WORKING PAPER 60

Effects of Sitka Alder Retention and Removal on the Growth of Young Lodgepole Pine in the Central Interior of British Columbia (E.P. 1185)

Establishment Report

2001

BRITISH COLUMBIA

Ministry of Forests Research Program

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PREFACE

This Working Paper constitutes the establishment report for Ministry of Forests E.P. 1185, "Effects of Sitka alder retention and removal on the growth of young lodgepole pine in the central interior of British Columbia." The intent is to preserve data of permanent value for the researchers and forestry practitioners who will use and interpret the results of this study.

This project originated from an informal March 1994 workshop in Prince George that involved Ministry of Forests soil scientists and silviculturists in a discussion of nitrogen fixation research needs. Among the knowledge gaps identified were the need for: (1) a better understanding of the interactions between Sitka alder and managed conifer species, and (2) stand level data on nitrogen fixation rates by Sitka alder in interior forests.

Later in 1994, R. Brockley (Kalamalka Research Station) conducted a reconnaissance search for candidate research sites in the Sub-Boreal Spruce zone of Quesnel, Vanderhoof, and Prince George forest districts. Brockley and P. Sanborn (Prince George Forest Region) were jointly responsible for preparing the working plan, selecting the research site in Vanderhoof Forest District, and installing and maintaining the treatment plots. C. Preston (Canadian Forest Service) joined the team in 1996 to undertake nitrogen fixation studies and provide the necessary stable isotope analyses.

For further information on the status of this project, the reader should contact either Paul Sanborn (Paul.Sanborn@gems9.gov.bc.ca) or Rob Brockley (Rob.Brockley@gems7.gov.bc.ca). The data files on which this report is based are archived at the Ministry of Forests Research Branch, under the supervision of the Branch Data Custodian.

ABSTRACT

A long-term field experiment was established in 1995 in the Stuart Dry Warm Sub-Boreal Spruce (SBSdw3) biogeoclimatic variant in the Vanderhoof Forest District to study the interactions between Sitka alder (*Alnus viridis* (Chaix) DC. ssp. *sinuata* (Regel) A.&D. Löve) and lodgepole pine (*Pinus contorta* Dougl. *ex* Loud.) in a 1987 cutblock. The main objective of the study was to determine the effects of differing levels of Sitka alder retention (0, 500, 1000, and 2000 clumps per hectare) on lodgepole growth after the pine stands were thinned to a uniform density of 1000 stems per hectare. Ancillary studies were planned to measure: (1) the nitrogen fixation rate of Sitka alder, using ^{15}N isotope dilution, (2) the long-term changes in soil nutrient pools, and (3) the decomposition rates and nutrient concentration changes in Sitka alder and lodgepole pine litter. This establishment report details the methods used and documents the initial soil and stand condition at the time of installation of the experimental treatments.

ACKNOWLEDGEMENTS

We wish to thank the numerous technicians and student assistants whose efforts in the field and laboratory made this project possible: Kevin McCullough (Pacific Forest Centre), Christine Unghy and Frank Rowe (Kalamalka Research Station), Megan D'Arcy, John Stigger, Luke Ferdinands, Luke Stiles, Joel Woode, James Froese, Alena James, Brenda Roosdahl, Katrina Froese, David Affleck, and Angie Dale.

Several colleagues provided constructive reviews that significantly improved our working plan: Vera Sit and Wayne Johnstone (Research Branch), Les Herring (Prince George Forest Region), Suzanne Simard (Kamloops Forest Region), and Rick Trowbridge (Boreal Research and Development). Wendy Bergerud (Research Branch) provided valuable statistical advice at several critical points, and reviewed this report. Keith Thomas (Research Branch) and Rick Trowbridge also reviewed the manuscript of this report.

Craig DeLong shared file information on earlier alder studies in the Prince George Forest Region, and Dave Coopersmith assisted with foliar sampling and tree measurements.

Funding was provided by FRDA II (1995–96), Forest Renewal BC (1996–present; projects HQ96157 and OP97077-RE), and the Prince George Forest Region.

We also thank Canadian Forest Products (Isle Pierre Division) and the Vanderhoof Forest District for their interest in, and support of, this work.

CONTENTS

TABLES

FIGURES

1 INTRODUCTION

Sitka alder (*Alnus viridis* (Chaix) DC. ssp. *sinuata* (Regel) A.&D. Löve) is an important shrub component of both mature and young lodgepole pine (*Pinus contorta* Dougl. *ex* Loud.) stands in the Stuart Dry Warm Sub-Boreal Spruce (SBSdw3) biogeoclimatic variant in the southwestern portion of the Prince George Forest Region (DeLong et al. 1993)[1]. In many cases, Sitka alder can provide 50% or more cover, and therefore may exert potentially competitive effects on the crop species. In such situations, silviculturists recognize the "Dry Alder" complex as a distinctive vegetation management challenge in the SBS and other interior biogeoclimatic zones (British Columbia Ministry of Forests 1997). Conversely, as an actinorhizal species, Sitka alder can benefit site fertility through nitrogen fixation, with estimates from the Pacific Northwest ranging from 20 to 150 kg N/ha annually (Binkley 1986).

Although including Sitka alder in their compilation of species that compete with conifers, Haeussler and Coates (1986) recognized a need for studies to determine whether N fixation by Sitka alder was beneficial to crop trees on interior sites. To date, the following are the only relevant studies.

- Simard (1990) observed that in retrospective sampling of 6- to 10-year-old naturally regenerated lodgepole pine in the Montane Spruce zone, Sitka alder cover of less than 35% did not generally reduce pine growth.
- Simard and Heineman (1996) refined this estimate in later work, observing pine growth responses when Sitka alder cover was reduced from 22% to 15–18%.
- Sachs (1992) estimated annual N fixation rates of 1.5 to 8 kg N/ha in similar stands.
- Mead and Preston (1992) used ^{15}N isotope dilution to demonstrate N fixation by Sitka alder in a fertilized lodgepole pine stand, with approximately 50 kg N/ha accumulated by above-ground alder biomass in 8 years.

Ballard and Hawkes (1989) observed that proximity of Sitka alder enhanced the foliar N concentrations of white spruce (*Picea glauca* [Moench] Voss) planted on windrowed sites north of Prince George.

The existing information does not provide clear guidance on where the balance of advantage lies; that is, at what level of alder density are the benefits of N addition offset by competitive interactions with the crop trees? This question arises in any attempt to use N-fixing species, either woody or herbaceous, in silviculture (Binkley 1986). A related issue is the comparative effectiveness of biologically fixed N versus fertilizer-derived N. In other words, is conventional fertilization a more efficient means of removing N limitation to conifer productivity than the retention of indigenous N-fixing shrubs? In cases where the economic returns from operational fertilization may not justify this practice, it is important to understand the potential contributions from symbiotic N fixation. It may

1 In this report, references to "alder" and "pine" indicate these two species.

be acceptable to incur some competitive impacts on conifer productivity if the long-term N status of the site is maintained biologically.

Field experiments involving the interplanting of alder and pine at varying densities would be one possible approach to study these interactions. Unfortunately, several investigators have reported poor success in establishing planted Sitka alder in the Interior of British Columbia (D. Burgess, R. Trowbridge, pers. comm., 1994). An alternative method would remove or retain established alder in young plantations or naturally regenerated stands of lodgepole pine. Because much of the Sitka alder cover in young pine stands appears to have re-sprouted from clumps established in the previous mature stands, this approach would produce stand conditions that are more representative of those in managed forests in this subzone.

2 OBJECTIVES

2.1 Original Objectives

The main objectives of this study, as stated in the working plan (Brockley and Sanborn 1995), are to:

- determine the effects of differing densities of Sitka alder on the long-term growth of a young, naturally regenerated lodgepole pine stand;
- compare the growth of lodgepole pine after conventional fertilization to that after removal or retention of Sitka alder;
- identify long-term changes in soil nitrogen availability associated with differing levels of Sitka alder retention; and
- assess litter fall quantity and composition in relation to alder retention or removal, and during subsequent stand development.

Two ancillary studies within the main study were also suggested:

- to compare N fixation rates by Sitka alder in both young and mature pine stands; and
- to compare mass loss rates and nutrient concentrations of both pure and mixed pine and alder foliage through litter decomposition studies.

2.2 Modifications to the Working Plan

As a result of the uneven distribution of alder clumps in the study area, we were unable to find sufficient area to accommodate the number of plots originally planned, and one of our proposed objectives and two of the treatments had to be eliminated (section 3.2). We were unable to include the upper end of the range of planned alder densities and, therefore, could not compare the effects of conventional fertilization and alder retention on lodgepole pine growth. Since several pine fertilization trials exist elsewhere in this and adjacent SBS subzones, we do have relevant comparative data available to enable at least a qualitative comparison of the relative value of fertilizer and alder as N sources for pine.

The ancillary objectives were refined in the Forest Renewal BC Research Program application (Project OP97077-RE), as follows:

- **Estimate rates of nitrogen fixation by Sitka alder using two independent methods (mass balance and isotopic).**

Rationale: We were uncertain whether conventional soil and biomass sampling would detect long-term changes in site N capital, given the unavoidably high degree of variability in soil properties. Since use of the acetylene reduction assay requires assumptions that limit its usefulness in

quantitative field studies (Minchin et al. 1994), and an estimate of root nodule biomass is needed (Binkley 1982; Sachs 1992) that may be impractical in very stony soils, we sought other methods. Shearer and Kohl (1989) made a strong case for using the natural abundance of ^{15}N as a tracer of fixed N, yet others have encountered fairly ambiguous results (e.g., Binkley et al. 1985; Sachs 1992). We decided to test this method on a pilot basis, and complement it with the isotope dilution method (e.g., Kurdali et al. 1990; Mead and Preston 1992; Warembourg 1993). Both methods rest on the same principle—plants deriving their N-supply primarily from the atmosphere by fixation will have N isotope ratios similar to that source, while plants depending on the soil for their N will have an ^{15}N abundance closer to that of the soil (usually higher than atmospheric). Isotope dilution merely accentuates this contrast by applying an ^{15}N-enriched material to the soil, which results in a much higher proportion of ^{15}N labelling in the non-fixing plants. By comparing ^{15}N abundance in N-fixing and non-fixing plants growing on the same labelled plots, the proportion of N derived from the atmosphere in the fixing species can be calculated. With both isotopic methods, measurement of biomass production is needed to estimate stand-level N fixation rates.

- **Determine the effect of incorporation of alder leaf litter on decomposition of lodgepole pine foliage.**

Rationale: Previous laboratory (Fyles and Fyles 1993) and field studies (Taylor et al. 1989) indicated that alder leaves decompose faster than those of other deciduous and conifer species; however, longer-term (4 years) field studies suggest a reversal of this trend, with eventual cumulative mass loss by pine needles exceeding that for alder leaves (Berg et al. 1995). This effect was attributed to the retardation of lignin degradation by high N concentrations. In field settings, mixed litters are more common, and shorter-term studies (< 2 years) indicate acceleration of litter decomposition rates when N-rich alder leaves are added to other litter types. Although longer-term interactions of this type have not been studied, there are implications for the accumulation of soil organic matter in lodgepole pine stands. For example, an increasing component of alder understorey could increase the accumulation of soil organic matter in pine stands.

- **Determine the influence of Sitka alder on the forms and amounts of sulphur in forest floors and mineral soils.**

Rationale: Trees and shrubs that fix nitrogen can affect the biogeochemical cycles of other macronutrient elements in conifer forests. For example, Homann and Harrison (1992) observed that red alder stands exhibited a pronounced shift in the forms of sulphur in forest floors and mineral soils, compared with Douglas-fir; under alder, a much higher proportion of the soil S occurred in organic forms. Short-term litter decomposition studies have observed between-species differences in the direction of change of sulphur fraction abundance with increasing decomposition of conifer and alder litter (Homann and Cole 1990). Whether such shifts affect the long-term accumulation and availability of S in mixed stands including alder and conifers is unknown. In the Interior of British Columbia, widespread S deficiencies in lodgepole pine stands are evident (Brockley 1996), suggesting that the effects of alder on the status and dynamics of S in these forests deserves attention.

3.1 Study Area

The main study site is located approximately 55 km southwest of Prince George, at kilometre 804.5 of the Bobtail-Berta (800) Forest Service Road in the Vanderhoof Forest District (Figures 1 and 2). This approximately 42.5-hectare opening was logged in 1987 and has naturally regenerated to a mixture of lodgepole pine and Sitka alder (Figure 3) without any subsequent thinning treatment. From our initial reconnaissance and subsequent field work, we were satisfied that conditions at this site reflected a degree of alder influence that is common in lodgepole pine forests in the SBSdw3. Unpublished data indicated that similarly abundant alder cover commonly develops in young pine stands in the adjacent biogeoclimatic subzone (Dry Cool Sub-Boreal Spruce [SBSdk]) and variant (Kluskus Moist Cold Sub-Boreal Spruce [SBSmc3]) in the Vanderhoof Forest District, with cover values ranging up to 50–70% (C. DeLong, pers. comm., 1995).

The aspect of the site is approximately west, with slopes ranging from 5 to 20% and an elevation of approximately 1030 m. The surficial material consists of a morainal blanket or veneer (Howes and Kenk 1997) over igneous bedrock, with surface soil textures ranging from loam to sandy loam. Coarse-textured glaciofluvial deposits occur in discontinuous eskers that extend across the western portion of the opening. This assemblage of landforms and materials is typical of the glaciated plateau which comprises much of the central Interior (Tipper 1971; Howes 1977). Plots were established only on the morainal landform.

Surface soils, and deeper exposures provided by road cuts, indicated a predominance of Brunisolic and Luvisolic soils at the study site.

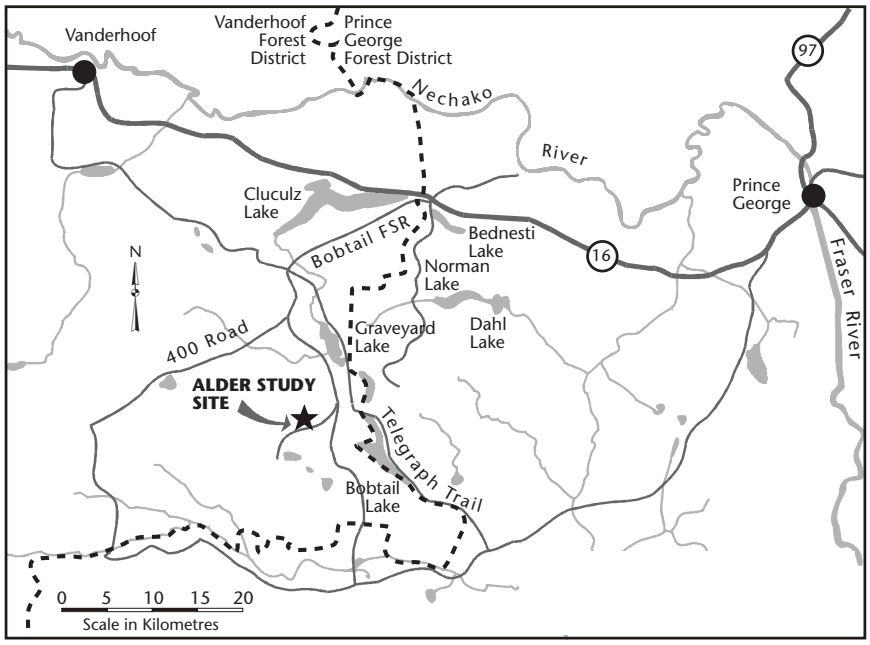

FIGURE 1 *Study site location, Vanderhoof Forest District.*

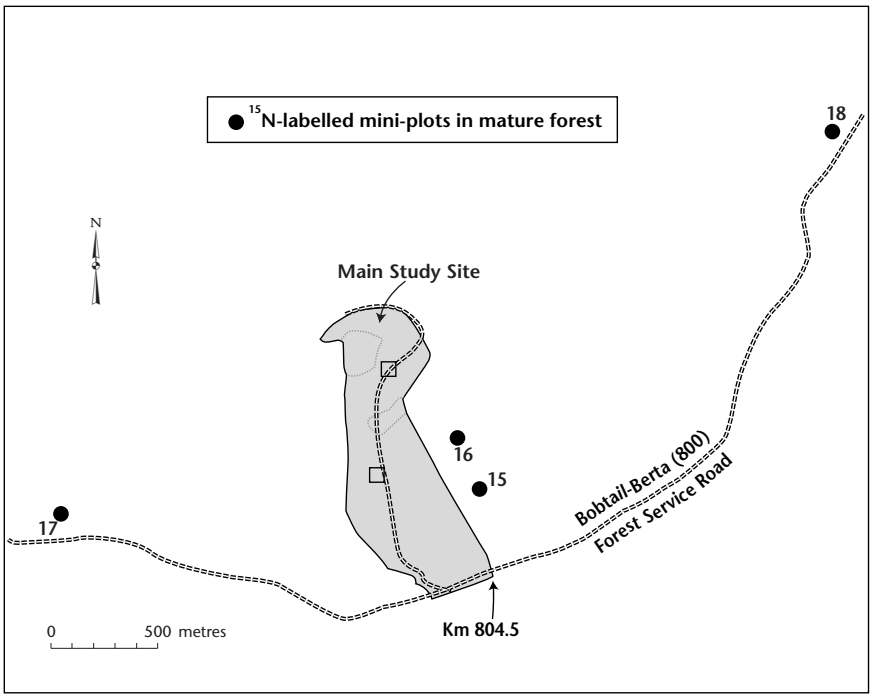

FIGURE 2 *Location of study site opening and ^{15}N-labelled mini-plots in mature forest.*

FIGURE 3 *Typical view of Sitka alder–lodgepole pine mixture at study site in July 1994 before installation of treatments.*

The pedon chosen for detailed study (Table 1), located 6 m downslope (west) from the southwestern corner of plot 6 (Figure 4), is representative of both this study site and an extensive area of the central Interior with similar morainal parent materials. Based on morphology (Table 1), classification (Brunisolic Gray Luvisol), and chemical and physical properties (Table 2), this pedon fits the concept of the Deserters Soil Association, the most extensive association in the Prince George soil survey area (Dawson 1989). Although this soil has more than 0.6% pyrophosphate-extractable Fe and Al in the Bf horizon, this horizon is insufficiently thick to meet the criteria for the Podzolic Order (Soil Classification Working Group 1998). The coarser surface textures may reflect a combination of both eluviation of clay to form a finer-textured (Bt) horizon, and initial stratification of the parent material through deposition of a surface veneer of ablation till during deglaciation. Additional discussion of the mineralogy and genesis of this pedon is provided by Arocena and Sanborn [1999].

Based on slope position, soil characteristics, and the dominant shrub and herb species (e.g., Sitka alder, birch-leaved spirea [*Spiraea betulifolia* Pall. ssp. *lucida* [Dougl. *ex* Greene] Taylor & MacBryde], prickly rose [*Rosa acicularis* Lindl. ssp. *sayi* [Schwein.] W.H. Lewis], twinflower [*Linnaea borealis* L.], bunchberry [*Cornus canadensis* L.], and heart-leaved arnica [*Arnica cordifolia* Hook]), this site most clearly matches the 04 site series for the SBSdw3 (DeLong et al. 1993). Other symbiotic nitrogen-fixing species common elsewhere in the central Interior of British Columbia, such as soopalallie (*Shepherdia canadensis* (L.) Nutt.) and lupines (*Lupinus* spp.) have not been observed at this site.

TABLE 1 *Morphological description of Brunisolic Gray Luvisol*[a]

Horizon	Depth (cm)	Description
L–Fa	4–0	Litter and semi-decomposed pine needles and alder leaves; abrupt, smooth boundary; 2–5 cm thick; extremely acid.
Ahe	0–5	Light olive brown (10YR 5/3 m) sandy loam; weak fine and medium granular; very friable; plentiful very fine and fine horizontal roots; abrupt, wavy boundary; 30–40% gravel and cobbles; 3–6 cm thick; extremely acid.
Bf	5–12	Olive brown (10YR 4/3 m) loam; weak fine subangular blocky; friable; plentiful very fine, fine, and medium oblique and horizontal roots; clear, broken boundary; 30–40% gravel and cobbles; 0–8 cm thick; extremely acid.
Bm	12–48	Dark greyish brown (10YR 4/2 m) sandy loam; moderate medium subangular blocky; friable; plentiful fine oblique roots; clear, wavy boundary; 30–40% gravel and cobbles; 12–48 cm thick; very strongly acid.
Bt	48–80	Dark olive brown (10YR 3/3 m) loam; moderate medium subangular blocky; firm; few fine oblique roots; common, moderately thick clay films; gradual, wavy boundary; 30-40% gravel and cobbles; 30-40 cm thick; medium acid.
BCk	80–90	Dark olive brown (10YR 3/3 m) loam; weak medium and coarse subangular blocky; firm; few fine oblique roots; few, moderately thick clay films; clear, wavy boundary; 25–30% gravel and cobbles; 10–20 cm thick; slightly acid.
Ck	90–115+	Olive brown (10YR 4/3 m) loam; massive; friable; no roots; common, streaked, and spotted secondary carbonates; moderately effervescent; mildly alkaline.

[a] Described and sampled September 5, 1995.

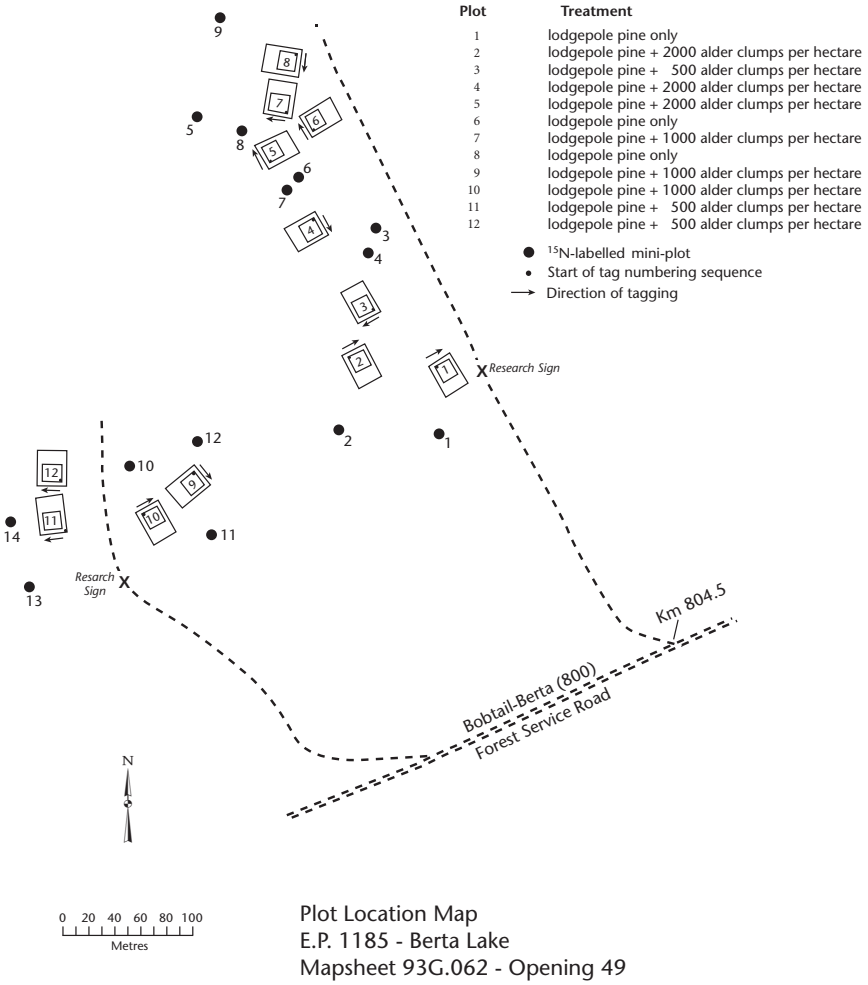

FIGURE 4 *Plot location map, main study site.*

The main study site, corresponding to opening no. 49, map sheet 93G.062, is protected by a Section 12 Map Reserve (B.C. Lands, Omineca Region, File No. 7407175, Reserve No. 967001) effective March 19, 1996.

3.2 Plot Establishment

During treatment installation at the main study site in May and June 1995, it became apparent that the Sitka alder clumps were not uniformly distributed over the study site. Although overall alder cover values usually exceeded 50%, with average densities of approximately 4100 clumps per hectare, the alder distribution was sufficiently patchy that we could not attain the desired distribution required for the planned 4000 clumps per hectare treatment, and for this reason, we eliminated that treatment. Even in the 2000 clumps per hectare alder retention treatment, we encountered "holes" requiring the transplantation of alder seedlings in April 1996. (Seedlings were obtained from the edge of a spur road along the eastern edge of the main study site.)

The experiment was laid out as a completely randomized design, with four treatments replicated three times for a total of 12 plots (experimental units).

TABLE 2 *Physical and chemical characteristics of Brunisolic Gray Luvisol profile, E.P. 1185 research site*[a]

Horizon	Depth (cm)	% Sand	Silt	Clay	Al_p[b]	Fe_p[b]	C	N	S	C:N	pH (H_2O)	pH ($CaCl_2$)	Avail. P (mg/kg)
L–Fa	4-0	n.d.[c]	n.d.	n.d.	n.d.	n.d.	50.48	1.04	0.1270	48.40	4.24	3.63	64.6
Ahe	0–5	55.3	37.8	7.0	0.182	0.244	1.53	0.08	0.0037	18.90	4.68	4.01	85.6
Bf	5–12	45.7	42.2	12.1	0.405	0.499	1.30	0.10	0.0058	12.80	5.04	4.42	88.7
Bm	12–48	63.1	31.0	5.9	0.074	0.097	0.25	0.04	0.0028	6.30	5.66	4.90	16.0
Bt	48–80	46.7	33.3	20.0	0.110	0.154	0.27	0.04	0.0029	6.50	6.54	5.79	1.3
BCk	80–90	45.8	36.5	17.6	0.059	0.084	0.15	0.03	0.0024	5.00	7.09	6.41	1.4
Ck	90–115+	46.1	34.9	19.0	0.034	0.066	0.24	0.02	0.0047	12.00	8.13	7.68	0.0

Horizon	Depth (cm)	Extractable cations (mg/kg) Ca	Mg	K	Al	Exchangeable cations ($BaCl_2$ method)(cmol(+)/kg) K	Ca	Mg	Na	Fe	Mn	Al	CEC[d]
L–Fa	4–0	2828	642	350	53	0.86	22.11	5.86	0.65	0.10	1.25	0.89	31.73
Ahe	0–5	281	81	38	131	0.10	1.84	0.80	0.08	0.43	0.13	1.08	4.47
Bf	5–12	461	115	48	154	0.14	3.02	1.14	0.08	0.09	0.04	0.78	5.28
Bm	12–48	428	153	32	24	0.09	2.70	1.53	0.13	0.11	0.02	0.03	4.63
Bt	48–80	1403	630	67	17	0.26	7.63	5.61	0.23	0.00	0.03	0.00	13.77
BCk	80–90	1315	610	64	22	0.18	6.84	5.25	0.19	0.00	0.03	0.00	12.50
Ck	90–115+	5204	678	60	21	0.17	7.46	4.80	0.24	0.00	0.00	0.00	12.67

[a] Ministry of Forests analytical laboratory requisitions s234 and s235; methods described in Section 3.3.2.
[b] Al_p, Fe_p = pyrophosphate-extractable Al, Fe.
[c] n.d. = not determined.
[d] CEC = cation exchange capacity.

The four treatments were:

- Pine + no alder (i.e., complete eradication of alder clumps) (Figure 5)
- Pine + alder (500 clumps per hectare)
- Pine + alder (1000 clumps per hectare)
- Pine + alder (2000 clumps per hectare) (Figure 6)

Numerous transects across the main study site were needed to locate areas of uniform, high-density alder cover suitable for plot installation. Our target was to have an initial condition of approximately 50% initial alder cover and 4000 alder clumps per hectare. We excluded areas with obvious bedrock outcrops and depressional or toe-slope positions, which would have wetter soil moisture regimes. Before plot installation, we arranged for a site visit by the Regional Pathologist to ensure that no root disease problems were evident.

All rectangular treatment plots are 25.28 × 31.60 m (0.08 ha) (Figure 7). Within each treatment plot, an 18.97 × 18.97 (0.036 ha) assessment plot containing 36 pine trees and reserved alder clumps was established. The assessment zone is offset at one end of the treatment plot to reserve an area for possible future destructive sampling. Both the assessment plot and the surrounding remainder of the plot were treated in exactly the same manner during installation of the treatments. Each treatment was randomly assigned to three treatment plots. In May 1995, the pine in each plot was manually thinned to a density of 1000 stems per hectare (80 per

plot), and the Sitka alder was thinned to its corresponding treatment density (Table 3).

The various alder retention regimes were created by manual cutting of the stem bases, followed immediately by application of glyphosate (trade name Vision™) to the cut stems at a rate of 2.136 kg active ingredient per hectare (Permit No. 402-093-95/97*SPL). All slash from thinning was left in place.

In October 1995, 10-m buffers were created around all plots, within which pines and alder clumps were thinned using brush saws to estimated densities of 1000 stems or clumps per hectare of each species. No herbicide was applied to these buffers.

In the summer of 1996, a visual assessment indicated that the initial treatment appeared to have achieved approximately 80% mortality in the alder, with no obvious damage to the retained pines. A follow-up treatment of the target alder clumps was carried out, in August 1996, using the methods previously discussed. Another visual assessment in the late summer of 1997 revealed that approximately 95% mortality of the treated alder clumps had been achieved. In subsequent years, manual clipping will be repeated, as needed, within the plots to ensure that the desired alder densities are maintained.

Treatment plot corners were surveyed with a Criterion Laser and permanently located with red-painted steel posts on which a yellow sign indicating the treatment and plot number was attached. In addition, the

FIGURE 5 *Plot 8: 0 alder retention treatment in June 1996.*

FIGURE 6 *Plot 5: 2000 clumps per hectare alder retention treatment in June 1996.*

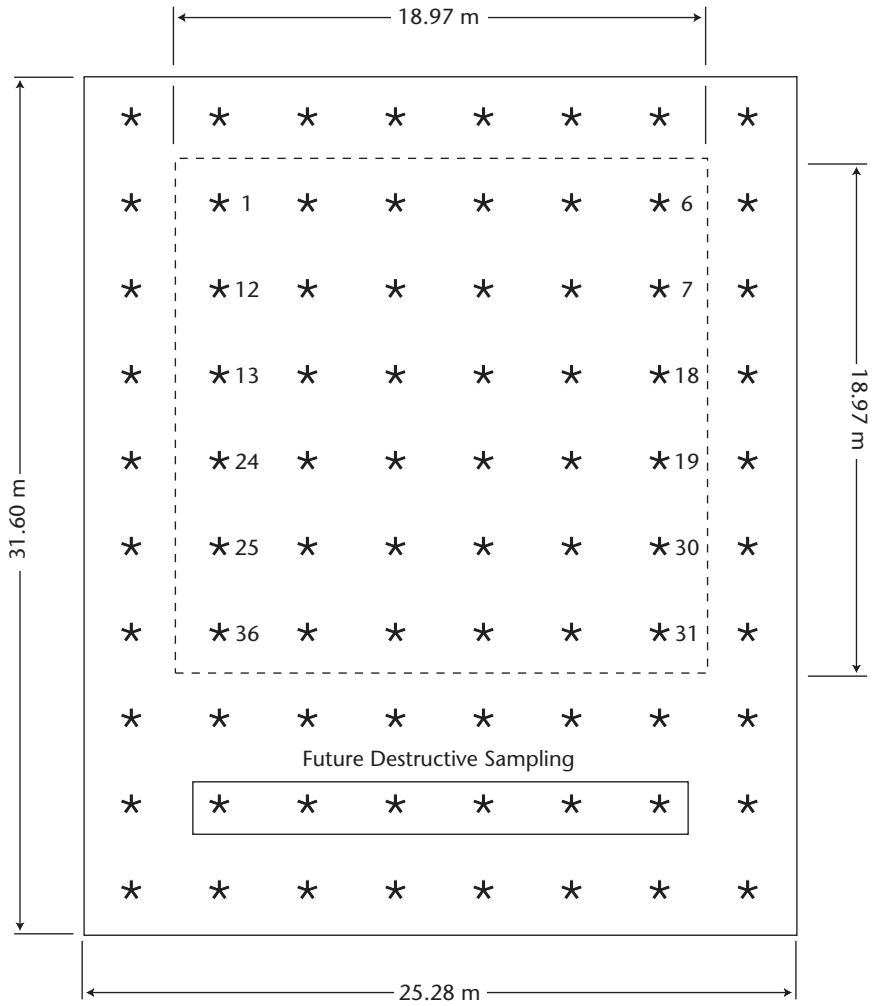

FIGURE 7 *Plot dimensions and tagging sequence within the central assessment plot.*

TABLE 3 *Treatment plot specifications*

	Treatment plot		Assessment plot	
Treatment[a]	No. of pine	No. of alder	No. of pine	No. of alder
0	80	0	36	0
500	80	40	36	18
1000	80	80	36	36
2000	80	170	36	78

[a] Alder clumps per hectare.

corners and centre points of the assessment plots were marked with smaller red steel posts. A larger yellow aluminum sign was placed on the mid-point of the outer plot boundary on the side closest to the nearest road access.

The detailed plot layout specifications for these four treatments were followed according to the working plan.

The pine trees and retained alder clumps within each central assessment plot were marked with consecutively numbered tags, as per the working plan. The specific numbering sequences are summarized in Table 4.

3.3 Measurements

3.3.1 Lodgepole pine and Sitka alder growth After plot boundaries had been located, the initial stand composition was assessed in two ways, by:

- counts of alder clumps and pine trees in 3.99-m-radius circular plots, centred on the corners and centre of each assessment plot, and
- line-intercept transects (along the four sides and two diagonals of the assessment plots).

For the latter, alder percent cover was based on the tally of points, at 1-m intervals on the transects, which fell beneath alder canopies. Post-treatment estimates of alder cover were obtained by repeating the transects in mid-June 1996.

In October 1995 after installation of the treatments, the following measurements were performed on the tagged pine trees and alder clumps: total height, diameter (dbh; pine only), and crown width (2 dimensions at right angles, alder only). These measurements, with the addition of basal diameter of the pine trees, will be repeated at three-year intervals, beginning in the fall of 1998. The free-to-grow status of the tagged pine trees will also be assessed, using the applicable Ministry of Forests standards in effect at the time of remeasurement.

3.3.2 Soil sampling One of the key objectives of this study is to estimate long-term treatment-related differences in N accretion by comparing pool sizes at widely spaced time intervals. This approach will only work if our experimental design and sampling intensity are robust enough to

TABLE 4 *Numbering sequence for lodgepole pine and Sitka alder in assessment plots*

Plot	Treatment[a]	Tag numbering ranges	
		Pine	Alder
1	0	1–36	
2	2000	37–72	1000–1077
3	500	73–108	1078–1095
4	2000	109–144	1096–1174
5	2000	145–180	1175–1252
6	0	181–216	
7	1000	217–252	1253–1288
8	0	253–288	
9	1000	289–324	1289–1324
10	1000	325–360	1325–1360
11	500	361–396	1361–1378
12	500	397–432	1379–1396

[a] Alder clumps per hectare.

overcome other factors: spatial variability, inconsistent procedures by different operators during field sampling, and the confounding effects of other natural processes.

The original working plan indicated that forest floor and mineral soil would be sampled at 10 random locations per treatment plot, with the samples of each type composited by plot for analysis. Based on the high level of soil variability observed in other forest nutrient cycling studies in this region (e.g., Trowbridge et al. 1996), we decided to increase the sampling intensity to 15 random locations per plot. This initial sampling was conducted in June 1995, before installation of the alder removal treatments. The position of each sampling point relative to the alder canopies was recorded (i.e., beneath or between canopies) so that any localized effects of alder on soil properties could be detected. We also decided to analyze samples individually to perform a subsequent power analysis that assessed the ability of this sampling scheme and experimental design to detect changes in soil properties.

Mineral soils (0–20 cm depth) were sampled immediately beneath the forest floor sampling locations in each plot. Samples were sieved to remove coarse fragments and roots (> 2 mm), and air-dry moisture content was determined. Immediately adjacent to five of the sampling points in each plot, we excavated samples to determine the bulk density of the 0–20 cm depth mineral soil, with water used to measure the volume of the excavation. For estimating nutrient content on an areal basis, the bulk density was calculated as the mass of the fine fraction (< 2 mm) divided by the excavation volume.

The following chemical analyses were done by the Ministry of Forests analytical laboratory.

- For mineral soil and non-woody forest floors: total C and N (LECO CHN-600 Elemental Analyzer); total S (LECO SC-132 S Analyzer); extractable cations (Ca, Mg, K, Al) (Morgan's extractant; Klinka et al. 1980); mineralizable N (ammonium extracted after 2-week anaerobic incubation at 30 °C); extractable P (Bray P1 method; Kalra and Maynard 1991); extractable sulphate (forest floors extracted with 0.01 M NH_4Cl; mineral soils with 500 mg/L P as $Ca(H_2PO_4)_2 \cdot H_2O$; SO_4^{2-} determined by ion chromatography); and pH (H_2O, 0.01 M $CaCl_2$).
- For woody forest floor components: total C, N, and S (as above).
- Additional methods used for the soil horizon samples (Table 2) consisted of exchangeable cations (Ca, Mg, K, Na, Fe, Al, Mn) and CEC ($BaCl_2$ method; Hendershot and Duquette 1986), and pyrophosphate-extractable Fe and Al (McKeague 1967).

  All data are reported on an oven-dry basis.

Soil particle size analysis was done by Soilcon Laboratories Ltd. on equally weighted composites of the 15 mineral soil samples from each plot, using the pipette method. The same method was also used for the individual horizon samples (Table 2).

Examination of the initial soil chemical data revealed a high degree of variability, especially in forest floor mass and nutrient content. Since a key objective of this study was to detect long-term changes in the mass balance of N on the site, our statistician advised us that additional forest floor sampling would be needed (see Section 5.2.3). Accordingly, we repeated our forest floor sampling in early September 1996, using the same

procedures as before (15 additional samples per plot at new random locations). At this time, however, we were unable to determine the location of sampling points in relation to the original alder canopy since the thinning treatments had already been applied.

3.3.3 Foliar sampling In October 1995, samples of current year's pine foliage were collected from two lateral branches within the upper one-third of the live crown on 10 representative healthy dominant or codominant trees evenly distributed within each treatment plot. These trees were flagged for future resampling. Samples were frozen following field collection, and then oven-dried at 70 °C for 20 hours before analysis. One composite sample consisting of equal amounts of foliage from each of the 10 trees per treatment plot was prepared for chemical analysis. Dried composite samples were ground in an electric coffee grinder and sent to Pacific Soil Analysis Inc. for chemical analysis.

Sub-samples of foliage were digested using a variation of the sulphuric acid–hydrogen peroxide procedure described by Parkinson and Allen (1975). The digests were analyzed colorimetrically for N on a Technicon Autoanalyzer using the Berthelot (phenol-hypochlorite) reaction (Weatherburn 1967). A spectrophotometer measured P, using a procedure based on the reduction of the ammonium molybdophosphate complex by ascorbic acid (Watanabe and Olson 1965). Total K, Ca, Mg, Mn, and Al were determined by atomic absorption spectrophotometry. Separate sub-samples were dry-ashed and Cu, Zn, and Fe concentrations were determined by atomic absorption spectrophotometry. Boron was determined colorimetrically using the azomethine-H method described by Gaines and Mitchell (1979). Total S was determined by combustion using a LECO sulphur analyzer. Sulphate sulphur was extracted with boiling 0.01 N HCl and determined colorimetrically on a HI-Bismuth reducible distillate (Johnson and Nishita 1952). Active iron was extracted with HCl (Oserkowsky 1933) and measured by atomic absorption spectrophotometry.

3.3.4 Litter fall sampling Circular, 34-cm-diameter litter traps, modelled on the design of Hughes et al. (1987), were installed April 25, 1996. Twenty traps were installed at randomly selected co-ordinates within the three, 2000-alder-clump-per-hectare treatment plots (Figure 8). No litter traps were installed in the complete alder removal treatment because the small amounts of litter generated at this stage of pine stand development simply could not justify the effort. The collector bags on the traps were changed twice yearly: at the beginning of the growing season (May 1), and immediately after the completion of most of the alder leaf litter fall, which occurs from early September through late October. Litter materials were removed from the collector bags, oven-dried (70 °C, 24 h), sorted, and weighed by components (alder leaves, pine needles, alder seed cones and seeds, herbs and grasses, leaves of other deciduous leaves, and other materials) for each trap, and composited by plot for chemical analysis. The following chemical analyses were carried out by the Ministry of Forests laboratory: total C, N, and S (see 3.3.2); Ca, Mg, K, P, B, Zn, Al, and Mn by inductive coupled plasma emission spectroscopy after microwave digestion (Kalra and Maynard 1991).

FIGURE 8 *Litter fall collector (litter trap) and installation of litter-bags for decomposition experiment.*

4 METHODS: ANCILLARY STUDIES

4.1 Estimation of Nitrogen Fixation Rates

Nitrogen fixation rates will be assessed in two ways:

- a long-term mass balance based on changes in total N pools in the soil and vegetation, and
- isotopic methods using ^{15}N.

The methods used to sample and analyze soil N pools are described in Section 3.3.2, and the ability of this sampling regime to detect and estimate long-term N accretion is discussed in Section 5.2.3. This section primarily describes the isotopic methods.

In a pilot study to examine the natural abundance of ^{15}N in major plant species at this site, we collected (in mid-August 1995) composite samples of foliage from alder, pine, and other shrub species, both in the main opening and in the adjacent mature forest to the east. The opening was arbitrarily divided into upper and lower slope portions, which were sampled separately. For each of these three sampling areas, we collected and composited foliage from 10 plants of each species, except for the mature forest, where we used a shotgun to sample five lodgepole pine trees. Foliage samples were oven-dried (70 °C, 24 h) and analyzed for total N concentration and ^{15}N natural abundance at the Canadian Forest Service's Pacific Forestry Centre in Victoria.

The isotope dilution experiment was installed in June 1996. Fourteen circular (2-m radius) mini-plots were located in the opening, each at least 20 m distant from the nearest main treatment plot (see Figure 4). Mini-plots were located by randomly choosing a corner of each main plot, from which a line was run on a random bearing to a random distance from the corner. At that point, the nearest alder clump was selected which was of average size (i.e., ± 1 standard deviation from the mean clump height and crown width measured in 1995). The mini-plot centre was marked with a red metal angle bracket post located in the middle of the clump (Figure 9), and pine seedlings within a 2-m radius were thinned so that no more than three average-sized seedlings remained. Additional thinning of pines to a density of approximately 1000 stems per hectare was performed out to a radius of 5 m to provide stand conditions similar to those in the main treatment plots.

Immediately after sampling foliage from alder, pine, and other major

woody and herbaceous species growing on the mini-plots, highly enriched (98 atom% $^{15}N)(NH_4)_2SO_4$ was applied in solution at the rate of 0.2 g $^{15}N/m^2$ on June 13, 1996 (Figure 10). Foliar sampling was repeated on August 20.

Plant samples were ground to pass a no. 40 sieve (0.425 mm) and analyzed for total N by the semimicro-Kjeldahl method, with mercuric oxide used as the catalyst. The distillates, collected in boric acid–ethanol, were dried at 70 °C. The NH_4^+-N was converted to dinitrogen gas using the Rittenberg reaction with alkaline lithium hypobromite, and analyzed for ^{15}N enrichment using a Vacuum Generators Sira 9 mass spectrometer.

In July 1996 we developed calibration equations, to monitor aboveground biomass increment in the labelled alder clumps. These equations related the basal diameter of individual stems to the weights of the entire stem and individual biomass components (woody stem + twigs, leaves, seed cones) (Binkley 1982; Wurtz 1995). The equations were based on

FIGURE 9 *^{15}N-labelled mini-plot no. 2 in June 1996.*

FIGURE 10 *Application of ^{15}N-enriched $(NH_4)_2SO_4$ solution to mini-plot in June 1996.*

complete sampling of all living stems (n = 133) from four randomly selected clumps that spanned the range of sizes occurring in both the main treatment plots and the ^{15}N-labelled mini-plots. Biomass samples were oven-dried to constant weight at 70 °C, sorted into components, and weighed. To estimate the July 1996 biomass of the 14 labelled clumps with these calibration equations, we loosely attached numbered disks at ground level to each stem, and made two basal diameter measurements at right angles.

These data, however, will not be sufficient to estimate stand-level N fixation rates in the main treatment plots. Although successive remeasurements of the clumps in the mini-plots will allow estimates of the relative growth rates, we also need biomass data for the main treatment plots. To estimate the biomass of large numbers of clumps, the approach based on allometric relationships between stem diameter and mass is quite impractical—each clump often contained 50 or more stems. Instead, we developed calibration equations based on the above-ground biomass of entire clumps (n = 50), which were measured (maximum height, maximum horizontal crown width, second width measurement at 90° to first) and weighed after destructive sampling in late May 1998. These equations were applied to the 1995 measurements of the alders (n = 234) retained in the three assessment plots of the 2000 clumps per hectare retention treatment in the main thinning study.

To determine if N fixation was occurring in alders under the mature pine forest canopy, we created four more mini-plots in 1997. The chosen mini-plot locations contained alder clumps of average size and an overstorey canopy density typical of the mature pine stands in the vicinity of the main study site (Figures 11 and 12). Two mini-plots were located approximately 200 m east of the main study site (mini-plot nos. 15, 16), while the other two were located in adjacent, but similar, stands near the Bobtail-Berta (800) Road: no. 17 at kilometre 806.2, approximately 150 m north of the road, and no. 18 at kilometre 801.6, approximately 150 m north of the road (Figure 2). Mini-plots were marked and labelled with ^{15}N on June 23 in the same manner as those established in 1996. Foliage of alder and associated shrubs was carried out immediately before labelling, as well as on August 12. The latter sampling also included the 14 mini-plots established in the opening in 1996.

4.2 Litter Decomposition

Litterbags were constructed in the fall of 1996, following the methods described in Trofymow et al. (1998). In September 1996, senescent alder leaves and pine needles were collected on a clean tarp near the main study plots by lightly shaking and brushing branches and stems. These materials were air-dried and the moisture content was determined (70 °C, 24 h). Litterbags were assembled by heat-sealing (National Instrument Co., model M-450-1) shade cloth (Synthetic Industries, product no. 525F/565) into 20 × 20-cm pouches after adding 10 g (air-dry weight) of either pure alder litter, pure pine litter, or a 50:50 mixture. The shade cloth had 0.25 × 0.50-mm openings, and was cleaned by rinsing in a dilute HCl bath, followed by rinsing in demineralized water. A uniquely numbered aluminum identification tag was attached to each bag by coated copper wire through a hole punched outside the sealed seam. To help maintain their integrity, the bags' seams were also fastened with stainless steel staples.

FIGURE 11 *Mini-plot no. 17, located east of main study site under mature pine forest.*

FIGURE 12 *Overstorey pine canopy above mini-plot no. 17.*

On October 15, 1996, the litterbags were pinned to the forest floor in groups of three (1 of each type) with aluminum nails, and anchored by coated copper wire to red-painted rebar posts located in a random direction 1 m from each of the 60 litter trap positions in the 2000-alder-clumps-per-hectare treatment (Figure 8).

Two sets of litterbags per plot will be recovered every 6 months for 5 years. If interim data after 3 or 4 years indicate that rates of weight loss and change in elemental concentrations have become relatively constant, then this experiment may be extended by increasing the recovery interval to 1 year.

On recovery, the bag contents were oven-dried (70 °C, 24 h), weighed to determine mass loss, and submitted to the Ministry of Forests laboratory for chemical analysis (total N, S, P, Ca, Mg, K, B, Cu, Fe, Mn, and Zn, and SO_4-S).

4.3 Soil and Forest Floor Sulphur Fractions

The 1995 non-woody forest floor and mineral soil samples were analyzed for HI-reducible S by Pacific Soil Analysis Inc. Taken together with the phosphate-extractable SO_4-S and total S data, three major S fractions can be calculated (Kowalenko 1993):

- extractable inorganic sulphate, both soluble and adsorbed (phosphate-extractable SO_4-S),
- organic sulphate esters (calculated as HI-reducible S *minus* phosphate-extractable SO_4-S), and
- carbon-bonded S (calculated as total S *minus* HI-reducible S).

5 RESULTS

5.1 Lodgepole Pine and Sitka Alder Growth

Height measurements taken in October 1995 reflected pre-treatment conditions, since the pine-thinning and alder-removal treatments were only completed in July, shortly before height growth ceased for the season. On average, the pine trees were approximately 30 cm shorter than the remaining alder clumps (Table 5).

Initial density measurements of alder and pine (Table 6) revealed much greater variability in pine density, both within and between plots. This pattern is typical of harvest-origin pine stands and reflects uneven cone distribution during drag scarification.

Although the maximum alder retention treatment (2000 clumps per hectare) represented an almost 50% reduction in the initial shrub density, we preferentially removed smaller clumps. As a result, this treatment maintained an average alder cover of almost 40%, which should be sufficiently high to maintain competitive interactions between the remaining pines and alders (Figure 13).

5.2 Soil and Forest Floor Properties

5.2.1 Forest floors As numerous other studies have demonstrated, forest floor physical and chemical properties have extremely high spatial variability, requiring intensive sampling both to characterize initial site conditions and to detect treatment effects from silvicultural practices. In consultation with a Research Branch statistician (W. Bergerud, pers. comm., 1996), we evaluated the results of our 1995 sampling to determine its adequacy. We felt that, if necessary, a doubling of our sampling intensity from 15 to 30 per plot would be feasible, but we needed to know whether this effort was worthwhile. For four key chemical properties (total N, mineralizable N, total S, available P), there was either marginal or no benefit from more intensive sampling of the mineral soils; however, for the forest floors (non-woody components), this additional effort would be worthwhile for all properties except available P. In the case of non-woody forest floor mass per unit area, this doubling of sampling intensity would be highly beneficial.

Examination of the data (Tables 7–11) revealed marked differences in several important properties between the years. One-way ANOVA with year of sampling as the independent variable suggested that significant differences existed for mass, total and mineralizable N, total S, available P, Morgan's extractable Ca and Mg, pH, and extractable SO_4-S in the non-woody forest floor components, and total C, N, and S in the woody components.

It seems quite unlikely that these apparent changes would be an immediate reflection of the 1995 treatments. The bulk of the forest floor still consists of material inherited from the previous mature stand harvested in 1987, but the period of rapid forest floor mineralization after logging should have already occurred. This change did not occur consistently across all plots and treatments, although we did not do a formal analysis to look for an interaction. One factor that did differ between years was the individuals doing the sampling. In particular, one person separated out woody components and removed inorganic contaminants

TABLE 5 *Initial alder and pine measurements: October 1995*

Alder						
			Total height (m)		Crown width (m)	
Treatment[a]	Plot	N	Mean	SD	Mean	SD
500	3	18	1.96	0.281	1.72	0.293
	11	18	1.93	0.347	1.82	0.447
	12	18	1.75	0.234	1.57	0.309
1000	7	36	1.92	0.304	1.64	0.389
	9	36	1.84	0.324	1.76	0.346
	10	36	1.85	0.234	1.78	0.247
2000	2	74	1.74	0.418	1.47	0.504
	4	78	1.81	0.349	1.56	0.421
	5	77	1.88	0.364	1.55	0.433
500	All	54	1.88	0.301	1.70	0.365
1000	All	108	1.87	0.289	1.73	0.336
2000	All	229	1.81	0.380	1.53	0.453
Pine						
			Total height (m)		DBH (cm)	
Treatment[a]	Plot	N	Mean	SD	Mean	SD
0	1	36	1.84	0.351	1.7	0.68
	6	36	1.49	0.420	1.5	0.53
	8	36	1.36	0.387	1.2	0.45
500	3	36	1.42	0.381	1.2	0.32
	11	36	1.17	0.426	1.2	0.38
	12	36	1.08	0.370	1.1	0.20
1000	7	36	1.66	0.405	1.4	0.56
	9	36	1.43	0.333	1.3	0.52
	10	36	1.41	0.414	1.3	0.36
2000	2	36	1.56	0.393	1.4	0.51
	4	36	1.49	0.401	1.3	0.49
	5	36	1.55	0.376	1.4	0.43
0	All	108	1.56	0.435	1.5	0.61
500	All	108	1.22	0.416	1.2	0.32
1000	All	108	1.50	0.399	1.3	0.49
2000	All	108	1.53	0.388	1.3	0.48

[a] Alder clumps per hectare.

(gravel, mineral soil) for the 1996 samples. More care was taken in 1996 to remove mineral soil contaminants, which would have the effect of reducing total mass, while increasing the final C and N concentrations, since mineral materials have much higher particle density and lower C and N concentrations. However, if this was the primary cause, such differences should be found more consistently across plots and treatments, which was not the case.

For future forest floor sampling, 30 randomly located samples per plot should be collected, and consideration should be given to using a larger sampling template (e.g., 25 × 25 cm) to reduce the variability caused by edge effects. However, regardless of how much care is taken to achieve internal consistency in future sampling operations, the problem of

TABLE 6 *Pre-treatment alder and pine density: May 1995*[a]

Plot	Treatment[b]	Alder (clumps per hectare)		Pine (stems per hectare)	
		Mean	SD	Mean	SD
1	0	4,160	654	21,840	2,872
2	2,000	4,120	1,853	15,520	6,094
3	500	3,640	358	7,440	1,424
4	2,000	3,800	1,030	10,680	8,549
5	2,000	3,800	927	16,760	4,881
6	0	4,400	1,476	9,000	6,524
7	1,000	4,520	934	9,560	1,774
8	0	4,560	623	6,760	3,309
9	1,000	3,800	245	8,280	4,204
10	1,000	4,000	678	6,920	1,911
11	500	3,200	1,058	4,400	2,429
12	500	5,120	1,128	8,000	6,282

[a] $n = 5$ density measurements per main plot.
[b] Alder clumps per hectare

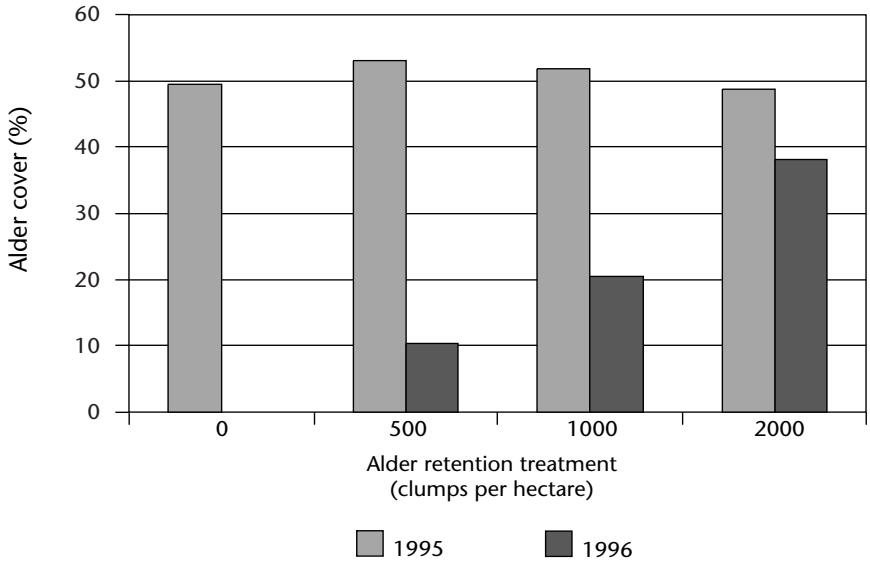

FIGURE 13 *Pre- and post-treatment alder cover: 1995 and 1996.*

deciding which forest floor data set should serve as the baseline for this long-term study still remains. Without a clear reason to prefer either data set, our preference would be to pool the 1995 and 1996 values.

Our separation of woody components was intended to assist in detecting future changes in nutrient pool sizes, the rationale being that these materials are more spatially variable in their distribution than other forest floor components. Effects of alder removal should show up first in the total N content of the non-woody components of the forest floor, since leaf litter fall is likely the largest annual N flux to the soil. Comparison of the 1995 and 1996 data showed no significant change in the mass of this component; however, as expected, the relative variability of woody forest floor mass remained much higher than for non-woody components

TABLE 7 *Summary of forest floor (woody and non-woody materials) mass data: 1995 and 1996*

		g/m^2			
		Non-woody		Woody	
Plot		1995	1996	1995	1996
1	Mean	5947.6	2787.5	1331.7	475.1
	SD	5615.1	2346.8	1454.2	529.3
2	Mean	5469.3	5398.5	840.8	915.5
	SD	2953.2	3473.1	709.0	771.9
3	Mean	5724.3	5446.6	1399.4	1395.2
	SD	3469.3	2871.8	1393.9	743.4
4	Mean	4212.9	4303.9	682.6	895.3
	SD	2268.0	2046.5	522.3	752.3
5	Mean	7167.1	4559.4	1419.7	1213.7
	SD	2785.3	1799.1	1257.3	776.3
6	Mean	6618.7	4279.5	835.7	1820.5
	SD	6594.1	2620.6	1144.4	2120.9
7	Mean	5518.2	3096.1	1467.6	644.7
	SD	2942.9	2225.9	1330.8	573.2
8	Mean	5340.4	3024.4	356.3	871.4
	SD	2953.5	2175.6	541.4	1114.6
9	Mean	5531.5	3927.3	1513.1	1620.6
	SD	1911.1	2391.9	1890.2	1351.6
10	Mean	6287.4	3414.8	1035.9	857.5
	SD	4210.8	2039.6	1673.2	840.0
11	Mean	3988.9	3320.2	615.3	1066.5
	SD	2316.6	1449.0	561.5	732.5
12	Mean	6114.6	6954.7	840.9	2155.8
	SD	3301.1	3959.8	766.2	1382.0
All	Mean	5660.1	4209.4	1028.2	1161.0
	SD	3681.4	2732.2	1213.9	1139.0

Treatment Summary

		Non-woody		Woody	
Treatment[a]		1995	1996	1995	1996
0	Mean	5968.9	3363.8	841.2	1055.7
	SD	5188.6	2425.3	1159.8	1497.2
500	Mean	5275.9	5240.5	951.9	1539.2
	SD	3142.9	3248.8	1008.2	1080.3
1000	Mean	5779.0	3479.4	1338.9	1040.9
	SD	3113.1	2200.1	1624.3	1043.9
2000	Mean	5616.4	4753.9	981.0	1008.2
	SD	2894.6	2534.6	923.3	763.6

[a] Alder clumps per hectare.

(Table 7). (The 1995 slash from alder removal was not included in the forest floor sampling, although this material will eventually become incorporated in the forest floor.)

Sulphur fractions in the non-woody forest floors, expressed both as concentrations and as proportions of total S, were very similar to values reported by Kishchuk (1998) for other central Interior soils. In all cases, C-bonded sulphur comprises a larger proportion of total S in the organic horizons than in the mineral soils—a pattern found generally in forest soils.

TABLE 8 *Summary of non-woody forest floor chemical properties: 1995*

Plot		%				mg/kg						
		C	N	S	C:N	Minrl. N[a]	Avail. P[b]	MorgxCa[c]	MorgxK[c]	MorgxMg[c]	pH_{H_2O}	pH_{CaCl_2}
1	Mean	39.96	1.14	0.0794	36.07	396.3	156.4	3675.1	733.5	745.1	4.72	4.16
	SD	11.95	0.41	0.0187	7.32	187.4	55.2	924.2	273.3	221.1	0.34	0.31
2	Mean	39.37	1.13	0.0850	36.19	430.3	116.1	3234.5	668.9	665.2	4.67	4.06
	SD	9.12	0.37	0.0256	6.62	212.8	31.7	846.7	347.6	229.1	0.25	0.27
3	Mean	39.70	1.13	0.0846	36.94	465.4	136.8	3521.9	618.8	529.7	4.67	4.01
	SD	8.61	0.38	0.0234	7.53	210.2	41.1	940.0	165.2	159.0	0.23	0.29
4	Mean	49.21	1.30	0.0950	40.10	490.5	90.0	3499.1	610.7	648.1	4.53	3.93
	SD	7.69	0.42	0.0182	10.17	204.9	37.3	745.6	190.5	182.1	0.25	0.32
5	Mean	45.26	1.00	0.0813	47.82	384.2	88.4	3335.4	523.9	704.5	4.44	3.93
	SD	9.15	0.26	0.0206	16.45	140.4	31.8	786.2	152.2	189.4	0.20	0.26
6	Mean	39.98	0.94	0.0696	43.77	487.1	107.5	3143.6	515.1	581.4	4.52	3.99
	SD	11.70	0.24	0.0210	15.34	251.9	36.0	700.4	184.5	185.0	0.25	0.33
7	Mean	44.56	1.08	0.0798	46.08	424.4	86.9	3412.8	594.9	652.7	4.48	3.95
	SD	10.65	0.44	0.0273	17.79	188.2	37.4	1015.4	225.7	220.3	0.14	0.19
8	Mean	48.00	1.31	0.0862	39.30	577.1	95.1	3461.1	472.2	634.7	4.62	3.98
	SD	7.50	0.43	0.0193	11.00	430.8	50.8	1019.5	120.9	170.2	0.22	0.30
9	Mean	45.59	1.26	0.0985	36.20	522.7	136.9	3783.8	573.0	688.0	4.62	4.03
	SD	9.93	0.27	0.0238	4.55	144.9	49.6	748.3	144.3	162.4	0.15	0.17
10	Mean	41.07	1.15	0.0834	36.45	491.8	141.4	3844.8	675.3	617.2	4.67	4.08
	SD	8.49	0.25	0.0210	7.84	198.7	66.1	983.2	185.9	152.9	0.28	0.33
11	Mean	43.44	1.33	0.1031	33.41	594.8	85.6	4017.3	524.6	693.0	4.64	4.05
	SD	5.32	0.18	0.0160	6.72	187.3	36.4	675.6	131.0	119.9	0.22	0.26
12	Mean	42.76	1.01	0.0810	45.31	369.7	73.9	2937.7	499.3	626.3	4.41	3.79
	SD	12.15	0.40	0.0211	15.64	197.9	37.6	705.2	174.1	163.4	0.20	0.26
All	Mean	43.24	1.15	0.0855	39.80	469.3	109.6	3485.9	585.5	649.2	4.58	4.00
	SD	9.80	0.36	0.0227	12.00	228.7	49.9	875.3	210.9	185.7	0.25	0.28

Treatment Summary

Treatment[d]		%				mg/kg						
		C	N	S	C:N	Minrl. N[a]	Avail. P[b]	MorgxCa[c]	MorgxK[c]	MorgxMg[c]	pH_{H_2O}	pH_{CaCl_2}
0	Mean	42.64	1.13	0.0784	39.71	486.8	119.6	3425.8	575.9	654.2	4.62	4.04
	SD	11.02	0.39	0.0204	11.86	309.8	54.0	895.5	230.8	201.7	0.28	0.32
500	Mean	41.96	1.16	0.0898	38.55	476.6	97.9	3479.5	548.1	614.5	4.57	3.95
	SD	9.07	0.35	0.0222	11.65	215.4	46.3	884.9	163.2	160.5	0.24	0.29
1000	Mean	43.74	1.17	0.0872	39.58	479.6	121.7	3680.5	614.4	652.6	4.59	4.02
	SD	9.71	0.33	0.0250	12.18	179.6	57.0	922.5	189.2	179.3	0.21	0.24
2000	Mean	44.61	1.15	0.0869	41.37	432.4	98.6	3349.7	600.8	673.7	4.54	3.97
	SD	9.42	0.37	0.0220	12.52	188.5	35.2	784.6	249.3	198.7	0.25	0.28

5.2.2 Mineral soil Based on colour, the surface mineral soils (0–20 cm) consisted mostly of Ae and Bm (or Bf) horizon material, with textures displaying the low clay content observed in the upper part of the soil profile (Tables 2 and 12).

Soil bulk density (Db) values (Table 13) were very similar to those observed for surface soils at other sites with morainal parent materials in the SBS. For example, the corresponding pre-treatment mean values for the three SBS installations of the Long-Term Soil Productivity Study (E.P. 1148) were: 1530 kg/m^3 for total Db, 1060 kg/m^3 for fine fraction Db (method 1), and 790 kg/m^3 for fine fraction Db (method 2) (Trowbridge et al. 1996).

TABLE 8 *Continued*

Plot		S fractions						
		HI-reducible S	PO_4-ext SO_4-S		Ester SO_4-S		C-bonded S	
		mg/kg	mg/kg	% of total S	mg/kg	% of total S	mg/kg	% of total S
1	Mean	81.2	9.4	1.2	71.8	9.4	712.9	89.4
	SD	16.2	3.6	0.4	14.7	2.5	179.0	2.5
2	Mean	96.2	10.1	1.2	86.1	10.7	753.6	88.1
	SD	20.4	3.5	0.4	18.4	2.9	247.9	3.1
3	Mean	110.0	9.6	1.2	103.0	13.0	736.0	86.3
	SD	31.3	2.8	0.3	29.3	4.5	228.3	5.0
4	Mean	116.2	11.5	1.2	110.4	11.7	834.0	87.7
	SD	31.9	3.3	0.2	24.7	2.8	169.5	3.3
5	Mean	111.9	25.2	3.2	86.7	10.4	700.9	86.5
	SD	62.2	29.2	3.5	43.0	3.7	174.5	5.2
6	Mean	84.4	10.1	1.5	74.4	11.4	611.7	87.1
	SD	26.4	3.9	0.6	25.0	5.5	198.8	5.6
7	Mean	93.4	8.2	1.1	85.2	11.0	704.1	88.0
	SD	32.1	3.1	0.3	30.2	2.8	250.2	2.8
8	Mean	114.2	9.3	1.1	105.0	12.4	748.0	86.5
	SD	33.2	2.3	0.2	32.0	3.7	183.4	3.8
9	Mean	109.4	10.0	1.0	99.4	10.4	875.5	88.5
	SD	17.8	1.9	0.2	17.1	2.2	227.8	2.3
10	Mean	105.4	9.2	1.1	96.1	11.9	728.4	87.0
	SD	29.8	2.2	0.3	28.2	3.7	202.1	3.9
11	Mean	109.4	10.3	1.0	101.2	9.6	921.4	89.5
	SD	28.4	2.1	0.2	27.3	1.9	141.3	1.8
12	Mean	93.6	8.7	1.1	84.9	10.8	716.4	88.1
	SD	24.4	3.8	0.4	21.2	2.7	195.6	2.9
All	Mean	102.1	11.0	1.3	91.7	11.1	753.3	87.7
	SD	32.7	9.8	1.2	28.6	3.4	212.5	3.7

Treatment Summary		S fractions						
		HI-reducible S	PO_4-ext SO_4-S		Ester SO_4-S		C-bonded S	
Treatment[d]		mg/kg	mg/kg	% of total S	mg/kg	% of total S	mg/kg	% of total S
0	Mean	93.3	9.6	1.2	83.7	11.1	690.9	87.7
	SD	29.7	3.3	0.4	28.7	4.2	192.1	4.3
500	Mean	104.5	9.5	1.1	96.4	11.2	793.0	87.9
	SD	28.6	3.0	0.3	26.8	3.4	209.4	3.7
1000	Mean	102.7	9.1	1.1	93.6	11.1	769.3	87.8
	SD	27.5	2.5	0.3	26.0	3.0	235.1	3.1
2000	Mean	107.9	15.8	1.9	93.7	10.9	761.2	87.4
	SD	42.2	18.5	2.3	32.1	3.2	204.0	3.9

[a] Minrl. N = mineralizable N.
[b] Avail. P = available P.
[c] Morgx = cations extractable with Morgan's reagent.
[d] Alder clumps per hectare.

Initial surface mineral soil chemical data (Table 14) are similar to those obtained for the morainal Luvisolic and Podzolic soils at the SBS sites of the Long-Term Soil Productivity Study for total C, N, and S, mineralizable N, available P, and pH (Trowbridge et al. 1996). (Data for exchangeable

TABLE 9 *Summary of non-woody forest floor chemical properties: 1996*

Plot		%				mg/kg					
		C	N	S	C:N	Minrl. N[a]	Avail. P[b]	MorgxCa[c]	MorgxK[c]	MorgxMg[c]	MorgxAl[c]
1	Mean	40.34	1.32	0.0845	31.14	580.1	81.8	3778.3	709.0	782.1	50.5
	SD	6.01	0.26	0.0124	5.25	221.5	33.5	780.6	332.5	225.6	11.8
2	Mean	45.00	1.18	0.0795	39.44	600.8	63.7	3492.1	637.6	695.6	49.7
	SD	6.09	0.28	0.0185	8.24	237.1	26.0	747.1	342.4	175.0	13.6
3	Mean	44.21	1.28	0.0832	36.10	633.1	95.0	3990.2	636.0	636.8	43.7
	SD	6.41	0.31	0.0324	8.82	292.1	61.3	1116.7	317.5	181.1	14.9
4	Mean	45.62	1.18	0.0676	40.02	556.4	55.7	3854.5	546.9	723.1	46.0
	SD	7.46	0.27	0.0179	10.31	187.2	21.6	822.1	180.7	163.3	17.8
5	Mean	45.99	1.31	0.0835	35.97	581.5	57.1	4486.0	477.1	899.0	44.2
	SD	4.76	0.27	0.0193	5.50	155.6	20.9	954.5	121.2	207.4	13.6
6	Mean	43.55	1.16	0.0665	39.16	542.9	73.2	4030.0	507.3	714.1	42.4
	SD	6.17	0.22	0.0114	10.24	184.5	43.9	894.4	162.5	175.5	13.2
7	Mean	41.75	1.30	0.0875	34.50	574.4	77.6	4126.5	561.8	808.1	33.7
	SD	4.50	0.31	0.0178	12.96	262.2	24.4	990.5	219.4	253.2	12.3
8	Mean	42.64	1.17	0.0770	38.95	579.4	75.4	4022.0	491.3	731.3	42.0
	SD	8.28	0.37	0.0235	12.38	344.8	29.9	836.1	135.1	149.7	13.3
9	Mean	46.16	1.45	0.0980	32.94	612.4	108.9	4404.1	594.7	772.8	47.3
	SD	6.62	0.31	0.0289	7.44	241.0	49.5	1450.6	193.5	327.7	17.5
10	Mean	41.90	1.36	0.0876	31.41	657.8	126.8	4386.9	714.1	758.5	57.8
	SD	7.00	0.29	0.0172	5.35	281.9	64.1	1144.4	179.5	177.6	20.7
11	Mean	47.81	1.34	0.0844	40.93	649.5	52.5	4335.9	631.7	874.0	58.6
	SD	4.35	0.35	0.0313	24.38	169.0	13.0	1128.3	173.9	245.2	17.8
12	Mean	51.24	1.17	0.0670	48.21	698.0	39.4	3407.1	522.2	787.3	49.2
	SD	6.25	0.32	0.0279	20.01	397.3	18.9	1192.7	178.2	229.6	18.2
All	Mean	44.68	1.27	0.0805	37.40	605.5	75.6	4028.8	585.9	764.3	47.1
	SD	6.71	0.30	0.0238	12.77	253.3	43.6	1047.7	230.1	219.3	16.5

Treatment Summary

Treatment[d]		%				mg/kg					
		C	N	S	C:N	Minrl. N[a]	Avail. P[b]	MorgxCa[c]	MorgxK[c]	MorgxMg[c]	MorgxAl[c]
0	Mean	42.18	1.22	0.0760	36.42	567.5	76.8	3945.4	567.8	741.8	44.9
	SD	6.88	0.29	0.0180	10.26	254.1	35.6	827.9	242.0	183.9	13.1
500	Mean	47.75	1.26	0.0782	41.75	660.2	62.3	3912.9	597.5	763.0	50.3
	SD	6.32	0.33	0.0310	19.15	295.4	44.1	1182.0	235.8	236.3	17.7
1000	Mean	43.27	1.37	0.0910	32.95	614.9	104.4	4309.9	624.9	779.2	46.6
	SD	6.34	0.30	0.0220	9.04	258.5	52.0	1193.4	204.0	255.1	19.6
2000	Mean	45.53	1.23	0.0769	38.48	579.6	58.8	3944.2	553.9	772.5	46.6
	SD	6.08	0.28	0.0194	8.26	192.6	22.7	924.7	238.3	200.5	15.0

Ca, Mg, and K could not be compared directly because of differing analytical methods.) The low concentrations of total S at all of these sites are consistent with a regional pattern of S deficiency observed widely across the central Interior (Kishchuk 1998). Such values below 100 ppm are at the low end of the range observed in mineral soils elsewhere in the temperate zone (Kishchuk 1998). For the E.P. 1185 site, the three major empirical S fractions comprise similar proportions of total S to those observed by Kishchuk (1998) for B horizons at six sites in the Prince George Forest Region: inorganic sulphate-S (5%), sulphate esters (27%), and carbon-bonded S (68%).

TABLE 9 *Continued*

Plot		mg/kg PO_4-ext SO_4-S	pH_{H_2O}	pH_{CaCl_2}
1	Mean	4.3	4.88	4.22
	SD	1.8	0.20	0.25
2	Mean	5.8	4.73	4.03
	SD	2.0	0.16	0.21
3	Mean	7.1	4.72	4.00
	SD	6.1	0.22	0.33
4	Mean	6.9	4.75	4.07
	SD	2.3	0.21	0.25
5	Mean	6.8	4.80	4.17
	SD	1.1	0.17	0.22
6	Mean	7.1	4.78	4.12
	SD	2.8	0.23	0.28
7	Mean	7.6	4.84	4.22
	SD	1.9	0.24	0.31
8	Mean	7.5	4.86	4.16
	SD	1.9	0.20	0.22
9	Mean	8.7	4.81	4.17
	SD	4.3	0.23	0.29
10	Mean	7.6	4.86	4.22
	SD	1.8	0.22	0.25
11	Mean	8.2	4.77	4.15
	SD	2.2	0.22	0.30
12	Mean	8.7	4.64	3.89
	SD	4.1	0.36	0.39
All	Mean	7.2	4.79	4.12
	SD	3.2	0.23	0.29

Treatment Summary

Treatment[d]		mg/kg PO_4-ext SO_4-S	pH_{H_2O}	pH_{CaCl2}
0	Mean	6.4	4.84	4.17
	SD	2.6	0.21	0.25
500	Mean	8.0	4.71	4.01
	SD	4.5	0.28	0.35
1000	Mean	8.0	4.84	4.20
	SD	2.9	0.22	0.28
2000	Mean	6.5	4.76	4.09
	SD	1.9	0.18	0.23

[a] Minrl. N = mineralizable N.
[b] Avail. P = available P.
[c] Morgx = cations extractable with Morgan's reagent.
[d] Alder clumps per hectare.

5.2.3 Nutrient pool estimates We calculated initial soil pool sizes for three elements: C, N, and S. For the forest floor components, both non-woody and woody, we multiplied the mass per unit area by concentration for each sample. For the mineral soils, we multiplied independent measurements of bulk density by concentration for the 0–20 cm depth interval, calculating the error term according to Bergerud and Chen (1997).

Pool sizes dropped by approximately 20–30% from 1995 (Table 15) because of the markedly lower non-woody forest floor mass that was

TABLE 10 *Summary of chemical properties of woody forest floor components: 1995*

Plot		% C	% N	% S	C:N
1	Mean	53.22	0.53	0.0492	107.28
	SD	2.23	0.14	0.0107	32.10
2	Mean	53.21	0.55	0.0392	104.00
	SD	1.82	0.18	0.0100	28.33
3	Mean	54.17	0.58	0.0414	105.82
	SD	2.45	0.24	0.0121	34.17
4	Mean	54.40	0.55	0.0446	107.09
	SD	2.22	0.17	0.0091	29.51
5	Mean	56.57	0.58	0.0372	104.59
	SD	3.74	0.14	0.0126	31.13
6	Mean	54.85	0.63	0.0452	95.03
	SD	2.58	0.19	0.0115	27.56
7	Mean	54.31	0.61	0.0488	95.78
	SD	2.48	0.15	0.0122	30.35
8	Mean	56.02	0.72	0.0463	87.87
	SD	3.22	0.30	0.0138	28.57
9	Mean	53.87	0.67	0.0460	82.75
	SD	1.77	0.10	0.0086	15.17
10	Mean	53.53	0.73	0.0464	76.20
	SD	1.67	0.14	0.0105	15.68
11	Mean	54.93	0.58	0.0445	101.94
	SD	1.42	0.15	0.0091	34.27
12	Mean	55.74	0.64	0.0407	96.41
	SD	3.02	0.20	0.0137	31.99
All	Mean	54.57	0.61	0.0441	97.06
	SD	2.62	0.19	0.0115	29.64

Treatment Summary

Treatment[a]		% C	% N	% S	C:N
0	Mean	54.70	0.63	0.0469	96.72
	SD	2.89	0.23	0.0119	29.92
500	Mean	54.95	0.60	0.0422	101.39
	SD	2.42	0.20	0.0116	32.96
1000	Mean	53.91	0.67	0.0471	84.91
	SD	1.98	0.14	0.0104	22.63
2000	Mean	54.73	0.56	0.0403	105.23
	SD	3.01	0.16	0.0109	29.03

[a] Alder clumps per hectare.

estimated from the 1996 sampling (Table 7). Possible explanations for this year-to-year difference were suggested in Section 5.2.1, but this does not reflect biological or treatment-related factors. In the case of N, if two consecutive samplings one year apart indicated an apparent difference of 11 g/m^2 N (110 kg N/ha) in the non-woody forest floor, it would be difficult to detect the effects of N fixation by the alder if accretion from this process is in the range of 5–10 kg N/ha per year.

TABLE 11 *Summary of chemical properties of woody forest floor components: 1996*

Plot		% C	% N	% S	C:N
1	Mean	52.99	0.60	0.0346	113.99
	SD	3.60	0.29	0.0118	76.75
2	Mean	55.73	0.53	0.0340	113.48
	SD	3.42	0.14	0.0089	35.67
3	Mean	55.29	0.46	0.0396	130.40
	SD	3.68	0.11	0.0073	49.92
4	Mean	56.79	0.47	0.0383	127.07
	SD	3.90	0.12	0.0121	33.07
5	Mean	53.73	0.51	0.0428	112.78
	SD	3.97	0.12	0.0111	32.39
6	Mean	53.18	0.52	0.0454	123.31
	SD	2.33	0.19	0.0148	69.63
7	Mean	51.20	0.53	0.0408	110.99
	SD	1.16	0.23	0.0153	38.19
8	Mean	53.12	0.45	0.0361	135.02
	SD	2.73	0.15	0.0134	54.66
9	Mean	50.46	0.46	0.0359	117.13
	SD	2.65	0.11	0.0092	32.20
10	Mean	49.28	0.59	0.0403	91.55
	SD	1.71	0.23	0.0107	25.67
11	Mean	51.10	0.48	0.0363	117.68
	SD	2.40	0.15	0.0108	43.75
12	Mean	52.32	0.46	0.0343	130.54
	SD	3.05	0.17	0.0089	56.75
All	Mean	52.93	0.50	0.0382	118.57
	SD	3.64	0.18	0.0116	47.65

Treatment Summary

Treatment[a]		% C	% N	% S	C:N
0	Mean	53.10	0.52	0.0388	123.86
	SD	2.87	0.22	0.0139	66.89
500	Mean	52.90	0.47	0.0367	126.21
	SD	3.58	0.14	0.0090	48.15
1000	Mean	50.31	0.53	0.0390	106.55
	SD	2.06	0.20	0.0119	33.54
2000	Mean	55.42	0.50	0.0384	117.78
	SD	3.90	0.13	0.0112	33.63

[a] Alder clumps per hectare.

Two lessons emerge from this initial sampling:

- the overwhelming need to ensure consistency during all phases of forest floor and mineral soil sampling and subsequent sample processing, and
- the requirement of more widely spaced intervals for subsequent resampling.

Instead of repeating the soil sampling every 6 years, as originally

TABLE 12 *Textures of surface (0–20 cm) mineral soils: 1995*

Plot	Sand	Silt	Clay	Class
1	54.2	38.3	7.4	SL
2	49.3	42.9	7.8	L
3	52.9	40.5	6.6	SL
4	47.5	45.2	7.3	L
5	54.7	39.3	6.0	SL
6	52.7	40.7	6.6	SL
7	52.1	42.2	5.7	SL
8	49.5	42.2	8.3	L
9	51.3	41.7	7.0	SL
10	49.6	43.2	7.2	L
11	46.3	47.1	6.5	SL
12	45.3	46.6	8.1	L
Site Mean	50.5	42.5	7.0	SL

TABLE 13 *Summary of 1995 mineral soil (0–20 cm), coarse fragment (C.F.), and bulk density (Db) data (5 measurements per plot)*

					Fine fraction Db (kg/m^3)			
	C.F Content (wt. %)		Total Db (kg/m^3)		Method 1[a]		Method 2[b]	
Plot	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	44.8	17.8	1367	155.1	952	217.2	743	237.3
2	49.7	10.0	1531	159.2	1076	194.7	770	181.5
3	54.8	18.0	1466	268.1	903	193.7	631	215.7
4	53.7	14.6	1659	277.7	1150	228.7	749	213.7
5	58.2	11.4	1636	175.2	1053	217.6	678	179.7
6	57.5	13.1	1492	295.1	935	266.3	620	167.9
7	48.2	6.8	1538	70.8	1103	111.2	796	107.0
8	60.2	6.5	1633	172.9	1038	191.5	650	119.3
9	51.6	13.5	1412	283.5	927	148.1	659	139.1
10	38.9	15.1	1336	114.9	1001	177.0	811	195.8
11	56.3	18.3	1964	155.8	1424	212.0	839	312.7
12	53.3	20.8	1813	423.5	1370	621.9	824	331.8
All	52.3	14.3	1571	274.6	1078	286.8	731	205.1

[a] Method 1: bulk density calculated using fine fraction volume.
[b] Method 2: bulk density calculated using total excavation volume (for nutrient pool estimates).

proposed in the working plan, intervals of 9 years may be better able to detect long-term nutrient pool changes under these treatments.

5.2.4 Effects of alder on mineral soil and forest floor properties We observed several significant differences in nutrient concentrations between sampling locations beneath alder clumps versus those between clumps (Tables 16 and 17). No such differences existed for total C, N, and S in the woody forest floor components (Table 18). As expected, we found significantly higher total N concentrations in both mineral soil and forest floors beneath alder canopies, reflecting the cumulative effects of decades of N

fixation and litter fall from these long-lived shrubs. Potassium concentrations in non-woody forest floor materials were significantly greater beneath alder, as were P, Ca, Mg, and S (Table 17), reflecting the higher litter nutrient concentrations for alder, compared with pine (see Table 25).

Three additional points are noteworthy:

- the small alder-related differences in the mineral soil, despite the long duration of occupancy by individual clumps (cf. Hudson 1993), suggest that it will be difficult to detect any future changes in mineral soil nutrient pools resulting from our alder retention treatments;
- the main site of soil nutrient accumulation in these young alder-dominated ecosystems is the forest floor, rather than the mineral soil; and
- the values for mass per unit area were not significantly different, despite the thicker, more friable nature of forest floors under the alder clumps.

Although total S concentrations in the non-woody forest floor components were affected by alder, no significant effects were evident on the relative proportions of the three empirical S fractions (Tables 16 and 17). This may simply reflect the limitations of existing analytical methods; newer and more specific techniques may provide additional insights (e.g., Strehl and Prietzel 1999). Alternatively, the very low S status of this site may lead to most of the available S being tied up for protein synthesis by higher plants and microbes, resulting in a similar assemblage of S compounds being returned to the soil in plant litter and microbial biomass, regardless of species composition. In contrast, if the site had excess S availability (e.g., from atmospheric deposition), but was otherwise N-limited, one might expect N-fixing plants to have a high proportion of their tissue S content in protein form, while non-N-fixers might accumulate inorganic sulphates in their tissues, leading to species-related differences in the relative proportions of S forms in litter fall.

5.3 Lodgepole Pine Foliar Analysis

Mean foliar N levels are very high relative to those commonly reported for young, harvest-origin pine stands in the Interior of British Columbia (Brockley 1996) (Table 19). Although this is probably partially explained by the young age of this stand, high foliar N concentration may also reflect higher soil N availability resulting from N fixation by Sitka alder.

Absolute foliar P, Ca, and K levels are adequate according to published foliar interpretative criteria (Ballard and Carter 1986). However, nutrient ratio data indicate a probable imbalance of P and K in relation to N (Table 20). According to Linder (1995), P:N and K:N ratios below 10 and 35, respectively, indicate P and K deficiency.

Foliar Mg and S levels indicate slight to marginal deficiencies of these two nutrients. Foliar Mg:N and S:N data confirm this conclusion (Huettl 1993; Kelly and Lambert 1972). Furthermore, foliar SO^4 levels are extremely low for unfertilized pine (Brockley 1996) and indicate that insufficient S may be present in foliage to balance N in protein synthesis (Kelly and Lambert 1972).

Foliar Cu, Zn, and Mn levels are adequate according to published interpretative criteria. However, foliar Fe (and active Fe) and B concentrations indicate possible deficiencies of these two micronutrients (Ballard and Carter 1986). Sub-acute B deficiency has had a negative effect on height increment in pine fertilization research experiments (Brockley 1990).

TABLE 14 *Summary of mineral soil (0–20 cm) chemical properties: 1995*

Plot		%				mg/kg						
		C	N	S	C:N	Minrl. N[a]	Avail. P[b]	MorgxCa[c]	MorgxK[c]	MorgxMg[c]	pH_{H_2O}	pH_{CaCl2}
1	Mean	1.39	0.07	0.0047	19.7	17.5	83.4	549.3	64.4	110.5	5.41	4.61
	SD	0.63	0.03	0.0022	2.7	18.2	31.9	157.5	29.9	45.1	0.25	0.22
2	Mean	1.33	0.07	0.0046	19.5	18.1	57.0	486.0	50.5	121.2	5.33	4.48
	SD	0.55	0.02	0.0019	2.9	7.9	21.4	96.5	25.0	29.1	0.11	0.12
3	Mean	1.93	0.09	0.0060	20.3	22.5	137.8	572.4	75.4	58.9	5.44	4.65
	SD	0.72	0.03	0.0021	2.4	8.2	52.8	112.8	30.1	11.9	0.30	0.24
4	Mean	1.08	0.06	0.0032	18.6	20.0	42.1	436.3	45.8	95.8	5.16	4.33
	SD	0.32	0.01	0.0010	1.9	8.4	14.7	95.2	9.9	22.1	0.15	0.14
5	Mean	0.99	0.05	0.0045	18.1	21.7	32.1	491.4	44.3	130.9	5.24	4.44
	SD	0.22	0.01	0.0021	2.9	11.8	17.2	80.7	4.2	25.3	0.15	0.16
6	Mean	1.30	0.07	0.0051	19.6	21.5	49.5	394.1	47.9	94.8	5.18	4.37
	SD	0.50	0.02	0.0015	3.6	12.5	26.1	82.2	17.6	29.0	0.19	0.17
7	Mean	1.27	0.07	0.0047	18.1	18.7	59.8	511.6	57.4	109.3	5.33	4.48
	SD	0.40	0.02	0.0016	1.3	6.3	22.6	84.3	18.4	29.8	0.25	0.24
8	Mean	1.59	0.08	0.0038	18.9	22.6	58.3	453.0	59.7	93.4	5.29	4.43
	SD	0.35	0.02	0.0010	3.1	12.0	32.3	140.7	21.6	30.7	0.19	0.22
9	Mean	1.71	0.10	0.0059	17.2	19.0	66.3	350.3	53.0	56.1	5.36	4.54
	SD	0.28	0.02	0.0015	1.1	5.9	14.6	101.9	25.5	21.7	0.21	0.22
10	Mean	2.84	0.14	0.0067	20.3	36.3	110.3	606.7	73.2	61.6	5.35	4.53
	SD	1.06	0.04	0.0016	3.3	20.3	60.0	440.5	33.6	19.6	0.26	0.29
11	Mean	1.65	0.09	0.0042	16.9	35.0	15.3	595.3	42.1	165.0	5.11	4.33
	SD	1.23	0.05	0.0024	2.9	25.4	9.0	241.5	13.9	61.5	0.30	0.30
12	Mean	1.52	0.08	0.0041	19.8	34.0	20.4	607.4	51.6	181.4	5.11	4.31
	SD	0.57	0.03	0.0019	3.4	19.5	15.4	193.9	17.9	43.9	0.22	0.24
All	Mean	1.55	0.08	0.0048	18.9	23.9	61.0	504.5	55.4	106.6	5.28	4.46
	SD	0.78	0.03	0.0020	2.9	15.5	45.2	194.1	24.0	49.8	0.24	0.24

Treatment Summary

Treatment[d]		%				mg/kg						
		C	N	S	C:N	Minrl. N[a]	Avail. P[b]	MorgxCa[c]	MorgxK[c]	MorgxMg[c]	pH_{H_2O}	pH_{CaCl2}
0	Mean	1.44	0.07	0.0046	19.38	20.8	64.5	470.5	58.0	100.7	5.29	4.47
	SD	0.52	0.03	0.0017	3.10	14.5	33.3	144.6	24.4	36.1	0.23	0.23
500	Mean	1.72	0.09	0.0048	19.03	30.8	58.6	597.7	57.0	136.3	5.22	4.43
	SD	0.90	0.04	0.0023	3.23	19.8	66.3	189.5	26.0	70.5	0.31	0.30
1000	Mean	1.97	0.10	0.0058	18.55	25.1	80.1	497.3	62.1	76.8	5.35	4.52
	SD	0.96	0.04	0.0018	2.48	15.3	44.3	287.0	27.9	34.1	0.24	0.25
2000	Mean	1.14	0.06	0.0041	18.72	20.1	44.1	475.0	47.3	116.9	5.24	4.42
	SD	0.41	0.02	0.0018	2.61	9.5	20.6	93.5	15.8	29.4	0.15	0.15

In summary, high foliar N concentrations have apparently resulted in foliar nutrient imbalances in young pine growing on this site. Imbalances appear to be most severe for P, K, S, Mg, and B. Because foliar N levels will likely decline as the stand ages, it will be interesting to see whether nutrient balance improves over time.

5.4 Nitrogen Fixation

Data on the natural abundance of ^{15}N in foliage for samples collected in August 1995 and June 1996 present an ambiguous picture (Tables 21 and 22). According to the approach advocated by Shearer and Kohl (1989), we would expect to see $\delta^{15}N$ values for an N-fixing species to lie closer to the atmospheric standard (i.e., $\delta^{15}N = 0‰$) than those from plants deriving

TABLE 14 *Continued*

Treatment[d]		S fractions						
		HI-reducible S	PO_4-ext SO_4-S		Ester SO_4-S		C-bonded S	
		mg/kg	mg/kg	% of total S	mg/kg	% of total S	mg/kg	% of total S
1	Mean	13.8	1.6	3.9	12.2	29.6	33.9	66.6
	SD	4.1	0.5	1.8	3.9	12.1	21.1	13.3
2	Mean	14.5	1.4	3.4	13.1	32.5	31.7	64.1
	SD	3.8	0.4	1.0	3.7	16.5	19.1	17.2
3	Mean	17.6	1.4	2.5	16.2	27.9	43.1	69.6
	SD	4.8	0.5	1.1	4.6	6.0	17.1	6.1
4	Mean	13.0	1.0	3.4	12.0	39.4	19.2	57.1
	SD	2.8	0.7	2.7	2.8	10.5	8.8	10.7
5	Mean	11.7	1.2	2.8	10.6	26.8	33.5	70.3
	SD	2.4	0.8	2.4	2.5	10.5	20.8	10.6
6	Mean	11.6	1.5	3.1	10.1	21.4	39.8	75.5
	SD	3.0	0.3	0.8	3.0	8.3	14.7	8.7
7	Mean	13.9	1.4	3.2	12.5	28.5	33.5	68.4
	SD	2.8	0.4	0.8	2.7	8.2	15.8	8.6
8	Mean	12.8	1.5	4.4	11.3	30.4	25.8	65.3
	SD	2.2	0.3	1.9	2.4	7.5	9.0	8.4
9	Mean	16.8	1.4	2.4	15.5	27.4	42.6	70.2
	SD	2.5	0.3	0.8	2.6	7.6	15.3	7.9
10	Mean	17.6	1.4	2.2	16.2	24.5	50.4	73.3
	SD	3.4	0.7	1.3	3.4	5.1	14.0	5.0
11	Mean	10.5	1.4	3.9	9.1	23.9	32.2	72.2
	SD	4.3	1.0	2.8	3.9	7.2	20.7	8.1
12	Mean	11.3	1.4	4.1	9.9	25.4	29.8	70.5
	SD	3.8	0.8	2.4	3.7	6.1	15.9	7.1
All	Mean	13.8	1.4	3.3	12.4	28.1	34.6	68.6
	SD	4.1	0.6	1.9	4.0	10.1	17.9	10.6

Treatment Summary		S fractions						
		HI-reducible S	PO_4-ext SO_4-S		Ester SO_4-S		C-bonded S	
Treatment[d]		mg/kg	mg/kg	% of total S	mg/kg	% of total S	mg/kg	% of total S
0	Mean	12.8	1.5	3.8	11.2	27.1	33.2	69.1
	SD	3.3	0.4	1.7	3.2	10.2	16.4	11.2
500	Mean	13.2	1.4	3.5	11.7	25.7	35.0	70.8
	SD	5.3	0.8	2.3	5.1	6.5	18.5	7.1
1000	Mean	16.1	1.4	2.6	14.7	26.8	42.2	70.6
	SD	3.3	0.5	1.1	3.3	7.1	16.3	7.4
2000	Mean	13.1	1.2	3.2	11.9	32.9	28.2	63.8
	SD	3.2	0.7	2.1	3.1	13.5	17.9	14.0

[a] Minrl. N = mineralizable N.
[b] Avail. P = available P.
[c] Morgx = cations extractable with Morgan's reagent.
[d] Alder clumps per hectare.

their N primarily from the soil. However, our data do not follow this pattern, and we also note apparent seasonal or inter-annual differences for a given species—$\delta^{15}N$ values were consistently lower for all species in June 1996 than in August 1995. Such ambiguities limit the utility of the ^{15}N natural abundance method in N fixation studies, and are consistent with difficulties encountered by Binkley et al. (1985) and Sachs (1992). These

TABLE 15 *Soil nutrient pool estimates: 1995 and 1996*

Carbon (g/m^2)	Forest Floor					
1995	Non-woody components		Woody components		Mineral soil	
	Mean	SE	Mean	SE	Mean	SE
Plot Summary						
1	2339.8	555.2	719.5	205.4	2064.7	381.0
2	2035.7	242.3	445.9	97.8	2046.1	306.7
3	2166.3	329.5	759.4	194.1	2432.1	439.3
4	2084.0	318.0	371.3	72.5	1621.0	240.7
5	3356.9	435.7	810.3	183.9	1338.2	176.1
6	2984.9	1002.7	466.6	167.7	1611.8	253.5
7	2561.7	443.5	807.1	192.8	2024.4	205.2
8	2566.3	381.6	203.5	82.5	2063.5	206.8
9	2590.8	321.2	834.5	285.4	2248.3	232.8
10	2731.6	563.9	567.0	241.5	4602.2	665.1
11	1716.7	260.7	340.0	80.4	2766.6	703.7
12	2603.6	410.5	479.8	115.5	2508.2	512.3
All	2478.2	138.1	567.0	50.8	2264.9	117.8
Treatment Summary[a]						
0	2630.3	395.5	463.2	95.9	1913.0	165.3
500	2162.2	198.9	526.2	82.4	2598.8	321.9
1000	2628.0	256.2	736.2	138.2	2928.2	263.2
2000	2492.2	213.5	542.5	77.4	1658.8	138.7

	Forest floor			
1996	Non-woody components		Woody components	
	Mean	SE	Mean	SE
Plot Summary				
1	1071.5	225.9	255.9	74.0
2	2414.1	413.5	526.4	119.7
3	2398.6	331.5	779.7	111.8
4	2002.0	263.9	527.0	121.8
5	2096.2	236.5	655.9	109.6
6	1859.7	313.9	977.8	293.3
7	1287.9	252.4	333.2	77.1
8	1320.0	271.5	479.1	172.2
9	1786.3	260.2	833.5	187.9
10	1393.6	219.2	428.8	111.8
11	1578.2	186.4	551.1	101.3
12	3594.7	586.7	1116.8	180.8
All	1900.2	100.8	622.1	46.0
Treatment Summary[a]				
0	1417.1	161.7	570.9	122.2
500	2523.9	259.7	815.9	84.3
1000	1489.3	141.7	531.8	82.3
2000	2170.8	179.3	569.77	66.7

TABLE 15 *Continued*

Nitrogen (g/m^2)	Forest Floor					
1995	Non-woody components		Woody components		Mineral soil	
	Mean	SE	Mean	SE	Mean	SE
Plot Summary						
1	65.1	15.88	5.97	1.37	105.0	19.20
2	55.7	5.83	3.90	0.64	103.6	13.96
3	59.5	8.39	6.26	1.49	118.6	20.71
4	56.7	10.33	3.58	0.85	86.9	12.46
5	70.7	7.19	7.44	1.66	74.1	9.45
6	57.8	12.41	4.93	1.66	82.6	12.70
7	56.2	5.50	7.74	1.55	111.5	11.05
8	62.0	7.17	2.34	0.88	110.1	10.66
9	69.8	7.33	9.12	2.46	130.9	13.66
10	70.2	12.00	6.24	2.40	222.8	29.07
11	52.5	8.13	3.66	0.96	152.1	33.81
12	57.0	8.48	4.41	0.92	126.3	25.47
All	61.1	2.70	5.47	0.45	118.2	5.70
Treatment Summary[a]						
0	61.6	6.98	4.41	0.79	99.3	8.46
500	56.3	4.72	4.78	0.67	133.2	15.53
1000	65.4	5.02	7.70	1.24	154.4	12.05
2000	61.0	4.63	4.97	0.69	87.9	6.74

1996	Forest floor			
	Non-woody components		Woody components	
	Mean	SE	Mean	SE
Plot Summary				
1	34.7	6.99	1.97	0.46
2	57.5	7.77	4.19	0.81
3	66.3	7.79	6.20	0.82
4	51.1	6.30	4.23	0.97
5	57.2	4.68	5.75	0.90
6	47.1	6.90	7.47	1.98
7	35.9	5.10	3.27	0.74
8	33.6	6.43	3.33	0.93
9	54.4	7.33	7.62	2.05
10	45.0	7.10	4.78	1.21
11	43.4	5.28	4.85	0.70
12	75.2	10.16	8.30	1.21
All	50.1	2.15	5.16	0.36
Treatment Summary[a]				
0	38.5	3.93	4.26	0.81
500	61.6	4.94	6.45	0.57
1000	45.1	3.89	5.22	0.85
2000	55.2	3.63	4.72	0.52

TABLE 15 *Concluded.*

Sulphur (g/m^2)	Forest Floor					
1995	Non-woody components		Woody components		Mineral soil	
	Mean	SE	Mean	SE	Mean	SE
Plot Summary						
1	4.55	0.99	0.669	0.189	7.01	1.31
2	4.31	0.52	0.414	0.092	7.05	1.07
3	4.56	0.70	0.633	0.164	7.55	1.34
4	4.34	0.58	0.310	0.065	4.79	0.73
5	5.80	0.67	0.551	0.129	6.09	1.03
6	4.20	0.91	0.342	0.123	6.30	0.91
7	4.29	0.51	0.670	0.147	7.44	0.80
8	4.22	0.50	0.157	0.062	4.98	0.53
9	5.45	0.57	0.629	0.206	7.72	0.90
10	5.11	0.87	0.482	0.205	10.85	1.34
11	4.06	0.61	0.228	0.062	7.09	1.58
12	5.39	0.81	0.342	0.076	6.72	1.46
All	4.69	0.20	0.452	0.041	6.99	0.33
Treatment Summary[a]						
0	4.32	0.47	0.389	0.083	6.09	0.54
500	4.65	0.41	0.401	0.067	7.28	0.87
1000	4.95	0.39	0.593	0.107	8.67	0.61
2000	4.83	0.35	0.425	0.058	5.99	0.55

1996	Forest floor			
	Non-woody components		Woody components	
	Mean	SE	Mean	SE
Plot Summary				
1	2.35	0.510	0.138	0.032
2	3.88	0.531	0.286	0.059
3	4.31	0.601	0.543	0.071
4	2.97	0.424	0.315	0.062
5	3.61	0.279	0.503	0.083
6	2.69	0.356	0.657	0.190
7	2.54	0.388	0.255	0.064
8	2.31	0.455	0.291	0.094
9	3.78	0.570	0.589	0.139
10	2.89	0.445	0.329	0.082
11	2.75	0.383	0.373	0.063
12	4.58	0.764	0.671	0.100
All	3.22	0.148	0.413	0.029
Treatment Summary[a]				
0	2.45	0.252	0.362	0.077
500	3.88	0.361	0.529	0.048
1000	3.07	0.278	0.391	0.060
2000	3.48	0.246	0.368	0.041

[a] Alder clumps per hectare.

TABLE 16 *Effect of alder on mineral soil (0–20 cm) properties: 1995*[a]

	%				mg/kg						
	C	N	S	C:N	Minrl. N[b]	Avail. P[c]	MorgxCa[d]	MorgxK[d]	MorgxMg[d]	pH_{H_2O}	pH_{CaCl_2}
Alder[e]											
Mean	1.63	**0.09**	0.0050	18.68	24.8	64.4	504.5	**60.2**	102.1	5.28	4.45
SD	0.86	0.04	0.0021	2.83	15.1	45.9	227.0	26.8	49.0	0.240	0.230
Other[e]											
Mean	1.46	**0.08**	0.0046	19.19	23.0	57.2	504.5	**50.1**	111.6	5.27	4.46
SD	0.66	0.03	0.0018	2.91	15.9	44.3	150.6	19.3	50.5	0.247	0.249

	S fractions						
	HI-reducible S	PO_4-ext SO_4-S		Ester SO_4-S		C-bonded S	
	mg/kg	mg/kg	% of total S	mg/kg	% of total S	mg/kg	% of total S
Alder[e]							
Mean	14.3	1.4	3.2	12.9	28.0	36.2	68.7
SD	4.3	0.5	1.8	4.2	9.3	19.2	9.9
Other[e]							
Mean	13.2	1.4	3.3	11.9	28.3	32.9	68.4
SD	3.8	0.6	2.0	3.7	10.9	16.3	11.4

[a] Data in bold typeface differ significantly according to sampling location; analyzed as randomized block design, with plots as blocks; $p < 0.05$.
[b] Minrl. N = mineralizable N.
[c] Avail. P = available P.
[d] Morgx = cations extractable with Morgan's reagent.
[e] Alder = sampling location under alder clumps ($n = 95$); Other = sampling position between alder clumps ($n = 85$).

results provide additional justification for adopting the isotope dilution method.

In developing biomass calibration equations, consistent with the earlier work by Wurtz (1995), we found that equations of the following form provided the highest r^2 values: ln(weight) = $a + b$ ln(basal diameter) (Table 23).

For the 14 clumps in the labelled mini-plots, we applied these equations using the individual stem diameter measurements, to estimate the weight of the above-ground biomass components in mid-summer 1996 (Table 24). Above-ground biomass increment will be estimated by subtracting these weights from future values obtained through either:

- repeating the diameter measurements and applying the calibration equations, or
- directly measuring biomass by destructive sampling.

As the alder clumps expand, it may be necessary to create new calibration equations that include the full range of stem diameters and weights. In addition, after canopy closure occurs, the allometric relationships may change as the alder responds to a different light environment.

To estimate the biomass of entire clumps, we tested several simple and multiple regressions of the alder clump measurement variables and their

TABLE 17 *Effect of alder on non-woody forest floor properties: 1995*[a]

		%				mg/kg						
	g/m^2	C	N	S	C:N	Minrl. N[b]	Avail. P[c]	MorgxCa[d]	MorgxK[d]	MorgxMg[d]	pH_{H_2O}	pH_{CaCl_2}
Alder[e]												
Mean	5869.8	43.98	**1.24**	**0.0900**	**37.39**	**526.8**	**121.3**	**3730.8**	**623.4**	**695.5**	**4.60**	4.03
SD	3040.7	9.59	0.38	0.0238	10.77	257.5	50.7	914.8	192.7	196.9	0.223	0.264
Other[e]												
Mean	5425.6	42.42	**1.05**	**0.0805**	**42.50**	**404.9**	**96.7**	**3207.6**	**542.4**	**596.7**	4.56	3.96
SD	4292.8	10.03	0.30	0.0204	12.77	171.1	45.8	740.2	223.3	157.3	0.271	0.303

	S fractions						
	HI-reducible S	PO_4-ext SO_4-S		Ester SO_4-S		C-bonded S	
	mg/kg	mg/kg	% of total S	mg/kg	% of total S	mg/kg	% of total S
Alder[e]							
Mean	106.7	11.6	1.3	95.5	11.1	**793.7**	87.6
SD	33.7	10.2	1.0	28.4	3.9	226.1	4.2
Other[e]							
Mean	96.9	10.3	1.3	87.5	11.0	**708.2**	87.8
SD	30.9	9.4	1.4	28.4	2.9	187.2	3.1

[a] Data in bold typeface differ significantly according to sampling location; analyzed as randomized block design, with plots as blocks; $p < 0.05$.
[b] Minrl. N = mineralizable N.
[c] Avail. P = available P.
[d] Morgx = cations extractable with Morgan's reagent.
[e] Alder = sampling location under alder clumps ($n = 95$); Other = sampling position between alder clumps ($n = 85$).

TABLE 18 *Effect of alder on woody forest floor component properties: 1995*[a]

		%			
	g/m^2	C	N	S	C:N
Alder[b]					
Mean	1030.7	54.27	0.66	0.0462	89.36
SD	1127.3	2.23	0.20	0.0115	27.08
Other[b]					
Mean	1025.5	54.91	0.56	0.0418	105.67
SD	1310.7	2.96	0.15	0.0111	30.16

[a] None of these chemical properties differed significantly with sampling location; analyzed as randomized block design, with plots as blocks; $p < 0.05$.
[b] Alder = sampling location under alder clumps ($n = 95$);Other = sampling position between alder clumps ($n = 85$).

transformations. The best fit ($r^2 = 0.916$) was obtained for a regression with the Y-intercept forced through 0:

$$\text{Biomass} = 0.09311 \times DIAMS,$$

where *DIAMS* is the simple product of the two perpendicular diameter measurements for each clump. Including the numbers of stems per clump

TABLE 19 *Nutrient concentrations in current-year lodgepole pine foliage: October 1995*[a]

Treatment[b]		%						mg/kg							
		N	P	Ca	Mg	K	S	SO_4-S	Cu	Zn	Fe	Active Fe	Mn	B	Al
0	Mean	1.84	0.16	0.21	0.080	0.55	0.098	17	4	36	26	25	280	6	490
	SD	0.05	0.01	0.01	0.007	0.08	0.015	2.1	1	3.5	0.0	0.0	37.0	1	50.3
500	Mean	1.85	0.15	0.21	0.075	0.53	0.096	10	4	36	26	24	360	7	413
	SD	0.07	0.01	0.03	0.003	0.06	0.006	2.3	1	5.0	0.0	2.3	20.1	1	114
1000	Mean	1.78	0.16	0.22	0.072	0.54	0.095	11	4	35	26	25	322	7	513
	SD	0.21	0.02	0.01	0.005	0.05	0.002	1.7	0	1.5	0.0	0.0	12.7	0	12.6
2000	Mean	1.89	0.16	0.20	0.076	0.55	0.098	20	4	37	28	25	302	6	540
	SD	0.11	0.00	0.01	0.004	0.01	0.002	9.0	1	1.7	2.9	0.0	21.5	1	18.6
All	Mean	1.84	0.16	0.21	0.076	0.54	0.097	15	4	36	26	25	316	6	489
	SD	0.11	0.01	0.01	0.005	0.05	0.007	5.9	0	2.9	1.4	1.2	37.4	1	73.1

[a] $n = 3$ (1 composite sample per plot).
[b] Alder clumps per hectare.

TABLE 20 *Nutrient concentration ratios in current-year lodgepole pine foliage: October 1995*

Treatment[a]		P:N	K:N	Ca:N	Mg:N	S:N
0	Mean	8.9	29.8	11.4	4.4	5.3
	SD	0.2	3.6	0.7	0.3	0.7
500	Mean	8.1	28.5	11.3	4.0	5.2
	SD	0.3	2.0	1.1	0.2	0.2
1000	Mean	8.8	30.7	12.3	4.1	5.4
	SD	0.3	6.4	1.5	0.3	0.5
2000	Mean	8.5	29.4	10.6	4.0	5.2
	SD	0.5	2.1	1.1	0.5	0.4
All	Mean	8.6	29.6	11.4	4.1	5.3
	SD	0.4	3.4	1.1	0.3	0.4

[a] Alder clumps per hectare.

as a predictive variable in multiple regressions did not improve the strength of this relationship.

For the three main treatment plots with retention of 2000 clumps per hectare, we applied this equation to the individual alder clump measurements, summed the estimates for all clumps in a plot, and obtained a mean above-ground biomass of 4960 kg/ha (SD = 342.0).

5.5 Litter Decomposition

The initial chemical element concentrations of the litterbag materials are presented in Table 25. The between-species differences are most pronounced for the major elements, with much higher concentrations of N, S, P, Ca, Mg, and K in the alder leaf litter. For most of the micronutrients (B, Fe, Mn, Zn), the two species were much more similar. Since previous studies (e.g., Berg and Matzner 1997) have shown that the accelerating effect of higher nutrient concentrations (especially N) on litter decomposition is most pronounced in the early stages of breakdown, we should detect higher rates of weight loss by the alder leaves during the first two years.

When compared with the data for current-year foliage (Table 19), we can make some inferences about the relative retranslocation behaviour of the

TABLE 21 *Natural abundance of ^{15}N in foliage (August 1995)*

Species	Mature forest		Upper clearcut		Lower clearcut	
	Atom% ^{15}N	$\delta^{15}N$‰	Atom% ^{15}N	$\delta^{15}N$‰	Atom% ^{15}N	$\delta^{15}N$‰
Alnus viridis ssp. *sinuata*	0.36831	5.49	0.36825	5.32	0.36815	5.05
Pinus contorta	0.36808	4.86	0.36757	3.47	0.36779	4.07
Spiraea betulifolia	0.36842	5.79	0.36828	5.41	0.36818	5.13
Vaccinium membranaceum	0.36857	6.20	0.36791	4.40	0.36782	4.15
Populus tremuloides			0.36735	2.87	0.36809	4.89
Rosa acicularis			0.36903	7.45	0.36912	7.70
Rubus idaeus			0.36736	2.89	0.36745	3.14
Salix sp.			0.36807	4.83	0.36842	5.79

TABLE 22 *Natural abundance of ^{15}N in foliage sampled mini-plots before tracer application: June 1996*

Species	$\delta^{15}N$‰		
	n	Mean	SD
Alnus viridis ssp. *sinuata*	14	2.9	0.86
Pinus contorta	14	2.2	1.72
Spiraea betulifolia	5	3.1	1.03
Vaccinium membranaceum	9	2.1	1.38
Rosa acicularis	3	5.1	1.03
Rubus idaeus	7	1.6	0.90
Salix sp.	1	3.4	
Linnaea borealis	1	2.5	
Epilobium angustifolium	13	2.4	1.33
Cornus canadensis	1	1.7	
Arnica cordifolia	2	2.1	0.08
Pyrola sp.	1	3.5	
Grass (unidentified species)	6	1.8	0.82

TABLE 23 *Sitka alder biomass calibration equations*

Equation[a]	R^2
ln(stem weight) = -4.079 + 2.938 ln(diam.)	0.975
ln(leaf weight) = -3.205 + 1.956 ln(diam.)	0.840
ln(cone weight) = -8.923 + 3.459 ln(diam.)	0.724
ln(total weight) = -3.360 + 2.756 ln(diam.)	0.971

[a] Weights in grams; diameters in millimetres; n = 133; diameter range 2.42–37.50 mm.

TABLE 24 *Estimated mass of alder clumps from ^{15}N-labelled mini-plots: July 1996*

Clump no.	Stem (g)	Leaves (g)	Cones (g)	Total (g)
1	11876.05	960.33	587.45	12908.05
2	2959.88	305.97	129.75	3357.67
3	2708.36	293.98	115.36	3104.62
4	3457.57	371.01	148.53	3954.28
5	2054.95	284.20	76.17	2468.52
6	4098.17	506.33	159.15	4832.95
7	6327.30	611.78	278.91	7133.71
8	2221.99	292.10	82.96	2653.89
9	2210.80	300.42	81.66	2653.53
10	2671.32	363.25	99.41	3201.05
11	2549.88	389.11	88.97	3123.90
12	1321.59	234.89	42.61	1665.02
13	6359.28	577.65	293.57	7071.14
14	3550.65	346.90	160.42	3990.05
Mean	3883.41	417.00	167.49	4437.03
SD	2735.36	193.17	141.02	2917.72

TABLE 25 *Initial chemical composition of litterbag materials*[a]

Element	Alder	Pine
N (%)	1.47	0.56
S (%)	0.077	0.041
SO_4-S (**mg/kg**)	11.8	11.9
P (%)	0.347	0.063
Ca (%)	1.309	0.708
Mg (%)	0.256	0.078
K (%)	1.096	0.108
B (**mg/kg**)	8.7	6.6
Cu (**mg/kg**)	4.2	1.4
Fe (**mg/kg**)	56.8	42.0
Mn (**mg/kg**)	875.6	872.7
Zn (**mg/kg**)	47.4	60.5

[a] Ministry of Forests laboratory requisition no. T0413; $n = 3$.

various elements in pine. (Caution is needed because the two sets of samples came from different years, and the two data sets were obtained from different laboratories.) Nevertheless, we can observe that organically bound major nutrients (N, S, P) decrease in concentration substantially by factors of 0.5 to 0.75, while Ca increases almost fourfold. For alder, we are only able to examine the pattern for N. Using the total N concentrations for the mid-June (3.53% ± 0.188; $n = 14$) and mid-August (2.26% ± 0.269; $n = 14$) 1996 sampling of the tracer mini-plots, we observed a gradual decline over the growing season to the final value of 1.47%.

6 SUMMARY

The original scope of E.P. 1185 has been modified and expanded to address nutrient cycling processes in greater detail, while reducing the number of main treatments from six to four because of site constraints. The maximum alder retention treatment was set at 2000 rather than 4000 clumps per hectare because the uneven distribution of the clumps would have required excessive transplanting at the higher density. Although the fertilization treatment had to be sacrificed, it will still be possible to make comparisons with the performance of fertilized pine stands elsewhere in the Sub-Boreal Spruce zone.

The four alder removal treatments in 1995 created a spectrum of initial cover densities ranging from 0 to almost 40% cover, and exceeding the apparent threshold at which competitive interactions with pine are likely. Initially, after the 1995 alder removal treatments, the alder clumps were approximately 30 cm taller than the retained pine trees.

Pre-treatment mineral soil and forest floor sampling in 1995 indicated substantial spatial variability in nutrient concentrations and pool sizes. Future sampling should consist of at least 15 mineral soil and 30 forest floor samples per plot. However, it is doubtful that biologically meaningful changes in nutrient pool sizes will be detectable by resampling at 6-year intervals, so a wider sampling interval of 9 years is recommended.

Nitrogen fixation and nutrient cycling by Sitka alder has created pronounced localized zones of nutrient enrichment beneath the crowns of clumps that have re-sprouted since logging in 1987. These enrichments are most pronounced in the forest floor, which suggests that this is where the effects of the alder density treatments will be expressed first. Despite the pattern of nutrient enrichment in soils beneath alder clumps, no significant differences were evident in the relative amounts of empirically defined sulphur fractions.

The ^{15}N natural abundance method was of limited value for estimating the proportion of N in alder tissues that originated by fixation, justifying the decision to use the isotope dilution method.

Chemical analysis of 1995 current-year pine foliage indicated high concentrations of N, which are currently imbalanced with other nutrients (P, K, S, Mg, and B). Litter fall produced by alder is considerably enriched in most macronutrients (N, S, P, Ca, Mg, K), compared to pine needle litter.

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