Growth, development, and yield of mixed-wood stands in Alberta following partial cutting of white spruce

I.E. Bella and J. Gál

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ABSTRACT

In 1951 and 1952, 121 permanent sample plots were established at 16 locations in mixed stands of white spruce (*Picea glauca* [Moench] Voss) and trembling aspen (*Populus tremuloides* Michx.), which had undergone partial cutting that had removed the largest white spruce. These stands were re-examined in 1962 and 1993 to assess growth rates and productivity of mixed stands after partial cutting and determine whether a similar harvesting technique would ensure future harvests of white spruce. This study, based on plot data and increment core measurements of spruce sample trees, showed generally excellent diameter and volume growth response by the residual spruce. Wind damage was the main cause of mortality and averaged about 1.8% per year in terms of residual spruce volume. A multiple regression model with four independent variables fitted to the data provided reasonable predictions of spruce merchantable volume yield for similar stands. A model with two independent variables (residual spruce volume and years since logging) explained 74.1% of the variation in postlogging merchantable spruce volume yield. Highly variable mortality among deciduous trees prevented the development of practical volume prediction models for that component.

RÉSUMÉ

En 1951 et en 1952, 121 plages d'échantillonnage permanent furent établis dans seize pessières à faux–tremble (*Picea glauca* [Moench] Voss et *Populus tremuloides* Michx.), où les plus grands spécimens d'épinettes blanches avaient étés abattus. En 1962 et en 1993, ces peuplements furent examinés pour évaluer leurs taux de croissance et de productivité après leur coupe partielle et pour déterminer si ce type de récolte peut assurer la régénération des peuplements d'épinettes blanches pour les récoltes futures. La présente étude, basée sur les données recueillies dans les plages concernées et sur les carottages d'épinette effectués, a révélé que le diamètre et le cubage produits par les épinettes restantes étaient excellents. Elle a également révélé que le vent était la principale cause de mortalité détruisant en moyenne 1,8 % du cubage restant d'épinette par année. Un modèle de régression multiple basé sur quatre variables indépendantes adaptées aux données recueillies a permis d'obtenir des prédictions raisonnables du rendement volumique commercialisable pour des peuplements d'épinettes comparables. Un modèle à deux variables indépendantes (cubage d'épinette restante et années depuis la récolte) a permis d'expliquer 74,1 % de la variance observée dans la production volumique commercialisable après la coupe. Le taux de mortalité fort variable des caducifoliés n'a pas permis d'établir de modèle prédictif concernant le rendement volumique pratique.

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INTRODUCTION

As early as the 1930s and in the following decade, partial cutting of the white spruce (*Picea glauca* [Moench] Voss) component of mixed white spruce–trembling aspen (*Populus tremuloides* Michx.) stands of the boreal forest of Alberta was a common practice. These cuttings removed only the largest spruce trees and resulted in medium to dense residual stands. In the 1950s and later, increased demand for lumber and better utilization practices resulted in the use of harvesting systems that removed the white spruce component to a diameter limit of 30–33 cm (12–13 in.). Such cutting led to the removal of up to 94% of the white spruce volume (Blyth 1952).

All these cuttings were generally winter operations using chain saws and axes. Skidding was done with horses in earlier times or with light-wheeled farm tractors and later with caterpillar tractors. The season of operation and the means of logging resulted in minimal soil compaction, surface disturbance, and damage to the trunks of residual trees.

Before the 1950s, virtually nothing was known about the future development of such stands. To address this issue, the Department of Resources and Development, Forestry Branch, predecessor of the Canadian Forest Service, initiated a study in 1951 with four main objectives:

1. to assess growth rates and productivity of mixed white spruce–trembling aspen stands after partial cutting, with particular emphasis on white spruce;
2. to determine whether a similar system of partial cutting would ensure future harvests of white spruce;
3. to monitor and explain mortality dynamics in those partially cut stands, and;
4. to assess potential regeneration and advanced growth development scenarios after partial cutting.

This report provides information on the first three objectives.

METHODS

To investigate growth, productivity, and regeneration after partial cutting, suitable sample stands were selected between Rocky Mountain House in the south and Lesser Slave Lake in the north (Fig. 1). A total of 64 0.162-ha (0.4 acre) permanent sample plots were established in the summer of 1951 at 10 locations. An additional 56 permanent sample plots were established in the following summer at six locations. In 1962, 90 undisturbed plots were remeasured, and 40 were remeasured in 1993.

The following information was recorded for each plot at establishment:

1. geographical location;
2. complete tally of all trees by species in 2.54-cm (1 in.) diameter classes using diameter at breast height (DBH);
3. DBH to 0.25 cm (0.1 in.) and height to 30 cm (the nearest foot) on each third or fourth white spruce tree per diameter class (these were also tagged);
4. increment borings in two directions at right angles to each other on the tagged spruce trees at breast height 1.37 m (4.5 ft) and stump height 30 cm (1 ft). On these cores, current radius, and radius at time of logging, at 5 and 10 years before logging, and at 5-year intervals after logging were recorded. Elapsed time since logging was determined either from records or from tree-ring counts back to visible sign of release;
5. tally of spruce stumps by 2.54-cm (1 in.) classes;
6. ring counts on the five largest spruce stumps on each plot to determine age;
7. DBH tally of dead white spruce trees since logging, based on external signs;
8. height and DBH measurements (three to four trees per plot) for species other than white spruce for constructing height–diameter curves, and;

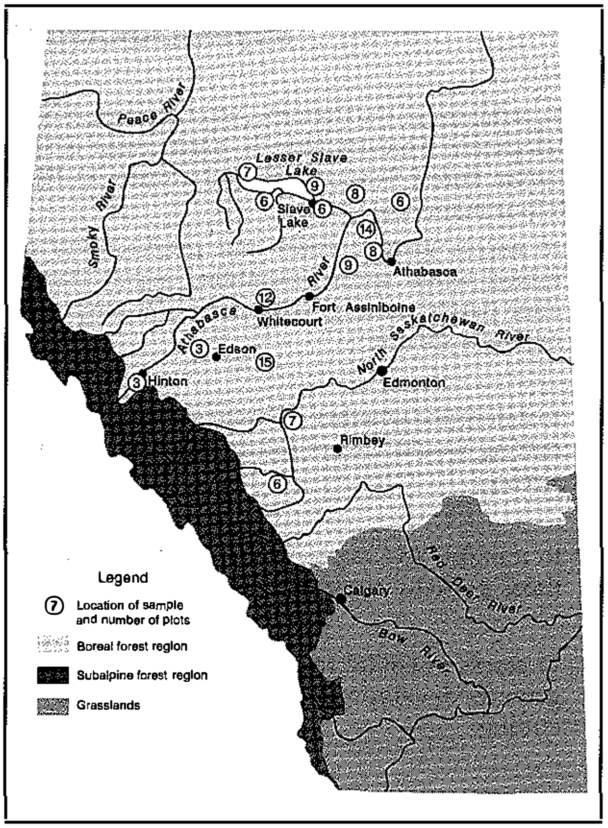

Figure 1. Sample locations and number of plots.

9. a regeneration tally on 80 4.047 m^2 (1 milacre) quadrats.

The first and second remeasurements included the following:

1. a complete DBH tally of all living trees by species, as at establishment;
2. measurement of height and DBH of tagged trees;
3. at the first remeasurement only, a tally of dead trees by DBH classes, along with the cause of death;
4. assessment of regeneration on 40 4.047 m^2 (1 milacre) quadrates on each plot, and;
5. a subjective visual assessment and ranking of the plots according to productivity class and moisture regime.

The distribution of the sample plots by age and years-since-logging is listed in Tables 1 and 2.

The data represent stands over a wide range of years-since-logging at study establishment (Table 2). At the first remeasurement in 1962, the plots still covered a years-since-logging range at establishment of up to 30 years, and, at the second remeasurement in 1993, of up to 23 years.

The reason for sampling stands cut more than 10 years before establishment was to get information on growth response and mortality immediately at the time of study establishment. The long timespan since logging introduced a fair amount of variation in the data for the following reasons:

1. mortality of the white spruce component could only be estimated indirectly, and there was no information on the time when the trees actually died;
2. errors were introduced into the retrospective estimation of white spruce volumes by the assumption that all trees in a specific diameter class grew according to present-over-past diameter regressions. Volume estimate errors from this source might be greatest for large diameter increments;
3. for companion tree species, neither mortality nor increment information was available so a retrospective estimation of their stand characteristics was not possible. These companion species include deciduous trees such as trembling aspen, balsam poplar (*Populus balsamifera* L.), white birch (*Betula papyrifera* Marsh.), and coniferous species such as balsam fir (*Abies balsamea* [L.] Mill.), jack pine (*Pinus banksiana* Lamb.), and black spruce (*Picea mariana* [Mill.] B.S.P.).

Data Screening and Processing

The average stump age of the residual spruce component on each plot was calculated from ring counts on the cores taken from stump height averaged within a diameter class, then weighting this average by the basal area of the diameter class.

To calculate stem volumes, height–diameter curves were fitted. First, height and diameter data of tagged trees for each plot were plotted to enable visual checking of outliers and for consistency of consecutive measurements (increasing height and diameter, missing remeasurements, etc.). These graphs also showed whether different height–diameter relationships were needed for the three

Table 1. **Number of sample plots by age of the spruce component at plot establishment**

Age (years)	Number of plots		
	Establishment	First remeasurement	Second remeasurement
40–49	1	1	0
50–59	3	3	0
60–69	10	8	1
70–79	24	21	14
80–89	29	21	10
90–99	15	12	3
100–109	22	16	7
110–119	8	4	2
120–129	5	4	3
130–139	0	0	0
140–149	2	0	0
150–159	1	0	0
160+	1	0	0
Total	121	90	40

Table 2. **Number of sample plots by years since logging at study establishment for all three measurements**

Years since logging	Number of plots		
	Establishment	First remeasurement	Second remeasurement
0–4	41	30	18
5–9	24	17	10
10–14	20	13	11
15–19	2	2	0
20–24	8	6	1
25–29	14	12	0
30–34	12	10	0
Total	121	90	40

measurements. The lack of consistent separation of the data by measurements, however, suggested that a single relationship be developed. Equation (1) provided a good fit to the height-diameter data for each plot.

$$H = 4.5 + p_1(1 - e^{p_2 D})^{p_3} \tag{1}$$

where:
H = total tree height (feet),
D = DBH outside bark (inches),
p_1, p_2, p_3 = parameters.

For species other than white spruce, a single height–diameter relationship was fitted for all plots per species from data obtained at the first measurement, again using Equation (1).

For each measurement, total and merchantable volumes were calculated for each plot using Honer's (1967) volume equations with a 30-cm (1 ft) stump height and a 7.62-cm (3 in.) top diameter inside bark merchantable limit. These calculations used data from DBH tallies and height-diameter relationships by species.

Stand statistics for the spruce component were reconstructed at the time of logging from stump measurement data, diameter tallies of living trees, increment cores, and mortality between the time of logging and establishment.

To reconstruct DBH of the cut trees from stump diameter recorded at study establishment, the new Alberta taper functions (Huang 1994) were used in conjunction with stump height. Tree heights for cut trees were estimated from the appropriate height–diameter relationship (Equation 1) as described above, then volumes of the cut spruce were calculated with Honer's (1967) volume equation.

To estimate the DBHs of residual spruce prior to study establishment, increment core data were used. A plot of past diameters, calculated from the ratios of corresponding radii, suggested the use of a second-degree polynomial regression with no intercept between past DBH and DBH at establishment. With these regressions, using the diameter-class midpoints at establishment as a starting point, past diameters were retrospectively estimated to points of time representing 5-year multiples after logging; to logging; and to 5 and 10 years before logging. These midpoints were then used with diameter frequencies in the corresponding classes at establishment to estimate the volume of the spruce component.

Mortality data between logging and establishment were available for white spruce. To adjust the retrospectively estimated white spruce volume, trees were assumed to die half-way through the elapsed period, so half of the diameter increment for the corresponding diameter class calculated from the increment core data was subtracted from the midpoint of the diameter class of dead trees.

The plot and stand volumes for white spruce at the time of logging were estimated as a sum of: the volume of white spruce trees cut, the retrospectively estimated volume of white spruce component, and the adjusted white spruce mortality volume.

Basal areas and volumes of the spruce component were also estimated for the different points in time specified above, i.e., 5 and 10 years before, and 5, 10, 15, etc. years after logging.

Cut percentage was calculated as a ratio of merchantable spruce volume cut and the merchantable spruce volume estimated at the time of logging. No information was available on the development of other stand components between logging and establishment measurement. This greatly hindered analysis and explanation of growth and mortality processes for this period.

The analyses consisted of producing various graphs of the tree and stand data and estimated statistics to discover trends and relationships. Simple linear and multiple regression techniques were used to develop models to predict future growth and yield for these stands.

RESULTS AND DISCUSSION

Diameter Growth Response to Partial Cutting

To analyze release effect on the diameter increment of residual white spruce, a ratio of average annual diameter increment in the first 5-year period after logging over that of the average of two 5-year periods before logging was calculated for the tagged white spruce trees from increment core data. Based on two increment periods, this average was assumed to provide a reasonable description of tree growth before logging, while the single 5-year increment period after logging should provide an indication of response. A ratio of these two values provides a good measure of response.

Increment core data generally give more stable and consistent diameter increment estimates because the fairly large variation inherent in routine field measurements of diameter is not present. By definition, this analysis included stands logged more than 5 years before study establishment, so they would have increment core data for the first 5-year period after logging.

Assuming that the trees have passed diameter increment culmination (that usually occurs around 40–50 years of age and was indicated by exploratory plottings of increment data), this ratio for the sample trees is likely to be declining, with a value less than one for trees growing in undisturbed stands. Most tagged trees were over 40 years and probably had passed increment culmination, so a ratio over one would indicate release response.

The average increment ratio was 1.98, meaning that in the first 5-year period diameter increment nearly doubled for these trees. Maximum responses were in the 5–20 cm (2–8 in.) diameter range, where the largest ratio values occurred (Fig. 2). In contrast, the largest trees (those above 20 cm [8 in.] that were in the main canopy even before logging) did not benefit as much from release as the smaller trees. Even among the smallest trees, however, there were ratios under one, indicating a lack of response. Possibly, some of these trees were in dense clumps, or under deciduous canopy. It is likely that a good portion of the increment variation and increment response is related to tree status and spatial location of trees, on which no information was collected in this study.

Overall, the greatest number of trees had diameter increment ratios between one and two, meaning a release response of up to 100%. About 20% of the sample trees did not respond to release (Table 3).

No significant trends emerged from relating individual tree diameter increment ratios to tree (diameter and age) and stand (productivity class and moisture regime) characteristics.

To conduct increment analysis on a stand basis, average diameter increment response, calculated as the average increment ratio on a plot, was related to site productivity and other stand characteristics. From these plot averages, three productivity and five moisture regime class averages were calculated (Tables 4 and 5). These averages showed no

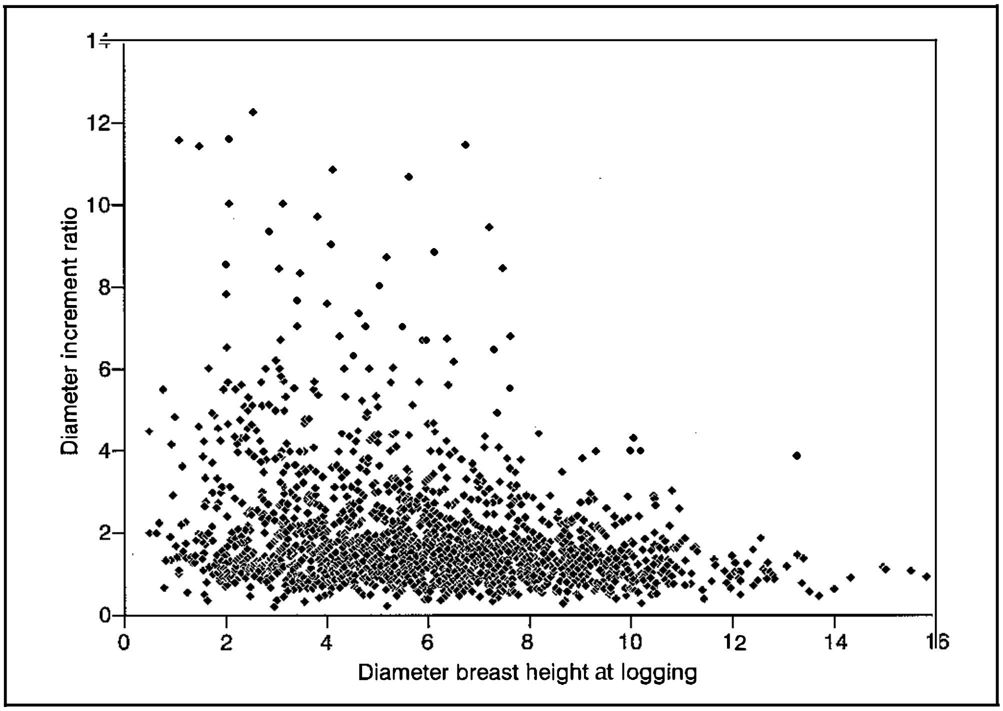

Figure 2. Diameter increment ratios over DBH at logging.

Table 3. **Percentage of tagged white spruce sample trees by diameter increment ratio categories**

Increment ratio	Trees (%)
0–1	20.2
1–2	46.7
2–3	17.2
3–4	6.6
4–5	4.5
≥5	4.8

Table 4. **Average diameter increment ratios in three arbitrary productivity classes (1 = best productivity class and 3 = worst)**

Productivity class	Number of plots	Average increment ratio
1	30	1.97
2	28	1.99
3	1	1.32

Table 5. **Average diameter increment ratios in five moisture regime classes (1 = dryest moisture regime class and 5 = wettest)**

Moisture regime class	Number of plots	Average increment ratio
1	1	1.32
2	9	1.90
3	20	1.53
4	23	2.17
5	5	2.70

discernible relationship between diameter increment response and estimated productivity class. Though these were rather subjective classes based on a quick field assessment by nonexperts in site description, there was an improved response with increased moisture regime (i.e., spruce trees seemed to have grown better as moisture conditions went from dry to fresh to moist within the sample range).

Additional analysis was done to determine if the average diameter increment ratios were related to other stand characteristics such as years since logging, total stand and white spruce merchantable volume at logging, age of the residual spruce, and cut percentage of the white spruce volume in terms of the whole stand. These analyses resulted in significantly increasing trends of diameter increment ratios both with age of residual spruce (Fig. 3) and cut percentage (Fig. 4). This suggests that trees in older stands had a greater response to cutting than those in younger stands. This was a relative DBH response; older and usually larger trees in a well-stocked stand before cutting would have fairly slow growth, so even a modest increase in growth after cutting would appear as substantial in terms of a ratio.

High increment ratios with high cut percentages mean that residual white spruce trees in heavily cut stands had greatly increased growing space, to which they responded with substantial increases in diameter increments. In some instances, a plot's average diameter increment ratio quadrupled after logging, indicating a fourfold increase in increment.

Stand Volume Growth Response

To analyze volume growth response of the spruce component immediately after partial cutting, volume increment ratios were calculated for the first 5-year period after logging. These calculations were determined by dividing volume increment values for that period by the average volume increment for the two 5-year periods prior to logging. To remove the confounding effect of mortality from this analysis, volume at the first remeasurement was estimated as the sum of the spruce volume component and the mortality between establishment and first remeasurement.

This analysis showed that volume increment response increased with cutting intensity, as indicated by the plotting of increment ratios in 3 years-since-logging classes (0–10, 11–20, and 21 and more). This relationship was highly significant for stands in the first two classes (i.e., within 20 years of logging) and nonsignificant for stands logged more than 20 years before establishment (Fig. 5). This could be due to the variation introduced by retrospective estimation of spruce volumes. Using this procedure, variation is likely to increase with elapsed time because of the mortality effect that had to be ignored. Lack of data on companion tree species at the time of logging further increased variation and confounded the estimates.

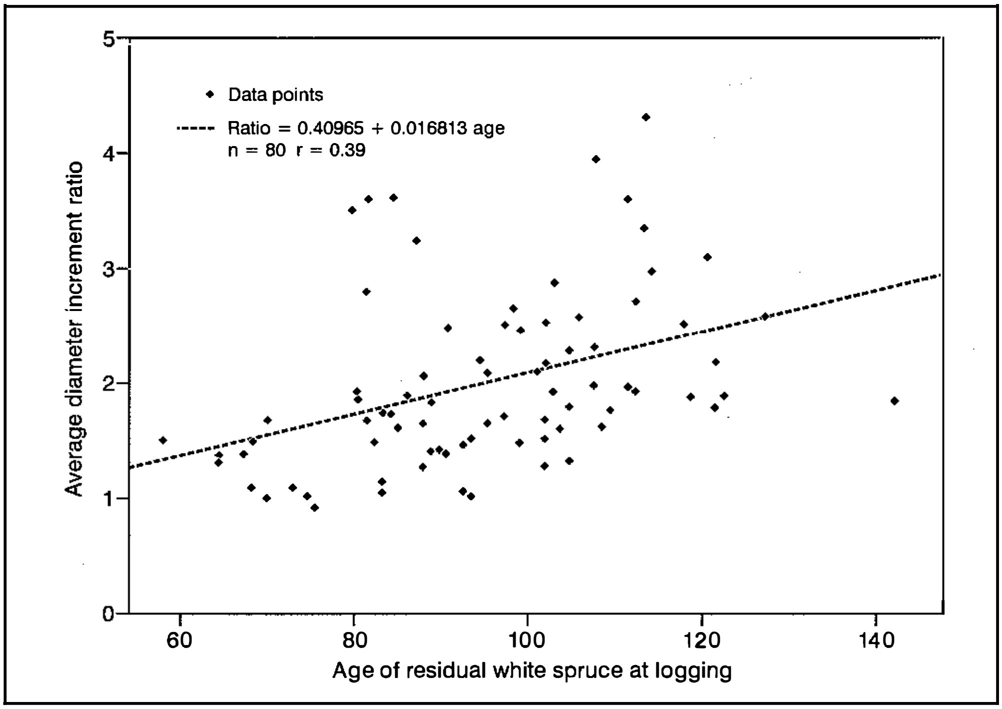

Figure 3. Average diameter increment ratio per plot over age of residual white spruce.

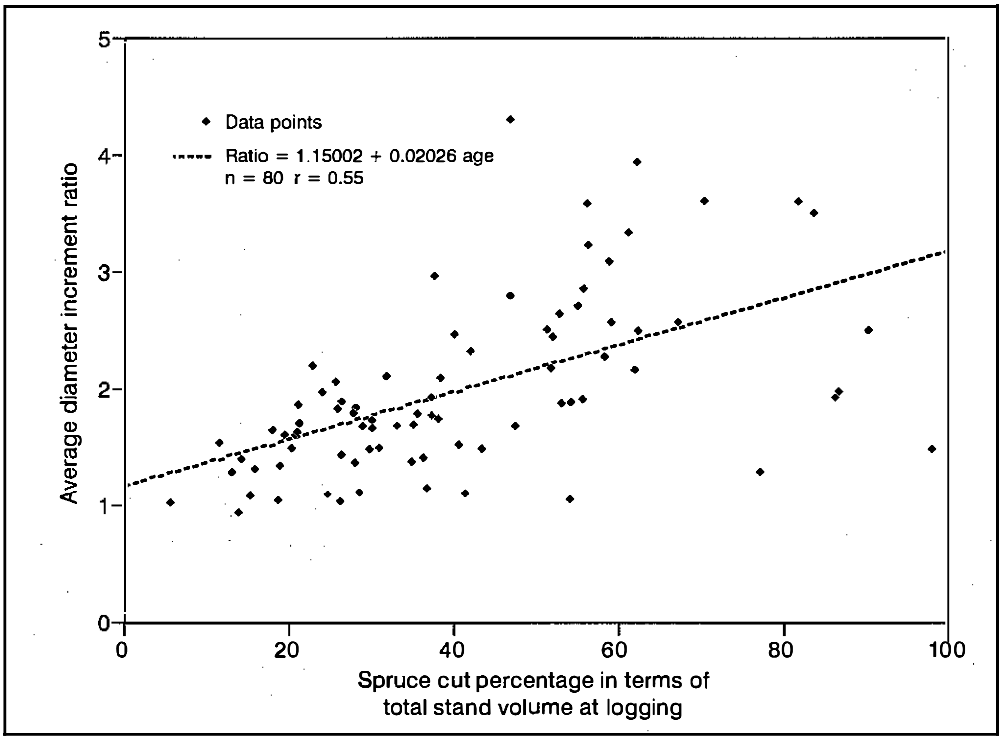

Figure 4. Average diameter increment ratio over cut percentage in terms of total stand volume before logging.

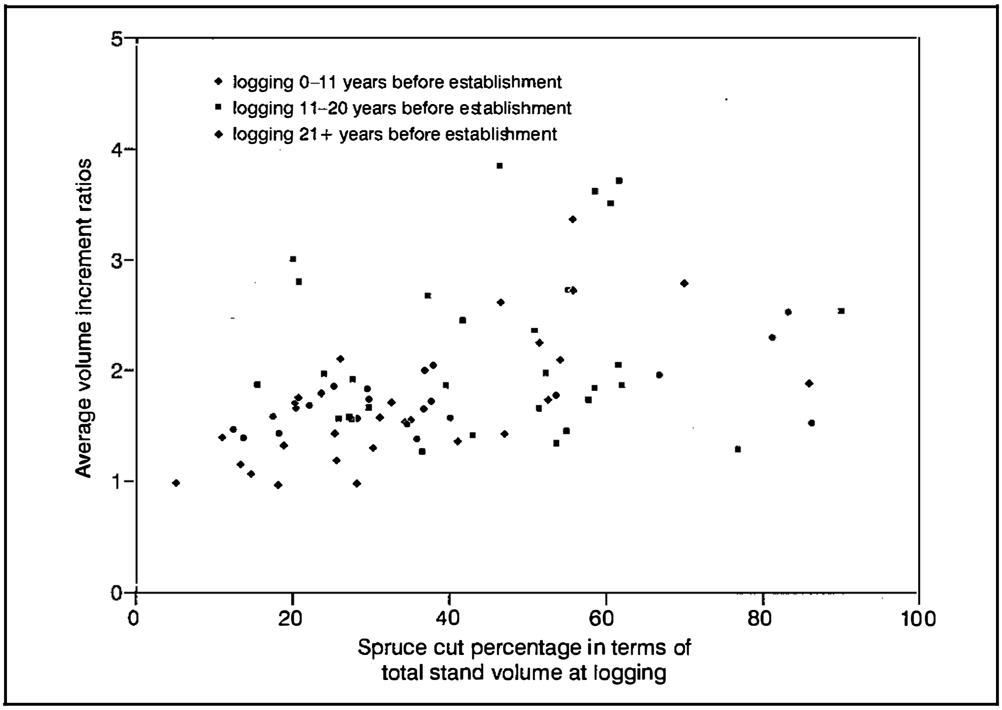

Figure 5. Average volume increment ratio over age in three years-since-logging classes.

To analyze release response dynamics for the entire assessment period covered by this study, volume increment percentages (Equation 2) of the residual spruce were estimated for the periods represented by the increment core data, and for the two periods between plot remeasurements using the formula:

$$VIP = 100 \cdot \frac{\frac{V_{i+1} - V_i}{t_{i+1,i}}}{V_i} \qquad (2)$$

where:

VIP = volume increment percentage,
V_i = volume at time period i,
V_{i+1} = volume at time period i+1,
$t_{i+1,i}$ = time elapsed between periods i and i+1.

To facilitate analysis, these increment percentages were presented in two groups: stands logged 10 or more years before study establishment (Table 6), and; the remaining stands (Table 7). In the first group, longer-term increment dynamics can be observed based on comparably stable increment core data, whereas the other group only showed some very crude trends because of the high variation present in the remeasurement data used.

The majority of the stands (67% of the plots, denoted as category "A" in Table 6 and representing ratio of increment percentages before and after logging greater than 1.5), showed an immediate and substantial response to release within the first 5 years after logging. The release response culminated in the period 5–15 years after logging and diminished afterwards.

For about one-third of the stands (30% of the plots, denoted as category "B" in Table 6, with increment percentage ratios from 1.0 to 1.5), the residual spruce component showed little response to the partial cut. This could be caused by the clumpiness of residual spruce, where only the trees on the edges would benefit from the release, or because the cut removed only a small proportion of the total volume and left an abundance of residual trees.

In a few stands (4% of the plots, denoted as category "C" with increment percentage ratio less than 1.0 in Table 6) increment percentage of the

Table 6. Plot volume increment percentages for residual white spruce by three response categories for different time periods for plots logged 10 or more years before study establishment

		Volume increment percentage by period										
Plot number	Category[a]	–10 to –5[b]	–5 to logging[c]	Logging to 5 yr[d]	5–10 yr after logging	10–15 yr after logging	15–20 yr after logging	20–25 yr after logging	25–30 yr after logging	Estimate[e]	First remeasurement	Second remeasurement
9	A	1.3	1.5	3.1	3.6	3.0	2.5	1.6	2.0	–	–1.4	–[f]
10	A	1.6	2.7	6.8	8.7	7.3	5.7	2.6	–	3.1	–1.4	–
11	A	1.6	1.7	5.4	6.0	4.6	2.4	–	–	2.3	–1.4	–
15	A	2.2	2.0	6.9	7.3	6.0	3.8	–	–	3.4	–0.8	–
16	A	2.3	1.9	6.4	8.1	6.9	4.0	–	–	4.6	0.9	–
18	A	2.6	2.3	4.9	–	–	–	–	–	–	–	–
23	A	2.9	2.0	3.5	5.6	–	–	–	–	–	4.2	3.1
38	A	0.9	1.1	2.5	2.9	2.7	3.0	–	–	2.0	–	–
40	A	5.8	4.3	6.3	10.3	10.5	7.8	5.6	–	4.7	–	–
41	A	3.8	2.8	6.2	8.0	8.0	5.6	4.6	–	3.5	–	–
42	A	3.6	2.8	3.7	4.8	5.7	4.7	4.0	–	3.7	–	–
43	A	3.9	3.2	5.5	8.6	9.4	8.1	5.6	4.8	–	2.2	–
44	A	3.1	2.6	3.9	8.8	9.8	8.4	5.4	4.4	–	2.4	–
45	A	3.7	3.3	3.6	9.5	12.5	11.6	7.4	5.8	–	3.7	–
46	A	2.8	2.3	4.0	8.0	10.4	9.6	6.4	5.3	–	2.3	–
47	A	5.5	3.8	6.4	10.3	10.3	8.3	5.8	4.9	–	–	–
48	A	3.6	2.7	4.7	8.2	8.5	6.7	4.8	4.6	–	3.2	–
49	A	9.6	6.8	6.7	8.8	11.5	9.9	6.7	5.0	–	2.9	–
50	A	3.3	2.7	6.2	12.1	9.9	8.6	7.0	5.3	–	2.6	–
51	A	5.2	3.6	9.0	14.5	11.2	9.2	6.6	5.2	–	–	–
102	A	3.7	2.4	4.1	6.4	–	–	–	–	3.2	–	–
105	A	3.9	3.0	6.3	9.1	–	–	–	–	7.3	3.2	3.2
106	A	2.9	1.9	2.9	4.4	–	–	–	–	–	–	–
108	A	3.8	2.9	3.7	4.9	–	–	–	–	4.6	0.9	2.1
111	A	3.3	2.8	5.6	5.7	–	–	–	–	–	0.9	2.2
112	A	2.8	2.6	4.7	4.3	–	–	–	–	–	–0.2	1.1
113	A	3.0	2.0	3.6	4.9	–	–	–	–	–	4.6	2.3
115	A	4.7	3.4	8.0	8.5	–	–	–	–	–	4.5	–
116	A	5.0	3.4	10.7	8.1	–	–	–	–	–	6.0	–
117	A	2.5	2.1	5.4	6.5	–	–	–	–	–	6.6	–
118	A	4.7	2.9	8.0	7.7	–	–	–	–	–	–	–
133	A	5.2	4.2	8.7	10.3	–	–	–	–	7.0	4.3	4.6
134	A	2.4	2.4	4.0	6.0	–	–	–	–	4.6	3.8	2.3
135	A	4.7	3.9	5.0	8.4	–	–	–	–	8.4	5.0	2.6
136	A	3.5	2.9	4.5	4.4	–	–	–	–	–	–	–
137	A	3.8	3.8	5.2	4.7	–	–	–	–	–	–	–
39	B	1.6	2.2	2.6	2.4	2.8	3.1	–	–	3.4	–	–
82	B	2.8	3.2	3.9	4.6	4.6	–	–	–	3.6	0.8	–
83	B	4.0	4.2	4.9	4.7	4.8	–	–	–	3.9	2.3	–
84	B	5.1	6.2	8.0	6.9	5.4	–	–	–	4.5	1.8	–
86	B	5.0	9.0	12.6	10.6	8.3	6.8	5.0	–	4.6	1.7	–
89	B	7.6	5.4	7.1	6.6	5.3	3.7	2.9	–	2.3	2.3	–
90	B	4.9	4.4	4.3	5.7	6.0	5.3	4.3	–	3.4	–1.2	–
91	B	3.9	4.5	5.0	4.6	4.9	3.9	–	–	2.8	0.9	–
92	B	2.8	3.0	3.8	3.7	3.2	2.7	–	–	2.4	0.8	–
93	B	3.7	4.0	6.1	7.2	7.1	5.9	–	–	4.6	2.2	–
96	B	2.6	2.6	3.1	4.9	4.9	4.5	3.5	–	2.8	2.3	–

Table 6. concluded

		Volume increment percentage by period										
Plot number	Category[a]	−10 to −5[b]	−5 to logging[c]	Logging to 5 yr[d]	5–10 yr after logging	10–15 yr after logging	15–20 yr after logging	20–25 yr after logging	25–30 yr after logging	Estimate[e]	First remeasurement	Second remeasurement
125	B	2.3	2.8	3.9	4.4	3.7	–[f]	–	–	3.7	3.6	–
126	B	3.8	4.4	4.6	4.1	3.4	–	–	–	4.7	0.1	0
127	B	2.0	2.0	2.6	3.3	–	–	–	–	3.9	–	–
129	B	3.8	3.4	3.9	4.1	–	–	–	–	3.3	2.6	−0.4
130	B	3.1	2.8	2.5	2.5	–	–	–	–	4.0	1.8	0.7
131	B	2.3	2.1	2.7	1.9	1.4	–	–	–	1.5	0.6	2.3
81	C	49.0	24.2	17.1	12.1	8.6	6.5	4.8	–	3.9	2.6	–
85	C	31.8	22.0	24.6	19.1	11.3	8.3	5.5	–	4.5	2.4	–
87	C	21.5	15.4	14.0	10.7	7.2	5.4	–	–	4.5	3.0	–
88	C	10.2	10.6	10.7	8.9	8.8	7.1	–	–	4.6	5.6	–

[a] A = ratio of increment percentages before and after logging of greater than 1.5; B = ratio of increment percentages before and after logging of 1.0–1.5; C = ratio of increment percentages before and after logging of less than 1.0.

[b] Values in this column are for the period between 10 and 5 years before logging.

[c] Values in this column are for the period between 5 years before logging and logging.

[d] Values in this column are for the period beween logging and 5 years after harvest.

[e] Values in the estimate column represent the increments between the end of the period of the last column with a real value and the establishment measurement for a plot. No value in the establishment column means the establishment coincided with 5, 10, and 15 years after logging time sequence.

[f] Dashes in the columns denote lack of data.

spruce actually declined after logging. This decline occurred among the youngest stands, where the spruce was 54–61 years old at study establishment and 32–36 years old when logged. Such decline was the result of high increment percentages just before logging that arise from low volumes and rapid growth among younger trees. This declining trend was typical for stands in this age group. An exception was plot 85, where the volume increment percentage increased from 22% before logging to 24.6% in the first 5 years after logging, and then declined. This temporary increase was likely due to release effect.

Virtually the only statement that can be made about volume increment percentages for the period between establishment and first remeasurement is that they show a high variation, to the extent that even some negative increment percentages are present. Some of this variation is no doubt due to high mortality in this period.

Volume increments estimated from increment cores always include a positive bias because this method allows no consideration for mortality. A similar problem can arise in the analysis using plot remeasurement data if dead trees were not recorded. Increment was calculated simply as a difference between present and past volume (Table 7). In such a situation, heavy mortality would result in serious underestimation of increment response. For example, heavy mortality from random factors such as windbreaks or insects and diseases could give rise to negative increment, rendering this analysis unsuitable for detecting release response.

Mortality

Mortality was analysed for two periods: between logging and plot establishment, and; between plot establishment and first remeasurement. As the length of the period for which mortality was estimated varied considerably among plots, average annual statistics were calculated and used in this analysis. No mortality information was available for the period between the first and second remeasurements.

For the period between logging and study establishment, the average annual mortality percentage for spruce (relative to residual spruce total volume after logging) was 1.8%, and ranged between 0 and 11.9%. These statistics were very similar when expressed in terms of merchantable

Table 7. Plot volume increment percentages for residual white spruce for different time periods for plots logged less than 10 years before study establishment

Plot numbers	Volume increment percentage by period					
	–10 to –5[a]	–5 to logging[b]	Logging to 5[c]	Estimate[d]	First remeasurement	Second remeasurement
1	3.3	2.9	4.3	–[e]	3.6	–
2	1.4	1.6	–	2.5	1.1	3.0
3	3.9	4.6	–		4.6	3.1
4	4.5	4.9	–	4.5	5.7	3.1
5	1.5	1.3	–	3.2	1.9	–
6	2.5	2.4		2.1	1.9	2.8
7	3.8	2.3	2.9	2.4	1.2	2.6
8	7.7	5.4	5.0	5.3	4.9	3.9
12	8.0	5.6	–	–	4.8	–
13	1.9	2.0	–	–	–0.2	–
14	6.1	6.3	–	–	9.8	–
17	1.7	2.0	–	–	–2.0	–
19	2.5	1.9	1.8	2.4	–	–
20	3.1	3.0	4.3	7.5	5.3	–
21	4.2	3.0	3.7	5.0	3.4	2.5
22	4.5	3.4	4.7	6.5	–	–
24	1.7	1.6	–	1.2	0.4	1.6
25	2.1	1.9	–	1.2	–4.8	2.4
26	3.6	3.4	–	3.1	3.1	0.7
27	1.3	1.7	–	2.0	1.1	0.5
28	2.8	2.9	–	2.8	–	–
29	1.4	1.8	–	1.4	–	–
30	2.2	2.0	–	1.2	–	–
31	1.7	1.9	–	1.3	–	–
32	1.4	1.2	1.6	1.7	1.9	0.3
33	1.7	1.7	2.5	2.6	0.1	2.0
34	2.9	3.0	4.2	–	6.6	–
35	2.4	2.1	3.1	2.3	3.5	2.5
36	1.2	1.0	1.6	2.0	1.5	–
37	1.9	1.3	2.6	2.3	–	–
52	3.3	2.5	3.4	–	–	–
53	2.6	1.9	2.6	–	–	–
54	7.0	6.4	6.8	5.9	3.8	–
55	1.4	1.6	–	2.2	–	–
56	1.2	1.6	–	2.3	–	–
57	1.6	1.7	–	1.4	–	–
58	1.6	1.4	–	2.6	–0.5	4.4
59	1.5	1.2	–	2.6	–2.2	3.3
60	2.5	2.6	–	2.2	1.2	3.6
61	2.6	2.4	–	2.9	–	3.8
62	1.6	1.5	–	1.7	1.3	5.0
63	1.6	1.4	–	1.9	2.1	3.8
64	1.4	1.4	–	1.4	–1.1	3.1
94	3.7	3.1	–	2.5	1.3	–
95	4.2	3.1	–	3.0	1.5	–
97	3.2	3.1	–	3.1	9.3	–
98	2.7	2.8	–	2.8	4.3	–
99	2.2	2.5	–	2.7	–	–

Table 7. concluded

Plot numbers	Volume increment percentage by period					
	–10 to–5[a]	–5 to logging[b]	Logging to 5[c]	Estimate[d]	First remeasurement	Second remeasurement
100	4.3	3.9	–[e]	4.1	5.3	–
101	6.2	5.7	–	5.6	–	–
103	1.5	1.6	2.9	3.9	–	–
104	4.3	4.3	6.1	7.2	–	–
107	2.2	2.0	3.6	5.0	2.7	2.9
109	2.0	2.0	3.2	3.6	–0.4	1.5
110	2.0	1.7	2.3	2.6	–0.8	–0.1
114	3.8	3.3	–	3.3	2.7	–
119	3.5	2.8	2.5	2.7	–0.4	–
120	2.3	1.9	1.8	–	1.2	0.3
121	2.9	3.1	–	3.8	–	–
122	2.1	1.7	–	2.6	1.5	–
123	1.9	1.3	–	3.6	2.5	3.3
124	2.0	1.9	–	2.6	–	–
128	1.6	1.6	–	1.9	0.8	–

[a] Values in this column are for the period between 10 and 5 years before logging.

[b] Values in this column are for the period between 5 years before logging and logging.

[c] Values in this column are for the period between logging and 5 years after harvest.

[d] Values in the estimate column represent the increments between the end of the period of the last column with a real value and the etablishment measurement for a plot. No value in the establishment column means the establishment coincided with 5, 10, and 15 years after logging time sequence.

[e] Dashes in the columns denote lack of data.

volume. Additional analysis showed that neither absolute mortality nor mortality percentage had a significant relationship to stand characteristics such as: age of the residual white spruce, years since logging, percentage of cut in terms of white spruce before logging, and total white spruce volume before cutting. This suggests that mortality in this period was determined largely by random factors.

Annual volume mortality percentage for spruce for the period between study establishment and first remeasurement (relative to the white spruce volume at study establishment) averaged 0.94% and ranged between 0 and 5.5%. This was a lower mortality than the rate between logging and study establishment. These statistics were very similar for merchantable volume.

Most importantly, the results showed that wind damage was the main cause of mortality for white spruce, and suppression for young trembling aspen (Table 8). Wind-related mortality might have been in part the result of decay weakening the stem. This would have made the stem less-able to withstand wind forces, as suggested by the analysis of mortality frequencies by diameter classes for both white spruce and deciduous trees. These frequencies showed that wind-related mortality occurred mainly among large trees, while suppression mortality occurred among smaller trees (under 8 cm [3.25 in.]). This trend was particularly strong for deciduous trees. These results also indicated that the deciduous component, particularly trembling aspen in older stands, would likely sucker even before, but particularly after, partial cutting; however, many of the suckers generally succumb unless released and light conditions become adequate for their survival.

Although these results indicated that the main cause of mortality for large spruce and deciduous trees was wind facilitated by decay, several other factors might have had some influence, such as topography, the surrounding stands, and spatial distribution of the residual trees. No information on these factors was collected for this study, therefore no quantitative evaluation was possible.

The stand characteristics analyzed for the period between logging and study establishment were reanalyzed to determine any relationship to annual white spruce volume mortality for the period between study establishment and the first

Table 8. Summary of dead trees by species and cause of death between establishment and first remeasurement

	Species					
Cause of mortality	White spruce	Jack pine	Balsam fir	Trembling aspen	Balsam poplar	White birch
Windfall and windbreak	371	0	11	224	65	34
Rot and decay	21	0	0	37	3	23
Suppression	284	1	21	640	145	63
Overmature	1	2	0	61	9	5
Other	51	0	0	5	1	5
Not recorded	255	1	9	360	76	150
Total	983	4	41	1327	299	276

remeasurement. None of these analyses showed a significant relationship to mortality.

The long time period (31 years) that elapsed between the first and second remeasurements made a reliable assessment of individual tree mortality impossible. There was therefore no attempt to collect any explicit mortality information for this period. Changes in basal area and volumes, however, do provide some indirect information on mortality.

Stand Volume Growth and Yield

The forest manager's prime interest is the volume yield that can be expected following partial cutting in these mixed spruce–aspen stands. Of particular interest is the amount of spruce that will be available at the next logging entry.

To provide some answers, merchantable spruce volume over elapsed time since logging was plotted, starting with residual volume and then continuing with volume estimates that came either from estimates obtained by retrospective analyses of increment cores taken from spruce sample trees or from actual field measurements.

To determine whether merchantable spruce volume before logging had an influence, the data were subdivided into two spruce volume categories: high (over 200 m^3/ha) and low (200 m^3/ha and less). Two other categories were imposed on the data to determine how the proportion of spruce removed in these two categories would influence subsequent growth. These two additional categories were based on the proportion of spruce removed: heavy cut (over 60% removed) and light cut (60% or less removed) (Fig. 6).

Trends of merchantable volume yield showed consistently increasing and nearly parallel trajectories over elapsed time since logging, some variation between trends notwithstanding. The volume of residual spruce after logging largely determined the expected growth and the amount of future yield of a stand. No dramatic differences appeared among the above four categories, although the least response in spruce volume growth seemed to have occurred after light cutting where the initial spruce stocking was low. This seems reasonable both from the release viewpoint and from that of spruce initial density.

The consistently increasing trends of spruce volume growth notwithstanding, the data showed considerable variation. Examples of this variation can be seen in the trends for plots 10, 11, 15, 17, and 59 in Figure 6a, plots 47 and 90 in Figure 6b, plots 9 and 33 in Figure 6c, and plots 25, 58, 110, and 119 in Figure 6d. Examination of the plot records revealed these inconsistent plot trajectories mainly arose from excessive mortality, primarily due to wind damage (windbreak or windthrow) within the first 10-year period after logging. On some of the plots (e.g., plots 9, 10, 11, 15,33, 47, and 90), such damage might have occurred in a later period. The other important causal agent in this regard was butt rot near the stump, which weakened the stem and made it particularly vulnerable to windbreak. Overall, 10–15% of the plots had suffered from wind damage.

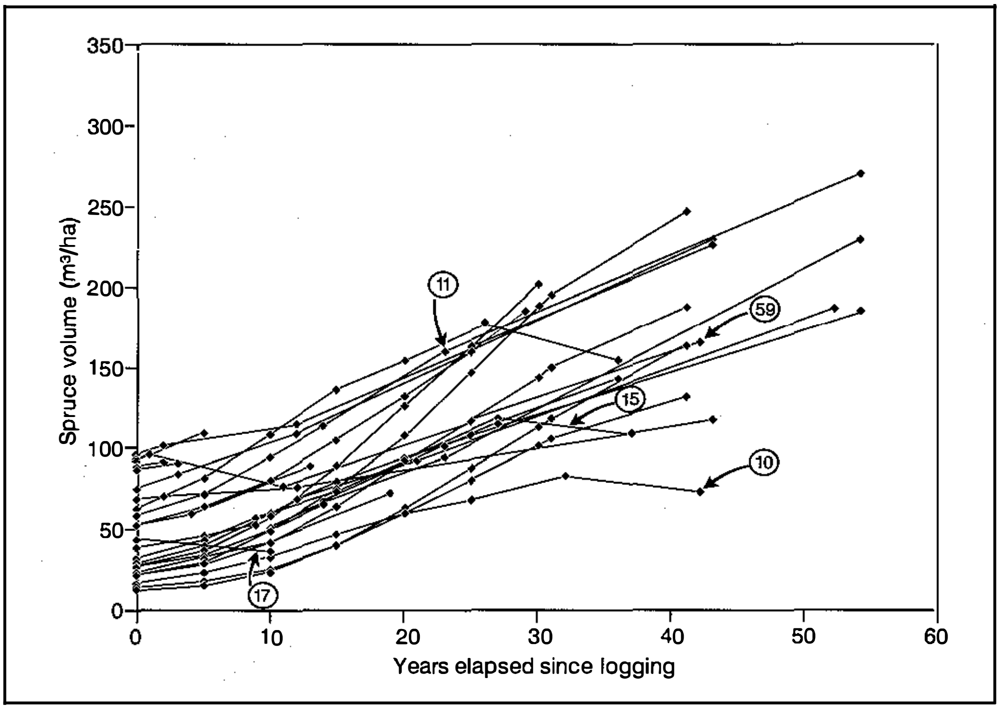

Figure 6a. Spruce volume over years elapsed since logging; cut percentage in terms of total volume >60%, volume of spruce before logging >200 m³/ha.

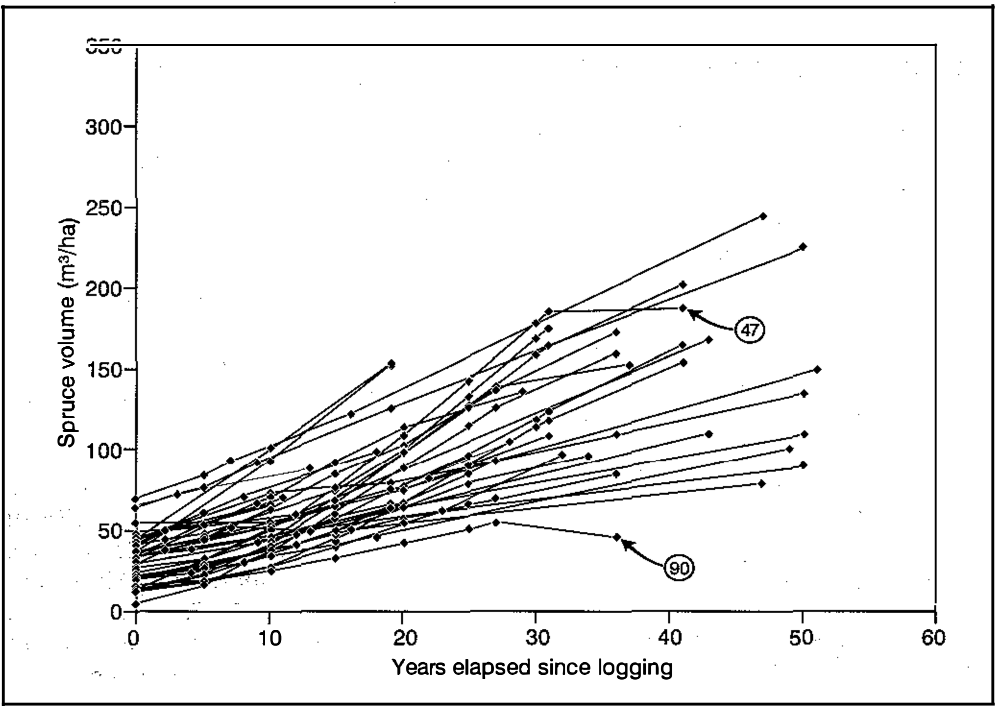

Figure 6b. Spruce volume over years elapsed since logging; cut percentage in terms of total volume >60%, volume of spruce before logging ≤200 m³/ha.

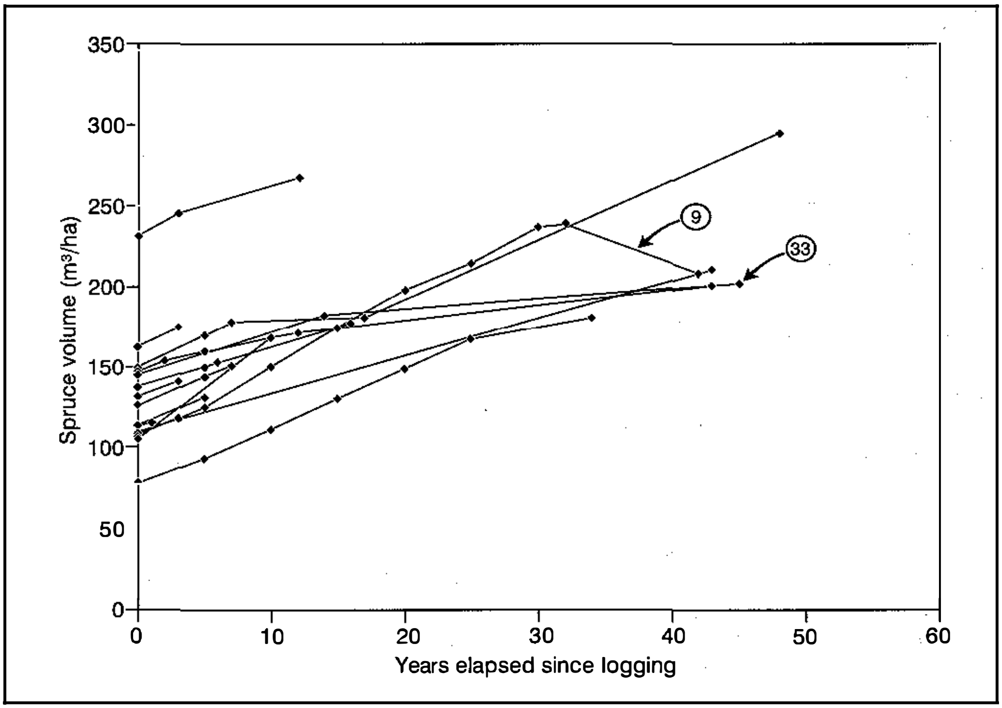

Figure 6c. Spruce volume over years elapsed since logging; cut percentage in terms of total volume ≤60%, volume of spruce before logging >200 m³/ha.

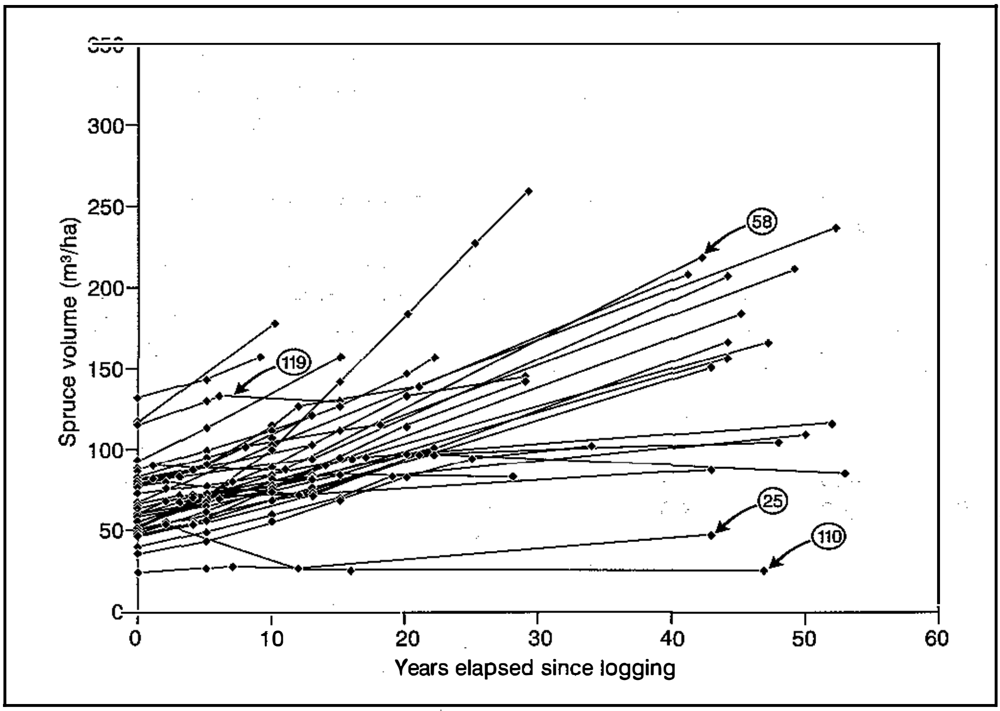

Figure 6d. Spruce volume over years elapsed since logging; cut percentage in terms of total volume ≤60%, volume of spruce before logging <200 m³/ha.

Simple linear multiple-regression procedures were used to develop a rough general model to predict expected future merchantable spruce volume yield in these stands. (Although some nonlinear models provided a reasonable fit, the use of such complex models seemed unjustified, given the high variation and the general nature of the data.) The independent variables in these analyses included: residual spruce volume at logging, number of years elapsed since logging, spruce volume relative to complete stand volume at logging, spruce volume just before logging, percentage of spruce cut in relation to spruce volume before logging, percentage of spruce removed in relation to total volume, and age of the residual spruce component at the time of observation.

Residual spruce volume at logging and years elapsed since logging were the two most-important variables, and explained a highly significant 74.1% of the variation in postlogging merchantable spruce volume yield. Including the percentage of spruce removed in relation to spruce volume before logging as a variable increased the explained variation to 75.9%. Including age of the residual spruce component at the time of observation further increased this value to 77.2%. As expected, this variable had a negative effect, indicating slower growth for older trees and faster growth for younger trees (Tables 9 and 10).

These results show the overriding importance of residual spruce volume and elapsed time since logging on future expected volume yield. A simple interpretation of this model is that at a given level of residual spruce volume (within the data range), the annual increase in spruce volume was equal to the years-since-logging coefficient, i.e., 2.6229. A rough yet useful prediction of merchantable volume yield following a partial cut can be estimated with the following formula:

$$VY = 5.1793 + 0.9359RESVwS + 2.6229YSL \tag{3}$$

where :

VY = volume yield per ha of the residual white spruce,

$RESVwS$ = volume of residual white spruce per ha just after logging,

YSL = years since logging.

Using this relationship, an illustration of growth trajectories is presented for a hypothetical stand with 54 m^3/ha of residual spruce volume after logging, which is roughly the mean of the present sample data (Fig. 7). Trajectories are also presented for stands at the low and high ends of the sample range of residual volumes: 5 m^3/ha and 130 m^3/ha, respectively.

The development of the deciduous component is also of interest in this analysis, especially in light of the upswing in aspen utilization during the last 10 years, which has led to nearly 80% commitment of the available deciduous annual allowable cut in Alberta. Aside from this, examining the development of the deciduous component could help to understand its influence on spruce development.

Table 9. Summaries of independent variable values, by two observation categories, used in the multiple regression analyses

	Observation category					
	Retrospective estimation (n = 324)			Actual measurements (n = 244)		
Variable[a]	Mean	Minimum	Maximum	Mean	Minimum	Maximum
VwS	71.2	4.7	234.5	113.8	23.4	292.4
AGE	82.7	27.0	207.0	100.5	54.0	210.0
PwSVCOTV	40.3	3.4	91.0	35.5	3.4	91.0
PwSVCOTwS	65.8	8.3	94.5	60.6	8.3	94.5
PwSVOTV	59.4	15.8	100.0	56.5	15.8	100.0
RESVwS	45.2	4.7	230.2	57.6	4.7	230.2
TVwSBL	173.5	26.7	350.3	172.0	26.7	350.3
YSL	8.3	0.0	30.0	21.7	1.0	60.0

[a] VwS = spruce volume after logging; AGE = age of spruce at logging; PwSVCOTV = percentage of spruce removed relative to complete stand volume before logging; PwSVCOTwS = percentage of spruce removed relative to spruce volume before logging; PwSVOTV = residual spruce volume at logging; RESVwS = spruce volume relative to complete stand volume at logging; TVwSBL = spruce volume just before logging; YSL = years since logging.

Table 10. Stepwise regression statistics (four models) for estimating white spruce yield in partially cut mixed-wood stands (number of observations n = 568)

	Model							
	1		2		3		4	
Variable[a]	Parameter estimate	SEE[b]	Parameter estimate	SEE	Parameter estimate	SEE	Parameter estimate	SEE
INTERCEPT	57.657	2.5821	5.1793	2.4149	–12.054	3.5265	5.0952	4.5944
YSL	2.2584	0.1307	2.6229	0.08319	2.5965	0.080404	2.9442	0.09980
RESVwS	–[c]	–	0.93588	0.031851	0.90170	0.031189	0.98240	0.03360
PwSVOTV	–	–	–	–	0.33216	0.051003	0.46444	0.054967
AGE	–	–	–	–	–	–	–0.37438	0.066616
Model								
R^2	0.3454		0.7411		0.7592		0.7720	
F ratio	298.67		808.54		592.67		476.51	

[a] YSL = years elapsed since logging; RESVwS = residual spruce volume after logging; PwSVOTV = spruce volume percentage relative to complete stand volume before logging; AGE = age of residual spruce.

[b] SEE = standard error of estimate.

[c] Dashes in columns denote no parameter was estimated.

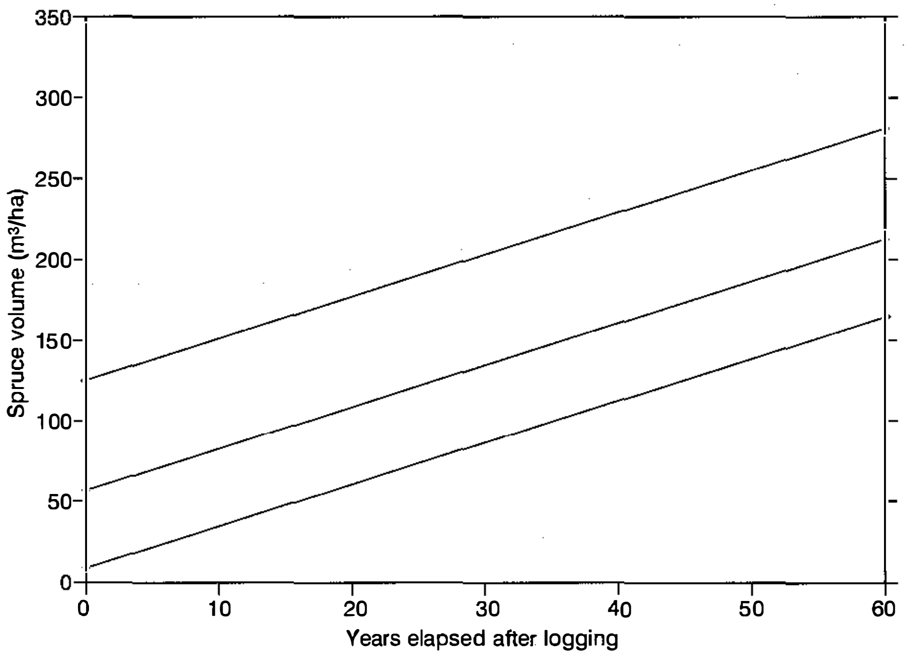

Figure 7. Projected spruce volumes using the yield equation [Equation 3] for residual white spruce with three different initial volumes (5, 54, and 130 m^3).

Plots of deciduous stand volumes over elapsed time after logging showed high variation and generally fairly level trajectories. Stands with high initial deciduous volume were more likely to suffer dramatic mortality, and thus would show a declining trend in volume yield. Such dramatic mortality often occurred in the period shortly after logging, although in some stands heavy mortality could have continued over a prolonged period. In contrast, the best growth and an increasing trajectory of deciduous volume yield was found in stands with low initial deciduous volume that was mainly from smaller-sized trees, and particularly in stands that had good stocking of trees from sapling size to 20–25 cm (8–10 in.) DBH. Such stands are at an early stage of development characterized by vigorous growth.

To develop a model to predict deciduous volume yield following partial cutting, multiple regression techniques, similar to those described above for spruce, were used, along with essentially the same independent variables.

Spruce volume relative to complete stand volume at logging and spruce volume just before logging were the important variables, and accounted for 68% of the variation in deciduous volume yield (Table 11). As noted above, elapsed time after logging had no significant influence on deciduous volume yield.

A simple model that used only spruce volume relative to stand volume at logging as an independent variable provided as good a predictor as one is likely to construct for the deciduous component for the conditions sampled in this study. This variable, however, is likely to lose accuracy as the elapsed time since logging increases. As no growth or mortality information was available for the deciduous component, the volumes for this component were assumed to be the same as estimated at establishment. This might be a bold assumption, but it is supported to some extent by the apparent stability of deciduous volume in these older stands, where increment and mortality are more or less in balance, as shown by plots not presented here.

SUMMARY AND CONCLUSIONS

Partial cutting that removed the large spruce from mixed-wood stands generally improved diameter and volume growth of the residual spruce. The magnitude of release depended on the volume of spruce removed and the age and size of the residual trees. Most of the residual spruce trees had a dramatic increment response within the first 5 years of release; during this time, their diameter increment might have doubled compared to that before logging. The best response occurred among young, pole-, and medium-sized trees. The release response, however, was highly variable. Even some

Table 11. Stepwise regression statistics (two models) for estimating deciduous volume yield in partially cut mixed-wood stands (number of observations n = 568)

	Model			
	1		2	
Variable[a]	Parameter estimate	Standard error of estimate	Parameter estimate	Standard error of estimate
INTERCEPT	320.93	8.8439	309.10	8.2277
PwSVOTV	−3.0874	0.15308	−4.3048	0.2186
TVwSBL	–[b]	–	0.4761	0.06580
Model				
R^2	0.6165		0.6825	
F ratio	406.77		270.81	

[a] PwSVOTV = spruce volume percentage relative to complete stand volume before logging; TVwSBL = spruce volume just before logging.

[b] Dashes in columns denote no parameter was estimated.

small trees did not respond, possibly due to their inferior crown position. Overall, about 20–30% of the spruce sample trees did not respond to release.

Generally, residual spruce trees grew better as soil moisture regime increased from dry to moist. Even old stands with large trees showed good relative response. Trees in such stands would normally have rather slow growth, so even a modest absolute growth increase after logging might be substantial as a relative growth increase. The best improvement in diameter growth occurred after a heavy cut, which results in a substantial increase in growing space.

Volume increment response analysis confirmed the results of diameter increment analysis; namely, increased response occurs with increased cutting intensity. Volume increment response was immediate and substantial within the first 5 years after logging, culminating between 5 and 15 years, and might show some increment decline in subsequent years.

Substantial mortality can occur in the spruce component after partial cutting. In the years following logging, average annual mortality percentage based on total volume for the spruce component averaged just under 2%, and later this dropped below 1%. The heaviest mortality occurred within the first 5–10 years after logging. Wind was the main causal factor, particularly among the larger trees. Stem decay and root rot that weakens the tree are also important contributing factors. Suppression was the main cause of death among young aspen, unless sufficient growing space became available from the cut. Other factors, such as topography, surrounding stand structure, and spatial distribution of trees, might be important, but this study did not evaluate these potential factors.

Notwithstanding the considerable mortality that followed cutting, trends of merchantable volume yield showed consistently increasing trajectories over time since logging. Residual spruce volume after logging largely determined the expected growth and the amount of future yield of a stand. A simple regression model (Equation 3) explained nearly three-quarters (74.1%) of the variation in postlogging merchantable spruce volume yield. As usual, the model should be used only within the range of the original data.

The development of the deciduous component was much more variable in these partially cut stands, and yield prediction was consequently much less reliable. Stands with high initial deciduous volume are more likely to suffer dramatic mortality, and were thus more likely to show a declining trend in volume yield. The best deciduous growth and yield occurred in stands with low initial deciduous volume made up of small-size trees. The percentage of spruce volume of the total volume after logging is a fairly good predictor of future deciduous yield.

In summary, these partially cut mixed-wood stands that were logged up to the 1950s by removing the largest spruce (to a certain diameter limit) using chainsaws, horses, and small tractors, will yield another softwood harvest, the size of which will depend on residual spruce stocking. Logging equipment, techniques, and systems have changed dramatically since the 1950s, however, so the results and information presented here are at best only an indication of what could be expected after present-day partial cutting with current equipment and techniques. The difficulties experienced in establishing spruce after clear-cuts are forcing the forest industry to re-examine current practices and to adopt new, innovative techniques such as spruce understory protection in harvesting these mixed stands (Brace and Bella 1988; Navratil et al. 1994) in order to ensure a future supply of softwoods.

The purpose of this analysis was to learn about the development of these spruce–aspen stands where a logging entry removed the largest spruce. The amount and the minimum size of trees removed were determined by market forces and utilization practices at the time, without much consideration to the future crop. Basically, the operation was simply high-grading, and not an improvement or stand renewal cut, and as such would be unacceptable today. This report is intended neither as a critique of such cutting practices, nor as a discussion paper to present suitable alternative harvesting systems.

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