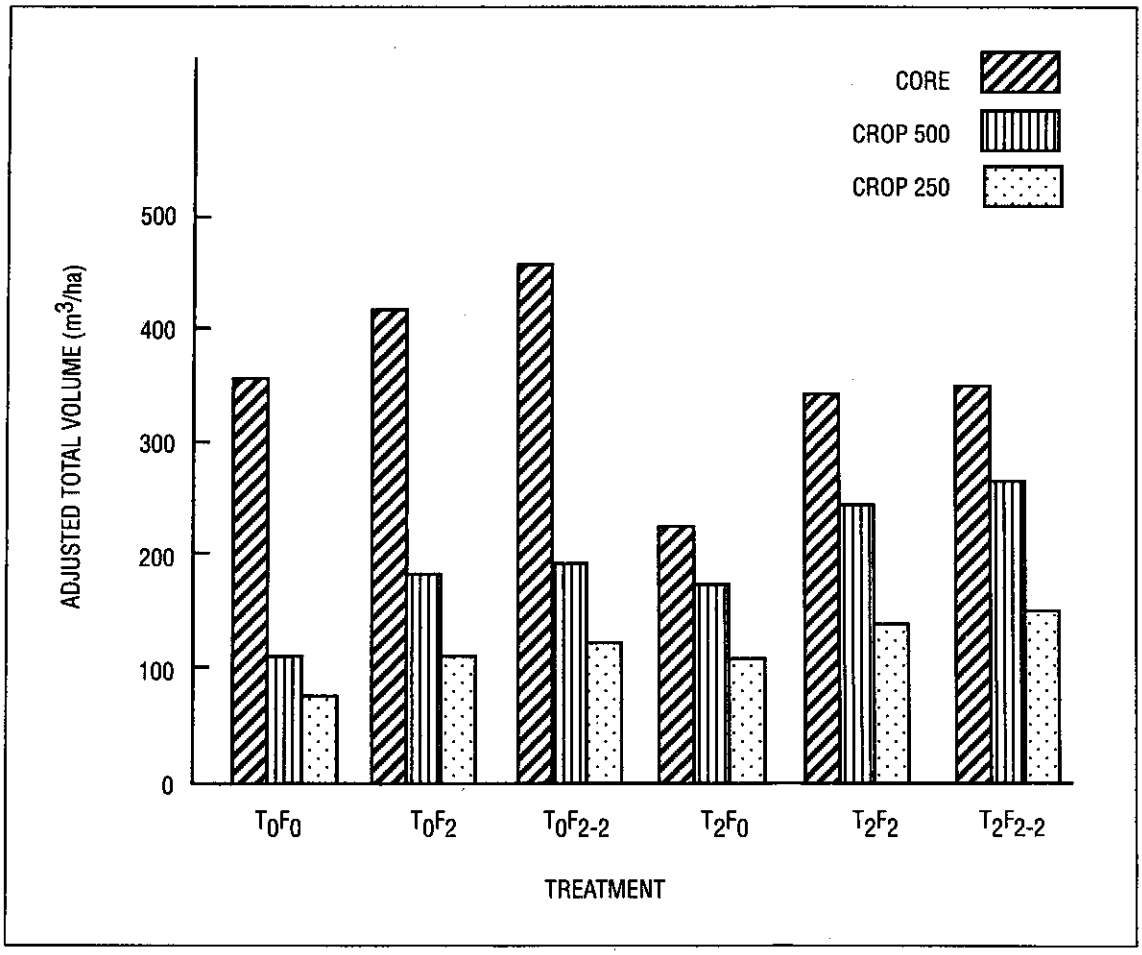

FIGURE 3. Adjusted total stand volume of core and crop trees for the six extreme treatments 15 years after initial treatment (from Gardner 1990).

4.1.6 Mortality

The number and volumes of trees that died in the 3-year periods since treatments are shown in Table 3. Adding these volume losses to the net volume increments shown above will give gross volume increments. The mortality and volume losses were high in unthinned stands but minor in T2 plots. Fertilization, and particularly refertilization, accelerated mortality greatly in unthinned plots and accounted for a volume loss as high as 1.65 m^3/ha per year for the 15-year period with T0F2-2 versus 0.43 m^3/ha per year in control plots. Mortality was primarily confined to small suppressed trees; snow and wind damage caused minor mortality, and a few trees died from root rot (Gardner 1990).

TABLE 3. Number and volume per hectare of trees that died during 3-year periods following thinning and fertilization

Year	0–3		3–6		6–9		9–12		12–15		0–15	
Treatment	No.	m^3/ha	No.	m^3/ha	No.	m^3/ha	No.	m^3/ha	No.	m^3/ha	No.	m^3/ha
T0F0	56	0.42	62	0.58	111	2.81	130	1.07	210	1.64	569	6.52
T0F1	37	0.16	74	0.45	87	0.40	222	2.33	173	3.26	593	6.60
T0F1-1	124	0.90	297	2.47	222	5.11	235	3.14	284	10.03	1162	21.65
T0F2	62	0.30	346	2.02	309	3.15	260	5.65	210	5.71	1187	16.83
T0F2-2	37	1.07	247	2.61	198	3.45	222	3.57	260	14.02	964	24.73
T1F0	12	0.48	6	0.25	12	0.48	0	0	19	1.03	49	2.24
T1F1	0	0	12	0.28	12	0.04	12	0.11	62	5.65	98	6.08
T1F1-1	0	0	0	0	0	0	37	0.50	49	1.13	86	1.64
T1F2	0	0	49	1.35	25	0.15	25	0.37	0	0	99	1.87
T1F2-2	0	0	49	1.07	62	1.27	74	2.08	136	10.20	321	14.62
T2F0	0	0	0	0	0	0	0	0	0	0	0	0
T2F1	0	0	0	0	0	0	0	0	25	1.99	25	1.99
T2F1-1	12	0.45	0	0	0	0	0	0	12	1.05	24	1.50
T2F2	0	0	0	0	0	0	0	0	0	0	0	0
T2F2-2	12	0.48	0	0	0	0	0	0	12	1.77	24	2.25

4.1.7 Diameter distribution

The distribution of trees in different diameter classes was influenced initially by thinning and subsequently by fertilization through effects on growth and mortality of suppressed trees (Gardner 1990). Heavy thinning in combination with all fertilizer levels resulted in a more uniform diameter distribution. Fertilization in unthinned stands had a similar effect by acceleration of mortality of the smaller trees. Most of the trees at year 15 were in the 5–15 cm dbh range in control plots and the 20–30 cm range in the T2F2-2 plots.

4.1.8 Inter-tree competition

Use of a competition index as a predictor of growth and mortality was investigated by Barclay and Layton (1990). They used the Competition Stress Index (CSI) developed by Arney (1973), which was incorporated in the Shawnigan growth and yield study at an early stage. The relative importance of CSI, initial dbh, thinning, and fertilization to 12-year increments of dbh, height, and volume was analyzed by stepwise linear regression. All thinning levels (T0, T1, T2) and four urea fertilization rates (F0, F1, F2, F4) were included. The initial dbh was the best predictor of dbh and volume increments, and fertilization was the best predictor for height increments; they both outperformed CSI. Mortality was related to CSI, although a clear distinction of a CSI leading to mortality was not obtained.

4.2 High Rates of Nitrogen

Some plots were fertilized with 672, 896, and 1344 kg N/ha (F3, F4, F6, respectively), also as urea, to study possible beneficial or harmful effects of these high application rates. These were applied at three thinning levels (T0, T1, T2) except for F3, which was only applied at the T2 level. The diameter and volume increments

over a 9-year period increased with rate of application at all thinning levels but with the best response at T2 (Barclay and Brix 1985b). The fertilizer efficiency, as measured by stem volume response per unit of N applied, decreased with rate of N application. The efficiency with F6 was only about one-third of that with F1 at T2 thinning, but this may improve with time. An analysis of foliar nitrogen concentrations following fertilization showed a low concentration with F6 in the fall of the first year but the highest concentration with this rate in the second year (see Section 8.1). This could indicate a temporary harmful effect of F6 on N uptake, possibly as a result of root injury or a drastic change in soil pH.

4.3 Source of Nitrogen

Urea has been used exclusively in operational fertilizer applications in the U.S. Pacific Northwest and in British Columbia as a result of a good response in empirical trials. Its high concentration of nitrogen also provides a cost advantage in application. However, insufficient trials have been conducted with ammonium nitrate. In Sweden, growth has generally been better with ammonium nitrate and it has been used exclusively there for a number of years.

Ammonium nitrate and urea-fertilized plots (0, 224, and 448 kg N/ha), both thinned and unthinned, were used to compare nitrogen source growth response over a 7-year period (Dangerfield and Brix 1979) and after 9 years (Barclay and Brix 1984). The source of N did not affect height growth but ammonium nitrate was superior to urea in diameter and stand volume growth and more so in thinned than in unthinned plots (Barclay and Brix 1984). In thinned stands (T2) with the fertilizer rate of 448kg N/ha (F2) ammonium nitrate produced 3.8 m^3/ha per year more than the urea source over 9 years. A possible explanation is that thinning slash may bring about a greater microbial immobilization of urea than of ammonium nitrate; this is also indicated by a considerably higher foliar N concentration in ammonium nitrate plots during the first year as shown in Section 8.1. Aspects of soil solution chemistry and soil microbiology with these N sources are presented in Sections 9 and 11.

4.4 Understory Effect

The understory at Shawnigan is predominantly salal, bracken fern, and Oregon grape (see Section 2). The understory can affect tree growth in many ways— through allelopathy, by its effect on nutrient cycling, and by competition for water and nutrients. To obtain an indication of its overall effect on tree growth, one T2F2 plot (0.04 ha) established in 1973 had all its understory removed in early spring of that year and in years thereafter by clipping. Only one plot was available for this treatment and growth was compared with that in two other 1973 T2F2 plots with understory intact. Lack of replication prevented a proper growth analysis but in each of the plots eight co-dominant trees with the same dbh were selected for dbh growth comparisons (Fig. 4). Using this as a basis, it appears that understory removal during the first 5 years had a beneficial effect on tree growth, but there was possibly some slight negative effect after that time. Soil and tree water stress and tree foliar nitrogen concentrations were compared for these plots but no significant differences were detected.

5 BIOMASS

As a contribution to studies of treatment effects on total productivity and carbon cycling in the ecosystem, the aboveground biomass of overstory and understory and distribution to tree components were studied. Associated analysis of nutrient contents was done as part of nutrient cycling studies and is reported in Section 10.3. Sampling was done at years 9 and 18, but only the 9-year results have been analyzed for presentation.

5.1 Overstory

The effect of thinning (T0 and T2) and nitrogen fertilization (F0 and F2) on aboveground biomass of Douglas-fir and the distribution of biomass to seven tree components, were studied 9 years after treatments (Barclay *et al.* 1986). Trees of different dbh classes were destructively sampled and regressions of tree biomass components to dbh were determined for each treatment. Using the plot dbh distribution, the

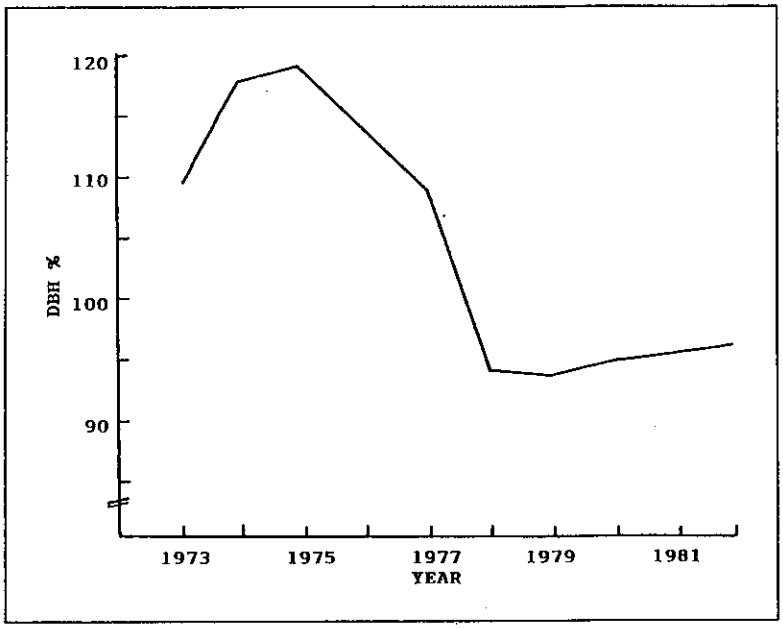

FIGURE 4. Diameter growth at breast height for trees in plot without undergrowth as a percentage of growth of trees in plots with undergrowth (Brix, unpubl. data).

aboveground biomass components after 9 years were calculated. The initial biomass at the time of treatment was not measured, but was estimated on the basis of the dbh of all plot trees at that time and the use of the T0F0 regressions in the above study. The net biomass productivity of each tree component during the 9 years was then calculated (Tables 4(a) and 4(b)).

The proportion of total biomass in wood decreased for both thinning and fertilization treatments while the proportions of new and old foliage and branches increased. In addition, thinning decreased the proportion of bark and dead branches. The total production of foliage was increased by both treatments. The treatments also increased the efficiency in wood production (i.e., production per unit of foliage), with the amount of foliage during the production period calculated as the mean of the amount present at the beginning and the end of the 9-year period (Barclay *et al.* 1986).

The study of tree component biomass for the different treatments, together with the nutrient element analysis, provided the basis for determining aboveground nutrient content and distribution and relationships to nutrient cycling (Section 10.3). Sampling for a similar study at year 18 has been completed and data are being analyzed.

Another study showed the effect of the same treatments after 5 and 7 years on biomass of aboveground tree components for the purpose of analyzing the relative importance of foliage quantity and efficiency in tree growth response (Brix 1983). This is discussed in Section 8.5.

5.2 Understory

The aboveground biomass of the two dominant understory species (salal and bracken fern) was determined by destructive sampling in 1977 (Stanek *et al.* 1979). The 38 plots used were from the basic experiment. Thinning increased the biomass of both species and fertilization decreased the biomass except with heavy thinning (T2) where there was no significant effect (Table 5). Treatment effect was related to stand canopy development and the changes in light intensity below the canopy. The nitrogen content of these species is reported in Section 10.3. An evaluation of understory competition for tree growth is given in Section 4.4.

TABLE 4(a). Accumulated component dry weights of Douglas-fir for four thinning and fertilizer combinations at 9 years following treatment (Barclay *et al.* 1986)

	Mean component weight (t/ha)			
Component	**T0F0**	**T0F2**	**T2F0**	**T2F2**
Wood	98.895	100.410	47.816	69.336
Bark	17.034	17.034	7.963	11.051
Dead branches	7.096	7.174	1.667	2.038
New foliage	2.186	2.516	1.557	2.168
Old foliage	7.580	9.133	5.833	8.907
New twigs	0.517	0.617	0.313	0.478
Branches	9.328	12.518	8.320	13.456
Total	**145.200**	**151.100**	**74.054**	**108.300**

TABLE 4(b). Production for each component during the 9-year period following treatment

	Mean component weight (t/ha)			
Component	**T0F0**	**T0F2**	**T2F0**	**T2F2**
Wood	38.211	53.557	30.744	48.257
Bark	6.635	9.008	4.979	7.426
Dead branches	2.652	3.737	0.369	0.515
New foliage	0.991	1.604	1.225	1.722
Old foliage	3.544	6.062	4.737	7.380
New twigs	0.217	0.387	0.226	0.370
Branches	4.512	8.866	7.320	11.605
Total	**57.871**	**83.791**	**49.646**	**77.561**

TABLE 5. The aboveground biomass (kg/ha) of salal and bracken fern for plots with different thinning and nitrogen fertilization treatments (Stanek *et al.* 1979)

	Bracken fern			Salal		
	F0	**F1**	**F2**	**F0**	**F1**	**F2**
T0	76	38	46	2315	1221	1056
T1	327	189	89	3111	3194	1841
T2	468	488	382	3950	4869	3925

6 WOOD QUALITY

With increasing use of thinning and fertilization in forest management it has become a high priority to know the effects of these practices not only on wood volume but also on wood quality. The assistance of Forintek Canada Corporation was obtained to analyze the wood quality at Shawnigan.

A total of 48 trees was sampled in the early spring of 1984 from the 1971 plots that received the four treatments T0F0, T2F0, T0F2, and T2F2, and the 1972 plots that initially received the same treatments but were refertilized 9 years later (F2-2). The 1972 plots therefore had 3 years of refertilization effect on growth. Increment cores were collected at four stem heights — at breast height and at 25, 50, and 75 % of height above breast height. Ring width and ring density were determined (by X-ray densitometer) from pith to bark for all cores (Jozsa and Brix 1989).

Wood density was chosen as an indicator of wood quality because it is regarded as the single most important indicator of clear-wood quality, affecting many wood properties. Fertilization reduced wood density in the lower half of the stem for the initial 3–4-year period despite a continued response in ring width. The reduction period corresponds to the initial increase in foliar nitrogen concentration. The reduction averaged 16% and resulted from a decrease in percent latewood and in density of both earlywood and latewood. Thinning increased wood density slightly in the lower half of the stem and decreased density in the top. The trend was an increase in density from pith to bark and a decrease with increasing stem height. This pattern can be related to the distribution of low-density juvenile wood. The overall picture for both treatments is that changes in wood density, and therefore in associated wood properties, were not related to changes in ring width. Present log and lumber grading rules consider wide rings undesirable but the rules are the result of the fact that wide rings are often produced close to the pith and in treetops where density is low and juvenile wood is produced, thus giving low quality products (Megraw 1986). Wide rings in other stem positions resulting from thinning and fertilization could, as we have seen, produce high-density wood although the rings are wide. Nevertheless, the wide rings produced with thinning and fertilization treatments at Shawnigan will not meet the present grading requirement for peeler logs and better grades of lumber and sawlogs (6 rings or more per 2 cm diameter for best grade). A conversion to machine stress grading, which can be expected in the future, may alleviate this problem for lumber and sawlogs.

Of great concern is the increase in proportion of juvenile wood for a given log size with the increase in diameter growth during early stand development. The greater tendency for longitudinal shrinkage and twisting of lumber products as well as low wood density makes juvenile wood undesirable. Formation of juvenile wood appears to be associated with the region of the active crown (Smith and Briggs 1986). Stand management regimes affecting length of crown and its physiological activity may therefore influence the amount and location of juvenile wood. As shown in Section 7.3, thinning had doubled the length of the live crown 15 years after treatments and reduced the height to live crown compared to control. If the relationship between juvenile wood formation and crown size becomes more firmly established, it appears that pre-commercial thinning would increase, and fertilization without thinning decrease, the percentage of juvenile wood.

The section above deals with clear-wood properties but treatment effects on the number and size of knots, and whether they are tight (from live branches) or loose, are of primary concern. The average branch diameter (measured 3 cm from base) in different crown positions13 years after thinning and fertilization (together with the number of live branches) is given in Table 6 (Brix, unpubl. data). Both thinning and fertilization increased branch diameter although branches are still smaller than the limit of 4 cm for the best peeler and lumber grades. Fertilization had an effect on number of branches produced during the first 3-year period (whorl 12) and thinning influenced the number of live branches retained in the lower crown. However, both treatments increased the annual height growth (the distance between whorls), and thereby decreased the number of knots per unit stem length to almost one-half over the 15-year response period compared to control.

Stem taper, and thereby log utilization, has not been affected by fertilization but has been increased by thinning. This effect is reduced over time, as discussed in Section 4.1.3.

TABLE 6. Branch diameter (mm) 3 cm from branch base, and number of live branches in different whorls in relation to thinning and fertilization; fall 1983 sampling in 1971 treatment plots (Brix, unpubl. data)

	T0F0		T0F2		T2F0		T2F2	
Whorl	diam.	no.	diam.	no.	diam.	no.	diam.	no.
3	9.0	4.4	10.2	4.6	10.3	4.4	12.5	4.4
6	11.9	4.7	15.4	4.5	13.5	4.3	18.6	4.4
9	15.7	4.4	19.6	4.9	17.0	4.6	21.3	4.5
12	17.9	4.1	21.7	5.4	18.9	3.9	26.6	4.7
15	16.2	3.2	24.4	2.1	21.1	4.6	26.0	4.8
18	–	0.9	23.0	0.3	21.9	5.1	27.6	3.3

7 TREE GROWTH

7.1 Seasonal Patterns of Tree Growth

To relate tree growth response to stand treatment and site conditions, including climate, we should know when during the season the important growth events occur. To further explain growth, it is important to know how internal tree conditions and physiological processes progress during the season. For instance, a drought in July will have no effect on height growth in that year because height growth is completed. The seasonal pattern of growth and some physiological processes of Douglas-fir at the Shawnigan location are given in Figure 5 (Brix 1991). Diameter growth occurs from late April to early September, whereas height growth and shoot and needle elongation are usually limited to the month of June. Photosynthesis can take place all year, but the highest rate of photosynthetic activity occurs from March to October except for a slow-down during drought in July and August.

Diameter growth at breast height was measured weekly during the growing season with dendrometer bands on six co-dominant trees of initial uniform size per plot. Thinning increased dbh from the beginning of the first season even before new foliage was produced in June. The response to both treatments was more pronounced early (May–June) than late in the season (Figure 6; Brix unpubl. data). Measurements with dendrometer bands, however, are confounded by stem shrinkage when drought becomes critical in July and August and by stem swelling during soil re-wetting in September.

7.2 Xylem and Sapwood Development

Thinning, nitrogen fertilization, and the combined treatments increased diameter growth. A detailed study of xylem development investigated whether this was caused by a longer seasonal growth period, a higher rate of tracheid production, a greater width of individual tracheids, or a combination of these factors (Brix and Mitchell 1980). The rate of tracheid production, but not the duration, was highly affected by both treatments

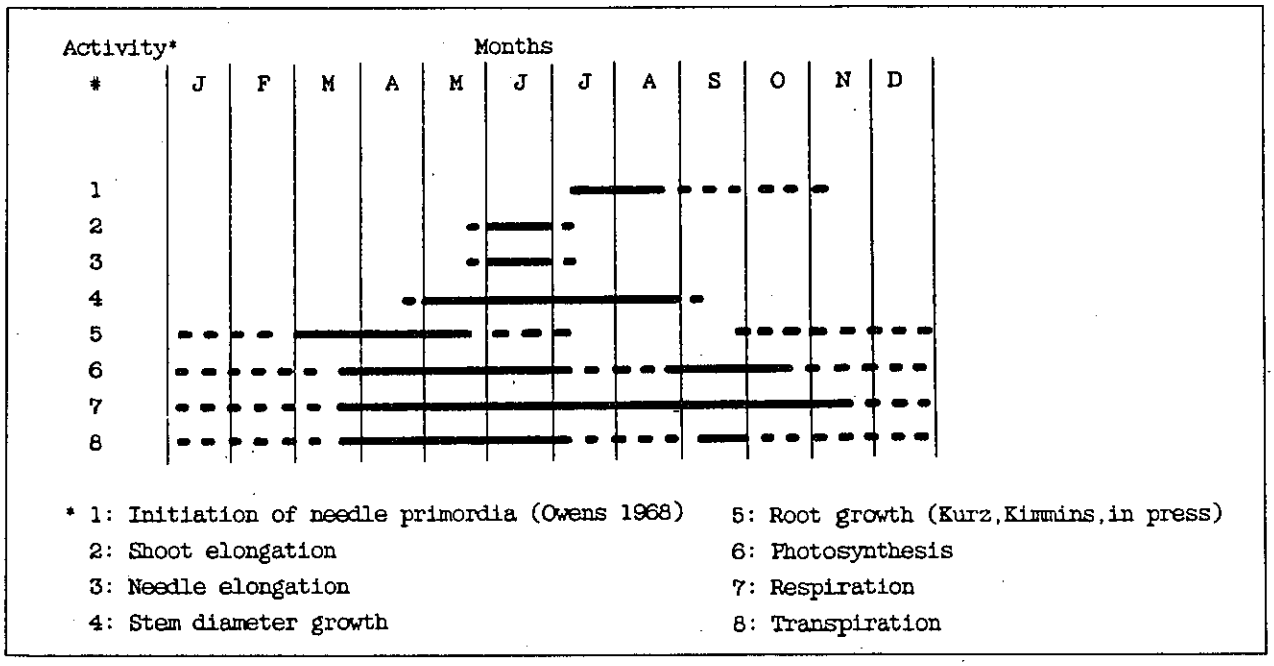

FIGURE 5. Periodicity of growth and of some physiological processes of Douglas-fir as related to the Shawnigan Lake, B.C. location (activities #1 and 5 have not been determined there). Solid lines indicate highest activity. Low activities in 5, 6, and 8 during July and August are caused by high soil water deficits (from Brix 1991).

individually and in combination (Fig. 7). Seasonally the rate was influenced by temperature until mid-July and thereafter some effect of soil water stress was apparent. Thinning had a minor effect on radial diameter of tracheids with a 6% increase in earlywood and 14% increase in latewood cells. Fertilization had no significant effect on tracheid diameter. No effect was found on the duration of cell production, which was from April 14 to September 15; the period of maximum cell production was in June to mid-July. The wall thickness of earlywood tracheids was increased by thinning but not by fertilization. The wall thickness of latewood tracheids was reduced by fertilization and the combined treatments. As a follow-up to this study, Mitchell (1984) investigated the effect of nitrogen fertilization at Shawnigan on seasonal cambial activity in lateral twigs. Mitchell showed that the increase in tracheid production in lateral twigs was related to an increase in the number of potentially dividing cells in the cambial zone whereas the rate of cell division in individual cambial cells was slightly reduced.

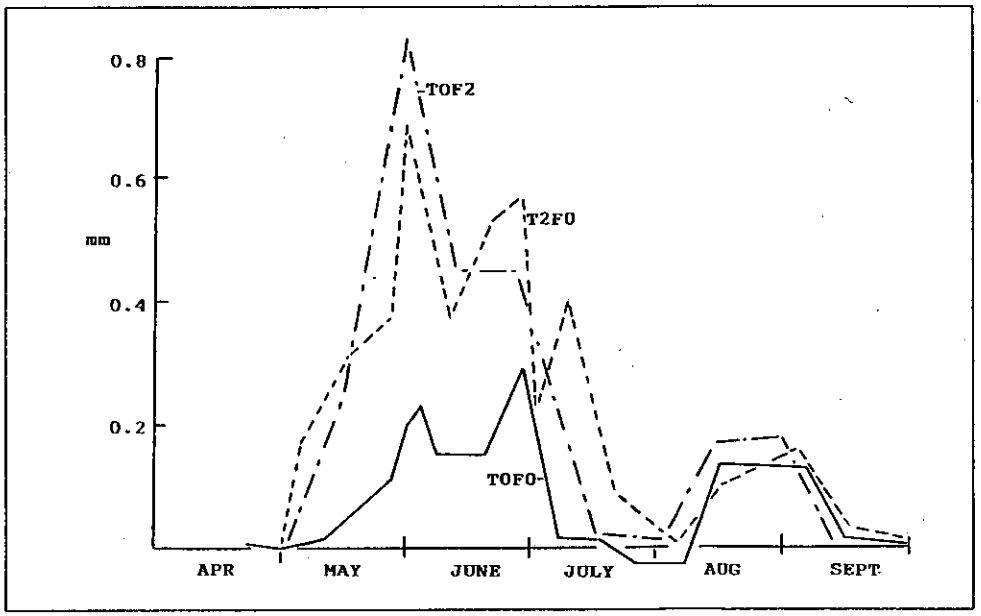

FIGURE 6. Weekly dbh increments in 1975 for 1972 plot trees (Brix, unpubl. data).

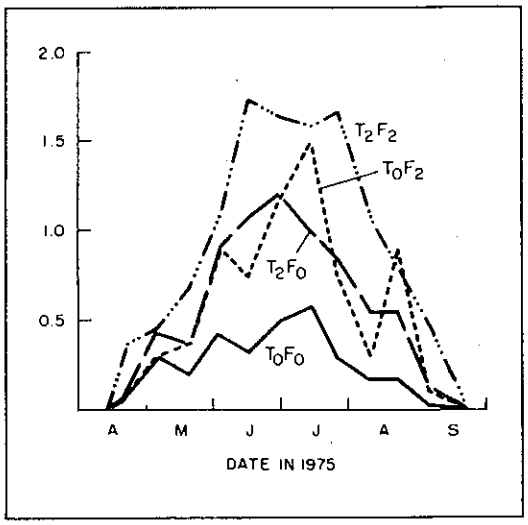

FIGURE 7. Rates of radial file tracheid production during the 1975 growing season, with four thinning and fertilization treatments (from Brix and Mitchell 1980).

Sapwood serves as a transport pathway for soil nutrients and water to tree crowns. Some recent studies have indicated a relationship between sapwood cross-sectional area and foliage quantity that could be based upon the functional role of sapwood in water translocation (Whitehead and Jarvis 1981). This relationship could provide a convenient means of determining the otherwise difficult to measure quantity of crown foliage and was the reason for studying a possible influence of stand treatments on relationships between sapwood and foliage. Furthermore, wood quality is also influenced by the quantity of sapwood, which is less durable than heartwood. The fertilization and thinning treatments did not affect the percent of sapwood at breast height. The width of sapwood remained relatively constant up the stem where heartwood was present, but the number of annual rings in the sapwood decreased with stem height. The relationship of sapwood to foliage quantity is discussed in Section 7.3.

7.3 Crown Development

The development of the crown with respect to branch elongation and quantity and distribution of foliage was studied as a basis for investigating its effect on growth response to thinning and fertilization. Treatments investigated included two levels of thinning (T0, T2) and three levels of urea fertilization (F0, F1, F2). Crown development was followed over a 7-year period (Brix 1981a).

The needle mass per tree after 7 years was increased 90% by thinning as well as by heavy fertilization, and by 271% with combined fertilization and thinning. The leaf area index (LAI: one-side leaf area per unit of ground area) for the stands at year 7 was 5.9, 3.0, 8.8, and 6.4 for T0F0, T2F0, T0F2, and T2F2, respectively. Reduction in growing stock with heavy thinning (T2) still had a considerable effect on the LAI at year 7 when applied alone, but when combined with fertilization (T2F2) the LAI recovered to the control level.

Crown development following thinning and fertilization was distinctly different. With fertilization the annual needle production was highest 23 years after treatment and resulted from an increase in shoots, needles per shoot, and size of needles (Fig. 8). The total mass per tree was highest 7 years after fertilization. The effect of thinning was a gradual increase in needle mass throughout the study period. Fertilization had most effect in the top half of the crown whereas thinning had most effect in the bottom half (Fig. 9; Brix 1981a).

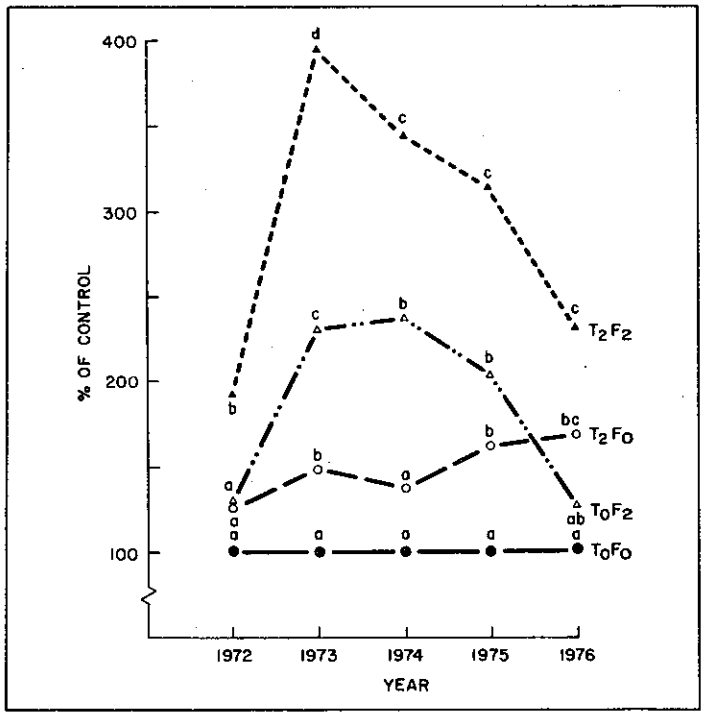

FIGURE 8. Yearly needle production for the crown each year since thinning and fertilization treatments (spring 1972) as a percentage of needle production for control trees. Data for the same year not followed by the same letter are significantly different ($P = 0.05$) (from Brix 1981a).

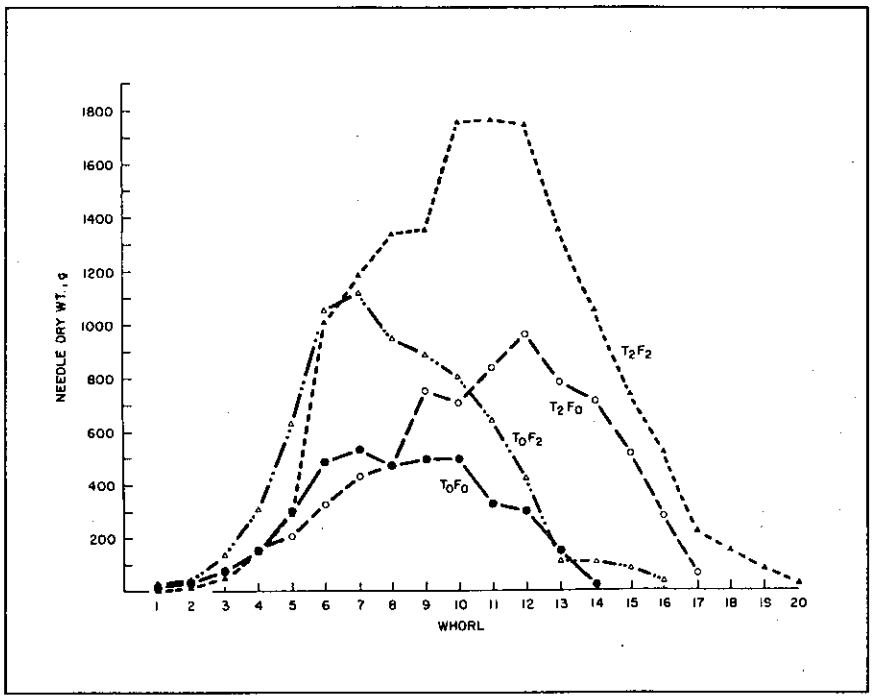

FIGURE 9. Distribution of needle dry weight within the crown 7 years after thinning and fertilization treatments (from Brix 1981a).

Branch elongation was studied for co-dominant trees over a 5-year period after treatments (Brix 1981a). Fertilization increased branch elongation at all crown levels in the first year. The effect lasted 4 years at whorls 6 and 9 but only 2 years at whorl 12. As was the case with stem leader growth, thinning decreased branch leader growth for the first 23 years but increased it later; there was little overall effect for the 5-year period down to whorl 12. However, by retaining the longer branches below this whorl, the crown width was increased by thinning. For the 5-year period, the average shoot length on main branches in whorl 9 was increased 5, 26, and 12% by thinning, fertilization, and the combined treatments, respectively.

Live crown length for different treatments is given in each of the 3-year growth and yield reports. At year 15, crown lengths (m) and percent of tree height were 5.3 (37%), 6.0 (38%), 10.6 (63%), and 10.5 (54%) for the control, T0F2, T2F0, and T2F2, respectively (Table 10; Gardner 1990). This revealed a small effect of fertilization but a considerable effect of thinning. Heights to live crown for these treatments were 9.0, 9.8, 6.2, and 8.9 m, respectively.

Crown structure is affected by foliage distribution within the crown, proliferation of shoots, as well as crown length and width. These properties are influenced differently by thinning and fertilization (Brix 1981a). In turn, these properties will affect the light regimes in the crown and light utilization (Section 8.4) and, thereby, growth.

Quantification of tree and stand foliage by direct sampling is very time-consuming and possible relationships to other more easily measured tree parameters have therefore been the subject of many studies. A relationship to sapwood cross-sectional area at breast height was gaining acceptance without consideration of possible effects of stand and site conditions. There was a considerable influence of thinning and fertilization on this relationship even when the sapwood area was measured at the base of the live crown (Brix and Mitchell 1983). This limits the usefulness of this index in determining foliage quantity. Also, the attempt to quantify foliage from light measurements below the crown has not been successful.

7.4 Root Growth

The Shawnigan project plan called for root studies as staff became available. Heavy commitments in other project areas and resource restraints meant that only a few attempts were made to study root growth and no significant contribution was made. Studies by others during the course of the project (e.g., Keyes and Grier 1981, Kurz 1989) showed that Douglas-fir root production, particularly of fine roots, can be greatly influenced by site quality with a decreasing proportion of the total production being allocated to root growth with increase in site quality. Kurz (1989) found that fine root production could account for over 50% of the total net primary productivity in some second-growth coastal Douglas-fir ecosystems.

As shown in Section 8.5, fertilization effect on aboveground dry matter production per unit of foliage during the first 3–4 years after treatment at Shawnigan was more than twice the production that could be accounted for by an increase in the rate of photosynthesis. This suggests a shift in dry matter allocation with fertilization during this period, with more of the total production being allocated to aboveground components and less to roots (Brix 1991).

A contract under the Canada–British Columbia Forest Resource Development Agreement (FRDA) provided for studies of thinning effects and resulting changes in soil moisture regime on fine root growth and mortality at Shawnigan (Kurz *et al.* in press). Greenhouse studies of soil moisture effects on seedling root growth using root observation boxes and the technique of split root systems were also included. At Shawnigan the seasonal dynamics in live and dead fine-root biomass were similar in thinned and unthinned plots. Live-root biomass did not decrease until September, when soil moisture deficit had increased greatly. Reduction was higher in thinned plots (70%), in spite of less water deficit, than in unthinned plots (54%). Factors other than soil water deficit, such as higher soil temperature, may therefore have contributed to fine root mortality in thinned plots.

8 TREE PHYSIOLOGY

To explain stand treatment effects on growth we should know how treatments affect the environment, and how this in turn influences internal tree conditions and physiological processes. As Professor P.J. Kramer at Duke University used to tell his forestry students "to grow trees successfully we must know how trees grow." With regard to environment changes in soil chemistry and soil water relations were studied and these have been related to tree nutrient and water status. The light regime in the canopies was determined. The most important processes in explaining forest productivity are photosynthesis and respiration. About 75% of the tree mass is comprised of carbohydrates — the direct products of photosynthesis. Photosynthates form the basis of all organic compounds, which make up some 85–90% of tree dry matter. A considerable proportion of photosynthates is subsequently expended in respiration, whereby energy is made available for maintenance and growth of living tissues. Dry matter production is therefore primarily determined by the difference in rates of these two processes.

The photosynthetic capacity of a forest stand depends upon several characteristics of the canopy affecting the utilization of available light: 1) the size of the crowns; 2) the structure of the crowns; 3) the total amount of foliage; and 4) the photosynthetic efficiency of the foliage. This last characteristic is influenced by internal factors, including the water and nutrient status, the light and temperature regime during foliage development, and the demand for photosynthates (sinks) in other parts of the tree. Changes in efficiency will occur during aging of foliage. Actual rates of photosynthesis will be influenced not only by environmental effects on internal foliage conditions, but also more directly by light and temperature. Production of usable wood depends upon partitioning of total photosynthates into this component of the tree.

These studies have dealt with thinning and nitrogen fertilization effects on the environment of light, temperature, nitrogen, and water, and the resulting effects on foliar nitrogen and water status and rates of photosynthesis. Rates were measured for foliage of different ages and stages of development and during different seasons. Interactions of environmental and internal conditions (light, temperature, water, and

nitrogen) on rates of photosynthesis have received special attention in order to clarify the effects of nitrogen fertilizer on growth in different environments and with different thinning regimes. Rates of respiration of branches have been studied for different seasons and stages of development in relation to nitrogen status.

Crown development was studied focussing on size (crown depth and branch elongation), structure (branch number and distribution), and amount and distribution of foliage of different age classes. Analysis of growth response addressed the question of the relative importance of treatments to amount of foliage and efficiency of foliage (production per unit of foliage) during the growth response period. The dry matter production per unit of foliage over a period of time (net assimilation rate) takes into account respiratory losses. This rate also provides a useful integration of all other factors under study that affect the efficiency of foliage in dry matter production.

8.1 Foliar Nutrient Status

The nutrient content of aboveground tree components has been reported by Webber (1974, 1977) and Pang *et al.* (1987) and is under study in the Shawnigan plots 18 years after treatments. These studies are primarily related to the effect of treatments on nutrient use and nutrient cycling and are reviewed in other sections. Here we deal with the effect of treatments on foliar nutrient status as it affects physiological processes and growth.

Trees sampled for foliar analysis were treated with various sources (ammonium nitrate and urea) and rates of nitrogen applications (i.e., 0, 448, 896, and 1344 kg N/ha, designated F0, F2, F4, and F6, respectively). Fertilization treatments were combined with two levels of thinning (T0 [control] and T2 [⅔ of basal area removed]). Changes in foliar N concentration in years since treatments are shown in Figures 10 and 11. The N source effect was presented in Brix (1981b) and Dangerfield and Brix (1979).

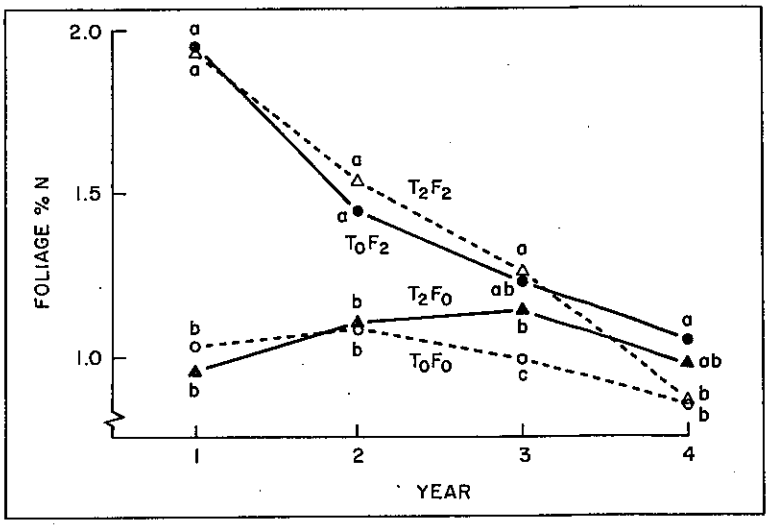

FIGURE 10. Foliar N concentration (% of dry weight) in years since N fertilization (F2:448 kg N/ha as urea) and stand thinning (T2: two-thirds of basal area removed); F0 and T0 are control treatments. Data means with same letters in any one year are not statistically different ($P = 0.05$) (from Brix 1991).

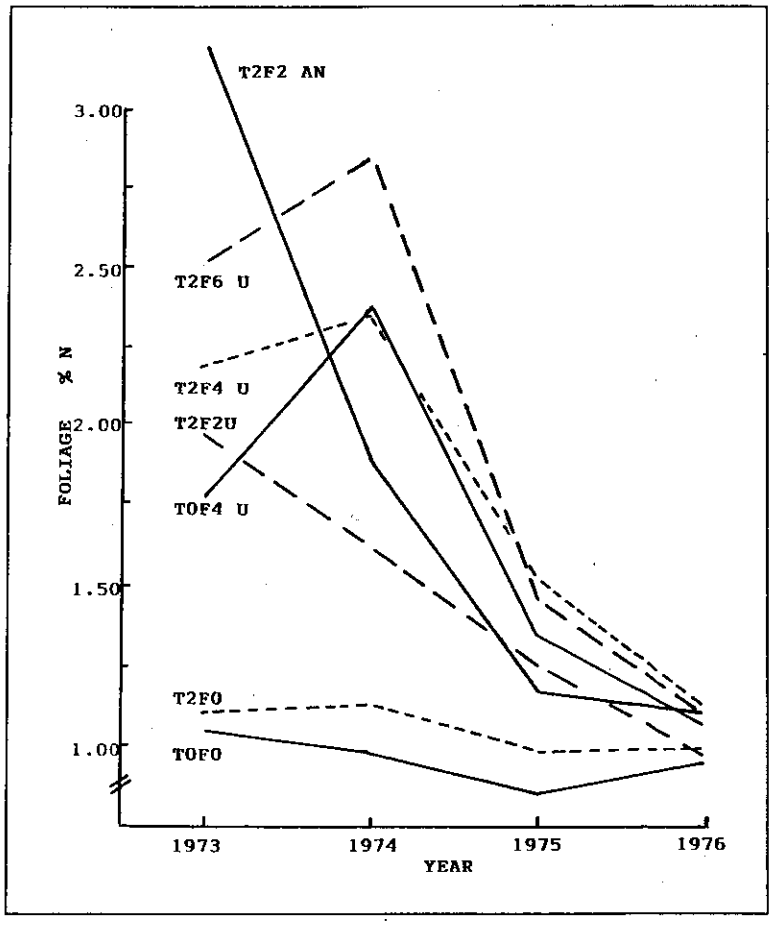

FIGURE 11. Foliar N concentration (% of dry weight) in years since N fertilization with different rates and sources (U = urea, AN = ammonium nitrate) and at different thinning levels (Brix, unpubl. data).

Foliar nitrogen concentrations increased greatly during the first growing season following fertilization in March and more so with ammonium nitrate than with urea. Concentrations were higher in the fall (October) than in the summer (mid-July) during the first 2 years (Table 7). After the first year the foliar N concentration decreased rapidly and was close to the control 4 years after application of 448 kg N/ha. With the high fertilizer rates (F4,F6) the concentrations increased in the second year but were back to control levels by year 4. The decrease is attributed to a dilution effect resulting from increased growth and immobilization of the remaining fertilizer in the soil.

Thinning had little or no influence on foliar N concentrations, with or without fertilization. Growth responses to thinning cannot, therefore, be attributed to improved nitogen nutrition.

TABLE 7. Changes in foliar nitrogen concentrations (% of foliage dry weight) for current foliage with season and with years since fertilization (March 1973) for trees with different thinning and fertilization treatments (Brix, unpubl. data)

	Summer			Fall			
Treatment	1973	1974	1975	1973	1974	1975	1976
T0F0	0.92d[a]	0.93e	0.94d	1.04d	0.99e	0.85e	0.98b
T2F2	1.33c	1.40d	1.15c	1.96c	1.62d	1.26cd	0.98b
T2F2[b]	2.90a	1.63c	1.19c	3.21a	1.87c	1.18d	1.12ab
T2F4	1.54b	1.99b	1.36b	2.21bc	2.33b	1.35bc	1.08ab
T2F6	1.25c	2.28a	1.47a	2.52b	2.83a	1.48ab	1.19a
T0F4	1.31c	2.01b	1.54a	1.78c	2.37b	1.52a	1.14ab
T2F0	–	–	–	1.10	1.13	0.98	–

[a] Means followed by same letter in the same column are not significantly different ($P = 0.05$) using the Student-Newman-Keuls' multiple range test.

[b] Fertilized with ammonium nitrate; urea used in other treatments.

Studies of foliar concentrations of N, P, potassium (K), and S following refertilization with N in 1981 indicated a possible N-induced deficiency of P and S (Brix *et al.* 1988). Growth response to P and S with N fertilization is being investigated in plots established in the spring of 1987.

8.2 Tree and Soil Water Relations

The foliage area of Douglas-fir at Shawnigan was increased by as much as 50% by nitrogen fertilization by year 7 (Brix 1981a) and it seems possible that transpiration could therefore be increased to the extent that an induced water stress would lead to no response or even a negative response on dry sites and in dry years. This has been found with radiata pine in Australia (Landsberg 1986). Thinning, on the other hand, could have the opposite effect by reducing total foliage area.

Soil and tree water potential were measured at Shawnigan over a 10-year period following fertilization and thinning (Brix and Mitchell 1986). Thinning increased soil water potential (reduced the stress) by as much as 1 MPa with and without fertilization during the dry summer periods, July–September (Fig. 12). This improved

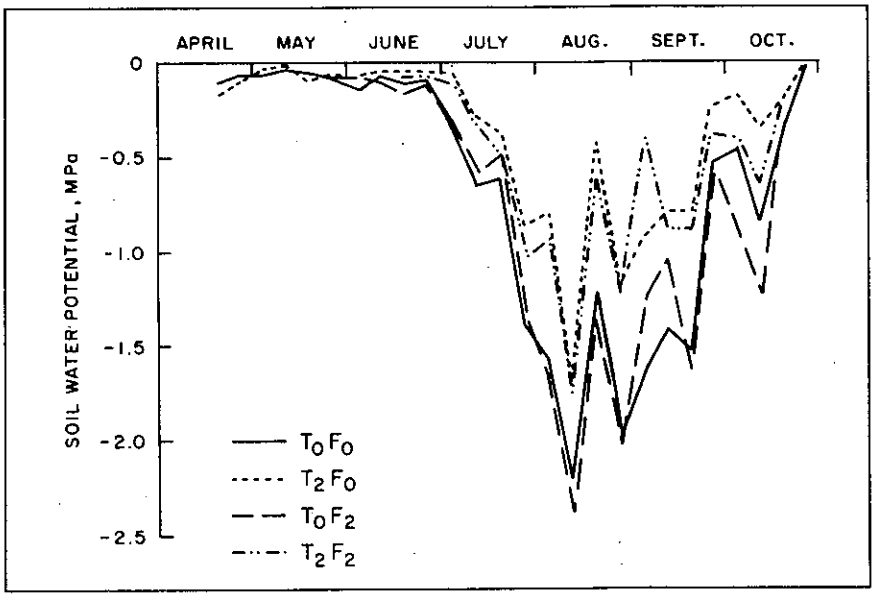

FIGURE 12. Seasonal changes in soil water potential for different thinning and N fertilization treatments averaged for three soil depths and for the years 1972–1981 (from Brix and Mitchell 1986).

the shoot water potential during pre-dawn and early morning but not later in the day because of greater crown exposure. The effect of nitrogen fertilization was slight and only apparent later in the study, in spite of the increased foliage area. This was possibly because of improved stomatal control of water loss. The understory, which was removed in one plot, had no significant effect on soil and tree water stress. The relationship of the rate of photosynthesis to water stress and interactions with foliar nitrogen and light intensity are given in the next section.

8.3 Photosynthesis and Respiration

Studies were done primarily in the laboratory under controlled conditions of light, temperature, CO_2, and water using excised shoots from a Douglas-fir stand in the Greater Victoria Watershed. Trees were similar in age and size to those at Shawnigan and their location provided easy access for study on the day of collection.

The first study (Brix and Ebell 1969) was done with trees fertilized two years previously and did not show a pronounced effect on rates of photosynthesis. A subsequent, more intensive study measured rates of these processes at different stages of shoot development throughout the first and second year following a spring application of nitrogen (Brix 1971). Rates were measured periodically for detached shoots under controlled, favourable light and temperature conditions (photon flux density of 500 µmol/m^2 per second; 20°C). Except for brief periods, fertilization increased the rate of photosynthesis from early July of the first season until the end of July of the second season but not thereafter (Fig. 13). This lack of response was related to a decline

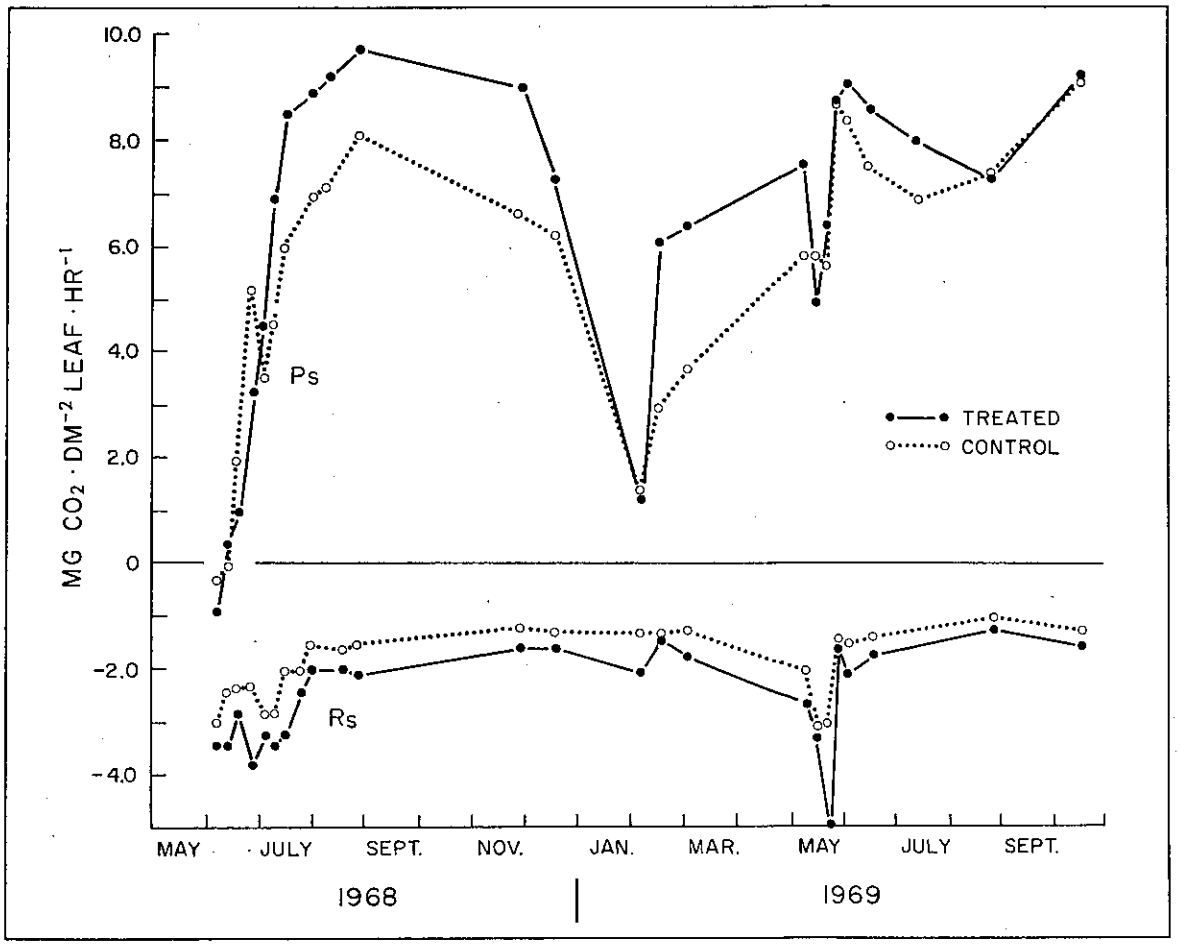

FIGURE 13. Net photosynthesis (Ps) and dark respiration (Rs) for current shoots in 1968 and 1-year-old shoots in 1969 of Douglas-fir trees treated April 1968 (from Brix 1971). (Reprinted from *Forest Science* [vol. 17, no. 4] published by the Society of American Foresters, 5400 Grosvenor Lane, Bethesda, MD 20814-2198. Not for further reproduction.)

in foliar nitrogen concentration of fertilized trees. The photosynthetic capacity of fully developed foliage remained high all year except for a period in February following a cold spell. This indicates that considerable amounts of photosynthates can accumulate during the growth dormant season and fertilization response may be present during periods when light and temperature are favourable. Rates of dark respiration of shoots were increased by fertilization throughout the 2-year period and particularly during peak rates in mid-May when buds were expanding.

The previous study indicated that the response of photosynthesis to nitrogen fertilization was affected by changes in foliar N during the study period. A subsequent study established the relationship of photosynthetic rate to foliar N concentration for trees treated with a range of N rates from 0 to 896 kg N/ha using ammonium nitrate and urea as N sources (Brix 1981b). A significant relationship was established with an optimum rate at 1.74% foliar N and a 30% increase in rate from a foliar N of 1.0% (Fig. 14). The rate decreased at above optimum N. The relationship was not affected by the N source.

The above studies were done with shoots kept well watered and under favourable light and temperature conditions. The effect of light and temperature and water stress on the reponse in rate of photosynthesis to nitrogen nutrition has also been investigated to interpret and predict nitrogen effects under different environmental conditions. No significant effect of N was found with a photon flux density (PFD) below 400 $\mu mol/m^2$ per second, and the effect increased with increase in PFD up to 1000 $\mu mol/m^2$ per second (1000 ft-c) at 20°C (Brix 1971) (Fig. 15). A study of N interaction with temperature is preliminary and was only done for shoots collected in September and October (Brix, unpubl. data). A 20–30% increase in photosynthesis was found in the temperature range of 0–25°C. The response was reduced with higher temperatures, and photosynthesis ceased at 42°C. The water potential of the shoots had a pronounced effect on the rate of photosynthesis, but the effect was not influenced by the nitrogen status of the foliage (Brix 1972). The response to N remained the same in relative terms, although not in absolute terms, irrespective of the shoot water potential (Fig. 16). Rates began to decrease at a water potential of -1.0 MPa and photosynthesis ceased at -3.5 MPa.

The mechanism of the response in rate of photosynthesis to nitrogen nutrition has received some attention (Brix 1971; Mitchell 1988). Nitrogen fertilization increased chlorophyll (a+b) concentrations up to 130% for current shoots. In spite of this, the photochemical reactions were only slightly enhanced, as indicated by the minor increase in rate of photosynthesis at low light intensities (Brix 1971). The major increase in photosynthesis rate at light saturation for fertilized shoots can result from an increase in activity of biochemical reactions as shown for the enzyme Rubisco by Mitchell (1988) and as also shown by an increase in stomatal conductance to CO_2.

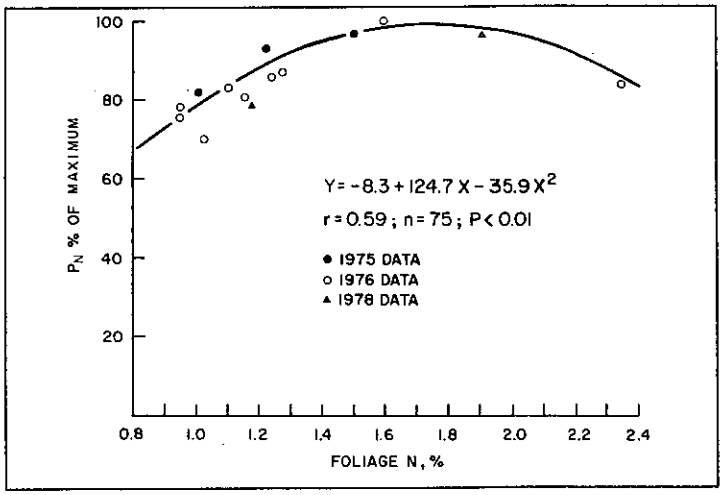

FIGURE 14. The rate of net photosynthesis (Pn) for current shoots of Douglas-fir in relation to foliar N concentration using trees fertilized in different years. Rates are expressed as a percentage of the highest treatment mean which was obtained with 448 kg N/ha as ammonium nitrate (from Brix 1981b).

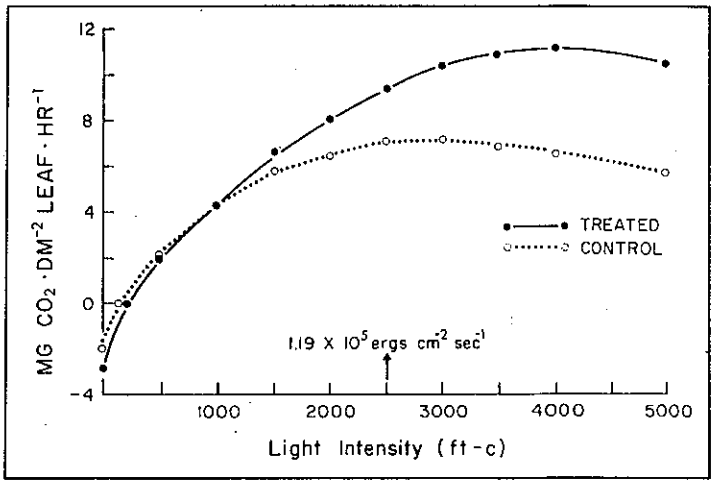

FIGURE 15. Effect of light intensity on net photosynthetic rate of current shoots of Douglas-fir trees treated in 1969. Rates were measured during the period 25 June to 10 July 1969 (from Brix 1971). (Reprinted from *Forest Science* [vol. 17, no. 4] published by the Society of American Foresters, 5400 Grosvenor Lane, Bethesda, MD 20814-2198. Not for further reproduction.)

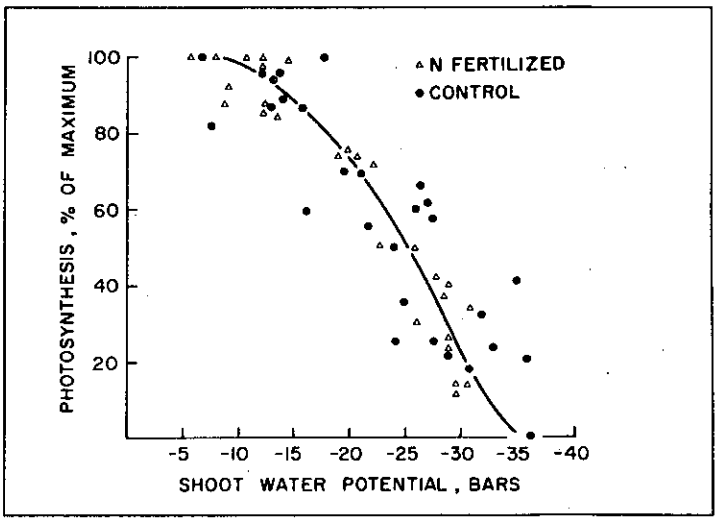

FIGURE 16. Effect of shoot-water potential on the rate of photosynthesis for N fertilized and unfertilized trees (from Brix 1972).

8.4 Light Regime

The change in stand density and crown structure following thinning will affect the light regime in the crowns and will thereby affect the rate of photosynthesis. To get an indication of this effect, the light intensity (photosynthetically active radiation [PAR]) was measured in 18 locations in tree crowns in thinned (T2) and unthinned stands. These locations were on the top of main branches in whorls 6, 9, and 12 at three equal distances from the stem and for branches from the north and south sides of the trees. The relationship between PAR and rates of photosynthesis was established and on this basis PAR was converted into rates of photosynthesis. This was expressed as a percentage of the rate under optimum light conditions for a sunny day in July 1973 one year after treatments (Fig. 17; Brix 1976). Thinning had no significant effect on the photosynthetic conditions in the upper third of the crown but improved it drastically at the lower levels. Considering that N had no effect on rates of photosynthesis at low light (Fig. 15) the rate would not have been

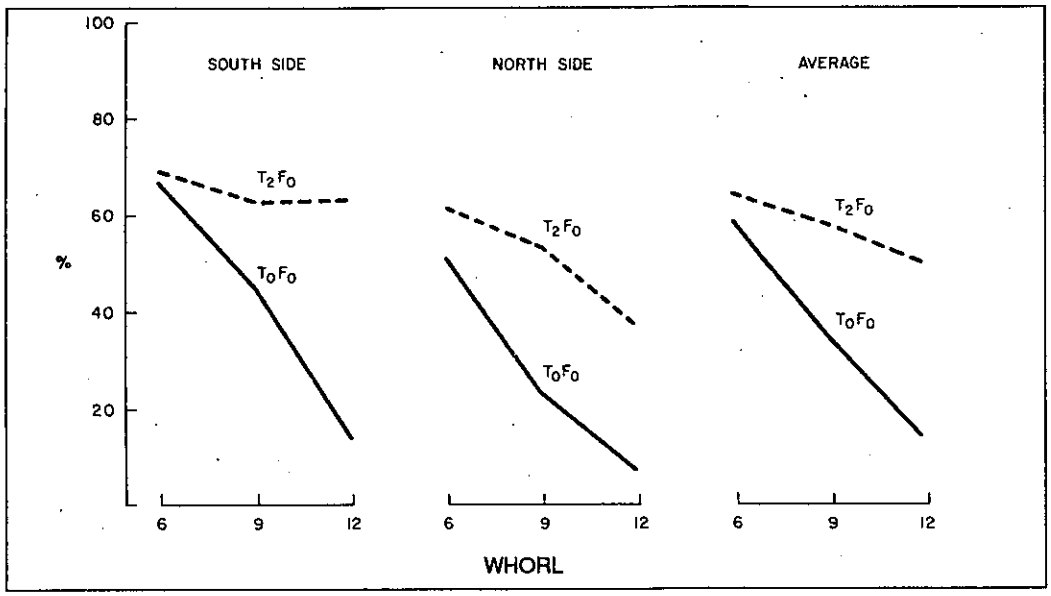

FIGURE 17. Photosynthesis in tree crowns in relation to light regimes in the crowns, expressed as a percentage of the rate under optimum light intensity; data from a sunny day in July 1973 (from Brix 1976).

improved by fertilization in the lower third of the crown in unthinned stands but would have been improved for the whole crown in thinned stands. This would assist in explaining a thinning × fertilization interaction during the first 4 years after fertilization. After this time the foliar N concentration had decreased to the control level and had no further effect on photosynthesis.

Light intensity data for a clear day in July 1978 at midday are given for the 1972 treatment plots T0F0, T2F0, T0F2, and T2F2. The intensity was measured for eight trees per treatment and for three positions along the branches for south and north sides of the trees at each whorl (Fig. 18; Brix, unpubl. data). Thinning improved the light regime at all positions below whorl six and fertilization decreased light intensity. This is to be expected from the study of treatment effects on foliage production and crown development (Brix 1981a) and provides an explanation for the decrease in foliar efficiency with fertilization at that time (Section 8.5; Brix 1983). Thinning also decreased foliar efficiency at year 7 in spite of an improvement in light regime (Brix 1983). However, the major addition of foliage with thinning is in the lower part of the crown where light intensity is low (Brix 1981a), and this would reduce the average efficiency.

8.5 Foliage Quantity and Efficiency Effects on Growth

Nitrogen fertilization and thinning have affected both foliage quantity and rates of photosynthesis. The question then is how much of the growth response can be attributed to each of these two factors and how do their contributions change with time. An answer to these questions will help explain the longevity and magnitude of the response, the response to fertilization with and without thinning, and implications for refertilization effects, as discussed by Brix (1991).

The annual stem and total aboveground biomass production was determined over the first 7-year period following thinning and N fertilization at Shawnigan (Brix 1983). This data, combined with that for foliage quantities following these treatments (Brix 1981a), provided the basis for determining annual biomass production per unit of foliage or, foliage efficiency (E). The value E integrates rates of photosynthesis during the time period as well as reductions in dry matter as a result of respiration. Furthermore, E can be calculated on the basis of total, aboveground, or stem production and E will be influenced by changes that may occur in the distribution of total dry matter to these components.

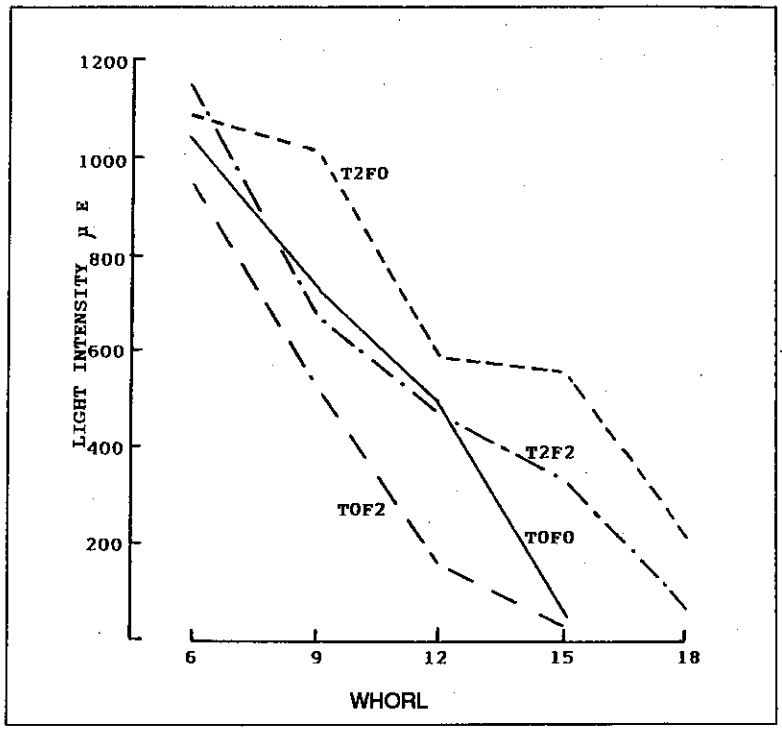

FIGURE 18. Light intensity at different crown positions in 1972 treatment plots T0F0, T2F0, T0F2 and T2F2 measured at midday on a clear day in July 1978 (from Brix, unpubl. data).

The foliar efficiency, E, increased during the first 4–5 years with both thinning and fertilization but was at or below control level after 7 years (Figs. 19, 20). More favourable light and water conditions in the crown, as shown previously, would increase E following thinning. The increase in E was as much as 100% with fertilization when E was based on aboveground production. This is more than can be explained by increases in rate of photosynthesis (up to 30%). A likely explanation is that a greater percentage of the total production is allocated to aboveground and less to belowground, such as fine roots, as a result of fertilization (Keyes and Grier 1981). As mentioned in Section 8.4, the decrease of E below control at year 7 can be explained by a greater mutual shading of foliage following fertilization and a deeper crown with thinning.

The initial increase in dry matter production was therefore primarily caused by more efficient foliage and greater dry matter allocation to aboveground production. However, the long-term response (from year 4 on) was associated with increases in foliage quantity for both treatments. The increased E accounted for 20, 37, and 27% of the stemwood response to thinning, fertilization, and the combined treatments, respectively, over the 7-year period (Figs. 21, 22); over a longer period, the contribution of E would decrease. Since foliage quantity is the main basis for tree growth response to fertilization, this treatment will be most effective in spaced stands where foliage is deficient. This can be seen from the relationship between the LAI and the aboveground dry matter production at Shawnigan (Fig. 23; Brix 1991). With an increasing LAI the production in unthinned stands is still increasing but at a slower rate than found in thinned stands. The duration of the response will also depend on the foliage longevity, which at Shawnigan is 5–6 years (Brix 1981a). A single fertilization did not achieve the most beneficial combination of a high foliar efficiency and a high foliage quantity and, therefore, the maximum response to fertilization. This, however, was attained with the refertilization at year 9.

As shown in Appendix 5, refertilization at year 9 did increase the volume production to a height not previously attained through a combination of increased photosynthetic efficiency and a high foliage quantity that had lasted from the first fertilization. However, in the unthinned stands with a high LAI following the first fertilization, there was little or no additional benefit from an increase in foliage quantity so the growth response was only enhanced for a 3-year period. In thinned stands that were still below optimum LAI, a benefit from added foliage was attained and a growth response was evident in the second 3-year period after refertilization.

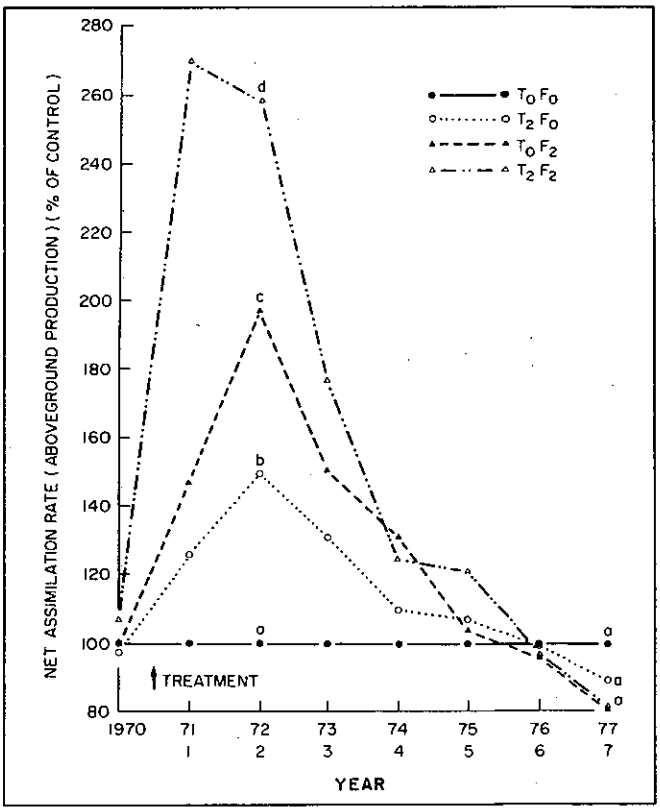

FIGURE 19. Net assimilation rates (E) by years based on total aboveground dry matter production; rates with thinning and fertilizer treatments are expressed as a percentage of rates for control trees. Means within 1 year are significantly different ($P = 0.05$) if not followed by the same letter (from Brix 1983).

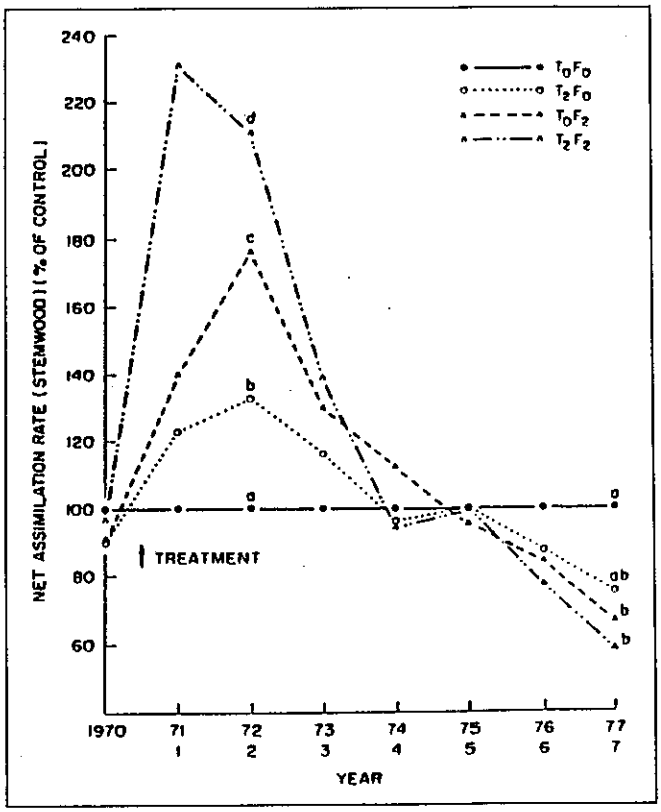

FIGURE 20. Net assimilation rates (E) by years based on stemwood dry matter production; rates with thinning and fertilizer treatments are expressed as a percentage of rates for control trees. Means within 1 year are significantly different ($P = 0.05$) if not followed by the same letter (from Brix 1983).

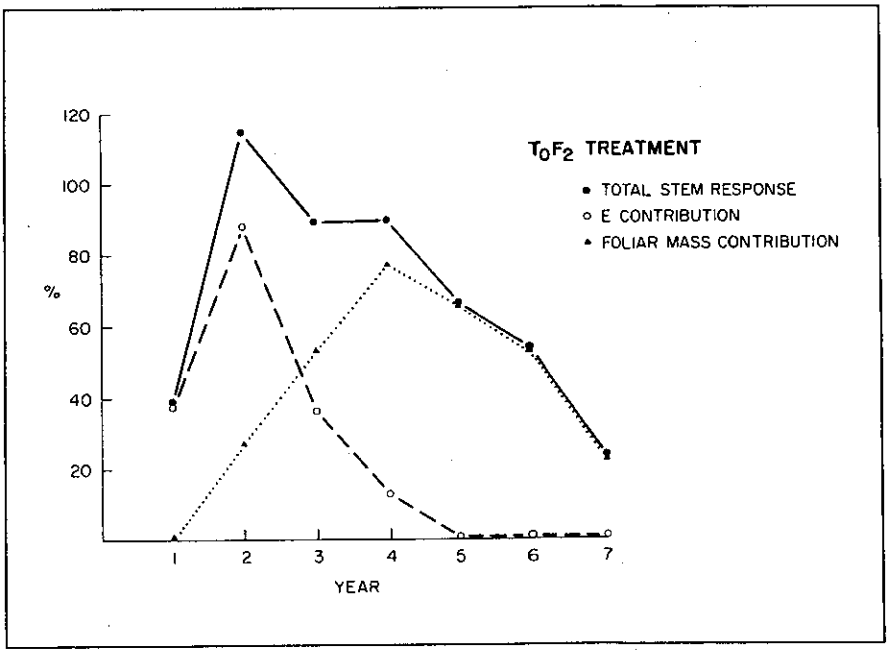

FIGURE 21. Stemwood growth response to T0F2 treatment (no thinning, 448 kg N/ha), percent above control, and contribution of foliar efficiency (E) and foliage biomass to the response in years following treatment (from Brix 1983).

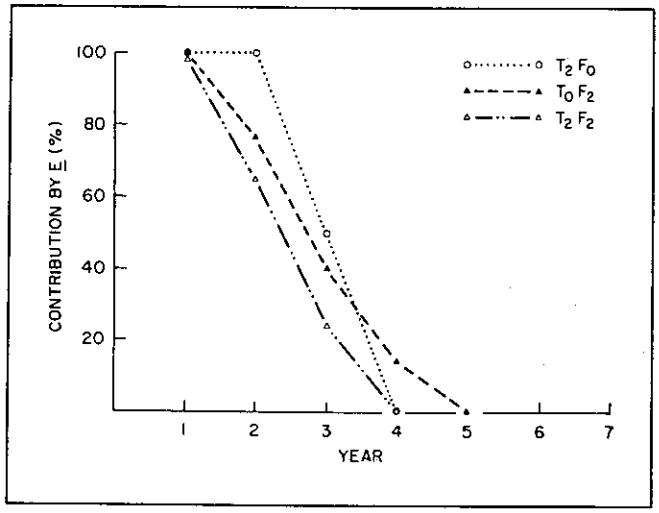

FIGURE 22. The contribution of E to the stemwood growth response following treatments as a percentage of the total response (from Brix 1983).

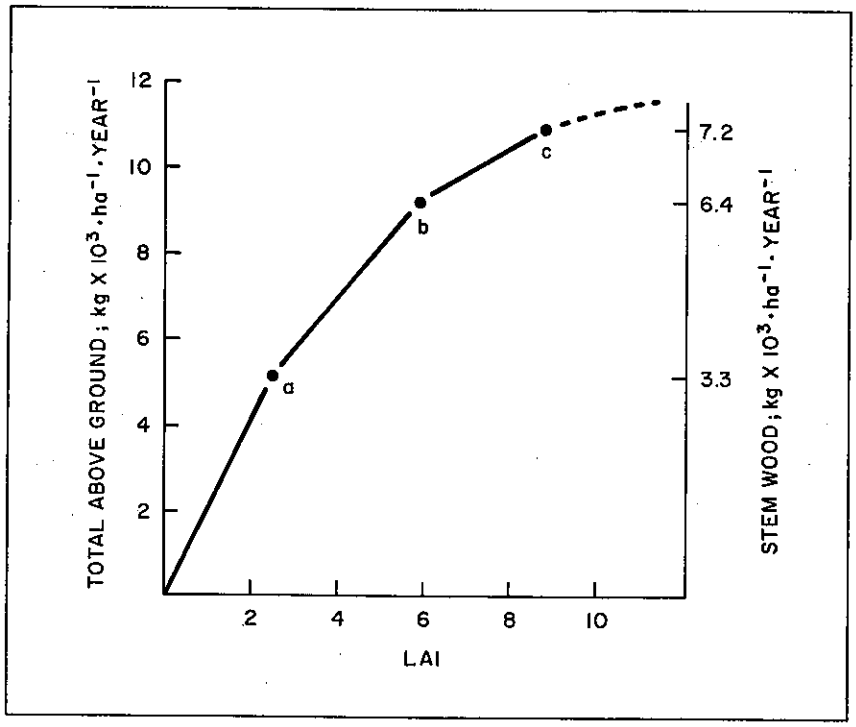

FIGURE 23. Total aboveground and stemwood biomass production of Douglas-fir at the Shawnigan Lake installation in relation to leaf area index (LAI). Data are based on Brix (1981a, 1983) with: "a" for thinned plots (T2) after thinning shock was overcome (year 3); "b" for untreated control plots (year 7); and "c" for unthinned, fertilized plots (T0F2) when foliar N concentration had returned to control level (year 7) (from Brix 1991).

9 SOIL CHEMISTRY

9.1 Thinning and Fertilizer Effects

Changes in soil water chemistry following stand treatments have been the subject of several studies within the Shawnigan Project. A knowledge of transformation and movement of urea and ammonium nitrate fertilizers in the soil and interactions of these processes with thinning is important in understanding N availability with these N sources and subsequent effects on tree nutrition.

Leachates were collected from tension lysimeter plates at three depths: immediately below the forest floor, and in the mineral horizons at 10 and 30 cm depths (Pang and McCullough 1982). Plates were installed in plots treated with T0F0, T0F2 (urea), T0F2* (ammonium nitrate), T2F0, and T2F2 (urea). The leachates collected over a 31-month period were analysed for NH_4^+, NO_3^-, Ca_2^+, Mg_2^+, and K^+ and for soil pH and electrical conductivity. The pH of leachates below the forest floor rose about 1.0 unit immediately after urea fertilization, with a diminishing effect the next 6 months. Ammonium nitrate decreased the pH below the forest floor as well as at the 10 cm depth. The ion concentration increased in the forest floor leachates for the first 5 months with ammonium nitrate and for 10 months with urea but not thereafter. Substantially higher ion concentrations were detected at the 10 and 30 cm depths with ammonium nitrate than with urea fertilization. Thinning when combined with urea fertilization enhanced ion movement but thinning alone had no significant effect.

The ammonium concentration was only increased in the forest floor with urea but also at the 10 cm depth with ammonium nitrate. The maximum ammonium concentration in the forest floor following fertilization was reached within 1 month with ammonium nitrate and at 5 months with urea (Fig. 24).

Nitrification occurred following urea fertilization with an increase in nitrate concentration in the forest floor both with and without thinning (Fig. 25). This was detected 5 weeks after fertilization and lasted until the end of the first year. Only with thinning did urea fertilization increase the nitrate concentration at the 10 and 30 cm depths. This was probably because of better moisture conditions and less tree uptake with the reduced stand density.

Movement of nitrate with ammonium nitrate fertilization was rapid; high concentrations were found at a depth of 30 cm a month after treatment (Fig. 26). The effects of fertilization on soil water chemistry lasted only 10 months. Pang and McCullough (1982) discussed nitrogen source effects on nutrient transformations and availability.

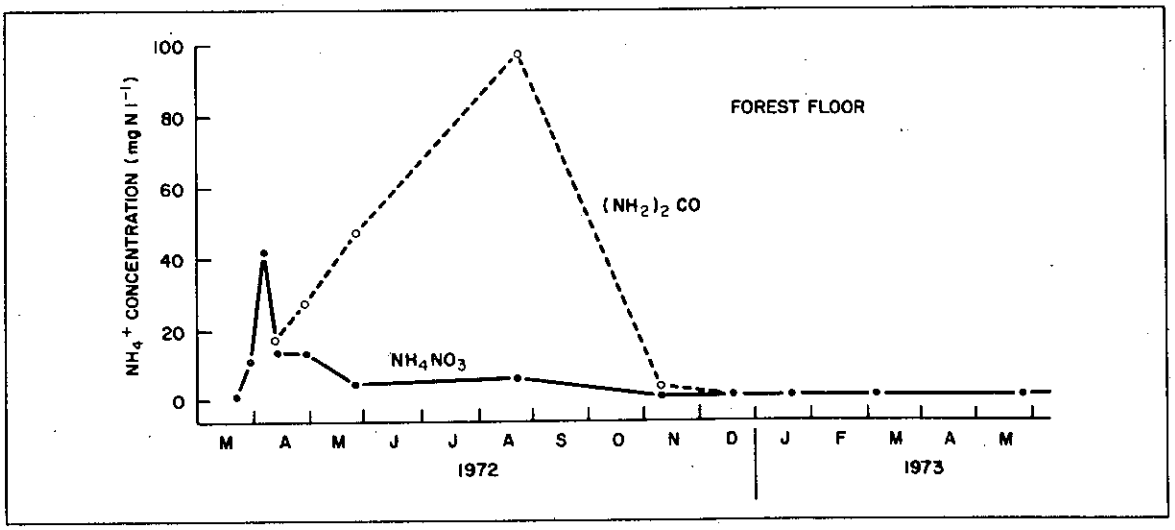

FIGURE 24. Changes in NH_4^+ of leachates collected from the forest floor after urea and ammonium nitrate fertilization without thinning (from Pang and McCullough 1982).

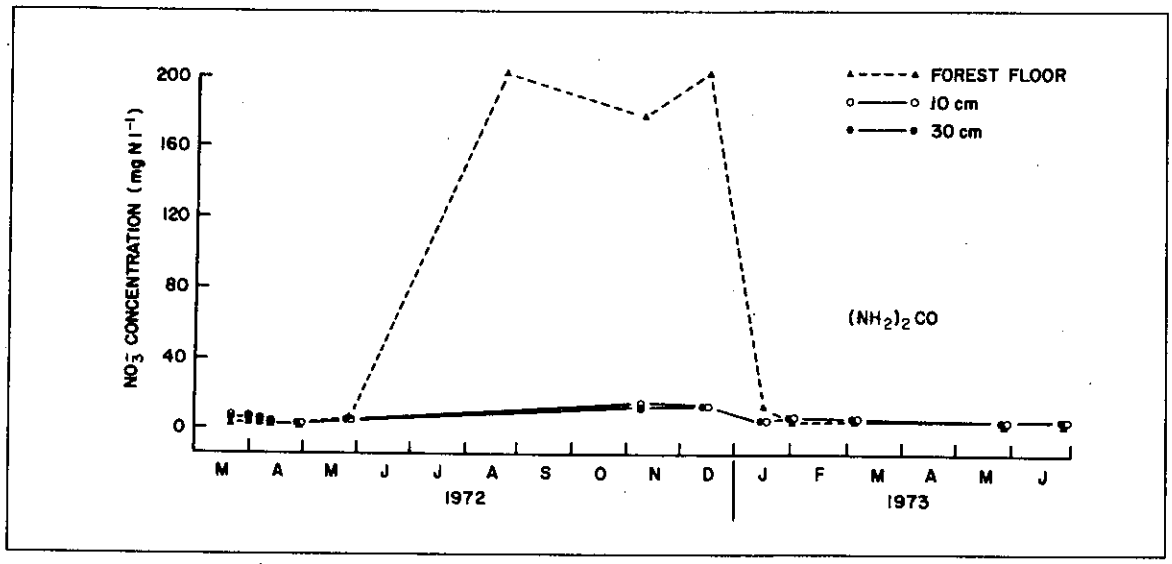

FIGURE 25. Changes in NO_3^- of leachates collected from forest floor, 10 and 30 cm depths after fertilization with urea and without thinning (from Pang and McCullough 1982).

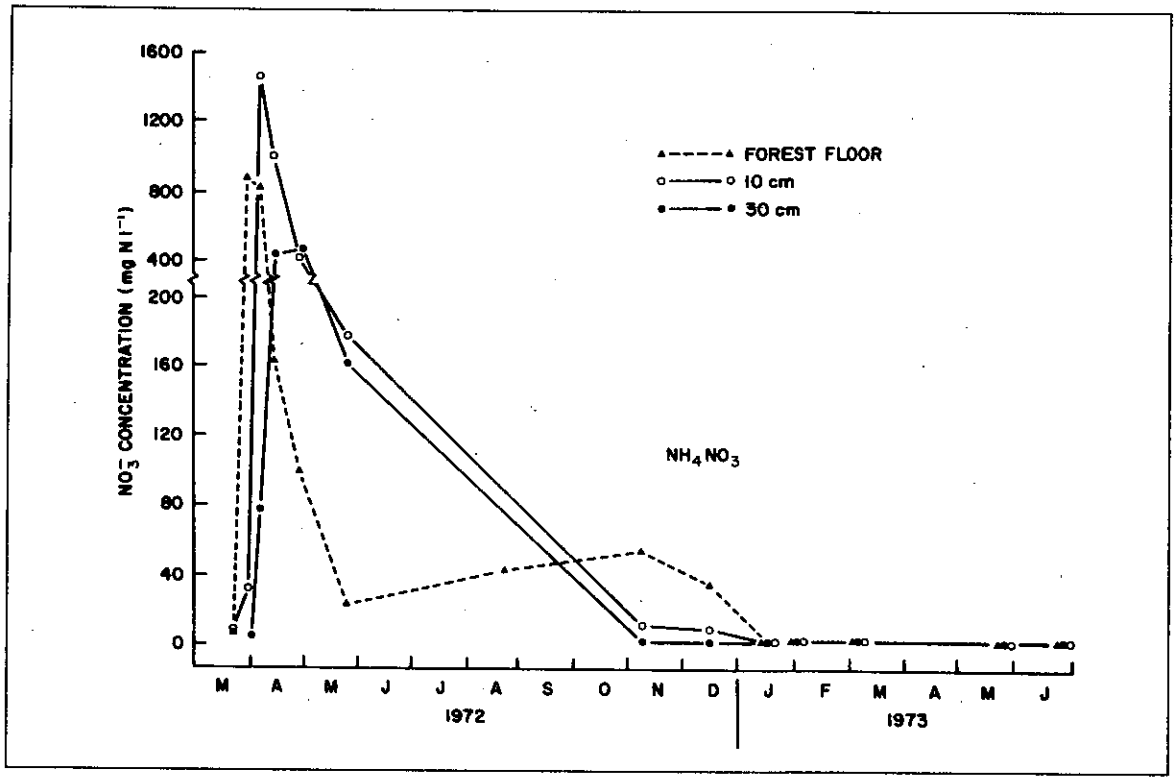

FIGURE 26. Changes in NO_3^- of leachates collected from forest floor, 10 and 30 cm depths after fertilization with ammonium nitrate and without thinning (from Pang and McCullough 1982).

A further study of changes and distribution of urea and ammonium nitrate fertilizers and their transformation products was undertaken with undisturbed soil cores from the Shawnigan site (Pang 1982). The cores were brought to the laboratory and fertilized with urea (200 and 400 kg N/ha) and ammonium nitrate (200 kg N/ha) followed by an incubation for 5 months. Some cores fertilized with 200 kg N/ha were given a simulated precipitation treatment. Only a low concentration of nitrate was detected with urea fertilization and the concentration decreased with soil depth. Leaching of nitrate was small and restricted to cores fertilized with ammonium nitrate. Recovery of the fertilizers as ammonium plus nitrate did not exceed 53% of the N applied. This is discussed in relation to biological immobilization of N and interactions with organic matter.

9.2 Soil Organic Matter

Fertilization and thinning have the potential of influencing the quantity and quality of organic matter in the forst floor and in deeper horizons, and may thereby affect nutrient cycling and short- and long-term productivity. The organic matter can also influence the availability of nitrogen fertilizer by affecting ammonia volatilization, urease activity, denitrification and immobilization and mineralization of nitrogen (Marshall 1991). Some studies of soil organic matter have been undertaken at Shawnigan. The lysimeter study in 1972 (Pang and McCullough 1982) indicated the presence of dissolved organic matter in urea-fertilized plots as a result of an increase in pH with urea hydrolysis. The study of soil nutrient budget by Trofymow (1988) showed a thinning and fertilization effect on quantity and distribution with soil depth of total C, N, P, and S. The organic matter in a Shawnigan soil profile was characterized by Preston *et al.* (in preparation). It appears from this study that the processes of decomposition and humification at the site are limited by the low soil C in HA and FA and the high proportion of poorly decomposed plant fragments at all depths. Further studies are planned on the quality and profile distribution of soil organic matter by C. Preston and J. Trofymow of the Pacific Forestry Centre, Victoria, B.C.

10 NUTRIENT CYCLING

Major processes in the biogeochemical nitrogen cycle in the soil influencing the quantity of NH_4^+ and NO_3^- available for plant uptake are: nitrogen fixation (N_2 to NH_4^+), nitrification (NH_4^+ to NO_2 to NO_3^-), denitrification (NO_3^- to NO_2^- to N_2O to N_2), immobilization (NH_4^+ to organic N), and mineralization (organic N to NH_4^+). Nitrogen losses from the soil system will occur through erosion, leaching, NH_3 volatilization, N_2O and N_2 gasses, and plant uptake. Gains will occur through precipitation, NH_3 absorption, litterfall, and fertilization. The overstory and understory vegetation enter and exit the biogeochemical cycle through nutrient uptake (roots and foliage) and litterfall (above- and belowground). These aspects are reviewed by Marshall (1991). The biochemical, or internal, cycle refers to redistribution of nutrients within the plants such as from old to new growing tissue.

Major studies in nitrogen cycling through biological and non-biological processes have been done under the Shawnigan project to gain an understanding of fertilizer source and thinning effects on soil and tree nutrition and consequently on tree physiology and growth. A nitrogen and carbon flow diagram as used in the SHAWN model is presented in Figure 27.

10.1 Losses

Losses of fertilizer nitrogen can occur in different ways by: 1) ammonia volatilization; 2) denitrification; and 3) leaching and runoff. Losses have been studied and compared with the use of urea and ammonium nitrate at Shawnigan and other locations. The special case of losses with fertilization on snow has been investigated at two sites. Losses from the point of view of environmental impact of forest fertilization are evaluated in Section 14. A review of nitrogen losses with different nitrogen sources was presented by Marshall (1991).

Pang (1984a) found that a high percentage (10–30%) of urea nitrogen was lost by volatilization even under the favourable conditions of precipitation soon after fertilization and cool temperatures. Most of the losses occurred during the first 2 weeks of the 8-week study period. He also showed that Douglas-fir foliage has the potential of absorbing ammonia, so some may be recovered in this manner (Pang 1984b). Four methods of measuring nitrogen volatilization losses were compared by Marshall and DeBell (1980). They recommended a closed-dynamic method for determining ammonia losses.

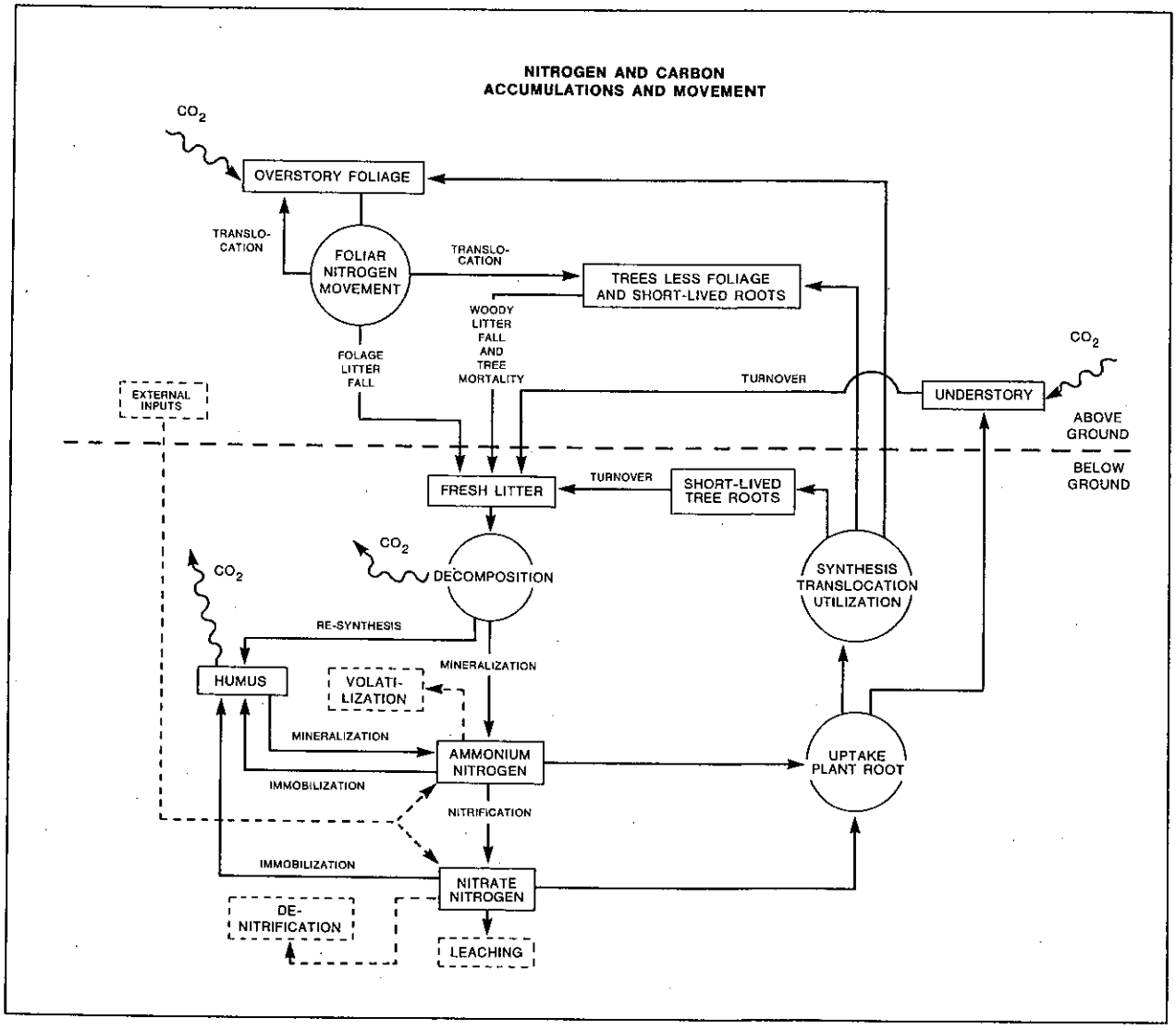

FIGURE 27. Schematic diagram of the nitrogen cycle on which the model is based (from Barclay and Hall 1986).

Shawnigan soils from different depths were collected in a study by Pang and Cho (1984) and the biological activity (oxygen consumption and CO_2 production rates) and denitrification activity was determined following addition of different nitrogen sources in the laboratory. With the nitrate fertilizers both biological activity and denitrification intensity were high in the surface samples but denitrification could not be detected at lower depths. No denitrification products were found with urea fertilization.

Leaching losses would be mainly in the form of nitrate (which moves freely with soil water) and were restricted to ammonium nitrate fertilization (Pang 1982). Urea usually is readily hydrolyzed to NH_4^+ within a few weeks and is held in the organic layer (Pang and McCullough 1982). Some nitrification of NH_4^+ did take place although only small amounts were detected at a depth of 30 cm and leaching losses would have been insignificant (Pang and McCullough 1982). With the gentle slopes at Shawnigan, losses by erosion and runoff are not of importance.

The fate of N fertilizer when applied on snow was studied on two sites. One site was located at Spillimacheen in the British Columbia interior with 11-year-old lodgepole pine, and the other site was at Green Mountain on Vancouver Island with 13-year-old Douglas-fir (Preston *et al.* 1990). Recovery of labelled N in

soil and biomass was monitored one growing season after application of 100 kg N/ha. With urea at Green Mountain the recovery was 5.5% in tree biomass, 10.8% in understory, and 33.4% in soil organic N for a total of 49.7%. Three 15N labelled sources were used at Spillimacheen, (15N) urea, $15NH_4NO_3$ and NH_415NO_3. The performance was similar and considered satisfactory for the first two sources but there were large losses with the $15NO_3$ application that were attributed to leaching and denitrification during snowmelt.

10.2 Uptake

Some studies have shown that fertilizer N is only available for plant uptake during the first year after application (Heilman *et al.* 1982; Miller 1986), and the rest is lost or immobilized. With the normal rate of application the amount of immobilized N is considered insignificant to the usually large native pool of soil N. In recent and heavily thinned stands with sparse root distribution and a limited requirement for N uptake, only a small amount of fertilizer N is likely to be utilized if the fertilizer N is only available the first year. One point addressed in the Shawnigan project is fertilizer utilization in thinned versus unthinned stands. This was calculated on the basis of net gain in N content of aboveground tree biomass plus N content of litterfall over a 9-year period after the treatments T0F0, T0F2, T2F0, and T2F2 (Table 8; Brix 1991). The first-year uptake was estimated from the first-year change in foliage N content. The additional N uptake with fertilization (448 kg N/ha) in unthinned stands was 57 kg N/ha and in thinned stands 71 kg N/ha or 13 and 16%, respectively, of the fertilizer N applied. The fertilizer N uptake in unthinned stands occurred in the first year, whereas the greatest amount (more than two-thirds) was taken up after the first year in thinned stands (Brix 1991). This was presumably due to a fertilizer priming effect, that is, by N mineralization of native organic soil N, or by remineralization of immobilized N fertilizer. If the major N uptake in thinned stands depends on priming or remineralization it will be greatly affected by many soil and climatic conditions, and fertilizer effect on growth would vary accordingly. It should be noted that the heavy thinning at Shawnigan only reduced the stocking to about 900 stems per hectare, or almost twice the stocking now commonly used in pre-commercial thinning in coastal Douglas-fir.

TABLE 8. Total aboveground N uptake (kg N/ha) during the 9 years after treatments based on aboveground net N gain plus litterfall N contents (Brix 1991)

Treatment	Biomass net N gain	Litterfall N content	Total N uptake	Total less control
T0F0	106	61	167	0
T0F2	133	91	224	57
T2F0	128	30	158	-9
T2F2	191	38	229	62

10.3 Tree and Understory Nutrient Contents

To investigate thinning and fertilization effects on nutrient uptake, nutrient requirements for growth, and the role of trees in nutrient cycling, the nutrient content of aboveground tree components was measured 9 years after stand treatments and calculated for year zero (Pang *et al.* 1987). This was done for the treatments T0F0, T0F2, T2F0, and T2F2. The biomass for these samples was reported in Section 5.1. A similar sampling was done in year 18 but results are not yet available. Seven aboveground tree components were analyzed for N, P, K, calcium (Ca), and magnesium (Mg). The total weight (kg/ha) of the five elements for the different treatments at the time of treatment and at year 9, and the net gain during this period, is shown in Table 9.

Fertilization increased the net gain over the 9 years for all elements except P, whereas thinning increased N and also P when combined with fertilization. Thinning increased the mean concentrations of N (mainly wood and bark) and decreased the concentrations of Mg, but had no significant effect on concentrations of the other elements (Table 10). Fertilization decreased concentrations of N (mainly wood and branches), P (all components), K (mainly foliage and branches), but had no effect on Ca and Mg.

TABLE 9. Total weights of the five elements (kg/ha) for each of the four treatments: (a) total weights at the time of treatment on all live trees; (b) total weights 9 years following treatment; (c) differences between weights (Pang *et al.* 1987)

Treatment	N	P	K	Ca	Mg
(a) At treatment					
T0F0	159.5	37.4	103.5	163.5	25.0
T0F2	122.9	28.7	79.3	125.8	19.3
T2F0	55.1	13.3	37.0	57.1	8.4
T2F2	56.2	13.6	37.8	58.2	8.5
(b) At 9 years					
T0F0	265.5	65.5	182.9	276.7	39.6
T0F2	255.7	47.2	174.2	304.5	44.7
T2F0	182.7	38.7	123.6	169.1	22.0
T2F2	247.2	53.4	147.7	249.8	34.8
(c) Net gain (0–9 years)					
T0F0	106.0	28.1	79.4	113.2	14.6
T0F2	132.8	18.5	94.9	178.7	25.4
T2F0	127.6	25.4	86.6	112.1	13.6
T2F2	191.0	39.8	109.8	191.6	26.3

TABLE 10. Mean concentration ($\mu g \cdot g^{-1}$ dry weight) of N, P, K, Ca, and Mg in each of the seven tree components and for each of the four treatments at 9 years (Pang *et al.* 1987)

Element and treatment	Wood	Bark	Dead branches	Current foliage	Non-current foliage	Current twigs	Branches
N							
T0F0	603	2711	2204	10932	10039	7875	3735
T0F2	417	2534	2210	10389	9237	7416	3002
T2F0	1094	3616	2578	10482	9329	7658	3494
T2F2	644	3017	2090	11509	9854	8108	3149
P							
T0F0	85	704	332	2528	3835	1639	721
T0F2	65	512	199	1774	2059	1203	515
T2F0	103	656	333	2367	3303	1308	625
T2F2	149	648	344	1970	2560	1409	581
K							
T0F0	413	2827	592	7198	6127	4734	2607
T0F2	421	2445	567	5916	4552	4039	2214
T2F0	632	3111	772	7311	5951	4864	2720
T2F2	552	2484	624	5920	4456	4002	1843
Ca							
T0F0	420	3469	5093	4632	9354	4493	5585
T0F2	443	2854	4434	5128	10501	4552	5091
T2F0	495	3078	6121	4776	9803	4466	5622
T2F2	451	2279	4394	5118	10972	4787	4953
Mg							
T0F0	76	450	376	1672	1573	1178	566
T0F2	85	406	444	1610	1600	1096	504
T2F0	94	365	387	1413	1339	947	469
T2F2	83	347	421	1505	1566	1068	470

The understory nutrient content of salal and bracken fern was measured 6 years after treatments (Stanek *et al.* 1979). The aboveground parts contained about 10, 18, 24, and 39 kg N/ha in treatments T0F0, T0F2, T2F0, and T2F2, respectively. These are minor amounts compared to the N content of the trees and the fertilizer utilization was also small (Table 9).

10.4 Litterfall

A study of thinning and fertilization effects on litterfall mass and nutrient content at Shawnigan was reported by Trofymow *et al.* (1991). Litter traps were placed above the understory so that only tree litter was sampled. More than 95% of the litter was foliage and the rest was mainly fine twigs. Here data are summarized for the 1981–87 period to show the effect of refertilization (F2-2) in 1981 together with the long-term effect for the stands fertilized in 1971 (F2) (Table 11).

TABLE 11. Annual weights of litterfall mass and N, P, K, Ca, and Mg contents (kg/ha) and nutrient element concentration as percent of dry weight, for the period 1981–87 (data from Trofymow *et al.*, 1991)

	Mass	N		P		K		Ca		Mg	
Treatment	kg/ha	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%
T0F0	1931	9.54	0.49	3.90	0.20	5.04	0.26	19.65	1.02	1.71	0.09
T0F2	2287	12.42	0.54	3.82	0.17	5.84	0.26	25.99	1.14	2.01	0.09
T0F2-2	2766	17.33	0.63	3.29	0.12	6.44	0.23	31.55	1.14	2.44	0.09
T0F2-2a	3318	27.43	0.83	3.40	0.10	7.65	0.23	39.98	1.20	2.98	0.09
T2F0	1484	7.54	0.51	2.79	0.19	3.22	0.22	17.94	1.21	1.27	0.09
T2F2-2	2430	14.47	0.60	2.64	0.11	4.51	0.19	31.16	1.28	2.15	0.09

Note: F2 fertilized in 1971.
F2-2 fertilized in 1972 and 1981 with urea.
F2-2a fertilized in 1972 and 1981 with ammonium nitrate.

Nitrogen fertilization increased litter mass and content of N, K, Ca, and Mg but decreased P. Concentrations of N and Ca increased and P decreased after N application. There was no effect on Mg and the decrease in K concentration was slight. The increases in litter mass and element content were greater with ammonium nitrate than with urea fertilization. Thinning reduced litter mass and contents of all elements but had little or no effect on element concentration except for an increase in Ca. Trofymow *et al.* (1991) showed that N fertilization reduced litter mass in the first 2 years but increased it thereafter. Thinning decreased litter mass by as much as 80% in the year of treatment but the rate was close to the control rate by the end of the sampling period in unfertilized plots, and it exceeded the control rate when fertilized. Rates of litterfall correlated well with basal area and stemwood increments but not with stand density. When comparing litterfall nutrient concentrations with those of non-current live foliage presented in Table 10, it is apparent that a considerable re-translocation of all nutrients except Ca occurred before abscission. Using different samples it was calculated that 33% of the N content of foliage was re-translocated before foliage abscission in unfertilized trees, but only 21% was re-translocated in fertilized trees (Brix unpubl. data).

11 SOIL FAUNA AND MICROFLORA

The soil fauna and microflora play a key role in decomposition of soil organic matter, which makes nutrients available for plant uptake. Some of the available nutrients, both native and applied, are immobilized by growth of both the fauna and particularly the microflora. Nutrient cycling is therefore greatly influenced by their activity.

Effects of ammonium nitrate and urea fertilization and thinning on soil fauna have been studied and reviewed by Marshall (1974, 1977, 1980, 1981, 1986, 1991). The fauna function largely through fragmentation and mixing of litter into lower soil layers. Their biomass and nutrient content are usually only a small fraction of the forest floor and their role in immobilization is minor. Four major groups of soil animals (nematodes,

enchytraeids, mites, and collembolans) are found in great quantity at Shawnigan. Thinning had no significant effect on the population of any of these groups. Ammonium nitrate fertilization had no immediate impact on soil animals, whereas urea caused a temporary decline in numbers of all groups during the first few months after application, as exemplified in Figure 28. The enchytraeids were affected the most, and they required 2 years for full recovery, but this was balanced by an increase in nematodes for most of this period (Marshall 1974). The CO_2 production during this time was not affected significantly, suggesting that fertilization had no overall adverse effect on the soil biota. Soil fauna effect on decomposition and nutrient release was studied with the use of litter bags with different mesh sizes with the hypothesis that fewer animals will be excluded as larger meshes were used. This was generally true, and more nutrients were released with increasing faunal numbers.

Soil microflora studies were conducted by J. Dangerfield and early effects of ammonium nitrate and urea fertilization were summarized by Dangerfield and Brix (1979). Both fertilizer sources initially increased the microbial populations, but they declined over a 30-month period to near normal levels. The microbial composition also changed after urea fertilization, but not with ammonium nitrate fertilization for the fungi. Changes in populations during the first season are shown in Figure 29 for proleolytic bacteria and in Figure 30 for cellulolytic fungi (Dangerfield and Brix 1979). The microflora had a high nutrient requirement and the build-up of bacteria populations after urea fertilization brought about a substantial immobilization of N. This tied up 25 kg N/ha more N with urea than with ammonium nitrate 2 months after fertilization (Dangerfield and Brix 1979). This is one reason, in addition to the greater mobility of nitrate than of ammonium, for the better availability and uptake of N with ammonium nitrate than with urea during the first year.

Thinning adds to the litter mass and may also indirectly enhance soil organism activity by providing a more favourable soil temperature and moisture regime. These conditions were recorded in thinned and unthinned stands and in a cleared area at Shawnigan. Some plots were also fertilized with urea. Soil respiration was used as a measure of soil activity (Trofymow 1991). Respiration was measured over a 2-year period in trenched plots (excluding root and heterotrophic respiration) and also in untrenched plots. The degree of stocking affected temperature and moisture differently throughout the year. Temperature had a major effect on soil respiration as long as moisture was adequate. Peaks in soil respiration were found in mid-summer and late fall, but this was partly caused by root respiration.

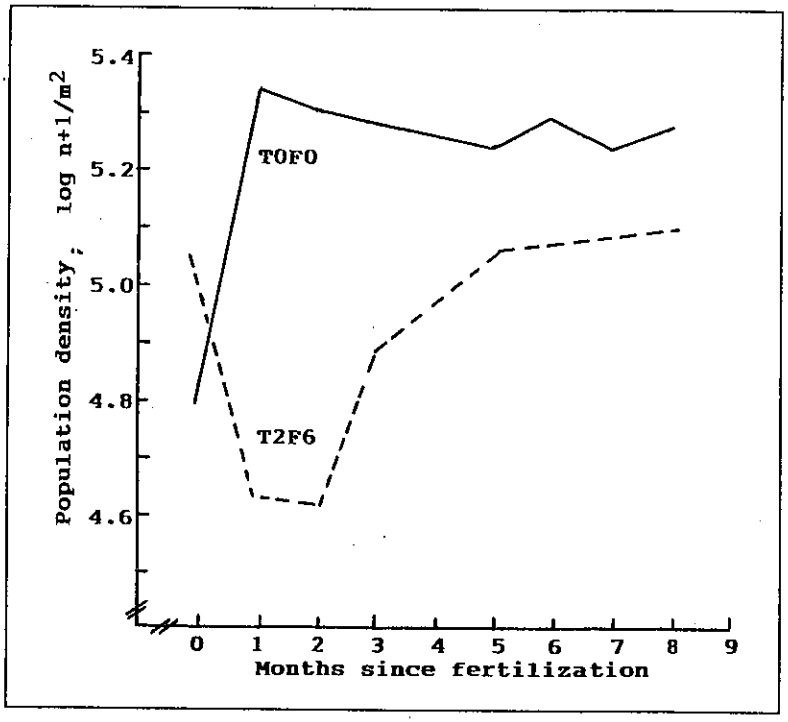

FIGURE 28. Immediate impacts of urea fertilizer on soil mites at Shawnigan Lake (Marshall, unpubl.).

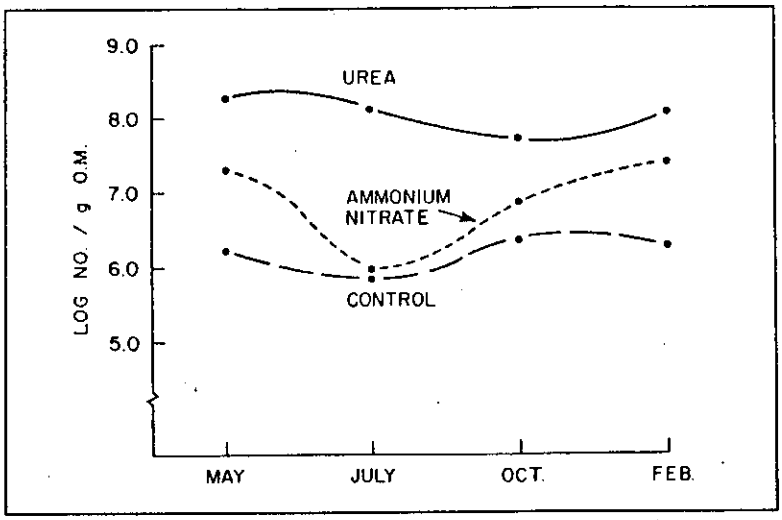

FIGURE 29. Total numbers of proteolytic bacteria isolated the first growing season after fertilization (March) with ammonium nitrate and urea at 448 kg/ha (from Dangerfield and Brix 1979).

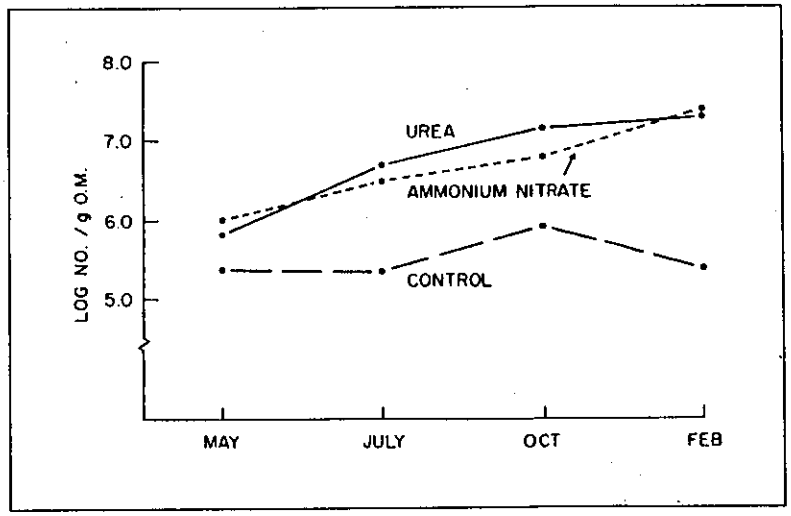

FIGURE 30. Total numbers of cellulolytic fungi isolated the first growing season after fertilization (March) with ammonium nitrate and urea at 448 kg/ha (from Dangerfield and Brix 1979).

12 SOIL WATER BUDGET

It was previously shown (Section 8.2) that thinning reduced the soil and tree water stress during the dry summer months (Brix and Mitchell 1986). Considering the importance of soil and tree water stress and soil water content in soil nutrition and tree growth, a more detailed knowledge of how thinning affects the soil water balance was needed. This also provided a means for calculating seasonal changes in evapotranspiration. Two new thinning plots (T2) were established at Shawnigan in 1983 to be compared with the untreated plots and plots heavily thinned in 1971 on the site. The effects of thinning on precipitation throughfall, stemflow, soil water contents, and water use at different soil depths were studied during the growing season over a 3-year period. Results are being analyzed and prepared for publication by Trofymow, Blashill, Mitchell, and Brix.

13 WATER–NITROGEN FERTILIZATION INTERACTION

The previous discussion has dealt with fertilization effect on soil and tree water stress (Section 8.2). Here we will deal with the effect of site water conditions on growth response to fertilization. This is an important question in site selection for fertilization and has been studied and reviewed by Brix (1979, 1989, 1991).

One study, conducted at the Greater Victoria Watershed, compared tree growth in plots that were fertilized (448 kg N/ha), irrigated (25 mm water per week in the summer), given the combined irrigation and N fertilization treatment, and untreated (Brix 1972). The dbh for similar-sized trees was increased by 16, 15, and 59%, respectively, over that of the untreated control during the first year and similar effects were found the second year. The considerable growth interaction between N and water indicates that N fertilization will be most effective on sites and in years with a favourable water supply. At Shawnigan, height growth response to fertilization has also been best in years with a normal (40 mm) or above normal June rainfall, whereas height growth response to thinning has been best, relative to control, with low June precipitation (Brix 1989). This thinning response supports the finding that thinning improved soil water condition and that the precipitation requirement would consequently diminish.

Although a considerable Nwater interaction was found on the Victoria Watershed site, Shawnigan is a very dry site and has responded well to fertilization. The interaction may well depend on the degree of water and N deficiency, as well as on other site conditions yet to be identified (Brix 1989).

14 ENVIRONMENTAL IMPACTS

Thinning and fertilization have many effects on ecosystem conditions and processes that influence tree growth. Potentially they will also influence other environmental attributes of importance to management of land resources such as water quality and wildlife habitat.

In Sweden, ammonium nitrate replaced urea in forest fertilization in the 1970s because of a better tree growth response to ammonium nitrate. Now with more awareness of acid rain problems and concern for the acidifying effects of ammonium nitrate, urea is being used again in many regions.

At Shawnigan, N rates as high as 1344 kg N/ha were included in order to study effects on tree growth but also to observe possible detrimental effects that could occur with accidental application of such amounts. No visual problems such as mortality, frost or drought damage, or stem breakage were observed within or outside these plots. However, a reduced N uptake in the first year was indicated from foliar analysis following a high rate of N application.

Changes in soil water chemistry were temporary and were generally confined to the first year. Leaching of nutrients beyond the rooting zone was insignificant when urea was applied in March, in spite of the shallow soil with low water-holding capacity. Fertilization in the fall with ammonium nitrate and, followed by heavy rain, could result in significant leaching of nitrate. Tree growth outside the border of fertilized plots was used as an indicator of nutrient leaching along the hardpan. No effect on radial growth could be found in trees 10 m outside the border (Brix unpubl. data).

The water quality in a watershed (Lens Creek, Vancouver Island) was monitored following a fall application of 224 kg N/ha as urea (Hetherington 1985). The peak N concentration in two tributary streams for the first 14 months was considerable and amounted to as much as 14.5 % of the nitrogen applied. This was attributed to a high nitrification rate and high winter rainfall, as well as to a direct application to streams. Concentrations did not exceed drinking water standards. Another study, with careful application outside streams and with stream buffer zones, recorded only minimum stream contamination and for a short duration (Hetherington unpubl. data). By exercising care in timing of operations and placement of fertilizers, most hazards in fertilization with regard to water quality can be avoided (Nason 1991).

Thinning had no significant effect on the populations of four major groups of soil animals at Shawnigan (Marshall 1974). Fertilization with urea initially caused a decline in all groups but full recovery was obtained within 2 years. The soil microbial population was initially increased by both N fertilizer sources but the numbers declined over a 30-month period to near normal levels.

A more lasting effect of potential importance to wildlife was found in growth of understory (salal and bracken fern), both in nutrient content and dry matter. Changes in light regime with thinning resulted in increased growth of understory, which presumably will last until crown closure. Fertilization in unthinned stands reduced the light intensity at the forest floor because of increased tree foliage mass and decreased the understory close to the point of elimination. Extremes in deer browsing habitat were therefore obtained with these two treatments.

15 MODELLING GROWTH AND PROCESSES

The Shawnigan Project was initiated with consideration of important ecosystem processes but without any modelling approach. However, it became clear after some years that this approach was needed to synthesize results and to identify important gaps in our knowledge. This would assist us in setting research priorities. The intent was to develop a mechanistic model at the ecosystem level, incorporating biological and chemical information for testing hypotheses of processes of growth response to thinning and nitrogen fertilization, rather than attempting a quantitative prediction of growth. The model SHAWN was developed in the late 1970s and the model structure and properties are described in Barclay and Hall (1986).

The model is driven primarily by the N cycle and for conceptual convenience it can be divided into aboveground and belowground processes and vegetation components as shown in Figure 27. The model includes nine soil-based processes affecting N availability and losses. The aboveground processes are nitrogen translocation, tree mortality, foliage litterfall, photosynthesis, and growth. Growth depends directly upon photosynthesis (leaf area index and net assimilation rate), which in turn depends on environmental conditions including available N. The model deals with 54 parameters tested against each of 36 variables in a sensitivity analysis for identification of parameters of importance to the system. The initial analysis pointed out the need for parameter values and mechanisms relating to transfer of nitrogen in soils. Comparisons were made of model behaviour with empirical data from the Shawnigan project for the four extreme thinning and fertilization treatments. Model testing has continued as research results became available. Further model development has taken place and the model now includes a range of stand age classes and a more detailed carbon balance account.

A separate model of evapotranspiration and soil water balance in relation to thinning is under development by H. Barclay and J. Trofymow.

The Shawnigan trials have provided needed information on long-term growth and yield and ecosystem functioning, which has been used to test and evaluate the FORCYTE-11 ecosystem-based model for short- and long-term prediction of biomass production (Trofymow and Sachs 1991; Sachs and Trofymow 1991).

16 ECONOMICS

An economic analysis of the thinning and fertilization treatments at Shawnigan was conducted by Duke *et al.* (1989). They found that the economic benefits from thinning and fertilization include: 1) increased tree size, which increases log value; 2) more uniform tree size with thinning, thus reducing harvesting and manufacturing costs; and 3) reduced rotation age, providing higher allowable annual cuts and earlier return of investments.

The tree growth simulator Y-XENO (Northway 1988) was used to project the growth data from Shawnigan from age 24 to 120 years, and the financial analysis was done with the E-XENO model. It was concluded that on a poor site such as Shawnigan, basic silviculture investments should only be made if costs are treated as harvest costs and if price increases are expected. With these provisions, heavy thinning was better than either

light thinning or no thinning, according to all the four economic ranking criteria considered. Combinations of fertilization and thinning were better than thinning alone. The T2F2 treatment ranked the highest of the nine treatments included in the analysis, both on an incremental and regime basis, according to two of the four ranking criteria used.

17 THE FUTURE

The Shawnigan Lake Project on the growth and biology of a Douglas-fir ecosystem in relation to thinning and nitrogen fertilization has been discontinued. Various aspects are continued at the Shawnigan Lake installation as studies under other projects with a wider scope in the fields of growth and yield, biodiversity, and carbon balance in forest ecosystems. Also, some studies already in progress at Shawnigan are to be completed. The following is a summary of the studies and reports in progress or to be undertaken.

Growth and yield:

24-year growth response to basic thinning and fertilization treatments
Response to first (F1, F2) and second (F1) refertilization
Response to P, S, and N
Response to source of N
Response to high rates of N

Biomass:

18-year biomass

Tree growth:

Crown development from 18-year sample trees

Tree physiology:

Foliage quantity and efficiency effect on growth from 18-year samples
Light regime report
Fine root production and effects of thinning and soil water deficits
Report on Rubisco activity and stomatal conduction in relation to N

Soil chemistry:

Organic matter in a soil profile
Organic matter quality and profile distribution
Nutrient distribution in a soil profile, and thinning and fertilization effects

Nutrient cycling:

Fertilization on snow; further reports
Tree nutrient contents from 18-year sampling

Soil water budget:

Report on effect of thinning

Soil biology:

Effects of thinning on soil temperature, soil moisture, and soil respiration; report

Modelling:

Expansion of SHAWN model to include carbon balance in a range of age classes; further input from project results

18 GENERAL DISCUSSION

The crown is the factory of the tree and in stand tending we attempt to influence the size and efficiency of the crown. Thinning provides room for crown expansion thus redistributing the total foliage mass to fewer trees. The better light regimes and water conditions following thinning will enhance individual tree growth. There is no input of new resources and total production may not be improved, although changes in canopy structure could improve light utilization and more of the total production may be channelled into stem growth. With forest fertilization, we do add to the resources of the site. The efficiency of the crown is increased for a few years and the total foliage mass is increased to provide a long-term response. These treatments together will have the combined effect of concentrating growth on fewer trees, improving the efficiency of the crown through better light, water, and nutrients, and accelerating development of the crown for a long-term response.

18.1 Direct and Indirect Growth Responses to Fertilization

Some recent studies have partitioned the fertilizer growth response with time into direct and indirect effects (Comerford *et al.* 1980; Miller and Tarrant 1983; Auchmoody 1985; Opalach and Heath 1988). The rationale and methods of their approaches have been evaluated by McWilliams (1990). The direct effect is taken as the result of nutritional improvement and the indirect as caused by changes in stand structure, tree size, or volume. This separation is not always distinct. The growth response is usually presented in 2-year to 4-year growth periods following fertilization. In the beginning of the first period, trees and stands are similar so any growth response would result from the so-called direct effect. In subsequent periods, however, improved growth could result from different stand structure, tree size, and volume between fertilized and control stands at the beginning of the periods. This improved growth is the so-called indirect effect not associated with improved nutrition. Several covariance and regression methods and use of a "specific volume" (Comerford *et al.* 1980) have been described in the above studies to separate these effects. The reason for doing this, as pointed out by Opalach and Heath (1988), is that this may aid modellers in developing fertilizer response equations for yield simulators.

The above studies do not clearly indicate under which stage or condition of stand development this indirect response may be important. If the stand is at the development stage when stand volume does not affect volume growth, there is no reason to analyze for indirect effects in volume response as proposed by Opalach and Heath (1988). At Shawnigan, the volume PAI has been at a plateau for the 15-year measurement period in untreated stands although stand volume has more than doubled over this period. The entire response to fertilization in unthinned stands has therefore nothing to do with a change in volume or tree size. These unthinned stands had reached the closed canopy and maximum current annual increment (CAI) development stage. Only in the thinned stands before crown closure do we deal with a fertilizer response resulting from a combination of the direct and indirect effects.

Miller (1981) emphasized the importance of considering growth response for different stages of stand development. The volume response achieved before maximum CAI is attained, i.e., before crown closure, will give an overly optimistic view of the long-term effect of fertilization. Part of the gain in accelerating stand development will be lost in later years by an earlier decline in CAI. However, accelerating stand development will have the additional benefit of reducing rotation age.

18.2 Thinning versus Fertilization

Pre-commercial thinning is two to three times as expensive as N fertilization, and a comparison of tree growth with these treatments as presented by Gardner (1990) is of interest to the forest manager.

If a commercial thinning is not part of a forest management plan, we are primarily interested in performance of crop trees. The adjusted total volume and the average diameter were the same with the two treatments T0F2 and T2F0 for the 250 and 500 crop trees at year 15 (Gardner 1990). There is no interaction in crop tree growth with the combined treatments. The response of crop trees to fertilization in unthinned stands will depend on the stand at the time of treatment. As pointed out by Carter (1989), potential crop trees must have clear dominance and must have large crowns to secure good growth with fertilization in unthinned stands. Also, the future growth of crop trees with these treatments at Shawnigan will depend upon their crown

development and the stand structure. This will be studied as part of the analysis of the 1988/89 biomass sample trees. The benefit of thinning is likely to last longer for crop trees than the benefit of fertilization. Considering the difference in cost of the treatments a refertilization may be justified, although its effect on crop tree growth cannot be expected to be long-lasting in these very dense stands. As shown by Gardner (1990) the effect of refertilization at year 9 was diminishing in the second 3-year measurement period in unthinned stands, but was still considerable in thinned stands.

18.3 Predicting Growth Responses

A wide range of variation in growth response of coastal Douglas-fir to nitrogen fertilization has been found and much research has been directed towards improving site-specific response prediction. The cooperative Regional Forest Nutrition Research Project (RFNRP) in Washington and Oregon has provided a major data source for growth prediction studies. The more than 270 research installations comprising this project include different thinning levels, fertilizer rates, refertilizations and stand ages (Chappell 1991). Extensive analysis of soil physical and chemical conditions has been done for studies of relationships to growth response. Soil variables include total and mineralizable N, extractable P, and other nutrient elements, as well as forest floor C/N ratio and N content. Other variables considered include site index, stand age, stand density, basal area, stand location, and foliar nutrient contents.

In a study by Edmonds and Hsiang(1987) the 4-year volume growth responses to 448 kg N/ha were stratified according to thinning level, site location, and site quality, and regressed against 28 stand and site variables. They found that S may be limiting in southwest Oregon and P in coastal Washington. The forest floor C/N ratio was the dominant variable in both thinned and unthinned stands and was most significant in thinned stands on high-quality sites. On such sites, more of the variation was explained by inclusion of surface soil exchangeable K. The volume response increased with increase in C/N ratio. The critical ratio would depend on the type of carbon substrate in the forest floor and some sites with C/N ratios in the 28–45 range gave no growth response. If the litter is made up mainly of decomposing needles with a C/N ratio of 30 or less, the release of N would likely be sufficient for good growth and no response to N fertilization would occur. It should be noted, however, that immobilization of NH_4^+ following urea application will also increase with an increase in the C/N ratio. Radwan and Shumway (1984) studied 8-year basal area response of Douglas-fir at 26 sites. Site index, total N, and mineralizable N were the only variables correlated (negatively) with growth response. They pointed out that any one of these indices may not be useful when other nutrients and growth factors are limiting.

Site index integrates many growth factors and can be easily measured. One cannot expect, however, that these factors are uniquely associated with response to N fertilization for all sites and stand conditions. Accordingly, relationships of response with site index have been weak or insignificant in several studies or have been dependent on other site and stand conditions. An early study of RFNRP installations (Peterson and Gessel 1983) showed that volume response in unthinned stands was negatively related to site index over the first 4 years but positively related to the index thereafter. No relationship to site index was found in thinned stands. A later study in several regions indicated that site index had an increasingly inverse effect on response as basal area increased, and in both thinned and unthinned stands. For other RFNRP installations Miller *et al.* (1989) applied multiple regression models to determine the best equations for estimating volume response to N fertilization. They found that the response decreased with increase in site index, stand age, and relative density. The only soil variable of significance was the C/N ratio in the surface soil.

Empirical regression equations for predicting basal area growth response in thinned and unthinned immature Douglas-fir stands were developed from the B.C. Forest Productivity Committee trials (EP 703) (Omule 1990). No relationship could be found of the 9-year response to the initial stand attributes of total age, basal area, and site index. The range of site and stand conditions, however, was considered to be relatively small. An earlier report for these installations indicated the poorer sites gave a better response to 448 kg N/ha but not to 224 kg N/ha (Miller *et al.* 1986).

A promising approach has been taken by Carter and Klinka (1988) for development of site-specific guidelines of spaced immature coastal Douglas-fir. Their stratification is based on the ecological framework of the biogeoclimatic ecosystem classification system. This system considers the individual site factors that

directly affect tree growth. Klinka (1991) outlined an interesting method for evaluating site characteristics for forest fertilization. This is based on a stepwise elimination of biologically, edaphically, and operationally unsuitable sites from an original stand-site selection. This requires a knowledge of relationships among climate, soil moisture, soil nitrogen, and forest productivity, which at this time is poorly developed. For instance, Klinka characterized the Very Dry Maritime CWH subzone as biologically unsuitable for fertilization, yet the Shawnigan site is in this subzone and has given excellent response to N fertilization. Even the effect of one of the variables, soil moisture, on growth response to fertilization is not clearly defined as reviewed and studied by Brix (1972, 1979, 1989, 1991) and Brix and Mitchell (1986) and discussed earlier in this report.

The above results indicate that there is a need for different, simple, and inexpensive tests that will indicate whether or not a site will respond to fertilization with different nutrient elements without quantifying the response. A method now gaining wide acceptance is that of a foliar analysis screening trial. This diagnostic technique involves first-year changes in foliar nutrient concentration and content and foliage unit weight following single tree fertilization (Timmer and Morrow 1984; Weetman and Fournier 1986). An even simpler method, which only takes into account changes in foliage weights, is being studied (R. Carter, pers. comm. 1992). Carter (1991) and Ballard and Carter (1986) reviewed the use of foliar analysis in identifying nutrient deficiencies, including the DRIS system that describes critical nutrient element ratios and relationships rather than critical levels of individual elements. A knowledge of critical levels may tell you where not to fertilize rather than where to fertilize because other factors may limit the response.

18.4 Monitoring in New Installations

Permanent installations such as those established by the RFNRP and the Forest Productivity Committee are needed to determine the response duration, magnitude, and variability under different stand and site conditions. Weetman (1991) has stressed the importance of incorporating such thinning × fertilization installations as part of the province's growth-and-yield research strategic planning. More of our research and forest planning will depend on growth simulation models but they need to be calibrated with "real" long-term growth records.

Empirical trials have usually started with stand selection based on some site and stand criteria and proceeded with periodic growth analysis. The variable and often unexplainable responses that result can, with some simple and inexpensive analysis during the response period, be separated into distinct phases and categories. This will help to explain the response pattern, duration, and magnitude. The opportunity is lost if we wait until the end of the experimental period.

The first major question is whether or not the fertilizer applied became available and was taken up by the tree. This can be determined by a foliar analysis in the fall following the application. A later uptake cannot be expected with our normal rates of application. The next step would be an analysis of foliar mass response, considering that an increase in foliar mass is responsible for the long-term growth response and that the foliar efficiency is only enhanced for up to 4 years. This sampling could be done 4–5 years after fertilization at a fixed crown level such as node 6. An attempt can be made to relate variations in foliage production and shoot extension to climatic conditions such as soil moisture. If no foliage response occurs, no growth response can be expected past the fourth year. If foliage mass is increased but stem growth is not, other growth-limiting factors may be responsible. Alternatively, the stand may already have achieved its optimum leaf area index and a thinning would have been needed. In fact, a sampling scheme such as this is being carried out in the B.C. Ministry of Forests Inventory Branch Pre-harvest Sample Plot Program (PSP) (Barber 1991).

18.5 Fertilization of Low-density Stands

It is not the intent of this report to arrive at research priorities in forest fertilization. However, one aspect is in need of an early clarification, and that is fertilizer utilization in low-density stands, since fertilization in these stands has become an operational practice with some potentially serious associated problems.

As shown earlier, the N uptake after fertilization was similar in unthinned and heavily thinned plots at Shawnigan over the first 9-year period. The uptake took place in the first year in unthinned plots, whereas the greatest amount was taken up later in thinned plots. In such plots N availability would depend on a fertilizer priming effect that involves N mineralization of native organic soil N or a mineralization of immobilized N fertilizer.

The spacing (900 stems per ha) was considered heavy when the project was initiated but now a stocking with one-half this number is common in coastal Douglas-fir where no commercial thinning is planned. A pre-commercial spacing of 500 stems/ha for Douglas-fir is recommended by the B.C. Ministry of Forests in the Vancouver Forest Region (Vancouver Circular letter VR91-558, Oct. 1, 1991) and stands should preferably be thinned when leave-trees are between 3 to 5 m. As stated in this communication, the highest priority for fertilization (from a growth response point of view) should be given to 25–50-year-old thinned stands. For young stands (less than 30 years), priority should be given to thinned stands with 10–25m^2/ha basal area on site index 25–35. This would require many years of growth between spacing and fertilization, a condition that is not usually met.

Major research installations have not yet investigated fertilizer effect with the heavy spacing applied today. The RFNRP installations in Washington and Oregon have the lowest stocking level (740 stems/ha) in the Phase IV installations. The heaviest thinning in the B.C. Forest Productivity installations (EP 703) only reduced the basal area by 35% versus 66% at Shawnigan. Only in the study by Carter and Scagel (1989) at Courtenay was a density as low as 500 stems/ha applied and with a good fertilizer response. Their conclusion was that the 750 stems/ha would be the best of the spacings for fertilization if commercial thinning was anticipated, but if not then 500 stems/ha would be more appropriate.

Obviously there is a lower limit of stand density below which root coverage, tree storage capacity, and N requirements for growth will reduce utilization of fertilizer to an unsatisfactory level. At this time the common operational practice of fertilizing very low density stands is not sufficiently supported by research experience. More studies in line with the one conducted by Carter and Scagel (1989) are needed. These could possibly be done in established fertilizer operations. If warranted by these studies, 15N investigations of fertilizer priming and re-mineralization effects that could prolong the long-term nitrogen availability in thinned stands should be undertaken.

In the Shawnigan Project a wide range of studies was covered to quantify and explain the long-term growth responses obtained to thinning and fertilization. Study leaders involved have concluded that the cooperative approach taken to obtain a holistic picture of ecosystem functioning was to their mutual benefit. A similar approach in other ecosystems, to confirm the findings and test the hypotheses developed at Shawnigan, would be desirable.

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19.3 Subject Index to Shawnigan Lake Project Reports

Shawnigan Site and Stand:

Environment Canada 1978, Crown 1974, Crown and Brett 1975

Mensurational Responses:

Dbh, height, basal area, volume, mortality after different reponse periods:

3 years: Crown *et al.* 1977

6 years: Hall *et al.* 1980

9 years: Barclay *et al.* 1982

12 years: Barclay and Brix 1985a

15 years: Gardner 1990

Inter-tree competition: Barclay and Layton 1990

Methodology: Quenet and Crown 1976; Hall *et al.* 1978; McWilliams 1990

Stem form: Brix 1983; Thomson and Barclay 1984; Barclay and Brix 1985a

High rates of nitrogen: Barclay and Brix 1985b

Source of nitrogen: Dangerfield and Brix 1979; Barclay and Brix 1984

Biomass:

Overstory: Webber 1977; Brix 1983; Barclay *et al.* 1986

Understory: Stanek *et al.* 1979

Wood quality:

Jozsa and Brix 1989

Tree growth:

Seasonal pattern: Brix 1976, 1991

Xylem and sapwood development: Brix 1972; Brix and Mitchell 1980, 1983; Mitchell 1984

Crown development: Brix 1981a

Root growth: Kurz *et al.* 1990

Tree physiology:

Foliar nutrient status: Webber 1974, 1977; Dangerfield and Brix 1979; Brix 1981b; Pang *et al.* 1987

Tree and soil water relations: Brix 1972, 1979; Brix and Mitchell 1985, 1986

Photosynthesis, respiration, net assimilation: Brix and Ebell 1969; Brix 1971, 1972, 1981b, 1983; Mitchell 1988

Foliage quantity, efficiency effect: Brix 1983, 1991

Soil chemistry:

Methodology: Marshall and DeBell 1980; Pang and McCullough 1983; Pang 1985b, Pang and Kolenko 1986; Marshall *et al.* 1990

Nutrient content, conversion, distribution, movement:

Webber 1974; Marshall and McMullan 1976; Dangerfield and Brix 1979; Pang 1982, 1984a,b, 1985a,b; Pang and McCullough 1982; Marshall 1991

Organic matter: Trofymow 1988; Marshall 1991

Nutrient cycling:

Losses: Marshall and DeBell 1980; Pang 1982, 1984a,b; Pang and Cho 1982, 1984; Hetherington 1985; Preston *et al.* 1990; Marshall 1991

Uptake: Pang 1981, 1985a; Pang *et al.* 1987; Brix 1991

Tree, understory nutrient content: Stanek *et al.* 1979; Pang *et al.* 1987

Litterfall: Trofymow *et al.* 1991

Soil fauna and microflora:

Fauna: Marshall 1974, 1977, 1980, 1981, 1986, 1991; Marshall *et al.* 1987

Microflora: Dangerfield and Olsen 1973; Dangerfield and Brix 1979; Trofymow 1991

Water-nitrogen fertilization interaction:

Brix 1971, 1979, 1989, 1991

Environmental impacts:

Hetherington 1985; Radwan and Brix 1986

Modelling growth and processes:

Barclay and Hall 1986; Sachs and Trofymow 1991; Trofymow and Sachs 1991

Economics:

Duke *et al.* 1989

APPENDICES

APPENDIX 1. List of variables measured for the core, volume, and extra height trees (from Gardner 1990)

Years since treatment	Core trees			Volume trees				Extra height trees		
	dbh	ht	htlc	dbh	ht	htlc	taper	dbh	ht	htlc
0	•	•	•	•	•	•	•	•	•	•
1	•			•	•			•		
2	•			•	•			•		
3	•	•		•	•		•	•	•	
4				•	•					
5				•	•					
6	•	•	•	•	•	•	•	•	•	•
7				•	•					
8				•	•					
9	•	•	•	•	•	•	•	•	•	•
10				•	•					
11				•	•					
12	•			•	•	•	•	•		
13				•	•				•	
14				•	•				•	
15	•			•	•	•	•	•	•	•

dbh = diameter at breast height (1.30 m)
ht = total tree height
htlc = height to live crown
taper = taper measurements, positioned on the stem at 2.54 cm diameter decrements at the time of treatment

APPENDIX 2. Supplementary tables (from Gardner 1990)

Quadratic mean diameter (cm) by treatment and year[a]

	Year						
Treatment	0 Before	0 After	3	6	9	12	15
T0F0	8.4	8.4	9.2	9.8	10.5	11.2	11.9
T0F1	9.0	9.0	10.2	11.2	12.0	13.2	14.0
T0F1-1	9.3	9.3	10.8	12.1	13.1	14.6	15.8
T0F2	7.8	7.8	9.4	10.9	12.0	13.2	14.2
T0F2-2	9.1	9.1	10.8	12.4	13.7	15.4	16.8
T1F0	8.4	10.0	11.3	12.4	13.5	14.5	15.3
T1F1	8.9	10.1	12.0	13.4	14.6	15.8	16.8
T1F1-1	9.2	10.5	12.5	13.7	15.0	16.4	17.6
T1F2	8.2	9.6	12.0	13.8	15.1	16.3	17.1
T1F2-2	9.5	10.1	12.5	14.2	15.6	17.3	18.7
T2F0	8.5	10.8	12.7	14.4	16.0	17.5	18.7
T2F1	8.8	10.8	13.8	15.8	17.5	19.1	20.6
T2F1-1	8.4	11.0	14.0	16.0	17.8	19.9	21.5
T2F2	8.3	10.8	14.5	17.1	18.9	20.6	22.0
T2F2-2	8.4	11.1	14.6	17.0	18.9	21.4	23.1

Periodic annual diameter increments (cm/yr) for each treatment combination[b]

	Year							
Treatment	0–3	3–6	6–9	9–12	12–15	0–15	0–9	9–15
T0F0	0.23	0.18	0.17	0.17	0.13	0.18	0.19	0.15
T0F1	0.36	0.25	0.19	0.23	0.17	0.26	0.28	0.20
T0F1-1	0.39	0.26	0.23	0.28	0.20	0.32	0.31	0.26
T0F2	0.48	0.33	0.23	0.25	0.19	0.34	0.38	0.22
T0F2-2	0.52	0.37	0.29	0.38	0.26	0.42	0.42	0.34
T1F0	0.40	0.36	0.34	0.32	0.24	0.33	0.37	0.28
T1F1	0.63	0.43	0.38	0.37	0.27	0.42	0.48	0.32
T1F1-1	0.66	0.39	0.38	0.42	0.29	0.44	0.48	0.36
T1F2	0.79	0.54	0.38	0.35	0.26	0.47	0.58	0.31
T1F2-2	0.75	0.51	0.37	0.46	0.31	0.51	0.55	0.40
T2F0	0.61	0.57	0.52	0.50	0.39	0.52	0.57	0.45
T2F1	0.98	0.66	0.57	0.53	0.41	0.64	0.74	0.47
T2F1-1	0.99	0.65	0.60	0.69	0.48	0.68	0.75	0.58
T2F2	1.22	0.87	0.60	0.57	0.45	0.74	0.90	0.51
T2F2-2	1.15	0.81	0.62	0.80	0.54	0.79	0.86	0.67

[a] These averages will differ slightly from previous reports because all species, not just Douglas-fir, are included.
[b] Trees dying during specified time period were excluded from the average.

Basal area (m^2/ha) by treatment and year

Treatment	Year						
	0 Before	0 After	3	6	9	12	15
T0F0	26.6	26.6	31.7	35.9	39.7	44.1	47.3
T0F1	22.7	22.7	29.1	34.1	38.2	42.9	46.1
T0F1-1	25.2	25.2	32.5	37.2	41.2	46.8	49.7
T0F2	19.1	19.1	27.5	33.7	37.8	41.9	45.0
T0F2-2	21.1	21.1	29.3	35.4	40.2	47.0	50.1
T1F0	24.0	15.6	19.7	23.7	27.7	32.1	35.4
T1F1	21.5	14.5	20.6	25.4	30.1	35.1	38.2
T1F1-1	24.9	16.3	23.2	28.0	33.2	39.4	43.7
T1F2	21.8	14.6	22.8	29.3	34.6	39.9	44.1
T1F2-2	27.2	16.8	25.5	32.2	37.6	44.7	48.6
T2F0	21.4	8.3	11.3	14.6	18.0	21.6	24.7
T2F1	24.2	8.6	14.0	18.3	22.6	27.0	30.4
T2F1-1	20.9	8.5	13.6	17.7	22.0	27.4	31.4
T2F2	20.0	8.4	15.0	21.0	25.7	30.6	34.8
T2F2-2	22.7	8.5	14.4	19.7	24.4	31.1	35.8

Net periodic annual basal area increments (m^2/ha•yr^{-1}) for each treatment combination

Treatment	Year							
	0–3	3–6	6–9	9–12	12–15	0–15	0–9	9–15
T0F0	1.70	1.40	1.27	1.47	1.07	1.38	1.46	1.27
T0F1	2.13	1.67	1.37	1.57	1.07	1.56	1.72	1.32
T0F1-1	2.43	1.57	1.33	1.87	0.97	1.63	1.78	1.42
T0F2	2.80	2.07	1.37	1.37	1.03	1.73	2.08	1.20
T0F2-2	2.73	2.03	1.60	2.27	1.03	1.93	2.12	1.65
T1F0	1.37	1.33	1.33	1.47	1.10	1.32	1.34	1.28
T1F1	2.03	1.60	1.57	1.67	1.03	1.58	1.73	1.35
T1F1-1	2.30	1.60	1.73	2.07	1.43	1.83	1.88	1.75
T1F2	2.73	2.17	1.77	1.77	1.40	1.97	2.22	1.58
T1F2-2	2.90	2.23	1.80	2.37	1.30	2.12	2.31	1.83
T2F0	1.00	1.10	1.13	1.20	1.03	1.09	1.08	1.12
T2F1	1.80	1.43	1.43	1.47	1.13	1.45	1.56	1.30
T2F1-1	1.70	1.37	1.43	1.80	1.33	1.53	1.50	1.57
T2F2	2.20	2.00	1.57	1.63	1.40	1.76	1.92	1.52
T2F2-2	1.97	1.77	1.57	2.23	1.57	1.82	1.77	1.90

Average heights (m) by treatment and year[a] (from Gardner 1990)

	Year					
Treatment	0	3	6	9	12	15
T0F0	8.4	9.5	10.4	11.3	12.1	13.2
T0F1	8.7	10.2	11.4	12.4	14.2	15.8
T0F1-1	9.3	10.8	12.8	14.8	16.7	17.8
T0F2	7.9	9.7	11.4	12.5	13.8	15.4
T0F2-2	8.9	10.6	12.4	14.4	16.3	17.8
T1F0	9.8	10.9	12.0	13.1	14.4	15.4
T1F1	9.2	11.0	12.4	13.7	15.5	16.6
T1F1-1	10.4	12.2	13.4	15.0	16.9	18.5
T1F2	8.4	10.3	12.0	13.4	15.3	16.5
T1F2-2	10.2	12.1	14.2	15.8	18.0	19.9
T2F0	9.9	10.9	12.2	13.6	15.3	16.9
T2F1	10.6	12.5	14.3	15.8	17.8	19.5
T2F1-1	10.5	12.3	13.9	15.7	18.0	20.0
T2F2	9.8	12.0	14.0	15.6	17.6	19.4
T2F2-2	10.3	12.2	13.8	15.7	18.2	20.3

Periodic annual height increments (m/yr) for each treatment combination[b]

	Year							
Treatment	0–3	3–6	6–9	9–12	12–15	0–15	0–9	9–15
T0F0	0.34	0.26	0.21	0.25	0.20	0.27	0.30	0.23
T0F1	0.50	0.38	0.23	0.37	0.33	0.41	0.44	0.36
T0F1-1	0.52	0.39	0.43	0.53	0.38	0.49	0.51	0.45
T0F2	0.60	0.47	0.29	0.42	0.34	0.47	0.51	0.40
T0F2-2	0.57	0.40	0.43	0.59	0.45	0.52	0.53	0.52
T1F0	0.39	0.36	0.35	0.44	0.35	0.38	0.37	0.40
T1F1	0.60	0.48	0.35	0.53	0.38	0.48	0.49	0.46
T1F1-1	0.58	0.42	0.46	0.56	0.44	0.51	0.51	0.51
T1F2	0.65	0.54	0.37	0.55	0.41	0.52	0.55	0.48
T1F2-2	0.65	0.56	0.54	0.66	0.53	0.61	0.61	0.61
T2F0	0.34	0.42	0.46	0.59	0.52	0.47	0.41	0.56
T2F1	0.64	0.61	0.50	0.65	0.56	0.59	0.58	0.61
T2F1-1	0.60	0.54	0.59	0.78	0.64	0.63	0.58	0.71
T2F2	0.76	0.65	0.52	0.69	0.58	0.64	0.64	0.64
T2F2-2	0.62	0.54	0.63	0.84	0.65	0.66	0.60	0.75

[a] These values will differ slightly from previous reports as they are based on only volume and extra height trees.
[b] Trees dying during specified time period were excluded from the average.

Total volume (m^3/ha) by treatment and year (from Gardner 1990)

Treatment	Year						
	0 Before	0 After	3	6	9	12	15
T0F0	143	143	191	233	276	329	373
T0F1	124	124	184	239	286	342	387
T0F1-1	146	146	217	271	329	405	461
T0F2	92	92	158	222	275	334	386
T0F2-2	112	112	182	244	310	392	446
T1F0	131	88	122	159	206	255	300
T1F1	116	79	131	180	228	289	339
T1F1-1	142	95	155	203	260	336	405
T1F2	111	76	141	204	255	320	383
T1F2-2	161	101	176	247	322	421	490
T2F0	114	46	68	95	133	173	212
T2F1	130	49	90	132	185	240	290
T2F1-1	111	48	88	126	180	247	309
T2F2	100	45	95	150	201	261	319
T2F2-2	122	48	93	140	192	275	346

Net periodic annual volume increment (m^3/ha•yr^{-1}) for each treatment combination

Treatment	Year							
	0–3	3–6	6–9	9–12	12–15	0–15	0–9	9–15
T0F0	16.0	14.0	14.3	17.7	14.7	15.3	14.8	16.2
T0F1	20.0	18.3	15.7	18.7	15.0	17.5	18.0	16.8
T0F1-1	23.7	18.0	19.3	25.3	18.7	21.0	20.3	22.0
T0F2	22.0	21.3	17.7	19.7	17.3	19.6	20.3	18.5
T0F2-2	23.3	20.7	22.0	27.3	18.0	22.3	22.0	22.7
T1F0	11.3	12.3	15.7	16.3	15.0	14.1	13.1	15.7
T1F1	17.3	16.3	16.0	20.3	16.7	17.3	16.6	18.5
T1F1-1	20.0	16.0	19.0	25.3	23.0	20.7	18.3	24.2
T1F2	21.7	21.0	17.0	21.7	21.0	20.5	19.9	21.3
T1F2-2	25.0	23.7	25.0	33.0	23.0	25.9	24.6	28.0
T2F0	7.3	9.0	12.7	13.3	13.0	11.1	9.7	13.2
T2F1	13.7	14.0	17.7	18.3	16.7	16.1	15.1	17.5
T2F1-1	13.3	12.7	18.0	22.3	20.7	17.4	14.7	21.5
T2F2	16.7	18.3	17.0	20.0	19.3	18.3	17.3	19.7
T2F2-2	15.0	15.7	17.3	27.7	23.7	19.9	16.0	25.7

Merchantable volume (m^3/ha) by treatment and year based on a dbh limit of 12.5 cm[a] (from Gardner 1990)

	Year						
Treatment	0 Before	0 After	3	6	9	12	15
T0F0	17	17	39	65	95	132	170
T0F1	22	22	53	92	125	174	214
T0F1-1	33	33	77	119	161	226	280
T0F2	4	4	31	72	113	166	211
T0F2-2	16	16	56	107	162	235	287
T1F0	19	16	38	66	100	138	176
T1F1	17	12	48	87	124	176	216
T1F1-1	30	23	65	103	148	213	269
T1F2	11	9	49	104	148	199	248
T1F2-2	40	18	71	131	190	271	334
T2F0	19	9	26	49	81	116	147
T2F1	19	7	45	80	121	167	208
T2F1-1	11	9	43	79	121	175	225
T2F2	10	9	48	98	140	188	234
T2F2-2	19	10	51	90	133	200	256

Periodic annual merchantable volume increments (m^3/ha•y r^{-1}) for each treatment combination based on a dbh limit of 12.5 cm

	Year							
Treatment	0–3	3–6	6–9	9–12	12–15	0–15	0–9	9–15
T0F0	7.3	8.7	10.0	12.3	12.7	10.2	8.7	12.5
T0F1	10.3	13.0	11.0	16.3	13.3	12.8	11.4	14.8
T0F1-1	14.7	14.0	14.0	21.7	18.0	16.5	14.2	19.8
T0F2	9.0	13.7	13.7	17.7	15.0	13.8	12.1	16.3
T0F2-2	13.3	17.0	18.3	24.3	17.3	18.1	16.2	20.8
T1F0	7.3	9.3	11.3	12.7	12.7	10.7	9.3	12.7
T1F1	12.0	13.0	12.3	17.3	13.3	13.6	12.4	15.3
T1F1-1	14.0	12.7	15.0	21.7	18.7	16.4	13.9	20.2
T1F2	13.3	18.3	14.7	17.0	16.3	15.9	15.4	16.7
T1F2-2	17.7	20.0	19.7	27.0	21.0	21.1	19.1	24.0
T2F0	5.7	7.7	10.7	11.7	10.3	9.2	8.0	11.0
T2F1	12.7	11.7	13.7	15.3	13.7	13.4	12.7	14.5
T2F1-1	11.3	12.0	14.0	18.0	16.7	14.4	12.4	17.3
T2F2	13.0	16.7	14.0	16.0	15.3	15.0	14.6	15.7
T2F2-2	13.7	13.0	14.3	22.3	18.7	16.4	13.7	20.5

[a] 10 cm top diameter, 30-cm stump.

Merchantable volume (m^3/ha) by treatment and year based on a dbh limit of 17.5 cm[a] (from Gardner 1990)

Treatment	Year						
	0 Before	0 After	3	6	9	12	15
T0F0	5	5	9	15	28	46	71
T0F1	6	6	16	39	55	86	122
T0F1-1	16	16	32	53	81	150	206
T0F2	0	0	2	11	30	79	114
T0F2-2	0	0	17	37	74	152	208
T1F0	4	2	9	15	38	70	101
T1F1	0	0	13	24	59	111	160
T1F1-1	4	4	15	38	87	148	207
T1F2	3	2	7	27	77	129	181
T1F2-2	10	2	19	59	117	207	272
T2F0	6	2	6	18	41	78	112
T2F1	0	0	8	39	89	138	186
T2F1-1	2	2	13	39	80	146	208
T2F2	0	0	15	58	110	168	221
T2F2-2	1	1	13	59	113	185	244

Periodic annual merchantable volume increments (m^3/ha•yr^{-1}) for each treatment combination based on a dbh limit of 17.5 cm

Treatment	Year							
	0–3	3–6	6–9	9–12	12–15	0–15	0–9	9–15
T0F0	1.3	2.0	4.3	6.0	8.3	4.4	2.6	7.2
T0F1	3.3	4.7	8.3	10.3	12.0	7.7	5.4	11.2
T0F1-1	5.3	7.0	9.3	23.0	18.7	12.7	7.2	20.8
T0F2	0.7	3.0	6.3	16.3	11.7	7.6	3.3	14.0
T0F2-2	5.7	6.7	12.3	26.0	18.7	13.9	8.2	22.3
T1F0	2.3	2.0	7.7	10.7	10.3	6.6	4.0	10.5
T1F1	4.3	3.7	11.7	17.3	16.3	10.7	6.6	16.8
T1F1-1	3.7	7.7	16.3	20.3	19.7	13.5	9.2	20.0
T1F2	1.7	6.7	16.7	17.3	17.3	11.9	8.3	17.3
T1F2-2	5.7	13.3	19.3	30.0	21.7	18.0	12.8	25.8
T2F0	1.3	4.0	7.7	12.3	11.3	7.3	4.3	11.8
T2F1	2.7	10.3	16.7	16.3	16.0	12.4	9.9	16.2
T2F1-1	3.7	8.7	13.7	22.0	20.7	13.7	8.7	21.3
T2F2	5.0	14.3	17.3	19.3	17.7	14.7	12.2	18.5
T2F2-2	4.0	15.3	18.0	24.0	19.7	16.2	12.4	21.8

[a] 10 cm top diameter, 30-cm stump.